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BSI Standards Publication

Tutorial and application guide for high-voltage fuses

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National foreword

This Published Document is the UK implementation of IEC/TR 62655:2013.

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Tutorial and application guide for high-voltage fuses

Guide explicatif et d'application pour les fusibles à haute tension

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CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

TUTORIAL AND APPLICATION GUIDE FOR HIGH-VOLTAGE FUSES

FOREWORD

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IEC 62655, which is a technical report, has been prepared by subcommittee 32A: High-Voltage Fuses, of IEC technical committee 32: Fuses

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
32A/296/DTR	32A/301/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

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The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

INTRODUCTION

0.1 Aims and objectives of this technical report

a) To help prospective users and protection engineers understand the basics of high-voltage (>1 000 V a.c.) fuse technology and applications involving high-voltage (HV) fuses;

b) to illustrate the particular and unique advantages of fuse protection for most service applications;

c) to minimise possible misapplications of fuses which could lead to problems in the field;

d) to list and describe the many types of fuse in use today, and the international standards that apply to them, including fuse types not specifically included in IEC or other recognized standards.

This technical report gathers information previously published in IEC and other publications, as well as new material. Duplicate information presently in these publications is therefore likely to be eliminated during their future revision.

0.2 How to use this technical report

0.2.1 General

If read from start to finish, this technical report will provide an in-depth study of HV fuses and their applications. It is essentially a tutorial covering all common (and some not so common) types of fuses and most fuse applications. However, it is assumed that few users will read the technical report in this way, but rather read the appropriate sections covering fuses and applications for which they require information. Based on this assumption, there is therefore some inevitable duplication of information. To assist the user in making best use of the document, a description of the content and relevance of each clause follows.

0.2.2 Fuse tutorial

After clauses on scope, references and definitions, Clause 4 contains primarily "tutorial" style information. The clause starts with a simple introduction to fuses, first with an explanation of how fuses work followed by information on basic fuse classifications and common fuse terms. Subclause 4.1.4 continues with lists of advantages gained by using fuses and then 4.1.6 provides a listing of basic fuse types for which application information will be given later. An in-depth look at the most common types of fuses is given in 4.2, current-limiting fuses and 4.3 expulsion fuses. The high level of detail given in 4.2 and 4.3, including information describing construction, operation, classification and published ratings and characteristics, may be necessary in order to understand the application information that follows in Clause 5. For completeness, 4.4 gives an overview of less common types of fuse (or fuse related) devices that may require additional testing to that covered in existing standards, and for which no further application information is provided. Subclause 4.5 covers fuse mountings.

0.2.3 Application information

Application information appears in Clause 5 and Annex A, and is split into four sections.

a) Subclause 5.1: this covers information common to nearly all applications.

b) Subclause 5.2: this contains information on specific applications.

c) Subclause 5.3: this covers installation, operation, maintenance, and replacement of fuses.

d) Annex A: this reproduces the current-limiting fuse temperature de-rating information previously published in IEC 60282-1:2009.

If a knowledgeable user requires application information on a specific subject in 5.2 (e.g. motor circuit fuses), it is possible that only the relevant subclause needs to be read – however in most cases additional information from 5.1 will be required for satisfactory fuse selection. It should be emphasized that the information contained in this report is intended to supplement information supplied by the manufacturer of a fuse and not replace it. If there is any doubt or conflict of information, the fuse manufacturer should be consulted.

TUTORIAL AND APPLICATION GUIDE FOR HIGH-VOLTAGE FUSES

1 Scope

This technical report provides information for understanding the construction, operation and application of high-voltage fuses in general. Current-limiting, expulsion, electronic, and other, non-current-limiting, fuses rated above 1 kV a.c. are all covered, as are North American, European and other application practices. As a technical report, this document contains no requirement and is informative only.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60038, *IEC standard voltages*

IEC 60071-1, *Insulation co-ordination – Part 1: Definitions, principles and rules*

IEC 60076-1, *Power transformers – Part 1: General*

IEC 60076-7, *Power transformers – Part 7: Loading guide for oil-immersed power transformers*

IEC 60076-12, *Power transformers – Part 12: Loading guide for dry-type power transformers*

IEC 60282-1:2009, *High-voltage fuses – Part 1: Current-limiting fuses*

IEC 60282-2:2008, *High-voltage fuses – Part 2: Expulsion fuses*

IEC 60549, *High-voltage fuses for the external protection of shunt power capacitors*

IEC 60644, *Specification for high-voltage fuse-links for motor circuit applications*

IEC/TR 60890:1987, *A method of temperature-rise assessment by extrapolation for partially type-tested assemblies (PTTA) of low-voltage switchgear and controlgear*

IEC 60909-0, *Short-circuit currents in three-phase a.c. systems – Part 0: Calculation of currents*

IEC 62271-100:2012, *High-voltage switchgear and controlgear – Part 100: Alternating current circuit-breakers*

IEC 62271-102, *High-voltage switchgear and controlgear – Part 102: Alternating current disconnectors and earthing switches*

IEC 62271-103, *High-voltage switchgear and controlgear – Part 103: Switches for rated voltages above 1 kV up to and including 52 kV*

IEC 62271-105:2012, *High-voltage switchgear and controlgear – Part 105: Alternating current switch-fuse combinations for rated voltages above 1 kV up to and including 52 kV*

IEC 62271-106, *High-voltage switchgear and controlgear – Part 106: Alternating current contactors, contactor-based controllers and motor-starters*

IEC 62271-107, *High-voltage switchgear and controlgear – Part 107: Alternating current fused circuit-switchers for rated voltages above 1 kV up to and including 52 kV*

3 Terms, definitions and abbreviations

3.1 Terms and definitions

For the purpose of this document, the terms and definitions contained in IEC 60282-1:2009 and IEC 60282-2:2008 apply.

3.2 Abbreviations

The following abbreviations are used in this document:

A^2s – Amperes-squared-seconds, also $A^2 \times s$, the unit of Joule integral (I^2t, see 4.2.4.4)

CL – Current-limiting

CLF – Current-limiting fuse

FEP – Fuse enclosure package

HV – High-voltage

I_{encl} – de-rated current (of a fuse in an enclosure)

I_r – Rated current (of a fuse)

u_c – TRV peak voltage in kV

t_3 – Time in microseconds to voltage u_c

I_1, I_2 I_3 – Prospective current in test Duty 1, Test Duty 2, and Test Duty 3 of IEC 60282-1, respectively

MAT – Maximum application temperature

TCC[1] – Time-current characteristic

TRV – Transient recovery voltage

4 Tutorial section

4.1 A simple introduction to fuses

4.1.1 General

Fuses have been in use since the very beginnings of electrical power distribution. While the true inventor of the fuse is not known, pioneers of electrical distribution soon incorporated them as "weak points" in their circuits to prevent overheating of wiring, due to excessive

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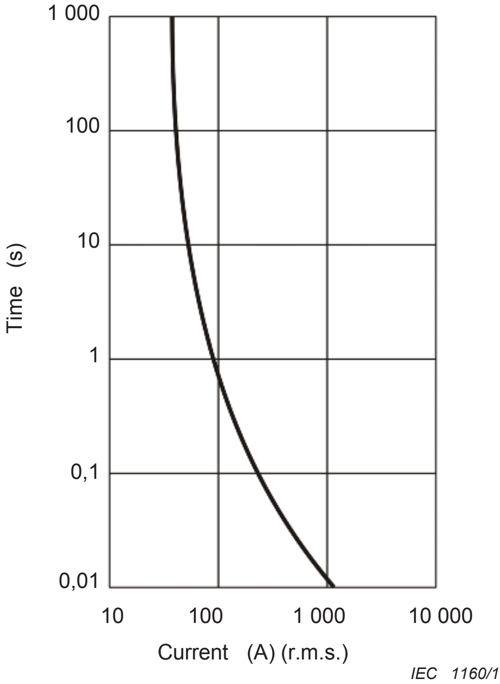
[1] Footnote 1 applies only to the French version.

current, and to prevent damage to fragile lamps from fluctuations in voltage. Fuses rapidly developed into devices able to sense a current higher than normal and quickly interrupt (break) that current, all in a self-contained easily replaceable unit. Although the variety and complexity of fuses has grown to the point where user's guides, such as this one, are necessary, fuses still provide the highest degree of protection for the lowest initial cost.

The simplest definition of a "fuse" is that it is a device that carries current through a conductive part called the fuse element that, when the fuse is subjected to an excessive current, melts due to self-heating and initiates the interruption of the current. All conventional fuses interrupt current after some arcing across breaks in the element produced by the melting process. The melting time of a fuse is therefore also termed the "pre-arcing" time. A characteristic of fuses is that, because current interruption is initiated by a melting process, there are almost no "mechanical" aspects involved in their arc initiation. Fuses therefore have a very inverse time-current relationship (higher currents giving shorter pre-arcing times) as illustrated in Figure 1. This enables extremely short pre-arcing times at high currents, virtually without limit. It is this apparently simple phenomenon that is primarily responsible for the universal success fuses have enjoyed for a very long time.



IEC 1160/13

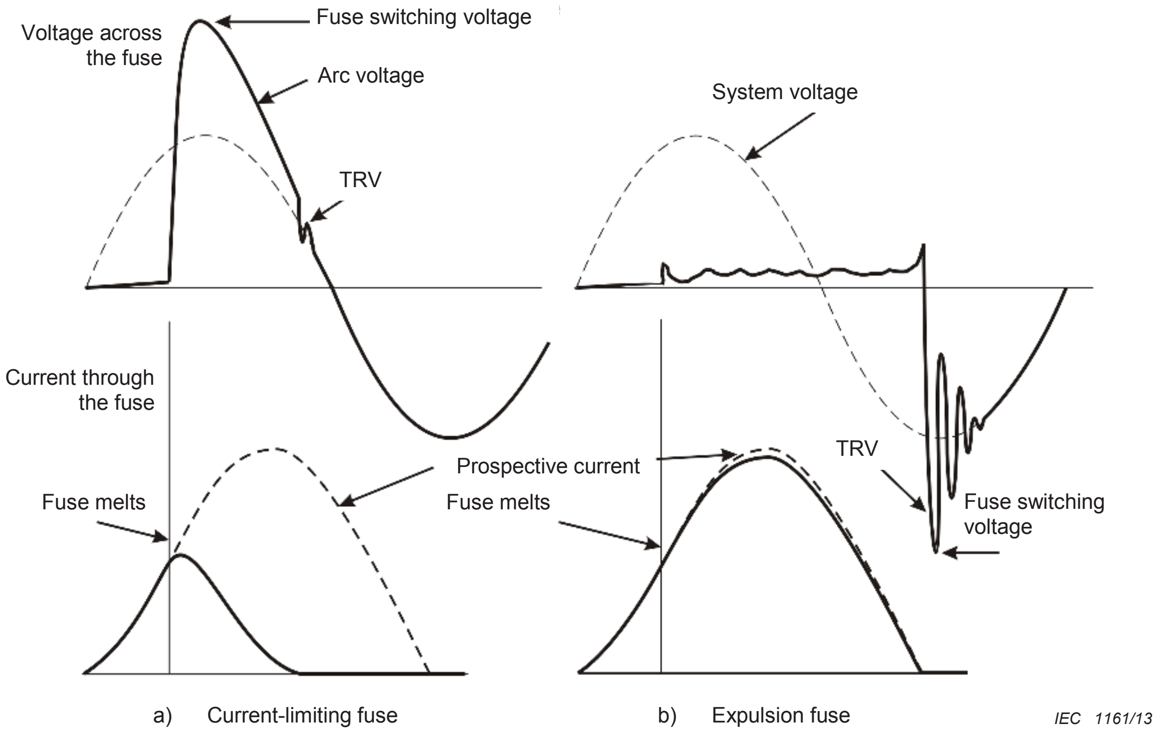
Figure 1 – Fuse pre-arcing time-current characteristic curve

In general, high-voltage fuses (defined as fuses rated above 1 000 V a.c.) are physically larger and generally more complex than low voltage fuses due to their need to operate at much higher voltages. HV fuses may perform one or both of two primary functions. The first function is to respond to moderately excessive currents, typically termed "overload" currents. In this case, the rated current of the fuse (the current it is designed to be capable of carrying indefinitely without deterioration) is exceeded by a relatively modest amount (typically less than 10 times). Such currents can be caused by too much load being connected to a circuit, or by a fault that by-passes only part of the load. It should be noted that not all types of fuses are designed to have the ability to operate successfully if melted by a very low overcurrent as some types are intended only for operation at high currents (see 4.1.2.1). If melted by a low current, such fuses may arc until a series device interrupts, possibly resulting in physical damage to the fuse and its surroundings. However, some fuses of this type can quickly initiate another device to interrupt such current, containing the arcing without damage until the second device interrupts.

The second function, which virtually all fuses are designed to perform, is to respond to overcurrents that are much higher, and that are usually termed "short-circuit" currents. In this case substantially all of the load is by-passed by a major fault and the available current (which, when not limited by a protective device, is termed the "prospective current") can be very high. However different types of fuse vary widely in exactly how high a current they can interrupt, and this may be a significant factor in choosing a fuse type for a particular application. The ways in which fuses respond to high and low overcurrents, as well as the ways in which they actually interrupt the current, causes HV fuses to be classified in various ways.

The first main classification is into "current-limiting" and "non-current-limiting" types (although because almost all commonly used non-current-limiting fuses are expulsion fuses, "expulsion fuse" is usually the term used in preference to "non-current-limiting"). "Current-limiting" (CL) describes a class of fuses defined by the behaviour that occurs when the current is so high that the fuse element melts before the first peak of the fault current (that is in less than a few ms). Upon melting, this type of fuse introduces resistance into the circuit so rapidly that the current stops rising and instead is forced quickly to zero (before a natural current zero would occur). Because the maximum prospective peak current is not reached, the fuse limits the current in magnitude as well as duration hence the "current-limiting" name. The current-limiting action is shown in Figure 2a. Note that during operation, the current-limiting fuse introduces a "spike" of overvoltage (the fuse switching voltage) into the system during the current-limiting action as shown in Figure 2a.

An expulsion fuse, melting under the same circumstances, introduces only a small resistance into the circuit, so the current continues to virtually the same peak as would occur if the fuse had not melted. An expulsion action (that is where gas is generated by the arc and expelled along with ionized material) produces a physical gap such that, at a natural current zero, the arc does not reignite and the current is interrupted. This type of fuse therefore limits the duration of a fault but not its magnitude. This action is illustrated in Figure 2b. For an explanation of TRV see 4.2.1.2).



a) Current-limiting fuse b) Expulsion fuse

Figure 2 – High current interruption by current-limiting fuse and expulsion fuse [2]

4.1.2 Fuse classifications and terms

4.1.2.1 Current-limiting fuse classifications

The ability of different types of CL fuse to interrupt currents lower than those that produce a current-limiting action result in different classes of CL fuse. Some CL fuses are designed to interrupt only high currents (i.e. their primary function is to provide a current-limiting action). They therefore have a limited low current interrupting ability and are termed "Back-Up" fuses. They are usually used in conjunction with another device in series; such devices include switches (most commonly tripped by a striker in a "switch-fuse combination", see 5.2.7.2), contactors, circuit breakers or another fuse having a lower current interrupting ability. It may be considered that they are "backing up" this other device and in addition to the important current-limiting function, also usually provide increased interrupting capability. This is because the series device frequently has a limited interrupting capability while Back-Up fuses can normally interrupt very high currents i.e. they have a very high "rated maximum breaking current".

High-voltage fuses having the ability to interrupt low values of overcurrent as well as high short-circuit currents are classed as either "General-Purpose" or "Full-Range" types. The term "General-Purpose" (which has historical origins, being used before Full-Range fuses were introduced) does not mean that the fuse can be used for any sort of application but merely that the fuse is designed to clear low values of fault/overload current. Testing is performed by the fuse manufacturer to show that fuse-links classed as General-Purpose can clear currents down to a value that causes melting of the fuse element in 1 h or more. This means that General-Purpose fuses can be used with overload currents that will cause them to melt in times of up to one hour, but no longer. The term "Full-Range" is used for the Class of fuse

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[2] *IEEE Std C37.48.1 -2012, "IEEE Guide for Operation, Classification, Application, and Coordination of Current-Limiting Fuses with Rated Voltages 1-38kV"* - Reprinted with permission from IEEE, 3 Park Avenue, New York, NY 10016-5997 USA, Copyright 2002, by IEEE.

designed to clear even lower values of fault/overload current; in fact any continuous current that causes the fuse element to melt must be interrupted by such a fuse. Full-Range fuses are often used in enclosures, sometimes with the enclosure at elevated temperatures; both factors can reduce the lowest current that causes them to melt, and Full-Range fuse test methods reflect this.

4.1.2.2 Current-limiting fuse terminology

There now follows an explanation of common terminology relating to fuses used in fuse standards and in this report. A fuse is defined as all the parts that form a complete device, which is everything needed to connect it into a circuit. After operation, at least some of a fuse must be replaced to return the protection to "as new" condition. The part that is replaced after operation is called the "fuse-link", and is the part that performs the active function of current carrying and interruption. In some usage (IEEE standards for example) fuse-link refers only to the replaceable part of a distribution fuse-cutout (see 4.3.2.1.1). Current-limiting fuse-links are often termed "cartridge fuses". This is because they are almost always cylindrical in shape and contain the fuse element surrounded by an arc absorbing filler, usually quartz sand.

A complete CL fuse may employ a fuse-base (sometimes called a fuse support or fuse-mount). This base usually consists of clips and spade terminals, which are in turn mounted on insulators. They are used with a fuse-link having ferrules that fit in the clips. Cables or bus-bars attach to the terminals. This type of fuse is still extensively in use, normally in "live-front" gear (that is equipment that would have live conductors accessible if the access doors can be opened with the equipment live). Alternatively, fuse-links may be found installed in canisters (that is relatively tight fitting enclosures) or be moulded into rubber or epoxy for use with cables in submersible/dead-front installations ("dead-front" meaning that no live conductors are exposed). They are also used under oil, either in quite elaborate fuse-holders (for ease of replacement) or in simple cradles inside transformers when they do not have to be replaced by the user (see 5.2.2.6.4).

In some cases the fuse-link is also the fuse, that is it may include all of the components necessary for connection into a circuit, e.g. if the fuse-link has tags or spade/eyebolt terminals. An example of this method of mounting is an external CL fuse that may be hung from an overhead line or mounted on a distribution fuse-cutout or transformer insulator (in which case the cutout or insulator substitutes for the "fuse base").

4.1.2.3 Expulsion fuse classifications and terminology

Expulsion fuses are divided into two classes Class A and Class B (in some parts of the world called "Distribution Class" and "Power Class"). The majority of Class A fuses are of a specific fuse type called "distribution fuse-cutouts". They are characterized by a fuse base that holds a fuse-carrier. The fuse carrier is lined with arc quenching material and holds a fuse-link. The link initiates the arcing and the fuse-carrier provides for arc elongation and most of the expulsion gas produced at high currents. After the expulsion operation, the carrier hangs open giving indication and isolation. Only the fuse-link, comprising a fuse element attached to a flexible cable (tail) and surrounded by a small arc-quenching tube, has to be replaced. Because they are so common, they are often referred to simply as a "cutout" or a "fuse-cutout" and except where otherwise specified, the word "cutout" or "fuse-cutout" used in this document refers to this type of Class A distribution fuse-cutout. There are also designs, called open-link cutouts, that use no fuse-carrier, but rather the fuse-link contains all the parts necessary to connect to the fuse-base. They have quite low maximum breaking currents. There is a third type of Class A expulsion fuse, common in some countries. It is termed an enclosed fuse-cutout. This has all of the live parts enclosed in a housing (usually made of porcelain). They may be of a drop-out design but commonly are not. Additional types of Class A expulsion fuses include those intended for capacitor applications, and those that surround the fuse element with a liquid.

Class B fuses (sometimes termed "Power Fuses") are designed for circuits having lower power factor and higher Transient Recovery Voltage (TRV, see 4.2.1.2) values than Class A, and the fuses normally have higher maximum breaking currents. The fuse-link tends to be more elaborate than that of a distribution fuse-cutout and may constitute most, if not all, of the fuse carrier. Some designs use a renewable fuse-link that, after operation, may be restored by means of installing a refill unit (containing an element and arc-quenching material). Unlike distribution fuse-cutouts, not all Class B expulsion fuses drop to an open position after operation.

4.1.3 Basic principles of fuse operation

The following basic principles of fuse operation are common to all types of fuse, both current-limiting and non-current-limiting varieties.

In its passive or current-carrying mode, a fuse must be capable of carrying load current and permissible cyclic or transient overloads without deterioration essentially indefinitely (with a service life often measured in decades, see 5.1.1.7). When load current is passing through the fuse, its element temperature rises but as heat is dissipated to its surroundings, the temperature stabilises at some value below that at which the element material and connections to the power system would deteriorate. Under these conditions, the heat lost through conduction, convection and radiation exactly balances the heat generated by the current flowing through the fuse resistance.

In its active or fault-interrupting mode, more heat is generated in the fuse element than can be dissipated before its melting temperature is reached. The relationship between current and melting time is described with a time-current characteristic (TCC) curve. An example of a fuse pre-arcing TCC curve is shown in Figure 1. For most fuses, the pre-arcing current becomes asymptotic to the time axis at very long times, and is termed the "minimum fusing current". Standards specify the time to which curves must be drawn, depending on the type of fuse. Not all curves are drawn to a time that shows the minimum fusing current, and not all fuses are capable of interrupting this current (see 4.1.2.1).

Upon melting, a current interrupting (breaking) process occurs that is different according to whether the fuse in question is of the current-limiting or non-current-limiting type. The interrupting process will therefore be described for each type of fuse in the appropriate section of the report.

After the interrupting process, fuses must be capable of withstanding normal system voltage. To assist with this phase of operation, some fuses drop open, providing a visual and physical "gap". This is relatively common with expulsion type fuses, but much less common with current-limiting types.

4.1.4 Advantages of fuse protection

While fuses and other forms of protective device (such as circuit-breakers) all have their own advantages and disadvantages for a given application, fuses do have some unique benefits:

a) because their operation is initiated by the melting of an element, there is no theoretical limit on how fast they can initiate the interruption process (the faster heat is generated in a fuse element the faster it melts). Generally there are no moving parts that require separation before the interrupting process can be initiated;

b) rapid operation of fuses under short-circuit fault conditions minimises voltage dips on the system and ensures more effective protection of lines and equipment;

c) fuses cannot be re-set when blown, thus the user is encouraged to identify and correct the fault condition before re-energising the circuit;

d) fuses have no, or very few, moving parts that could become damaged by dust, oil or corrosion;

e) fuse replacement after operation ensures protection is restored to its original state of integrity after circuit interruption unlike mechanical switching devices;

f) use of fuses usually gives the most economic solution for a high degree of system protection;

g) specific types of fuse are available for almost every service application.

4.1.5 Advantages of current-limiting fuses

4.1.5.1 General

In addition to the advantages detailed in 4.1.4, fuses of the current-limiting type offer additional important advantages:

a) limitation of current and energy let-through into the location of the fault ensures maximum protection and minimises the risks of possible fire damage, explosion, or injury to persons;

b) very high maximum breaking current ensures such fuses can always be employed on a given system even where the system is later modified to give a higher prospective fault level and hence there is no need to incur capital cost in installation of new more expensive protection equipment;

c) silent operation with no emission of gas, flame or arcing products;

d) compact size and much lower comparable cost than alternative forms of protection;

e) ability to reduce the size of cables due to reduced short-circuit stresses;

f) by reducing the I^2t (see 4.2.4.4 for an explanation of I^2t) flowing due to a fault, thermal stresses on all equipment in the fault circuit are reduced;

g) since the peak current is reduced, the electro-dynamic forces, resulting from the magnetic fields surrounding the conductors of transformers and other equipment in the fault circuit, are reduced;

h) because a current-limiting fuse reduces both the peak current and forces the current to zero before the natural current zero of the circuit, the fuse has a specific maximum operating (clearing) I^2t. Since upstream protective devices (see 5.1.4.1) require a minimum I^2t to initiate the interrupting process, it is possible to coordinate the devices to ensure that a failure at one point in a system will not cause operation of an up-stream device, thereby reducing the extent of the overall outage and helping to maintain service reliability.

4.1.5.2 Transformer protection

The most common application of high-voltage current-limiting fuses is for transformer protection. The use of such fuses for the primary-side protection of distribution transformers provides significant advantages due to their current-limiting action. Under most short-circuit conditions, they are able to interrupt fault currents within a few milliseconds after fault initiation. Hence, the prospective peak of the fault current will not be reached and the resulting let-through current and energy will be significantly reduced. This feature, that cannot be achieved by any other relay/switching device combination, makes current-limiting fuses particularly suited for distribution transformer protection since they are able to prevent or minimize any major consequences of internal transformer faults.

Figure 3 illustrates the operating I^2t versus prospective current for a non current-limiting fuse, which interrupts after one fully asymmetrical loop of current, and a current-limiting fuse. In principle, the lowest current rating of current-limiting fuse that meets the coordination requirements of 5.2.2 should be chosen. This is because a smaller fuse-link of a given design will generally have a lower operating I^2t. In the case of a low impedance internal transformer fault that produces a current-limiting action by the fuse-link, the I^2t limitation significantly reduces the likelihood of a disruptive failure, particularly with oil-filled transformers.

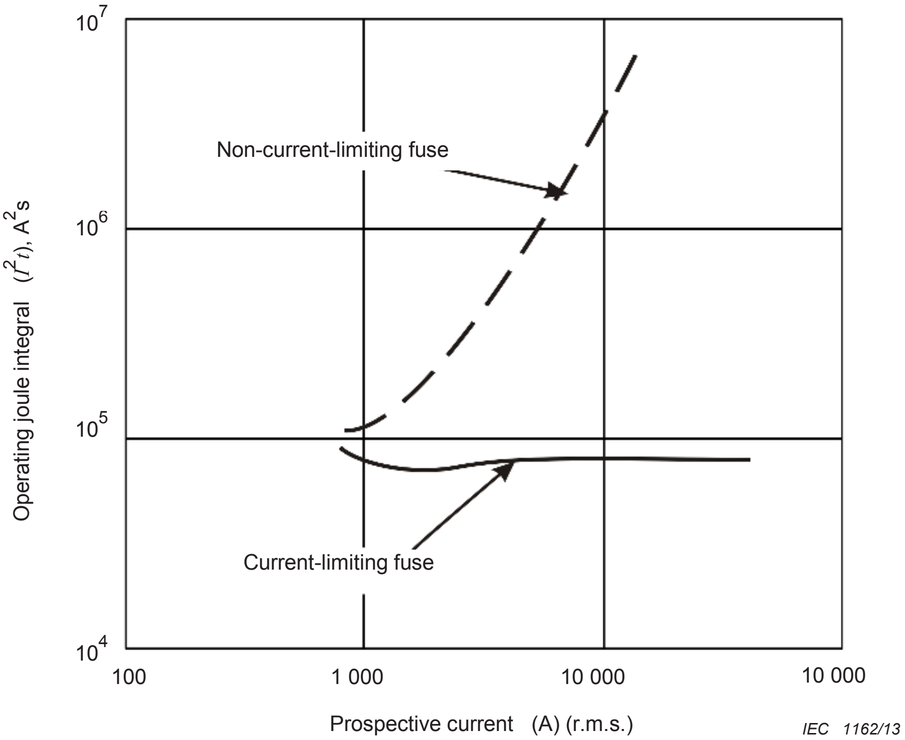


Figure 3 – Comparison of operating Joule integral (I^2t) versus prospective current for current-limiting fuses and non-current-limiting fuses

Experience has shown that the I^2t associated with a current-limiting fuse interruption is often an order of magnitude less than that causing a disruptive transformer failure, hence the effectiveness of current-limiting fuses in reducing the likelihood of such serious incidents.

It should be noted that the disparity in protection ability is even greater when the non-current-limiting device is a circuit breaker, due to the time delay introduced by the processes necessary to achieve current interruption. These are: the time needed for relay/current sensing, the time needed for the circuit-breaker contacts to open, and the time needed for the current to be extinguished. Therefore, in addition to the first loop I^2t, shown in Figure 3, I^2t from additional loops of current, that flow until the fault is interrupted, must be added. This has the effect of shifting the "non-current-limiting fuse" curve in Figure 3 upwards, typically increasing I^2t by a factor of approximately 2,5 times that shown.

Current-limiting fuses are available for the protection of distribution transformers up to approximately 5 MVA. For larger transformers with rated currents up to several thousand amperes, commutating current limiting devices (see 4.4.2.1 for a description) with high rated current can be applied. They are operated by an electronic sensing and triggering unit, which can be adapted to the required protection function. The electronics need to be able to distinguish between the fault current and the inrush current of the transformer.

4.1.6 Types of high voltage fuses

4.1.6.1 General

High voltage fuses of one type or another are available to meet almost every application for protection of high voltage circuits or equipment. It may be said that such fuses usually provide the simplest and most economical solution. There follows a listing of the most common types of fuse and fuse-related devices, that receive coverage in this report. They are grouped under four headings: current-limiting fuses, expulsion fuses, non-current-limiting fuses (that are not expulsion fuses), and fuse-related devices (devices that incorporate fuses into their operation, or are mounted in fuse-bases). A brief description is added for each device and places in the report where they are addressed can be found in the index. It is believed that some types of device listed are obsolete and/or either not being currently manufactured, or manufactured in very low quantities. Such devices are followed by the word "obsolete". They are covered (if somewhat briefly) in this document because examples may still be found in service, and because they may require replacement by more modern devices.

4.1.6.2 Current-limiting fuses

When this type of fuse melts with a current high enough to cause it to melt before the first natural peak (the threshold current for a particular fuse), it introduces a sufficient resistance into the circuit that the current is quickly reduced to zero. They are enclosed fuses, normally filled with quartz sand, and the higher the fault current above the threshold current, the greater is the percentage reduction in let-through current peak and energy. Table 1 lists the most common types, covered by this report:

Table 1 – Common types of current-limiting fuse

	Type of CL fuse	Brief description
1	Full-Range	Fuses intended to interrupt all currents that cause the fuse to melt, up to the rated maximum breaking current of the fuse.
2	General-Purpose	Fuses intended to interrupt all currents from a low value, equal to a current that causes the fuse to melt in one hour, up to the rated maximum breaking current of the fuse.
3	Back-Up	Fuses intended to interrupt currents from their rated minimum breaking current, up to their rated maximum breaking current.
4	Types 1 – 3 using an indicator or striker	Indicators provide indication of fuse operation; strikers operate on fuse element melting (or at high temperature) typically causing a pin to emerge from the fuse, and trip associated switching equipment.
5	Motor circuit applications ("motor-starter fuses")	Fuses used in circuits that supply motors, and that are subjected to repeated starting surges higher than their rated current.
6	Voltage transformer fuse	Fuses used in the HV circuits of voltage transformers (and typically having very low current ratings).
7	Capacitor fuse	Fuses used to protect capacitors and that are required to interrupt capacitive currents.
8	Types 1 – 7 for use indoors, outdoors or immersed in an insulating liquid	Outdoor fuses may have special dielectric requirements compared to indoor fuses and also requirements for UV protection and/or moisture ingress. Fuses immersed in a liquid have special sealing requirements to avoid liquid ingress.
9	Exothermically assisted triggered fuse (obsolete)	A Full-Range type fuse that used exothermic material to provide multiple element breaks at low currents.

4.1.6.3 Expulsion fuses

These are fuses that work through an expulsion action. After the fuse element melts, an arc is formed, during which ionised material is expelled from a housing with the assistance of gas generated as a result of the arc interacting with components of the fuse. This enables the "gap" so produced to withstand circuit recovery voltage at a current zero. They do not significantly reduce the magnitude of a fault current, only its duration, and so are also called "non-current-limiting" fuses. Table 2 lists the most common types covered by this report.

Table 2 – Common types of expulsion fuse

	Type of Expulsion fuse	Brief description
1	Distribution fuse-cutout (Class A expulsion fuse) (open cutout)	A class "A" expulsion fuse that uses a replaceable fuse-link in a fuse carrier, which drops open after interruption. Used outdoors.
2	Enclosed fuse-cutout	An expulsion fuse in which live parts are enclosed. They may or may not be of a type that drops open after operation. Used outdoors.
3	Open-link cutout	A cutout that does not use a fuse carrier but a special type of fuse-link attached to spring loaded arms. Used outdoors.
4	Boric-acid power fuse (Class B expulsion fuse)	A class "B" expulsion fuse that uses boric acid to generate expulsion gasses. May or may not be of a type that drops open. Indoor versions are available.
5	Liquid-submerged expulsion fuse	Fuse-link immersed in a dielectric liquid with the element in contact with the liquid.
6	Liquid fuse (Liquid filled fuse)	Sealed fuse containing a dielectric liquid. Used outdoors.
7	Capacitor fuses	Fuses used to protect capacitors and that are required to interrupt capacitive currents.
8	Distribution oil fuse cutout (obsolete)	Small oil filled tank containing rotating switch device that includes a fuse-link.

4.1.6.4 Non-current-limiting fuses (non-expulsion type fuses)

Like expulsion fuses they produce little resistance during arcing and rely on achieving a "gap" having dielectric conditions such that when the arc is extinguished at a natural current zero, it is not re-established and current flow ceases. Types of non-current-limiting fuses mentioned in this report are listed in Table 3.

Table 3 – Types of non-current-limiting fuse

	Type of non-current-limiting fuse	Brief description
1	Horn gap fuse (Arcing-horn fuse)	Fuse that uses a wire between two arcing horns
2	SF_6 fuse (obsolete – see 4.4.3.2)	Fuse uses a short element between two electrodes, in a small, sealed, enclosure with SF_6 gas.
3	Vacuum fuse (obsolete – see 4.4.3.3)	Fuse uses a short element between two electrodes, in a small, sealed, enclosure with vacuum.

4.1.6.5 Fuse related devices

These devices use fuses as part of their operation or employ fuse bases as part of their construction. Common types referenced in this report are listed in Table 4.

Table 4 – Fuse-related devices

	Type of fuse-related device	Brief description
1	Commutating current-limiting devices with integral fuses	Device incorporates low resistance conductor, capable of very quickly transferring current to a parallel current-limiting fuse upon a signal supplied by a separate sensing device.
2	Electronic automatic sectionalising link (ASL)	A device, mounted in a distribution fuse-cutout base that can sense fault current and drop open, providing isolation during the "off" time of a recloser or similar device.
3	Disconnecting cutout	A distribution fuse-cutout base fitted with a solid blade in place of the fuse carrier.

4.1.7 Application of fuse types

Some applications commonly use just one type of fuse (for example motor circuit applications almost always use current-limiting fuses). However in other applications, more than one type of fuse is often found. This may be either as alternatives (e.g. an expulsion fuse or a current-limiting fuse) or a combination of fuses (for example a distribution fuse-cutout in series with a current-limiting back-up fuse). Combination fuses are available in which a current-limiting fuse is attached to an expulsion fuse (for example for capacitor applications). Particular advantages and disadvantages of different fuse types drive the selection process. While this report will compare and contrast different fuse types, it is not the intention to suggest any one fuse type is "better" or "worse" than another, but rather that some fuse types are better suited for certain applications than others depending on the desired protection requirements and the budget available.

4.2 Current-limiting fuses

4.2.1 Construction and operation of current-limiting fuses

4.2.1.1 General

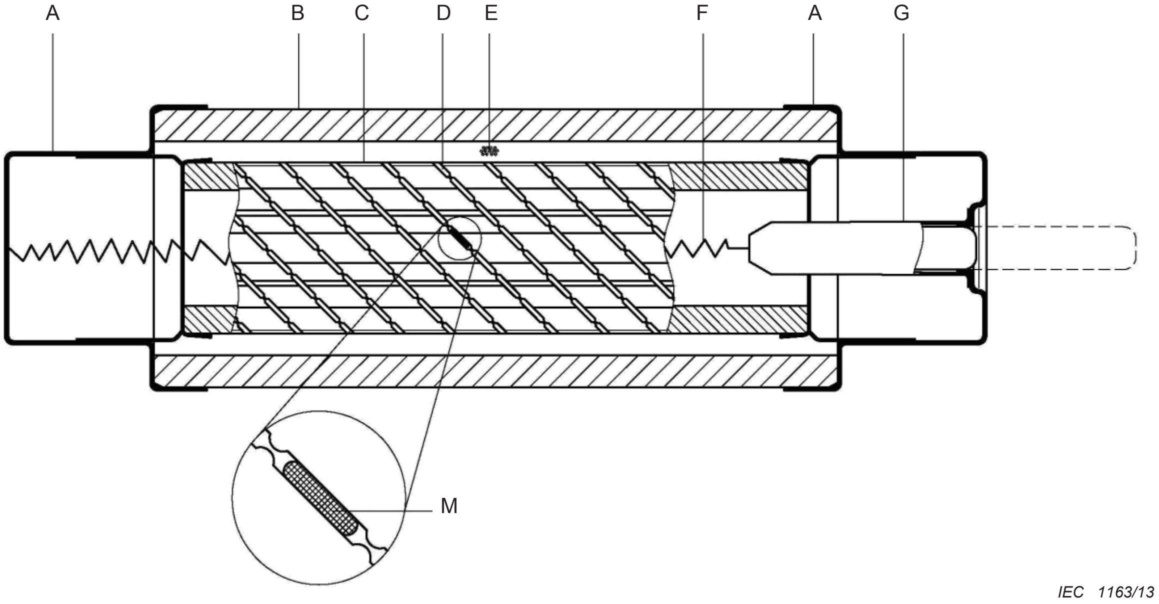
In its passive or current carrying role the fuse must carry load current and permitted cyclic or other transient overloads for an indefinite time without deterioration (see 4.2.4.7 and 5.1.1.7). In its active or overload/fault current interrupting role, the fuse must disconnect the circuit, either relatively slowly, based on its pre-determined pre-arcing or operating time-current-characteristics, or very quickly with high fault currents, absorbing perhaps many kilojoules of resultant arc energy within itself and limiting the energy passed into the protected faulty circuit as much as possible.

Figure 4 shows the construction of a typical back-up fuse-link having "DIN" dimensions. While other types of current-limiting fuse will show differences in construction, this figure illustrates the primary characteristics of such fuses. An insulating tube (the fuse body) of ceramic or organic resin/glass fibre material encloses parallel fusible current carrying fuse elements. These are connected at each end to metal caps, normally copper or brass, which seal the body and act as the electrical connections to the fuse. The body and caps are required to have the attributes of a pressure vessel, capable of withstanding the combination of high pressure and very high temperature that occurs at the instant of fuse operation. If the fuse is designed for use outdoors or under oil (or another dielectric liquid or gas such as synthetic or seed based oil, or SF_6), special additional sealing will usually be included to prevent ingress of moisture or fluid. For outdoor use, the manufacturer will use a material selection or special coating to prevent damage from weather and solar radiation over time.

The fuse elements are surrounded by granular insulating material, almost always compacted quartz sand of high purity and closely controlled grain size. The fuse shown, like many ratings, requires a fuse element length greater than the body length and so the fuse elements are wound in a spiral pattern around an inert former or "core", often, from its shape, known as a "star core". Other designs of fuse require fuse elements only of similar length to the body, and so are mounted parallel to the body (notably motor circuit fuses) as with low-voltage fuses. Low current ratings may often have only one fuse element while high current ratings will usually have many parallel fuse elements.

The fuse elements are the heart of the fuse, and are manufactured to a high degree of precision, normally from pure silver or copper wire or strip. The length of the fuse elements is proportional to the voltage rating of the fuse while the total cross-section and number of parallel fuse elements determine the current rating. The shape of the fuse elements together with their spacing and configuration determine many of the electrical characteristics of the fuse-link. They have a strong influence on the shape of the time-current characteristics, the degree of current limitation, and the peak overvoltage during high current operation (termed switching voltage or peak arc voltage – see 4.2.4.5).

Where fitted, strikers (often used to trip an auxiliary device) or indicating devices (to show that the fuse has operated), are wired in parallel with the fuse element system. During fuse operation, when the main fuse elements are melted, the current transfers into the striker circuit, before quickly switching back to the main elements. Depending on the design, the current will either ignite a small pyrotechnic charge to expel the pin (typically British Standard type fuses or fuses that require a striker of type "heavy") or else melt a small latch wire (typically DIN-type fuses) to release a coil spring that expels the striker pin. In some designs, the latch is made thermally sensitive so that the striker will be released and trip the associated switchgear once the fuse has reached a given temperature, irrespective as to whether the fuse itself has actually operated. In the case where an indicating device rather than a striker is used, a relatively weak spring loaded indicator device may operate in a similar manner to a striker, or it may use a non-conducting filament, released by heat from the fuse arcing.



Key

A	end cap (fuse-link contact)
B	body
C	former (core)
D	fuse element
E	granular filler
F	striker/indicator wire
G	striker or indicator
M	low temperature overlay ("M effect")

Figure 4 – Cut-away drawing of typical current-limiting fuse-link of the "DIN" dimensioned type

Fuses may be designed as simple ferrule fuses to fit into suitably shaped contact clips or they may be fitted with terminal tags for bolting onto bus-bars, etc. Some, intended for outdoor use, incorporate eye bolts for attaching cables or studs for mounting in eye-bolt terminals.

The high voltage current-limiting fuse has two distinct modes of interrupting fault currents, which will be described in 4.2.1.2 and 4.2.1.3. For a theoretical treatment of fuse interrupting phenomenon, see "Electric Fuses" by Wright and Newbery [2][3].

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[3] Numbers in square brackets refer to the Bibliography.

4.2.1.2 Operation under high-fault current conditions

At high fault currents (say more than ten to twenty times load current), all elements in a fuse-link reach melting temperature virtually simultaneously in only a few milliseconds or less. They break up along their length into multiple small series arcs. Strip fuse elements will usually include a pattern of holes or notches along their length to limit the number of these separate arcs, providing control over switching voltages (see also 4.2.4.5). Wire fuse elements also break up into multiple series arcs, due to complex thermal/magnetic forces. Since, for wires, the number of arcs tends to be very high, high switching voltages can result so wire fuse elements are normally used only for relatively low current ratings (see 4.2.4.5). The arcing, in effect, introduces a high resistance into the circuit and causes the current to be driven down long before the peak of the prospective fault current is reached (known as the cut-off effect). This is illustrated in Figure 2a. The arcs elongate, further increasing resistance. When the current has been driven down to a low value, the arcs are extinguished almost simultaneously within the first loop of fault current. Because the forced current zero occurs close to the circuit voltage zero, current-limiting fuses are much less sensitive to TRV than expulsion fuses, see Figure 2a) (TRV – Transient Recovery Voltage – is the brief transient oscillatory voltage that appears across an opened circuit, in this case across the fuse, after current interruption, and is due to damped current oscillation in the circuit inductance and intrinsic parallel capacitance).

Since both the peak value of the fault current and its duration are greatly reduced as compared with the operation of a non-current-limiting device, the energy released into the location of the fault or into the circuit being protected is very greatly reduced. The rapidity with which the fuse operates results in the appearance of a transient over-voltage in the circuit – the switching voltage. This is due to the collapse of the field associated with the circuit inductance and is more pronounced in circuits of low power factor. This switching voltage, appearing across the fuse, may be appreciably higher than the system voltage and should be allowed for when designing equipment clearances and creepage, and selecting lightning arresters.

The energy of the arcs within the fuse is dissipated in the formation of nodules of fulgurite from the sand filler surrounding the fuse elements. Fulgurite is the term used by fuse engineers to denote the mixture of sintered and fused sand grains together with globules of metal from the melted fuse elements. The amount of fulgurite produced during fuse operation is directly related to the quantity of arc energy absorbed by the fuse. Approximately 0,5 g of fulgurite are produced per kilo-joule of arc energy. Small increases in system voltage (above the rated voltage for the given fuse) cause a large increase in the arc energy and hence in the quantity of fulgurite produced. The fuse envelope has a definite upper-limit to the mass of hot fulgurite it can accommodate. Thus, in general, current-limiting fuses can only correctly interrupt short-circuit currents at system voltages not in excess of the fuse rated voltage.

4.2.1.3 Operation under low-fault current conditions

4.2.1.3.1 Temperature considerations

In the case of low faults currents, say up to around five times the fuse rated current, the fuse elements reach melting temperature gradually over a period of many seconds or minutes (or for Full-Range fuses, even hours). The melting temperature of silver is approximately 960 °C, that of copper, approximately 1 080 °C. If the melting time of a fuse is more than a few seconds (or for some types a few minutes), and the fuse as a whole had to reach such a high temperature during operation, damage to the fuse itself or its associated equipment could result. Various means are therefore employed to overcome this problem. Some fuse designs include a spot of low-melting alloy on the fuse element, known as M effect (after its discoverer Prof. Metcalf) as shown in Figure 4. If a typical tin alloy is used for the M-effect, at about 230 °C the alloy melts and the base fuse element material diffuses into it. This causes the fuse element to melt open at a lower temperature than its normal melting temperature, and initiate the process of current interruption. Where M-effect is not employed, other techniques that have been used include the incorporation of a low melting point section in series with a fuse element (common in some types of Full-Range fuse), the formation of a hot spot on the fuse element by creating a long narrow neck in the strip, or by enclosing part of the fuse element in thermal insulating material. The object, again, is to ensure that fuse element melting occurs without the strip as a whole having to reach an excessively high temperature.

An alternative solution, employed where the fuse is mounted in a striker-tripped switching device, is to use a thermal striker which is designed to operate and trip the associated switching device, when the temperature of the fuse reaches a pre-determined value. . In this particular case it is the switching device, and not the fuse, which performs the current interruption.

4.2.1.3.2 Low current interruption

In the case of low fault currents or overloads, with fuses having more than one fuse element, the parallel fuse elements do not melt and arc simultaneously, as with high fault currents, but instead melt randomly in turn, usually at one location on each element, until the last one melts. For fuses that employ fuse elements having a plain strip with restrictions, and that operate at more than a few thousand volts, more than one series break is necessary to interrupt current. The last fuse element to melt must therefore see sufficient current to achieve multiple melting during the arcing that then occurs. This arcing causes each of the remaining parallel fuse elements to re-strike and create multiple series arcs that, in turn, are extinguished when another element re-strikes. This process continues until all fuse elements have arced sufficiently to be able to withstand recovery voltage (including any TRV present).

Therefore, for many types of high voltage fuse, should the fault current be lower than a certain critical value (about 3 to 10 times rated current according to the particular design of fuse), the current density in each fuse element during arcing may be too low to initiate multiple series breaks in each element. The result is the formation of long single arcs that re-strike after each current zero, burning back and possibly causing eventual fuse failure. This type of fuse therefore has a defined "minimum breaking current" below which satisfactory circuit clearance cannot be assured.

Such fuses are termed Back-Up fuses (see 4.2.2 "classification") and are intended for use in applications where a) low fault levels are deemed very unlikely, b) where the fuse is used in conjunction with other protective devices which handle low level fault conditions or c) in the common application where the fuse is used in striker-tripped switchgear. In this latter case, under low fault conditions, the fuse striker pin is ejected immediately on the commencement of arcing within the fuse. The pin trips the switch in series with the fuse, thereby disconnecting the fuse from the fault current before it has time to overheat, so that satisfactory current interruption at all fault levels is assured. Back-Up fuses that are intended for use in series with other protective devices (expulsion fuses for example) may only have a rated minimum breaking current corresponding to a pre-arcing time of few seconds or less. In this case, the series device is coordinated with the Back-Up fuse’s current rating and pre-arcing time-current characteristic so that the fuse cannot get hot enough on overloads to be damaged.

Fuses having built-in ability to handle low fault currents are also available. They are termed General-Purpose or Full-Range fuses (see 4.2.2 "classification"). In one version, an improved very low minimum breaking current capability is obtained by use of a large number of parallel fuse elements, each of small cross-section so that each fuse element when arcing on its own, has a high enough current density to break up into full multiple arcing and clear the fault current. In other cases, gas-evolving materials are used to increase the effectiveness of series arcs and improve low current interrupting ability. In another popular version, each current-limiting fuse element is connected in series with a fuse element working on the expulsion principle (see under expulsion fuses). In this arrangement, the expulsion fuse elements handle any low-level faults. For higher fault levels, the current-limiting fuse elements take over to clear the short circuit fault current. Fuses using this principle (sometimes called "dual-element" fuses) will have been tested using special tests, I_t, specified in IEC 60282-1:2009. This checks operation in the cross-over region from the current-limiting fuse element to the low-current fuse element. General-Purpose and Full-Range fuses can usually be employed as sole protection for all fault levels without the need of associated equipment to handle the lower fault currents.

4.2.2 Classification of current-limiting fuses

The classification of such fuses is related to their ability to interrupt low level fault currents as explained in 4.2.1.3).

Back-Up Class: this type of fuse must be capable of interrupting all levels of fault current from the rated maximum breaking current, usually many kiloamperes, down to the fuse rated minimum breaking current, typically 3 to 10 times fuse rated current. Such fuses are intended mainly for short-circuit protection. The fuse is not expected to clear lower levels of fault current unaided.

General-Purpose Class: This type of fuse must be capable of interrupting all fault currents from the rated maximum breaking current, down to those that cause fuse operation in one hour. For certain applications, such fuses are suitable for use as sole protection where they can provide some degree of overcurrent protection as well as short-circuit protection.

Full-Range Class. This type of fuse may have no definite value of minimum breaking current. While there are different test requirements for fuses intended to operate in a surrounding temperature either above or below 40 °C, the intent is that a Full-Range fuse is able to operate correctly for all values of continuous current that cause melting of the fuse elements up to its rated maximum breaking current. It is therefore particularly suitable for applications where use in a small enclosure causes considerable de-rating and hence the possibility of operation near to fuse rated current (see 5.1.4.2.7).

Figure 5 illustrates the current ranges over which the different classifications of fuse are intended to be used, and for which they are tested. In the Figure, I_{ACC} represents the maximum continuous current permitted by the application (see 5.1.1.1.3). In an enclosure it may be I_{encl}, (see Annex A) while in free air it will likely be I_r. The shaded portions represent currents above the allowable continuous current for which the fuse may be damaged and/or melt but fail to interrupt.

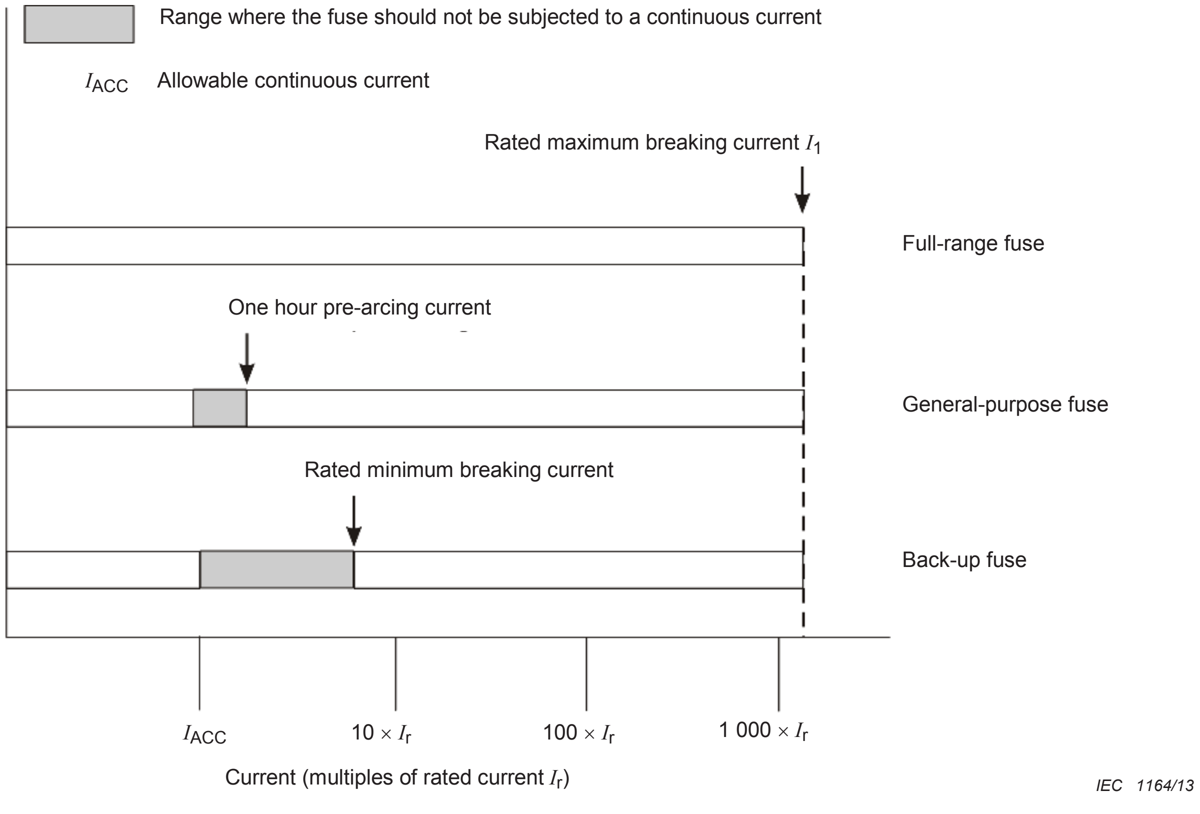


Figure 5 – Current ranges for which different fuse classifications are intended

4.2.3 Ratings of current-limiting fuses

4.2.3.1 Rated voltage

As explained in 4.2.1.2, current-limiting fuses are very voltage-sensitive. Hence, such a fuse must never be exposed to a recovery voltage even slightly higher than that used for testing. The recovery voltage that a fuse experiences in service depends not only on the system voltage but, in the case of three-phase circuits, also on the earthing of the system. Two aspects of an application must therefore be considered regarding fuse rated voltage. The first is that the rated voltage of a fuse must be at least equal to the "highest voltage of a system" (see IEC 60038) (i.e. maximum system voltage) not to the nominal system voltage (see also 5.1.3). Fuse voltage ratings therefore equate to "highest voltage for equipment" in IEC 60038. The second aspect is that unless the fuse is being used in a solidly earthed neutral three-phase system, an additional margin may be necessary. This is discussed in detail in 5.1.3.3. For example a fuse rated at 12 kV would be intended for use in a 10 or 11 kV system with solidly earthed neutral, but not in a single phase or resonant earthed system of the same nominal voltage.

Without special testing, fuses should not be connected in series in order to obtain an increased voltage rating since, due to manufacturing tolerances, one fuse of the series pair would probably operate before the other and so have more than its design voltage impressed upon it (see 5.1.6). It is permissible to use fuses of a given voltage rating in systems of lower voltage. The criterion here is that the spike of switching voltage during fuse operation should not exceed the insulation level of the system. A rule of thumb is that it is usually acceptable to use fuses down to about one half of their voltage rating.

4.2.3.2 Rated current

The current rating is determined largely by formalised temperature-rise tests in the design laboratory. Continuous load current should not normally exceed fuse rated current if deterioration of the fuse elements or other fuse components is to be avoided. However, in practice, high voltage fuses are generally run at load currents well below their rating for reasons connected with withstand against transient surge currents and de-rating due to use in thermally restrictive enclosures. To obtain higher rated currents, manufacturers often use parallel bodies permanently bonded together. Such fuses will be assigned an appropriate rated current by the manufacturer. Another way of providing an increased rated current is for the user to parallel individual fuses. The manufacturer should be consulted before this is done (see 5.1.5).

4.2.3.3 Rated maximum breaking current (rated maximum interrupting current)

Current-limiting fuses are usually tested at values of rated maximum breaking current (typically 25 kA to 50 kA) well above practical system fault levels. Manufacturers will not normally seek to find the highest current their fuses can interrupt, due to the high cost of such testing and/or test station limitations. However, a fuse should not be used at a higher prospective fault current than its rated maximum breaking current without consulting the manufacturer.

4.2.3.4 Rated minimum breaking current (rated minimum interrupting current)

It may not generally be realised that, unlike other circuit-breaking devices, current-limiting high voltage fuses of the Back-Up type (see 4.2.1.3)) do have a definite lower limit to the current that can be interrupted without external damage to itself or associated equipment. This rated value must be stated by the fuse manufacturer and has to be based on appropriate interrupting tests. It may be noted that the minimum breaking current value has no direct connection with the minimum fusing (melting) current of a fuse. The latter equates to the long-time end of the fuse time-current minimum pre-arcing curve (see 4.1.3) and may be typically 1,3 to 2 times fuse rated current, while rated minimum breaking currents are typically 3 to 10 times rated current.

4.2.3.5 Rated frequency

Within limits, this is not a critical parameter. A fuse tested at 50 Hz will be entirely suitable for use at 60 Hz. Also, in general, a current-limiting fuse tested at 60 Hz will be suitable for use at 50 Hz (unlike expulsion fuses see 4.3.4.4). While a fuse tested at 50 Hz or 60 Hz may be suitable for higher frequencies, no guidance can be given here, and the fuse manufacturer should be consulted for such applications. At lower frequencies than 50 Hz, more careful consideration may be needed since the longer half-loop time results in higher energy release in the fuse. Some de-rating in terms of voltage is usually necessary. In the extreme case of DC applications, the increase in arc energy can be so pronounced that a substantial voltage de-rating may be needed, and again the manufacturer should be consulted. Note that d.c. applications are not in the scope of IEC 60282-1:2009 or IEEE C37.41 [6]. For information on d.c. traction fuses see IEC 60077-5.

4.2.4 Characteristics of current-limiting fuses

4.2.4.1 General

The characteristics of a fuse, as published by the manufacturer, determine its suitability for use in a given application and enable comparisons to be made between fuses of different types so as to allow an optimum choice to be made.

4.2.4.2 Time-current characteristics

The most useful of the fuse characteristics, time-current characteristics enable co-ordination to be worked out between fuses and other protective devices on a given system. Manufacturers publish such data for all types and ratings of their products. Unless otherwise specified, the curves are drawn for an ambient temperature of 20 °C. For most fuses, the curve is valid for a range of temperatures. However depending on the type of fuse and the application, curves or correction factors valid for other temperatures may be produced. IEC 60282-1:2009 requires that Time-Current Characteristic (TCC) curves be drawn on a log-log scale and show the relationship between the virtual pre-arcing time and the prospective current. They may use mean or minimum values for current. European practice is to use mean values of current with a suitable tolerance to allow for manufacturing variance stated. They do not include the time during which actual arcing takes place. For very short melting times of less than 0,1 second the melting time could vary widely depending on the phase instant of the fault. Therefore, it is common to use "virtual time" rather than real time for the lower end of the curves. Virtual time is given by the joule-integral (I^2t) divided by the square of the prospective current r.m.s. value.

In North American practice, instead of a mean pre-arcing curve, a minimum pre-arcing curve is normally published (allowing for minimum manufacturing tolerances) together with a maximum operating (clearing) curve (including maximum manufacturing tolerances) which does include arcing time. Symmetrical currents are used to produce the pre-arcing curve to avoid the variability of asymmetry and "real" time, not virtual time, is normally used.

NOTE In practice the difference between a curve drawn with symmetrical current and a curve drawn using virtual time is small for most fuse designs. Therefore, time-current characteristic curves using either of these techniques can generally be used for coordination between fuses, and between fuses and other devices, down to approximately 0,01 s. Coordination at shorter time uses I^2t (see 4.2.4.4).

Time-current curves are developed with the fuse cold, i.e. off-load, In practice, preheating of the fuse, caused by the presence of load current causes operation to be slightly faster than shown on the published curves.

The value of the rated minimum breaking current for a Back-Up fuse is indicated by the point at which its TCC curve changes from a full line to a dotted line (see Figure 20).

Coordination between fuses and other devices (see 5.1 and 5.2) frequently require the use of minimum and maximum TCC curves (both pre-arcing TCC and operating [total clearing] TCC). If a nominal curve is published it must be shifted by the appropriate manufacturing tolerance (in terms of current). Pre-arcing TCC curve tolerances vary depending on the type of fuse; however fuses tested to IEC 60282-1:2009 are required to have a tolerance not to exceed ± 20 % for nominal curves and + 50 % for minimum to maximum curves. Modern fuses tend to have lower tolerances, more typically ± 10 %. This is similar to the North American practice, which is not to exceed + 20 % from the minimum to the maximum curve.

4.2.4.3 Cut-off characteristics

These curves show the highest maximum instantaneous values of current a given fuse will let pass under fault conditions for varying values of prospective fault current. The characteristics are of use in enabling checks to be made on the degree of protection afforded by the fuse to cables bus-bars, switch contacts, etc. However, since the operation of the fuse is extremely rapid, while damage to associated equipment is a function of time as well as instantaneous current, such checks err on the conservative side. Figure 6 shows a set of cut-off characteristic curves for a "family" of fuses. Each fuse has a curve consisting of two parts (normally drawn as two straight lines). The line to the left is common to all fuses and represents the maximum peak current of a fully asymmetrical prospective current (having a peak current of approximately 2,5 times the r.m.s. current at a typical power factor for 50 Hz and a ratio of 2,6 for 60 Hz). The second part of the curve (at a shallower angle) represents the current limitation produced by the CL fuse. The "knee" where the two curves join, represents the lowest current for which a particular fuse can achieve some current limitation.

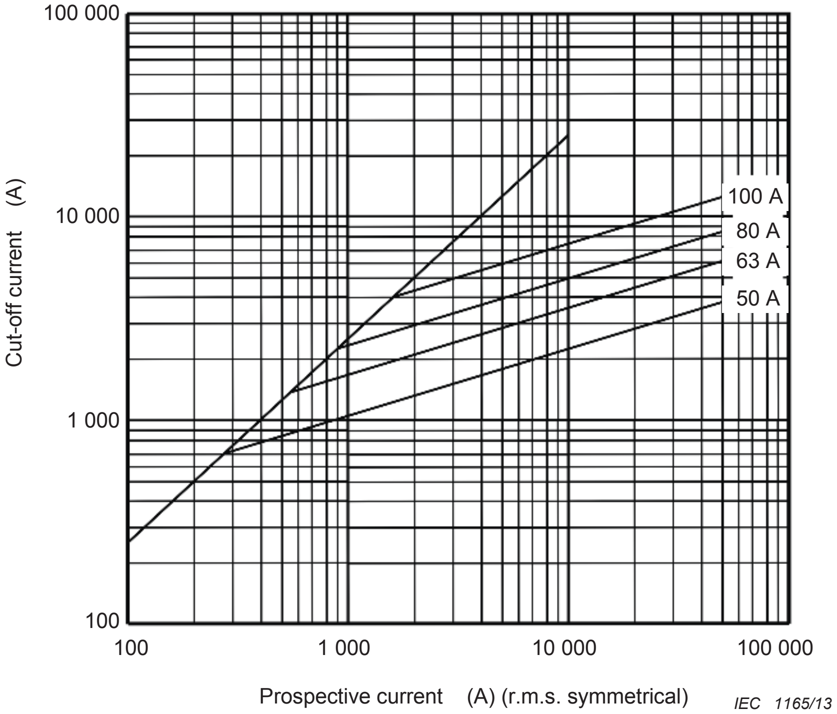


Figure 6 – Typical cut-off characteristics

4.2.4.4 Joule-integral (I^2t) characteristics

Joule–integral, or more commonly "I^2t" (which is more correctly $\int i^2 dt$) is an indication of the energy allowed through the fuse into the protected circuit under fault conditions. The energy released into a failure that results in an arc is the product of I^2t and the arc impedance. Because, for a given fuse, over a reasonable range of currents, I^2t tends to a somewhat constant value it is a helpful concept for co-ordination between the fuse and other protective devices in the zone of short operating times where the time of arcing becomes a significant factor. A manufacturer is required to publish two values "minimum pre-arcing (melting) I^2t " which represents the smallest I^2t to melt the fuse (at the maximum breaking current and with minimum manufacturing tolerances) and "maximum operating I^2t ", the highest I^2t likely to be experienced in service at any current that causes a current-limiting action. It can occur at any current up to the rated maximum breaking current of the fuse, depending on the fuse design. Operating I^2t is the sum of pre-arcing I^2t and arcing I^2t (arcing I^2t being that which "flows" during the time when the fuse is arcing). In some literature, other terms that have been used for maximum operating I^2t include "maximum clearing I^2t", "total I^2t value", maximum total I^2t", and "maximum let-through I^2t". The presentation of I^2t values may be in simple tabular or diagrammatic form (for example, histograms) or may employ graphical presentation with prospective current as abscissa and I^2t as ordinate, both scales being logarithmic.

The value of operating I^2t is affected by circuit conditions such as power factor and in particular by the applied voltage. In service, the values of operating I^2t will usually be less than those indicated in the published data, which are based upon the most severe test conditions.

4.2.4.5 Switching voltage (peak overvoltage, peak arc voltage) characteristics

The short-duration spike of overvoltage produced during the operation of a fuse at high fault currents is made up of two components, one due to the instantaneous value of the supply voltage, the other due to the rate of change of current in the circuit inductance as the current is abruptly reduced to zero. The value of the switching or "peak arc" voltage is thus dependant on both supply voltage AND prospective fault current and power factor. Limiting values of switching voltage are set by all relevant fuse standards and are generally kept below these values by fuse manufacturers.

The significance of any fuse design exceeding the proscribed limits would be in terms of possible external insulation breakdown or even flashover during fuse operation and arrester failure (see 5.1.4.4).

Since switching voltage falls, to some extent, with supply voltage, it is often possible to use a fuse of given voltage rating in a system having a lower voltage without exceeding the specified switching limits for a fuse at that voltage, or incurring any danger of insulation breakdown. The manufacturer should be able to provide guidance as to the switching voltage reduction with reduced supply voltage.

Small rating fuses, which often use wire fuse elements, tend to produce higher switching voltages, but of a very short duration. Due to this short duration, fuse standards permit higher values to be developed with low current ratings (less than or equal to 12 A or 3,15 A depending on the voltage series used for testing). Voltages produced by wire elements are less affected by a reduction in system voltage than strip elements.

4.2.4.6 Power dissipation

A high voltage fuse produces an appreciable amount of heat in service. Example, a 100 A 12 kV fuse may generate 100 watts or more when carrying its rated current. This heat has to be effectively dissipated into the surroundings if the fuse is not to deteriorate. In the case of totally-enclosed switchgear, the heat produced by the fuse may be a serious limiting factor on the current rating of the equipment protected.

Fortunately, it is unusual for high voltage fuses to be run at their full rated current because of other factors such as transient current withstand, e.g. transformer inrush or motor starts. Manufacturers normally supply data on power dissipation ("watts loss") at rated current. In general, fuses of lowest power dissipation are to be preferred. Such fuses will require less de-rating when used in enclosed environments and will waste less energy.

The method of measuring power loss in a high voltage fuse, for most practical purposes, is to multiply the volt-drop across the fuse by the current through the fuse (see Annex A).

4.2.4.7 Cyclic and transient load withstand

Fuses are required to withstand permissible transient pulses of overcurrent such as those due to transformer magnetising inrush, capacitor charging current, or the starting current of motor loads. Withstand has to be proved during design by extensive tests, from which graphs, tables or formulae are derived to enable the user to choose a fuse which will withstand the value, duration, and frequency of repetition of expected surge currents. It should be noted that if a transient current exceeds these acceptable limits, one or more fuse elements may be locally damaged. This can result in a fuse having its characteristics changed such that it could melt at a current that it is not capable of interrupting. The use of larger current rating fuses can relieve this concern, but it must be borne in mind that the protection provided by the fuse may then be reduced.

4.2.4.8 Fuse striker characteristics

In many applications, the striker has the important task of initiating operation of associated switching devices permitting the use of Back-Up fuses with low fault current conditions and providing three-phase interruption with a single fuse striker operation (see 5.2.7). Therefore, the fuse striker is available in several versions. Medium type spring-operated strikers, have a travel of at least 20 mm and an energy output of 0,5 J or greater. Graphs of striker characteristics are usually available showing the striker force, in Newtons, versus the length of striker travel. Spring driven striker pins have a continuing force that is proportional to the travel and spring rate of the spring.

Pyrotechnically operated strikers (heavy type) that utilise a small explosive charge to eject the striker pin have a minimum travel of 10 mm and energy output greater than one joule. Since this type of striker is a ballistic device (kicked rather than pushed as with a spring operated type) it is not possible to provide meaningful force/travel characteristic, but it is possible to measure the energy provided by the striker, allowing comparison with the energy needed to trip a device, such as a switch, that is to be initiated by the fuse.

4.3 Expulsion fuses

4.3.1 General operating principles

There are many types of expulsion fuse, but their primary characteristic is that they are vented devices in which, after their fuse element melts and arcs, the expulsion effect of the gases produced by the interaction of the arc with other parts of the fuse results in the current interruption in the circuit. Another common characteristic is that they are essentially non-current-limiting. They are characterized by a relatively low arc voltage and so do not significantly reduce the value of the first peak of a fault current. They also, therefore, extinguish current at a natural current zero, when the proper dielectric conditions have been established. This is illustrated in Figure 2b). Therefore, anything that increases the magnitude of the first major loop of an asymmetrical fault current makes interruption harder. Since the magnitude of this first major loop is a function of available fault current, the power factor (or X/R ratio) of the system, and the degree of asymmetry of the current, these fuse types are sensitive to low power factor (high X/R ratio) fault circuits (more so than are current-limiting fuses).

In addition to being sensitive to power factor, expulsion and other types of non-current-limiting fuses are sensitive to TRV (see 4.2.1.2 for an explanation of TRV). They do not significantly change the phase of the current relative to the circuit voltage, so at low power factor values the normal current zero occurs near the time of a system voltage crest. Upon reaching a current zero, they must be capable of dielectric recovery at a rate, and to a magnitude, greater than the TRV characteristic of the system. The TRV typically involves an overshoot of up to twice the power frequency voltage. If the recovery conditions are not met at the first current zero after melting, the device will conduct additional loops of current until interruption is achieved. At high currents, that produce melting in one or two cycles, this must occur in only a few loops or the fuse will not be able to interrupt. While, unlike current-limiting fuses (see 4.2.1.2), expulsion fuses are not particularly sensitive to the system voltage during a loop of arcing, they are very sensitive to the recovery voltage after a current zero. Therefore, like current-limiting fuses, they should never be used at a voltage higher than their rated voltage (see 5.1.3.2).

Because of their typical applications, expulsion and other types of non-current-limiting fuses have been designed to interrupt any current from the overload current at which the fuse element melts up to their maximum fault rating. This, as has been seen, is not necessarily true for all types of current-limiting fuses.

In common with all fuses, expulsion fuse elements have a defined melting characteristic. However, because their fuse elements are relatively short, and the interrupting process relatively independent of the fuse element size and construction, it is possible for a single expulsion fuse to be available with many different pre-arcing time-current characteristics. Thus, for example, a distribution fuse-cutout may accept, and be compatible with, a number of fuse-links that have different curve shapes (see 4.3.5) but the same current rating.

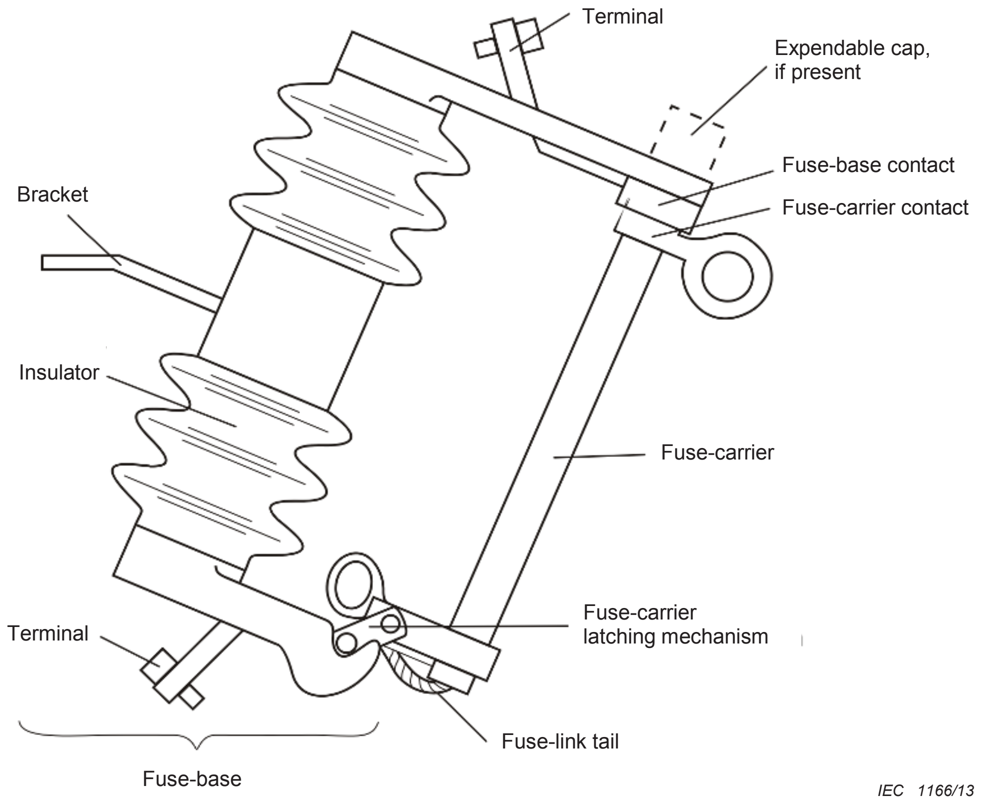
IEC standards recognize two classes of expulsion fuse Class A and B (see 4.3.3), which are similar to fuses recognized by other standards around the world. In theory, all types of non-current-limiting device can be tested to IEC 60282-2:2008, even if it would result in a very low rated maximum breaking current being assigned to them. However some common types of expulsion fuse are used where power factor and TRV values are less severe than called for in IEC standards, and so they may be tested to less onerous conditions either specified in a recognized standard (e.g. open-link cutouts in IEEE Std C37.41 [6]) or to no recognized standard. As they are similar to, or commonly used with, other types of fuse that are covered by standards, the most common types will be described in this document.

4.3.2 Construction and operation of expulsion fuses

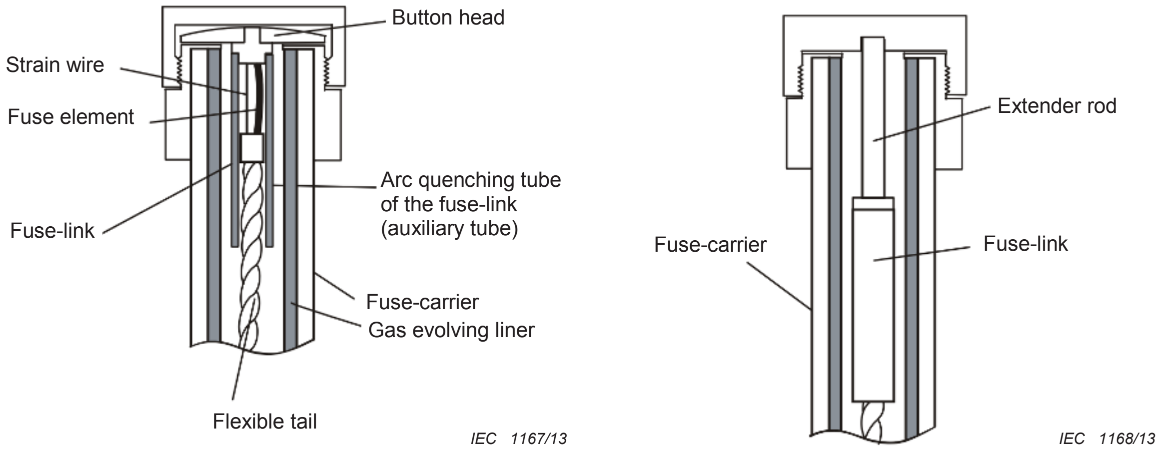
4.3.2.1 Class "A" expulsion fuses

4.3.2.1.1 Distribution fuse-cutouts

The most common type of "Class A" expulsion fuses are termed distribution fuse-cutouts. Indeed, in most countries, they are the most widely used type of outdoor fuse. Figure 7a shows the components of a typical distribution fuse-cutout. The fuse-base (support) consists of an insulator, traditionally made of ceramic, but increasingly of "non-ceramic" (i.e. polymer-based) material. A bracket, in its middle, supports it on a cross-arm, attached to a power pole. Terminals and contacts at the top and bottom are attached to the circuit and make electrical contact with a pivoted fuse-carrier. The fuse-carrier includes a tube lined with gas-evolving material, which contains the fuse element, typically mounted in a replaceable fuse-link.



7a) Distribution fuse-cutout components



7b) Typical fuse-link arrengement

7c) Fuse-carrier with extender rod

Figure 7 – Distribution fuse-cutout construction

Figure 7b) shows a typical fuse-link construction, mounted in a carrier, in which a small gas-evolving tube (termed arc quenching tube or auxiliary tube) surrounds the fuse element. The fuse element in this type of fuse is normally quite short (e.g. 30 mm) and is attached to a contact at the top of the fuse-link, and a flexible cable ("tail" or "leader") at the bottom. A strain wire in parallel with the fuse element permits the link to be mounted under mechanical tension. The flexible cable is attached to a contact at the bottom of the fuse-carrier, holding in place a latching mechanism that releases when the fuse element melts, enabling the fuse-carrier to swing open after current interruption. This provides an isolating distance (making it a "drop-out" fuse) and also visual indication of fuse operation. The current rating and melting characteristics of the fuse are governed mainly by the design of the replaceable link.

When the fuse element (and strain wire) melt in response to an overcurrent, the resulting arc is only moderately confined and burns in the fuse carrier bore of gas evolving ("arc-quenching") material. This material was traditionally made of fibre, but now tends to be made from a polymer material. When the fuse element melts with a low current, the arc burns only in the auxiliary tube, while at higher currents, this tube bursts and the fuse-carrier lining supplies the expulsion gasses. The liner is ablated by the arc and will give off gases, such as hydrogen and various hydrocarbons. This protects the tube wall from excessive erosion, while the arc burns stably with temperatures in the centre as high as 20 000 °C. These gases expel the metal vapour and the flexible tail out of the fuse tube. The movement of the flexible tail increases the arc length to that of the fuse carrier and is very beneficial to the dielectric recovery that occurs at a natural current zero. The gas produced is proportional to the heat released by the arc energy. The gas flow effectively cools and deionises the arc gap at current zero and allows the gap to withstand the TRV. This results in interruption of current flow in the circuit. Expulsion fuses, under some conditions, expel solid materials at high velocities upon fault current interruption. This should be considered in the mounting location of the device.

Some designs employ an expendable cap (Figure 7a)) at the top of the tube. At high fault currents it opens to relieve pressure and allow expulsion gasses to escape from both ends of the tube. Expulsion fuses that expel gas during operation from both ends of the carrier tube are known as "double venting types". This is one of the techniques that have been used to achieve higher rated maximum breaking currents for cutouts. An older design of distribution fuse-cutout uses a fuse-carrier permanently open at both ends.

Another technique that has been used to increase the maximum breaking current of a cutout is termed an extender rod or arc shortening rod. This is a conductive rod attached to the top contact of the fuse-carrier and the top of the fuse-link. Its effect is to move the fuse element further down the fuse-carrier, so that arcing commences closer to the open end of the tube. This reduces the pressure in the fuse holder. The technique is illustrated in Figure 7c). Making the fuse-carrier tube stronger, e.g. by using a filament wound glass epoxy construction, also assists in achieving a higher breaking current. Manufacturers will therefore often have several models of fuse-carrier, each having a different rated maximum breaking current suitable for different locations in a power system. An advantage of "single-venting" types is that there is no emission of ionised gas in an upward direction which could impinge on adjacent overhead lines.

4.3.2.1.2 Open–Link Cutouts

Open-link cutouts (see Figure 8a)) do not employ a fuse carrier, but rather suspend an open-link fuse-link between fuse clips. The fuse-link contains all the parts for extinguishing the arc, The clips include a spring action to tension the fuse-link. They operate in a similar manner to distribution fuse-cutouts described in 4.3.2.1.1, but typically have a relatively low interrupting capability, and are often used in conjunction with a Back-Up current-limiting fuse. Their use is declining. Despite being defined in IEC 60282-2:2008, they are not normally available tested to this standard but rather to a lighter duty (e.g. that specified for open-link cutouts in IEEE C37.41 [6]).

4.3.2.1.3 Enclosed fuse-cutouts

An enclosed cutout (see Figure 8b)) is similar to a distribution fuse-cutout, but has all of the live parts enclosed in a housing (usually made of porcelain). A hinged "door" supports the fuse-carrier. They may be of a drop-out design but commonly are not, this feature often being selectable by the user. They operate in a similar manner to distribution fuse-cutouts described in 4.3.2.1.1.

4.3.2.1.4 Capacitor fuses

A common type of capacitor expulsion fuse uses a fuse carrier mounted to a bus bar. A spring "arm" attached to a capacitor insulator connects to the fuse-link flexible tail, keeping it in tension. Operating principles are similar to those described in 4.3.2.1.1.

4.3.2.1.5 Liquid-submerged expulsion fuses

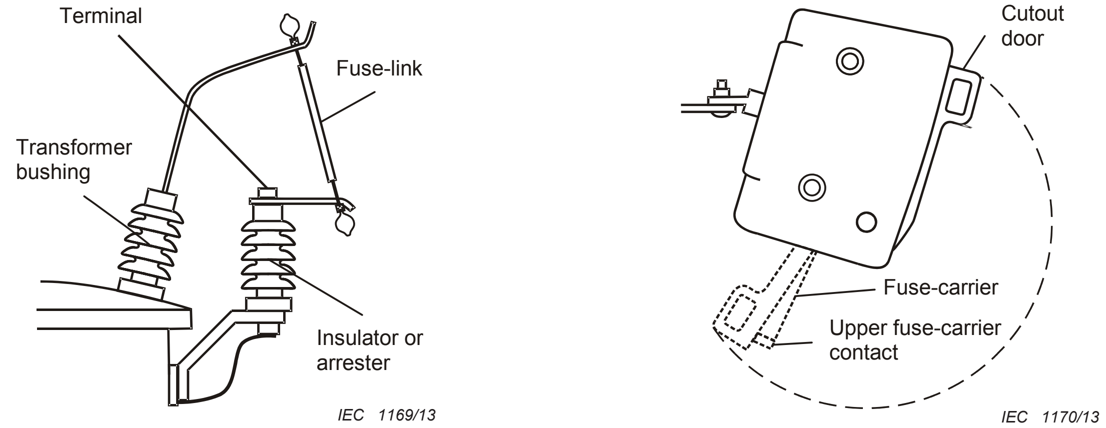
These are expulsion fuses in which arc extinction is effected by having the melting fuse elements immersed in an arc quenching liquid. They are very common in many parts of the world, mounted submerged in an insulating liquid (traditionally oil) in transformers or switchgear. They employ a strong, small diameter, tube with a fuse element suspended between terminals at each end. The tube is open to, and filled with, the surrounding liquid. Various names have been used for these fuses, including "cartridge" and "weak-link" fuses, but they are referred to as "liquid-submerged expulsion fuses" in IEEE Std C37.41 [6]. They operate on a similar principle to distribution fuse-cutouts (described in 4.3.2.1.1), except that insulating liquid (usually oil) is used as the dielectric medium. After the fuse element melts, the resulting arc heats, vaporizes, and dissociates the liquid. The gas and arc products vent from one or both ends of the fuse into a bulk tank containing the fuse and, typically, other components under the liquid. The deionising effect of the gas permits current flow to cease when appropriate dielectric conditions are met at a natural current zero. In many cases, the gas produced from the liquid is sufficient to complete the interruption process. At higher currents, the fuse tube wall also supplies gas to facilitate the interruption process. They have a very limited maximum breaking current.

A variation of this type of fuse positions the fuse-link in a fuse-carrier at the end of a draw-out rod, suspended in a supporting housing containing electrical contacts, as shown in Figure 8C. The assembly is mounted at an angle, so that the fuse-link is submerged while the top of the draw-out rod is above the liquid. After operation the fuse-carrier can be withdrawn from the liquid, and the fuse-link replaced. This type of fuse is commonly known as a "bayonet fuse".

Liquid-submerged expulsion fuses may be used alone for light duty applications, or in conjunction with current-limiting fuses where circuit conditions are more severe. Therefore, many types have been tested to conditions less onerous than the "Class A" requirements of IEC 60282-2. IEEE Std C37.41 [6] recognizes specific testing requirements for this type of fuse when used in switchgear applications, where they are referred to as "liquid-submerged expulsion fuses". While test conditions are similar to Class A fuses in IEC 60282-2, fewer test series are required due to their generally limited maximum breaking current.

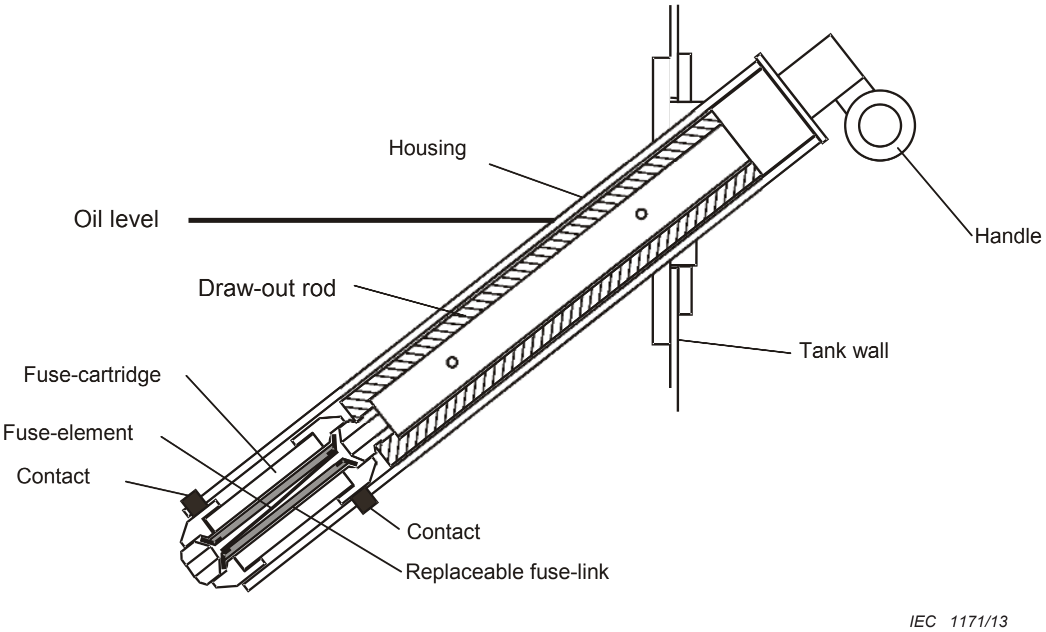
4.3.2.1.6 Liquid fuses

Another type of non-current-limiting fuse that surrounds the fuse element with liquid are called "liquid fuses" or sometimes "liquid power fuses" and are for outdoor use only. They usually consists of a glass tube sealed with ferrules at each end. The tube is filled with an arc extinguishing liquid, usually tetrachloroethylene and/or trichloroethylene. A short fuse element, usually a wire or notched strip, is connected to one end of the fuse. The fuse element is held in tension by a spring. A flexible lead connects the fuse element to the lower ferrule. These fuses operate in a similar manner to liquid-immersed expulsion fuses described in 4.3.2.1.5, except that no ablative tube is present to assist the interruption process at higher currents. However, when the fuse element melts, the spring draws the arc through the liquid increasing its length. To relieve the tube of excessive pressure, the fuse is fitted with a diaphragm at the upper end, which is ejected for all but the most modest of faults. They have a very limited maximum breaking current, and are tending to be replaced by more modern types of fuse.



8a) Typical open-link cutout arrangement

8b) Typical enclosed fuse-cutout



8c) Typical " bayonet fuse " assembly

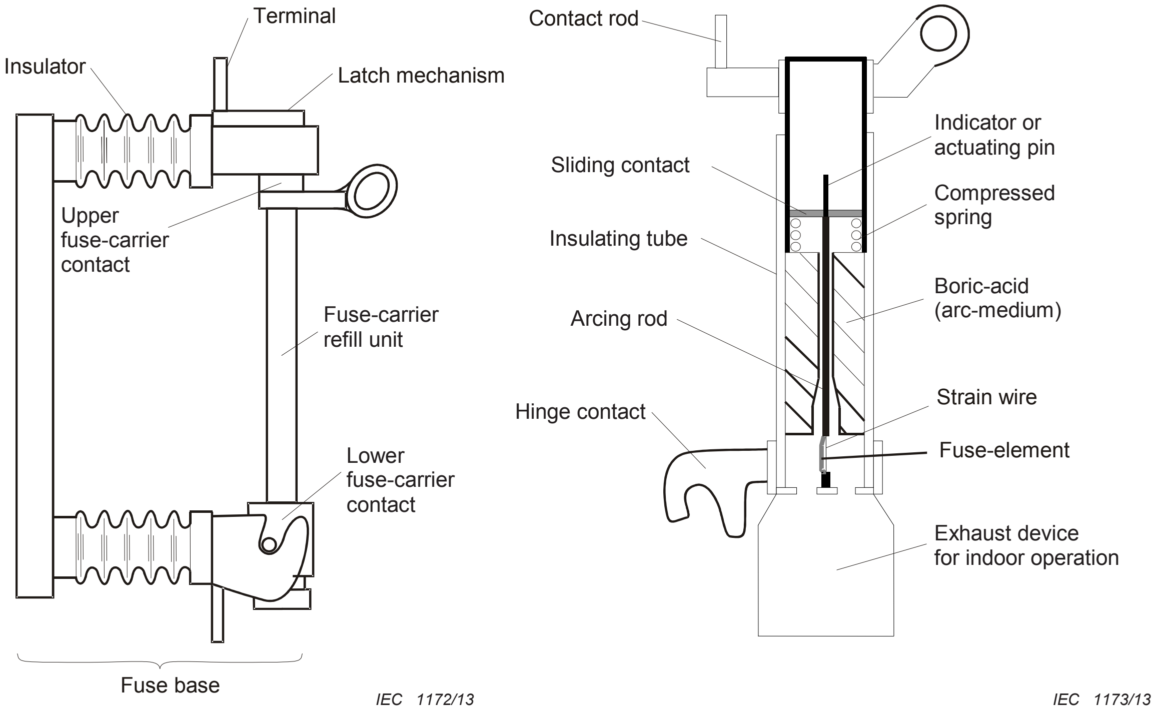
Figure 8 – Types of expulsion fuse

4.3.2.2 Class "B" expulsion fuses

These are commonly known as power-class expulsion fuses or boric-acid power fuses. The most common type, shown in Figure 9a), are expulsion fuses in which arc interruption is effected by use of a boric acid liner to the fuse-carrier tube. This gives them a higher interrupting capability, under more onerous circuit conditions, than Class A expulsion fuses. In addition, since water vapour is the primary gas produced during the interruption process, some power-class expulsion fuses can be provided with an exhaust-control device to condense the water vapour and virtually eliminate the effect of these gases. This allows their use indoors and in enclosures, in addition to outdoors. Some exhaust control devices do not require a reduction in the fuse's interrupting rating.

While in external appearance, Class B expulsion fuses can be similar to distribution fuse-cutouts described in 4.3.2.1.1, they employ a more complex internal structure, as shown in the simplified cutaway view of a typical fuse-carrier in Figure 9b). This includes a main bore for high-current interruption and, in some designs (not shown), a smaller, parallel, bore for low current interruption. They employ a rather short fuse element. Typically, the lower end of this fuse element is fixed within the carrier while the other end is connected to an arcing rod that is attached to a compressed spring. A strain wire usually parallels the fuse element to hold the arcing rod in place. When the fuse element melts (immediately followed by the strain wire), the arcing rod draws the arc through the boric acid block. This increases the arc length and length of boric acid exposed to the arc. Gasses produced by the arc are primarily water vapour, which cools the arc and produces a deionising effect. This effect is such that, at a natural current zero, the dielectric withstand of the arc gap is sufficient to withstand any transient and power frequency recovery voltage.

Boric-acid fuses typically use a replaceable refill unit, which contains the fuse element and associated parts necessary to restore a fuse to its original condition after an operation. Class B fuses can be drop-out fuses, like distribution fuse-cutouts, or remain in the fuse clips after operation like most current-limiting fuses.



IEC 1172/13

IEC 1173/13

9a) Typical Class B expulsion fuse

9b) Cutaway of typical boric acid power fuse

Figure 9 – Class B expulsion fuse

4.3.2.3 Application considerations

A consideration in the application of expulsion fuses is the criteria that the gases expelled are properly directed, and that the noise and pressure created is acceptable. Manufacturers' recommendations for the use of expulsion type fuses should be followed.

Distribution fuse-cutouts, or other types of fuses fitted with removable fuse-links, fuse-holders, or fuse carriers, have no inherent load-break ability when manually opened unless they are fitted, or used, with load-break means. There are three common ways to effect load breaking with such devices. The first is to use a separate load-break device, mounted on the switch-stick used to open the fuse. In this case no modification to the fuse is needed. The second way is to have a load-break mechanism, mounted to the fuse-base. Upon opening the fuse, the load current is initially carried by the separate device, which then effects the current interruption, often by a spring-loaded contact and gas evolving materials. A third way is to use a link-break mechanism. In this case, the fuse-link of the cutout is broken by a mechanical means, and current interruption is achieved through the usual fuse arc interruption process. It should be noted that some fuse-links use a coiled silver fuse element that may be too long to be broken by this means. Where, as is common, no such load breaking means is employed, then even for very light loads, it cannot be guaranteed that the cutout, when opened, will clear the circuit without damage. In this case the line should be disconnected, upstream of the device, before manual operation.

4.3.3 Classification of expulsion fuses

When selecting the Class and type of fuse that should be used at a particular location, factors such as power being supplied, dielectric properties of the equipment being protected, X/R ratios, fault currents available, and transient recovery voltage (TRV) severity require consideration. As a general guide the following may be considered.

- Class A (termed "Distribution Class" in IEEE standards)

  These fuses are generally applicable for the protection of small transformers and small capacitor banks used for power-factor correction or voltage control, located on power distribution systems of open-line type or cable type, and remotely placed from major substations. They are also applicable as protective devices at sectionalising points on such systems. TRV conditions are described by TRV test parameters, having lower values of u_c and longer values of t_3 than those for Class B fuses. They are generally used in single-phase applications, but are suitable for use in three phase applications where the high capabilities of the Class B (power) fuse are not required and other application requirements are met.

- Class B (termed "Power Class" in IEEE standards)

  These fuses are generally applicable to protect similar equipment as Class A fuses but in closer proximity to a major supplying substation and feeder circuits leaving such substations. TRV conditions are more severe than those for Class A fuse applications, and therefore have more severe TRV test parameters specified. They are more likely to be used in three-phase applications and in substations, cabinets or vaults where a large amount of electrical power is being supplied to a distribution system or some facility that requires large quantities of energy. They are generally used in that part of a system where high dielectric properties are required for all equipment. Alternatively, they may be used in single-phase applications in an area where distribution fuses would normally be used, but where severe faults, high X/R, or severe TRV is anticipated.

4.3.4 Ratings of expulsion fuses

4.3.4.1 Rated current

The rated current of an expulsion fuse is equal to the rated current of the fuse-link or refill-unit used. The rated current assigned to a fuse-link is the maximum current that a new fuse-link will carry continuously, without exceeding specified temperatures and temperature rises, when mounted on a fuse-base and, if applicable, within a fuse-carrier specified by the manufacturer, at ambient temperature of not more than 40 °C or as specified by the manufacturer. At surrounding temperatures higher than the specified temperature, surrounding temperature adjustment factors are usually available from the manufacturer (see 5.1.1.3).

4.3.4.2 Rated Voltage

System voltages vary greatly; however, one of the standard fuse voltages should be suitable. In all cases a rated fuse voltage equal to or higher than the maximum voltage impressed across the fuse during its operation should be chosen. In general it can be stated that a fuse rated voltage must be higher than the maximum system voltage measured phase-to-phase (line-to-line), in the case of three-phase circuits, and phase-to-neutral (line-to-neutral), in the case of single-phase circuits. However, in certain locations, operating experience has led to the use of fuses having a rated voltage at least equal to the phase-to-neutral voltage in certain three phase applications (generally those having a solidly earthed neutral). It must be recognized, however, that special conditions, and assumptions, must be valid to permit this, and additional testing by the fuse manufacturer may be required. In some cases fuses are tested with the intention that they will only be used in three-phase circuits. When such devices are used in single-phase circuits, special fuse voltage selection considerations apply (see 5.1.3.2).

In general, expulsion fuses can be used at any voltage lower than their rated voltage without adverse consequences.

4.3.4.3 Rated maximum breaking current (rated maximum interrupting current)

The rated maximum breaking current assigned to a fuse and a fuse-carrier is the maximum breaking current (in amperes r.m.s. symmetrical) specified when tested in accordance with the appropriate standard (test duty 1 or I_1). It is the highest current that the fuse has been demonstrated to be capable of interrupting under specified conditions of frequency, a.c. current component, TRV, power frequency recovery voltage and power factor (or X/R).

The specified power factors are generally more severe than those experienced on actual power systems. For the rare cases where the system power factor is less than that specified in the testing of the fuse, reduction of the interrupting rating may be necessary. The fuse manufacturer should be consulted.

In many applications, the available fault current is within the maximum breaking current of a single expulsion fuse. In some applications, particularly where Class A fuses are being used, the available fault current may be higher than the maximum breaking current of a single fuse. In this case it is quite common to add a current-limiting fuse in series to interrupt currents higher than the expulsion fuse’s rated maximum breaking current. The expulsion fuse is then used for clearing the low fault currents below the Back-Up fuse’s minimum breaking current. Coordination of these two devices is covered in 5.1.4.2.4 and 5.2.2.4.

Since Class B fuses are often used for three phase applications, some manufacturers provide equivalent three-phase interrupting ratings so they may be compared with other types of circuit interrupters that are rated for three-phase capability.

4.3.4.4 Rated frequency

Standardized values of rated frequency are 50 Hz, 50/60 Hz and 60 Hz. Tests are performed at a frequency between 48 Hz and 52 Hz for fuses rated 50 Hz and 50/60 Hz, and between 58 Hz and 62 Hz for fuses rated 60 Hz. They may be used in circuits having a frequency between 48 Hz and 62 Hz for fuses rated 50 Hz and 50/60 Hz, and between 58 Hz and 62 Hz for fuses rated 60 Hz. Expulsion fuses are therefore suitable for use at higher frequencies than they are rated, but not lower frequencies. This is because expulsion fuses are sensitive to the I^2t flowing before a current zero is reached. The I^2t of the first loop of a fully asymmetrical current waveform, having the same r.m.s. symmetrical current value, is 20 % higher for 50 Hz than for 60 Hz.

4.3.5 Characteristics of expulsion fuses

Expulsion fuse manufacturers supply two fuse operating characteristics. They are the fuse’s pre-arcing (melting) Time-Current Characteristic (TCC) curve and the operating (total clearing) TCC curve.

For coordination studies (see 5.1 and 5.2) a minimum pre-arcing curve is normally required. If only a nominal curve is available the minimum curve may usually be taken as 10 % less than the nominal curve (in terms of current) although for some fuse element types, a tolerance of 5 % is achieved. Consult the manufacturer for details. The operating time-current characteristic curve represents the maximum pre-arcing curve (nominal curve plus maximum tolerances) plus the arcing time of the fuse. This curve also is required to conduct coordination studies.

In addition to designating a current rating for a fuse and fuse-link, manufacturers designate individual time-current characteristic shapes with a letter code. While some of these letter codes are specific to one or more manufacturers, there are two types of fuse-link that are designated as "type T" or "type K", according to their compliance with specific pre-arcing time-current characteristics. These characteristics are specified in standards (e.g. IEC 60282-2:2008 and IEEE C37.42 [7]) in the form of "gates". These gates are designated at 0,1 s, 10 s, and 300 s or 600 s (depending on current rating). At each designated time, a maximum and minimum current is specified for each current rating. To comply with a "K" or "T" rating the pre-arcing time-current characteristic curve must lie between the maximum and minimum values.

Such designation may assist in allowing interchangeability between alternative manufacturer's fuse-links for use in distribution fuse-cutouts. However, as noted in IEC 60282-2:2008 in the definition for interchangeability of fuse-links, the protective and interrupting performance provided by the combination of the selected fuse-link and the selected fuse-carrier can only be assured by performance test on the specific combination.

The difference in the pre-arcing time-current characteristics of K and T links lies at the shorter melting times. The longest time "gates" (600 s for link size over 100 A and 300 s for 100 A and below) are the same for K and T links. However, if K and T links are compared at a shorter pre-arcing time, the T link requires a higher current to produce melting. T links are therefore said to be "slower" and thus have a better surge resistance for the same longer-time pre-arcing characteristic. T links are therefore often used for capacitor applications. Where the higher surge protection is not needed, the "faster" K links are often used to give, for example, closer transformer protection. Speed, or speed ratio, is defined as the ratio between a current from the fuse’s minimum pre-arcing TCC (normally at 0,1 s) to the current at 300 s (or 600 s). Thus for a 100 A K fuse-link, the ratio is 7,6 while for a 100 T fuse it is 13,1. The 100 A T link therefore requires approximately 72 % more current to cause melting in 0,1 s than a 100 A K link.

4.4 Other related protective devices

4.4.1 General

While all fuses can, in theory, be tested to IEC standards (or other standards derived from them, such as IEEE C37.41 [6]), there are devices that are fuse-like or fuse-related but that may not be adequately tested if only the tests presently specified are performed on them. Such devices, and the additional necessary testing, may not be specifically recognized in standards for several reasons, including being the product of a single manufacturer, or being produced in quantities that are insufficient to warrant the development of a standard. In fact, it is believed that several of devices referred to in 4.4 are no longer being manufactured – however a brief description will be given here for completeness and because they may still be in service (and may require replacement by more modern devices). However, because they are not fully addressed in standards, little application information will be presented, and the manufacturer of such a device should be consulted for application information.

The devices to be discussed fall into two broad categories, electronically activated devices and non-current-limiting devices.

4.4.2 Electronically activated devices

4.4.2.1 Fuses and fuse-like devices

One variety of current-limiting device is commonly referred to as commutating current-limiters, triggered current-limiters, or electronically actuated fuses. When this report was published, they were the subject of an IEC PWI (Preliminary Work Item) "Commutating current limiting devices, with integral fuses, for high current rating applications". These devices carry the current through a very low impedance, path compared to the typical fuse element. The result is a higher rated current than traditional current-limiting fuses may achieve. Compared to conventional fuses, such devices are relatively complex and expensive, but have applications where very large current ratings are required along with some degree of current limitation.

Thus, larger sized transformers can be protected than would be possible with conventional current-limiting fuses. A schematic of this type of fuse is shown in Figure 10. Upon occurrence of a fault, this main current path is opened (for example by a pyrotechnic charge) and the fault current is commutated to a parallel current-limiting fuse, before the first peak. The shunt fuse, of traditional current-limiting design, interrupts the circuit. During the time the parallel fuse melts, arcs and interrupts the circuit, the parallel high current path must develop a dielectric withstand level to be able to withstand the arc voltage generated by the fuse. These devices typically employ electronic sensing to initiate a means of achieving high-speed switching of the main conductor. The electronics may also be used to selectively initiate interruption in a non-current-limiting fashion.

Another non-commutating fuse design that uses augmentation of the normal element melting process to achieve low current interruption is shown in Figure 11. The fuse element has an overcurrent sensor (the black dot) that produces the fuse’s TCC. A number of pyrotechnic chemical charges are located at strategic points along the fuse element. These charges are fired by passing current through them at the desired time. Under normal conditions, this circuit is isolated by a spark gap. When the main element opens, the fuse’s arc voltage breaks down the gap, and fires the charges, cutting the element to create sufficient series arcs that are required to interrupt low currents. This type of fuse can also be triggered by an auxiliary control module in a similar way to a commutating fuse. It is thought that this type of fuse is no longer being manufactured.

One national standard that defines an "electronically actuated fuse" (but provides no guidance as to its testing) is the National Electrical Code (NEC) (NFPA 70-1999 [11]) of the USA. It defines an overcurrent device that generally consist of a control module, that provides current sensing, electronically derived TCCs, and energy to control tripping, and an interrupting module that interrupts current when an overcurrent occurs. Electronically-actuated fuses may or may not operate in a current-limiting fashion, depending on the type of control selected.

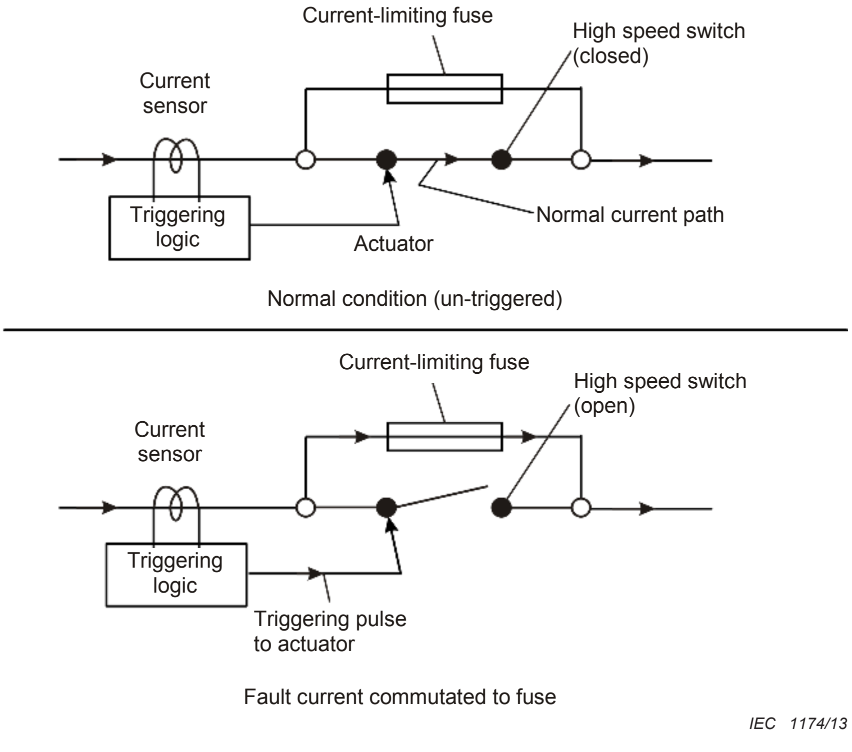


Figure 10 – Schematic of a commutating type of current-limiter

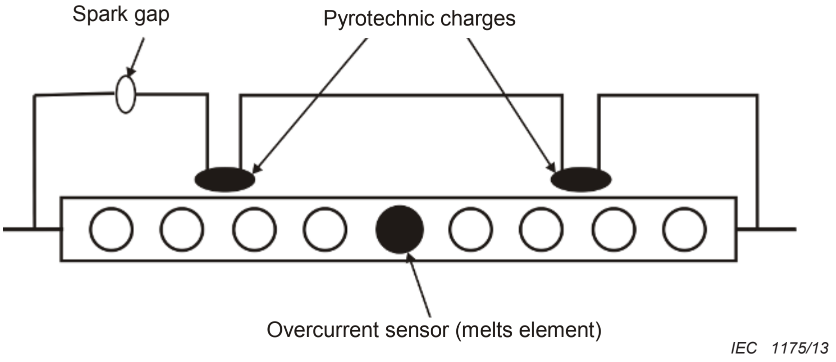


Figure 11 – Schematic of pyrotechnically assisted fuse

4.4.2.2 Automatic sectionalising links

Electronic automatic sectionalising links (ASLs) are designed to fit in place of the normal carrier tube of an expulsion fuse. The links contain a solid-state electronic circuit that is able to distinguish between transient no-damage faults and genuine permanent faults. In the event of the latter, the link disengages and drops down to provide isolating distance and visual indication. The link has no interrupting ability but operates during the dead time provided by the up-stream switching device (normally a recloser). While not in any sense a "fuse" they are included here because they utilize the fuse-base of a distribution fuse-cutout. Another "non-fuse" device that utilizes such a fuse-base is a "disconnecting cutout" (see IEEE C37.41 [6]) in which the fuse carrier is replaced by a solid blade. This is used for circuit switching (normally when used with an appropriate external switching device) and isolation.

4.4.3 Additional types of non-current limiting fuse

4.4.3.1 Horn gap fuses

Horn gap fuses are very simple devices in which two curved or angled metal strips are mounted on insulators and connected by a fuse wire (fuse element). The wire may be open to the air, or be enclosed in a glass tube for environmental protection. Each strip is connected to the circuit so that under overload conditions the fuse element melts and produces an arc. The natural interaction of the arc and the magnetic field produced by the current propels the arc up the "horns", elongating the arc. When the arc is long enough, it is extinguished at a natural current zero. Since quite long high-current arcs are relatively stable, these devices have a very low maximum breaking current. Although not generally tested to IEC or IEEE standards, because of their low cost they are widely used in developing countries.

4.4.3.2 SF_6 fuses

SF_6 fuses employ a tube filled with sulphur hexafluoride gas dielectric, axial contacts joined by the fuse element. SF_6 fuses have circuit interrupting capabilities similar to those of expulsion fuses. It is believed that this type of fuse is no longer being manufactured.

4.4.3.3 Vacuum fuses

Vacuum fuses typically have a very short fusible element attached to two opposing arc rotating plates that are mounted inside of a vacuum bottle. Vacuum fuses have circuit interrupting capabilities similar to those of expulsion fuses. It is believed that this type of fuse is no longer being manufactured.

4.4.3.4 Distribution oil fuse cutouts

Distribution oil fuse cutouts are devices that operate in a manner similar to liquid-submerged expulsion fuses. The oil fuse cutout typically contains a fuse carrier (tube) mounted on a rotating structure with contacts on each end, so that it may be used as a load breaking switch as well as a protective device. The contacts, fuse carrier, and fuse element are under oil in a vessel capable of withstanding very substantial pressures. Upon melting of the element, its ends are blown out of the carrier by a jet of vaporized oil. Hydrogen gas evolved by the dissociated oil cools the arc zone and causes rapid deionisation of the gases in the arc zone, which results in interruption of the circuit at a current zero. The carrier may also provide ablative effects to assist in the interruption process. It should be noted that these devices, while still possibly in service, are considered obsolete in some areas. While formerly recognized in IEEE standards, for example, references to testing these devices have been eliminated from current standards.

4.5 Fuse-bases (fuse-mounts or fuse supports)

4.5.1 General

A fuse-base, also called a fuse-mount or a fuse support, includes all of the parts required to hold a replaceable fuse-link or fuse-carrier together with insulators and terminals. The fuse base provides the dielectric properties of a fuse. It should be noted that some types of fuse-links are supplied for mounting by the user, as for example some liquid-submerged expulsion and current-limiting fuse-links and some external current-limiting fuse-links mounted on bushings, distribution fuse-cutouts, or attached directly to overhead distribution conductors. When only the fuse-link is provided, because a fuse-link has no inherent dielectric properties, the manufacturer can perform no dielectric testing of a fuse-link alone.

Fuses should be installed in accordance with the manufacturer's instructions. For multipole arrangements of fuses, when the distance between poles is not fixed by the construction, the poles should be mounted with clearances not less than those specified by the fuse and/or equipment manufacturer.

4.5.2 Insulation properties

The insulation properties of fuses are based on those of the fuse-base (fuse-mount or fuse support). The rated insulation level of a fuse-base is the voltage values (both power frequency and impulse) that characterize the insulation of the fuse-base with regard to its capability of withstanding dielectric stresses. IEC 60282-1 and IEC 60282-2 recognize groups of preferred voltages, series I based on common European voltages and series II based on common North American voltages.

Two levels of dielectric withstand are recognised for a fuse-base according to European practice (see Table 4 of IEC 60282-1 and IEC 60282-2). They are for voltage series I, and are termed "List 1" (lower values) and "List 2" (higher values). They relate to different severities of application and corresponding different values of test voltage for the dielectric tests. The choice between List 1 (lower values) and List 2 (higher values) should be made by considering the degree of exposure to lightning and switching overvoltage, the type of system neutral earthing, and the type of overvoltage limiting device (see IEC 60071-1).

Equipment designed to List 1 is suitable for installations such as the following:

a) in systems and industrial installations not connected to overhead lines:
    1) where the system neutral is earthed, either solidly, or through an impedance which is low compared with that for an arc-suppression coil. Surge protective devices, such as diverters, are generally not required;
    2) where the system neutral is earthed through an arc-suppression coil, and adequate overvoltage protection is provided in special systems, for example an extensive cable network, where surge diverters capable of discharging the cable capacitance may be required;
b) in systems and industrial installations connected to overhead lines through transformers where cables or additional capacitors of at least 0,05 μF per phase are connected

between the transformer lower voltage terminals and earth, on the transformer side of the fuses and as close as possible to the transformer terminals. This covers the cases:

1) where the system neutral is earthed either solidly or through an impedance which is low compared with that of an arc-suppression coil. Overvoltage protection by means of surge diverters may be desirable;
2) where the system neutral is earthed through an arc suppression coil, and where adequate overvoltage protection by surge diverters is provided;

c) in systems and industrial installations connected directly to overhead lines:

1) where the system neutral is earthed solidly or through an impedance which is low compared with that of an arc-suppression coil, and where adequate overvoltage protection by spark gaps or surge diverters is provided, depending on the probability of overvoltage amplitude and frequency of occurrence;
2) where the system neutral is earthed through an arc-suppression coil and where adequate overvoltage protection by surge diverters is provided.

In all other cases, or where a very high degree of security is required, equipment designed to List 2 should be used.

NOTE In case of application of rated lightning impulse withstand voltages of List 1, an agreement between manufacturer and user may be necessary concerning the maximum switching voltages specified.

The table of specified values for voltage Series II fuses does not have higher and lower rated lightning impulse values for each voltage. It does, however, differentiate between Class A and Class B expulsion fuses. Class A fuses (typically distribution fuse-cutouts) having comparable voltages to Series I have lightning impulse voltages slightly higher than the "List 1" values for voltages to 15 kV, and similar values to the List 2 at higher voltages. Class B expulsion fuses, and current-limiting fuses, have values slightly higher than List 2 values for indoor and outdoor fuses of all voltages.

Tables in the test standards specify withstand values "across the isolating distance". These values are valid only for fuse-bases where the clearance between open contacts is designed to meet the dielectric requirements specified for disconnectors (see IEC 62271-102).

Rated insulation levels may also be selected from values higher than those corresponding to the rated voltage of the fuse or fuse-base.

The manufacturer will state whether the fuse is suitable for indoor and/or outdoor service.

In selecting the rated voltage of the fuse-base, it is equal to "highest voltage for equipment" (IEC 60038) and should be selected from the rated voltage tables given in IEC 60282-1 and IEC 60282-2 (i.e. it should not be less than the highest phase-to-phase service voltage of the multiphase or single-phase system). It should be noted that successful completion of the dielectric withstand tests does not insure that fuses providing an isolating distance, when open, will always flash over to earth instead of across the isolating distance.

4.5.3 Current rating

The rated current of a fuse-base is a current that a new clean fuse-base will carry continuously, without exceeding specified temperatures and temperature rises, when equipped with a fuse-link, or fuse-carrier and a fuse-link of the same current rating designed to be used in the particular fuse-base. The fuse-base is connected to the circuit with certain specified conductor sizes and lengths, and is at an ambient temperature of not more than 40 °C.

The preferred values of the rated current of the fuse-base are 50 – 100 – 200 – 315 – 400 and 630 A for expulsion fuses, and 10 – 25 – 63 – 100 – 200 – 400 – 630 and 1 000 A for current-limiting fuses.

5 Application section

5.1 General application information

5.1.1 Service considerations

5.1.1.1 Temperature

5.1.1.1.1 General

Fuses complying with the IEC standards are designed to be used under the following conditions:

a) general conditions, all types of high voltage fuses:

   Equipment conforming to the relevant standards are rated for use at altitude that does not exceed 1 000 m, and the frequency of the power system is 50 or 60 Hz;

b) current-limiting fuses:
   - the maximum ambient air temperature is 40 °C and its mean measured over a period of 24 h does not exceed 35 °C;
   - fuse-links intended for use at surrounding temperatures above 40 °C (caused either by ambient temperatures above 40 °C or by use in an enclosure) have additional requirements, see 5.1.1.1.2;
   - the minimum ambient air temperature is –25 °C.

c) expulsion fuses:
   - the maximum ambient air temperature is 40 °C and its mean measured over a period of 24 h does not exceed 35 °C;
   - as expulsion fuses often are applied under outdoor conditions, it is furthermore required that the solar radiation does not exceed 1 kW/m^2;
   - for indoor application of expulsion fuses the preferred values of minimum ambient temperature are −5 °C, −15 °C and −25 °C;
   - for outdoor applications the preferred minimum values are –10 °C, −25 °C, −30 °C and −40 °C.

5.1.1.1.2 Application temperature

International standards recognize that fuses can be designed and tested as being suitable for two sets of usual service conditions. The difference between the conditions lies in the value of the Maximum Application Temperature (MAT) assigned to the fuse by its manufacturer.

a) If it is not intended that a fuse be applied under conditions where the temperature of the medium in direct contact with the fuse exceeds 40 °C, the usual service conditions listed in 5.1.1.1.1 apply. Interrupting (breaking) tests are performed at the temperature conditions prevailing at the site of the testing (within the service conditions of the fuse). This covers outdoor applications in most of the world, and use in large enclosures where there is a relatively free circulation around the fuse (for example in a vault).

b) If the manufacturer rates a fuse as being suitable for use in a higher surrounding temperature than 40 ºC, the second set of conditions apply, with the acceptable surrounding temperature now being from –25 °C/–40 °C to the Maximum Application Temperature (MAT) specified by the manufacturer. Fuses suitable for this second set of conditions are subject to the same testing as fuses of the first category, together with additional interrupting current tests, performed at the fuse’s MAT (with some exceptions for expulsion fuses).

Because surrounding temperatures above 40 °C typically occur if the fuse is mounted in an enclosure of some sort, this latter testing is often called "fuses in enclosures testing". If the fuse is in a relatively close fitting container, or if the container significantly changes the heat flow from the fuse, testing of the "fuse enclosure package" (FEP), that is the combination of fuse and enclosure, is normally necessary. Testing the FEP may be required even if the MAT of the FEP were not higher than 40 °C if, inside the FEP, the fuse itself is subjected to immediately surrounding temperatures above 40 °C, temperatures different than it would be subjected to in open air or liquid.

Obviously, the higher the surrounding temperature, the greater will be its effect on a fuse and its characteristics. See Annex A for advice on derating of current-limiting fuses in high surrounding temperatures.

It should be noted that in IEC usage, "ambient temperature" is the outside temperature and so is the temperature outside any enclosure. In other standards ambient temperature is used for the temperature of the fluid (liquid or gas) in contact with the fuse itself. Since ambient comes from the Latin "to go around" either interpretation is legitimate, but the difference can lead to confusion. In this report "surrounding temperature" is therefore frequently used to designate the temperature of the fluid that cools the fuse. A method to assess the temperature of the air inside an enclosure is presented in IEC/TR 60890 and Annex A.

5.1.1.1.3 Temperature influence on rated current (rated continuous current) and allowable continuous current

The rated current of a fuse (current assigned to a fuse-link or a fuse base) is the maximum current that the fuse can carry under normal service conditions without exceeding the maximum temperatures specified in the relevant fuse standard and without risk of long-term deterioration of the fuse elements. This latter point is of importance since, to ensure against such deterioration, many fuse designs will be assigned current ratings well below that which would result in the fuse reaching the limit of temperature allowed in the standard (in fact some designs of Full-Range fuses are intended to melt with overload currents that do not cause the fuse contacts to reach the maximum permitted temperatures). Therefore, for a given temperature of the cooling medium surrounding a fuse, a particular fuse design may be able to continuously carry a higher current, or only a lower current, than its assigned rated current. The current that a fuse can carry continuously, at a particular surrounding temperature, without deterioration and without exceeding the specified temperatures, is defined as its "allowable continuous current". When manufacturers assign such ratings to their fuses, the information is usually in the form of de-rating (re-rating) factors applied to the fuse's rated current, or presented as a table of current ratings related to temperature.

5.1.1.1.4 Temperature influence on time-current characteristics

The Time-Current Characteristic (TCC) curve of a fuse is determined at an ambient temperature between 15 and 30 °C, and drawn for 20 °C. If the temperature of the medium that surrounds the fuse differs from this, a shift in the TCC may occur, with higher temperatures causing the fuse to melt faster for a given current. The degree of change to a fuse's TCC is a function of the individual fuse design, and is different for different types of fuse. Ambient/surrounding temperature adjustment factors are usually available from the manufacturer.

The most significant area of concern is usually change to the long time melting characteristics of fuses, since this may change the way a fuse is affected by an overload.

5.1.1.2 Current-limiting fuses in enclosures

5.1.1.2.1 General

Many applications require the use of current-limiting fuses in enclosures where the fuse and the associated contacts may be subjected to air temperatures above 40 °C. Other applications may require the fuse to be immersed in a liquid such as transformer oil that may attain quite high temperatures. Current-limiting fuses intended for such service should comply with the applicable design tests specified in accordance with IEC 60282-1 and/or IEEE Std C37.41 [6] (ANSI), IEEE Std C37.46 [8] and IEEE Std C37.47 [9] (ANSI).

When current-limiting fuses are applied in enclosures of any type, the performance characteristics of the total system should be evaluated, as detailed in the following subclauses. Suitability for a specific application of the fuse-link in an enclosure is the responsibility of the supplier of the fuse enclosure package (FEP) and the user is recommended to follow the instructions of the FEP manufacturer.

5.1.1.2.2 Types of fuse enclosure packages

Fuse Enclosure Package (FEP) types covered by this clause are:

- type 1CL: A fuse mounted in a large enclosure with relatively free air circulation within the enclosure (e.g. a fuse mounted in a live-front pad mounted transformer or in a vault). The relevant fuse Maximum Application Temperature (MAT) is based on the temperature of the air that is cooling the fuse. It may be noted that, if a fuse were mounted outdoors but in an ambient temperature above 40 °C, conditions on the fuse would be the same;
- type 2CL: A fuse mounted in a fuse canister (fuse-container). This is a relatively small enclosure, defined as one supporting the fuse and restricting the air, gas or liquid flow surrounding the fuse (e.g. a fuse inside a canister in a transformer or a vault). However, the fluid flow (gas, liquid, or a combination of the two) that cools the outside surface of the canister has relatively free circulation. The relevant fuse MAT is based on the temperature of the fluid that is cooling the canister. Fuses tested for use in air no hotter than 40 ºC, that are encapsulated with solid insulation (e.g. rubber or epoxy) can be considered to be this type of FEP when so encapsulated. In this case the relevant fuse MAT is based on the temperature of the fluid that is cooling the encapsulated fuse;
- type 3CL: A fuse directly immersed in liquid and mounted in an enclosure with relatively free liquid circulation around the fuse (e.g., an oil-immersed fuse in a transformer or switchgear enclosure). The relevant MAT is based on the temperature of the liquid in contact with the fuse.

Canister applications of current-limiting fuses
Drywell canisters (FEP type 2CL) are utilized to provide access to a current-limiting fuse in a transformer or switchgear housing and permit replacement in the event of a fuse operation. Typically, the drywell canister may be surrounded by air, SF_6, or oil, although oil, or an oil substitute, is the most common. The fuses used are typically standard indoor Full-Range current-limiting types. Another common use of canisters is in switch-fuse combinations. In this case the fuses are fitted with strikers, and Back-Up fuses are usually employed. Canister applications may have an impact on a current-limiting fuse's current carrying rating. Not only must heat be transferred from the current-limiting fuse to air in the container, but the heat must also be transferred from the container to its surrounding medium. Fuses used in drywell applications need to be rated for such applications and the current carrying rating may be different than for non-drywell applications. For example, the long-time melting current may be a de-rated value compared to that where the fuse is applied with free air movement. A particularly severe application is where fuse drywells are placed in the top oil of a loaded transformer, which often reaches 105 °C and perhaps as high as 135 °C under overload conditions.

Current-limiting fuses for liquid-immersed applications
Uses used for this application must be designed with the appropriate sealing system for use under-oil or in other liquids (FEP type 3CL) since if liquid enters the fuse, improper fuse operation or a failure of the fuse to clear the fault current and interrupt the circuit may result.

Current-limiting fuses designed for direct liquid immersion have excellent heat transfer means by the liquid. Thus, the long-time melt current may be higher than with the same fuse in air, at the same ambient temperature. As such it may be possible for the fuse manufacturer to assign a higher ampere rating to fuses for use in an liquid-immersed design than in a drywell or in-air design. However, this may only be the case where the liquid is at, or relatively close to, ambient temperature; i.e. where there is no other significant heat source, apart from the fuse itself, within the liquid enclosure. If instead, the fuse is applied inside a transformer, the liquid temperature may reach much higher temperatures than normal ambient temperature, which must be considered when determining fuse suitability. Therefore the fuse manufacturer must be consulted when applying such fuses.

IEC 60282-1 contains testing requirements to demonstrate the liquid-tightness of fuse-links used in situations where the fuse was the primary source of heat in the enclosure (e.g. switchgear). Liquid-tightness testing for applications where significant heating comes from other equipment in the enclosure (e.g. transformers) is included in IEEE Std C37.41 [6]. It is anticipated that such testing will be included in IEC 60282-1 in the immediate future. The fuse-link manufacturer should be consulted for information as to the suitability of fuse-links for such applications.

The use of current-limiting fuses near adjacent heat sources
Adjacent heat sources may raise the temperature of the fuse to an unacceptable level that may affect the fuse rating. The manufacturer should be consulted for advice under such conditions. Furthermore, the design of the current-limiting fuse may differ between manufacturers so that the advice from one manufacturer may not be applicable to a replacement product from another manufacturer.

The use of current-limiting fuses where there is restricted air flow/cooling
Restricted air flow (FEP type 2CL) will reduce the ability of the environment to act as a sink for the heat produced by the current flowing through the current-limiting fuse over a long period of time. Since the fuse cannot dissipate heat as effectively, a de-rating of the continuous current-carrying rating may result.

The use of current-limiting fuses in vaults or underground sub-station
Current-limiting fuses in vaults (FEP type 1CL) should be rated for the highest surrounding temperature anticipated in the vault. If the vault also contains other heat producing devices, such as transformers, then increased ventilation may be required. The size of the vault may also influence the air circulation within the vault. A small enclosed vault may trap excess heat and reduce the heat transfer from the fuse, which, as a result, may need to be de-rated.

The use of current-limiting fuses in outdoor enclosures
Vented outdoor enclosures (FEP type 1CL) will be affected by solar heating and therefore, it may be necessary to de-rate any current-limiting fuses used in the enclosure. Non-vented or poorly vented outdoor enclosures may also require a further de-rating of the fuse. Consult the manufacturer. Also, note that replacement fuses from another manufacturer may have a different de-rating factor (see 5.1.1.1.3) due to a different design.

5.1.1.2.3 Clearances and spacing in enclosures

The use of adequate insulating barriers may permit reduced separations when verified by proper tests. It should be remembered that standards permit voltages across the fuse (during fault interruption) of slightly more than three times system voltage, thus a fuse rated at 12 kV could produce up to 38 kV phase-to-phase or phase-to-earth while very low current ratings (see Table 8 of IEC 60282-1:2009) are allowed even higher values.

5.1.1.2.4 Maximum application temperature

The FEP application should take into consideration any higher fuse operating temperatures caused by its confinement or by elevated surrounding temperatures. The supplier of the FEP specifies the Maximum Application Temperature (MAT), in degrees Celsius, preferably selected from the R20 series of preferred numbers (typically 56, 63, 71, 80, 90, 100, 112, 125, or 140). It is the maximum ambient temperature at which a device is suitable for use without causing any deterioration that would inhibit the ability of the fuse to interrupt the circuit. In addition to the usual testing, a fuse has to demonstrate successful current interruption in an enclosure, or with conditions equivalent to an enclosure, with the surrounding temperature equal to the MAT.

(The R20 series is comprised of the numbers 1; 1,12; 1,25; 1,40; 1,60; 1,80; 2,00; 2,24; 2,50; 2,80; 3,15; 3,55; 4,00; 4,50; 5,00; 5,60; 6,30; 7,10; 8,00; 9,00 and their multiples of 10).

5.1.1.2.5 Rated current and allowable continuous current for an FEP

Fuses used in an FEP may not be able to carry their rated current (nameplate rating or rating marked on the fuse) without deterioration or without exceeding the maximum temperatures specified in the standard. This would also be the case for a fuse not in an enclosure, but subject to a surrounding temperature over 40 °C. The current a fuse can carry continuously under these different circumstances, without exceeding the specified temperatures, is defined as its allowable continuous current. This current is linked to a specific ambient temperature. Such a value, when the fuse is a part of an FEP, should be available from the FEP manufacturer, or often the fuse manufacturer. Information would normally be provided in the form of de-rating (re-rating) factors applied to the fuse's rated current, and would allow for the effect of enclosure and/or ambient temperature. Alternatively, a table of current ratings related to temperature may be supplied.

5.1.1.2.6 Fuses having a Maximum Application Temperature (MAT)

Some fuses are assigned a very high MAT (for example fuses intended to be used in transformers) and the fuse will only experience such temperatures in equipment experiencing severe overload or failure conditions. Testing at the MAT shows that the fuse can still interrupt under these conditions. In some cases, therefore, the MAT assigned to a fuse may be higher than the maximum contact temperatures permitted (see Table A.1). In this case, the fuse cannot be assigned an allowable continuous current at its MAT, only at a lower temperature where they would be expected to operate continuously.

If a fuse is required, and able, to operate under conditions that produce higher component temperatures than those specified in IEC 60282-1, this application should be by agreement between the manufacturer and user.

5.1.1.2.7 Time-current characteristics

The modification of the thermal environment for the fuse due to it being in an enclosure will cause some shift of the fuse TCC towards the left (lower current). Whether this is significant will depend primarily on the fuse construction (fuse element material and design). For example, fuse elements that melt at high temperatures (over 900 °C) generally have non-significant shift, while fuse elements that melt at lower temperatures will have a more significant shift. While, for some designs, there is an effect on the whole TCC curve, shifts at the long time melting region are usually of the most concern due to possible nuisance operation. Details of the resulting effect on the TCC because of a particular enclosure should be available from the FEP manufacturer. It is normally in the form of multiplying factors applied to the fuse's TCC.

It may be noted that use of the general rule of thumb coordinating factor, that is maximum clearing time of the load side protective device should not exceed 75 % of the minimum melt time of the source side device, generally provides sufficient allowance for TCC shift in the 0,01 s to 1 000 s region. However, for General-Purpose and Full-Range fuses, this rule may be insufficient for times longer than 1 000 s. Consult the manufacturer for specific adjustment information.

A second de-rating factor may be published by the FEP supplier. This factor gives the percentage reduction of the melting current at long pre-arcing times as related to the temperature of the gaseous or liquid dielectric surrounding the FEP compared to the standard 20 °C (25 °C for fuses tested to IEEE C37.41 [6]).

5.1.1.2.8 Fuse selection, rated current

When a fuse is to be used at an ambient temperature over 40 °C, or in an FEP, it is important to assess the effect of the environment on the fuse. The actual maximum application temperature should be compared to the fuse's MAT and the effect on current rating and TCC are relevant. It is important that conditions are not such as to cause deterioration of the fuse and associated components; an example of such a condition would be overloading Back-Up and General-Purpose current limiting fuses. It is also very important to ensure that changes in the fuse's TCC do not result in a fuse being called upon to interrupt a current for which it is not designed and tested. Attention should therefore be given to fuse coordination under all anticipated ambient temperature conditions.

Change to the pre-arcing TCC due to enclosure and elevated ambient temperature is usually of significance to General-Purpose and Full-Range current-limiting fuses, while the change in TCC is usually much less significant for Back-Up fuses. Therefore, Back-Up-type current-limiting fuses that are coordinated with other fuses (or overload sensing devices) intended to operate at low overload currents require no TCC de-rating factors. However, care should still be taken to ensure that Back-Up fuses used at high temperatures are not subject to overloading and possible deterioration.

5.1.1.3 Expulsion fuses in enclosures

5.1.1.3.1 General

Additional testing requirements for expulsion fuses in enclosures are not presently covered by IEC standards, and so requirements are by agreement between the manufacturer and user. However, IEEE Std C37.41 [6] may be used as a basis for such testing since it contains requirements for expulsion fuses in enclosures testing (and the normal test requirements for expulsion fuses are almost the same as requirements in IEC 60282-2). Therefore application advice in 5.1.1.3 applies specifically to fuses tested to IEEE Std C37.41 [6], and may not necessarily be appropriate for fuses that have not been so tested. In IEEE standards the preferred term for a close fitting enclosure that restricts fuse cooling is "fuse-container" rather than "canister". For CL fuses the most commonly used container is a canister (a dry-well canister or insulated canister) but not for expulsion fuses so the term fuse-container is used in 5.1.1.3)

When expulsion fuses are applied in enclosures of any type, the performance characteristics of the total system should be evaluated.

The fuse, fuse-container (if present), and the enclosure produce a system with interacting effects. Each component may be supplied by a different manufacturer. Data should be available from the component manufacturers to permit proper application. Suitability of a specific application of a fuse inside a fuse-container ("fuse and fuse-container" or F/C) should be the responsibility of the manufacturer of the F/C. Suitability of a specific application of a fuse or F/C in an enclosure should be the responsibility of the switchgear manufacturer. Proper application of the switchgear, based on the recommendations of the switchgear manufacturer, should be the responsibility of the user.

5.1.1.3.2 Types of fuse enclosure packages

Fuse-enclosure packages (FEP) using expulsion type indoor Class B (power Class) fuses covered by this clause are:

- type 1E: A fuse mounted in an enclosure with relatively free air circulation within the enclosure (e.g., an expulsion fuse mounted in an enclosure or vault);
- type 2E: A fuse mounted in a fuse-container with restricted air flow surrounding the fuse, but with relatively free air circulation within the enclosure on the outside of the container (e.g., an expulsion fuse in an enclosure with insulating barriers that form a container that restricts the air flow);
- type 3E: A fuse directly immersed in liquid and mounted in an enclosure with relatively free liquid circulating around the fuse (e.g., an expulsion fuse in a switchgear enclosure).

It should be noted that testing requirements in IEEE C37.41 [6] for liquid immersed expulsion fuses are only intended for fuses used in switchgear (not directly associated with transformers).

5.1.1.3.3 Clearances and spacing

Expulsion fuses generate high-pressure gases that are expelled during the interruption process. These gases should not be directed in a manner which reduces the dielectric withstand between phases and from phases to ground to a level that will result in dielectric breakdown.

Three-Phase assemblies should be capable of withstanding the transient and power-frequency recovery voltages associated with the simultaneous operation of fuses in all three phases.

Clearances between fuses of adjacent phases and from each fuse to ground should be sufficient to maintain adequate dielectric withstand at all times. Manufacturer's recommendations for proper clearances and spacing should be followed.

The use of adequate insulating barriers may permit reduced separations when verified by appropriate insulation tests.

5.1.1.3.4 Maximum Application Temperature (MAT)

Expulsion fuses used in enclosures or containers are assigned a Maximum Application Temperature (MAT), in degrees C, preferably selected from the R20 series of preferred numbers (typically 56, 63, 71, 80, 90, 100, 112, 125, or 140). It is the maximum surrounding temperature at which a device is suitable for use without causing any deterioration that would inhibit its ability to interrupt the circuit. In addition to the usual testing, a fuse has to demonstrate successful current interruption in the enclosure with the surrounding temperature equal to the normal test ambient temperature, if the assigned MAT is 55 °C or less, and at the MAT if it is higher than 55 °C. It should be noted that, in IEEE standards, the term "rated maximum application temperature" (RMAT) is used instead of "maximum application temperature" (MAT).

5.1.1.3.5 Reduction of allowable continuous current capability

An application that subjects the fuse to high surrounding temperatures may result in a reduction of the allowable continuous current that the fuse or fuse and fuse container (F/C) is capable of carrying, since the capabilities are usually related to a lower ambient temperature.

Allowable continuous current is the designated value of current that the fuse is capable of carrying in a specified surrounding temperature without exceeding the maximum total temperature limits permitted by the device design.

The manufacturer of the fuse or F/C should provide the allowable continuous current for each fuse applied. Usually, these capabilities are available based upon a 25 °C ± 5 °C reference ambient. Factors normally published by the fuse manufacturer give the percent reduction of the allowable continuous current capability for surrounding temperatures above 25 °C.

An additional factor will be needed if a fuse normally intended to be used alone is placed in a close-fitting container, thus producing a F/C. This factor adjusts for the condition that the temperature of air surrounding the fuse inside the container will be higher than the temperature of the air surrounding the F/C.

5.1.1.3.6 Time-current characteristics

When an expulsion fuse is used in an enclosure or container, an increase in surrounding temperature can cause a change in the fuse's melting time-current characteristics. Information on the resulting effect on the TCC because of a particular enclosure should be available from the enclosure manufacturer. Care should be taken if the change in characteristics affects coordination with other devices in a system. In the case of liquid submerged expulsion fuses, some designs are significantly more sensitive to liquid temperature than are others and so it is difficult to generalize. Consult the manufacturer for information on the effect of temperature on the TCC of the expulsion fuse.

5.1.1.3.7 Operating forces for expulsion fuses in enclosures

The manufacturer of the fuse or F/C should be consulted for the direction and magnitude of the force exerted by the assembly when it operates at its maximum interrupting rating. This is to ensure that the strength of the mounting arrangement is adequate.

5.1.1.4 Altitude

For altitudes above 1 000 m (3 300 ft) correction factors for current-limiting fuses can be found in 2.1 of IEC 60282-1:2009 and for expulsion fuses in 3.1 of IEC 60282-2:2008.

5.1.1.5 Indoor/outdoor/liquid submersible

Before any fuse is used, consideration should be given to the physical environment of the application and an appropriate fuse should be chosen. Improper selection and application of a fuse can result in damage to the fuse and associated equipment.

Fuses designed for indoor applications may not be suitable for outdoor applications and should not be so applied unless approved for such use by the manufacturer. Indoor fuses may not be suitable for application in enclosures in which the outdoor air circulates freely into the enclosure. Circulating fog, moisture, and condensation under adverse weather or other application conditions, such as dust and particle accumulation on insulating surfaces, may degrade the dielectric withstand capability of the device and its supporting structures.

Fuses for outdoor use must be of a design that can resist deterioration of the tube due to weathering, ultraviolet, and ozone, and should be capable of withstanding system recovery voltage for a period of time sufficient for locating and correcting the over-current problem that caused the fuse to operate. Fuses designed for outdoor use will usually be suitable for indoor applications also, unless the fuses emit ionized gases during the interrupting process. Outdoor fuses of non-ceramic construction may be longer than indoor types and/or utilize special weather resistant coatings since they are exposed to contaminants that may accumulate on the body of the fuse.

Some guidelines for estimation of acceptable limits for pollution and humidity may be found for current-limiting fuses in 2.1 of IEC 60282-1:2009 and for expulsion fuses in 3.1 of IEC 60282-2:2008.

5.1.1.6 Shock and vibration

If the fuse-link during normal installation and service conditions is subject to severe mechanical stresses, for example, shocks, vibration, etc., acting in one or several directions, it should be verified by consultation with the fuse manufacturer that the fuse-link can withstand these stresses without damage or deterioration. In addition, care must be taken that the means for electrical contact with the fuse-link does not deteriorate (e.g. spring pressure). Practical tests to prove the mechanical withstand of the fuse-links and contacts may be carried out by agreement between the user and the manufacturer of the fuses and the switchgear. For switch fuse combinations, see IEC 62271-105.

5.1.1.7 Fuse anticipated lifetime

As fuses normally operate without any moving mechanical parts, except for an eventual striker or indicator system operation, the experience is that under normal standard service conditions typical lifetimes of several decades are common.

Possible (outside the standard conditions) causes for lifetime reduction could be the influence of corona discharges (see 5.2.5.5) from the fuse element (especially smaller ratings), or, for expulsion fuses, influence from corrosive atmospheres that could degrade the fuse elements or outside barrel etc. Sustained overcurrents, higher than the rated current or allowable continuous current (see 5.1.1.1.3) of a fuse could also result in lifetime reduction.

Degrading of the outside barrel may, to a large extent, depend on the material employed.

5.1.1.8 Storage

For recommendations concerning storage of fuses see 5.3.5.2.

5.1.1.9 Noise and exhaust

Expulsion fuses may produce intense short-term noise levels during fault interruption. The height, location, and exhaust control of expulsion fuses should be such as to minimize the noise level at any location normally occupied by personnel. Some Class B expulsion fuses can be provided with an exhaust-control device to virtually eliminate the noise produced during an interruption.

Current limiting fuses complying with referenced standards are inert devices during normal service. It is also a requirement that no significant external emission takes place. Therefore, they are regarded as environmentally acceptable devices in service and operation.

5.1.1.10 Special service conditions/requirements

The majority of fuses presently manufactured conform to the usual service conditions. Fuses can be designed for other service conditions and still conform to the relevant standard, providing they are designed and tested with those other conditions considered in the design and testing process.

By agreement between the manufacturer and the user, HV fuses may be used under conditions different from the normal service conditions as defined in the relevant standard. For any special service condition, the manufacturer should be consulted.

Some national standards include additional requirements, including classifications related to special conditions of fuse applications, some of these are:

- spark production tests (AS 1033 [1] for expulsion fuses used in areas prone to bush/grass fires);
- mechanical robustness of fuse-links (IEEE C37.41 [6]);
- measurement of the resistance of fuse-links;
- verification of mechanical forces to open and to close drop-out (expulsion) fuses after mechanical operations;
- radio influence tests/partial discharge tests (IEEE C37.41 [6]).

The following is a listing of some of the conditions that fuses have in the past been designed to accommodate:

a) altitudes in excess of 1 000 m;
b) power system frequencies other than 50 or 60 Hz;
c) ambient temperatures less than –30 °C;
d) exposure to damaging fumes or vapours, excessive or abrasive dust, explosive mixtures of dust or gases, steam, salt spray, excessive moisture, or dripping water;
e) exposure to abnormal vibration, shocks, or tilting;
f) exposure to abnormal transportation or storage conditions;

g) abnormal space limitations;

h) abnormal operating duty, frequency of operation, difficulty of maintenance, etc.

Environmental effects on ratings of fuses
The user should recognize that some organic insulating materials may degrade under exposure to ultraviolet radiation and/or ozone. Both are present in outdoor applications, and protection needs to be provided for by the manufacturer and considered by the user in this application. In addition, fuses used outdoors are exposed to contaminants, pollutants, rain, snow, fog, smog, and other conditions (e.g., very high temperatures from direct sunlight or freezing conditions). All of these can affect the fuse’s ability to interrupt a circuit and withstand voltage. The manufacturer designs the fuse so that it can withstand these conditions and ensures that it has an adequate sealing system. Only fuses specifically designed for outdoor use should be applied outdoors. If there is doubt concerning the suitability of a fuse for outdoor use, the fuse manufacturer should be consulted.

Use of current-limiting fuses in hazardous environments/conditions
Current-limiting fuses typically do not emit ionized gases from the arc extinguishing process and may be suitable for use where combustible gas may be present in the area surrounding the fuse. The manufacturer should be consulted for all such applications. Without the emission of ionized gases, mounting locations are less restrictive. Caution may still need to be exercised to ensure that disconnecting the fuse does not result in a small arc that could ignite combustible gases. In like manner, operation of indicators or striker pins could result in small external arcs that may pose a problem in some applications.

5.1.2 Current rating selection

Selecting the appropriate current rating of fuse involves not only considering its current carrying capability relative to the requirements of the application, but also the shape of its time-current characteristic relative to various application specific requirements. It should also be noted that different fuse designs that have the same current rating will generally have somewhat different TCC curves because, in general, there is no standardization of TCC. The specific selection of fuse current ratings is therefore covered in Clause 10 in the appropriate individual application sections. Selecting the correct current rating/TCC shape is particularly important in the case of current-limiting fuses because mis-coordination can result in problems for the fuse (e.g. see 5.1.4.2.1).

In the case of currents higher than rated current (i.e. faults, overloads, and surges) different types of fuse will respond in different ways. Most types of fuse will have levels and durations of current to which they should not be subjected. For example, General-Purpose type current-limiting fuses should not normally be subjected to sustained currents higher than their rated current but lower than the current that causes melting in one hour. Because some fault/overload conditions can damage the fuse elements or other vital components of fuses, leaving them unable to interrupt correctly or vulnerable to melting at currents they cannot interrupt, an extensive system of coordination rules exists. These rules are intended to prevent the type of damage mentioned in this paragraph, and are discussed extensively in this document, particularly in 5.2.

5.1.3 Selection of the rated voltage of the fuse

5.1.3.1 General

Fuses are single-phase devices, responding only to the current that actually flows through them. Almost all testing requirements are therefore based on a single fuse interrupting current in a single-phase circuit. While fuses are widely used in single-phase circuits many fuse applications are in three-phase circuits. The majority of IEC testing requirements therefore assume that fuses will normally be used in certain types of three-phase circuit. Because the same assumptions cannot be used for all circuits, and because not all countries’ versions of IEC fuse standards make the same assumptions, a simple description of fuse voltage selection is not possible. Subclause 5.1.3 therefore describes recognised rules for choosing the rated voltage of a fuse for various common applications, when fuses have been tested to the minimum requirements of relevant IEC standards. However, other practices, that may vary somewhat from IEC practice, are also covered briefly, for informational purposes. As always, the user should defer to the fuse manufacturer for further information. One reason for this is that the standards permit a manufacturer to test at conditions more severe than those specified, and so their application guidelines may vary from those given here.

Selecting the correct fuse rated voltage for an application is of great importance. As explained in 4.2.1.2 and 4.3.1, all fuses are very sensitive to applied voltage during fault interruption. A fuse which interrupts perfectly well with the correct value of applied voltage may fail to interrupt at a somewhat higher value.

When system voltage is considered, it is the maximum system voltage that must be used when selecting the rated voltage of the fuse, not nominal system voltage. IEC (and IEEE) fuse standards do not specify interrupting test voltages higher than the voltage assigned to the fuse, its "rated voltage". While test voltages have a tolerance of -0 % $+5$ %, and the manufacturer may permit the maximum tolerance to be exceeded, it is not permitted to assume that the actual tests have been performed with a tolerance above $+0$ %. System voltage variations must therefore be within the recovery voltage capability of the chosen fuse.

The voltage rating of fuses used to protect shunt capacitors is covered in 5.2.4.

5.1.3.2 Expulsion fuses

Testing in accordance with IEC 60282-2:2008 requires that interrupting current type tests are performed at a voltage equal to the rated voltage of the fuse. Therefore, a fuse that has a rated voltage (rated maximum voltage) equal to, or higher than, the maximum system voltage that the fuse may encounter during its interrupting duty should be used. In a three-phase system, the fuse rated voltage should therefore be equal to or greater than the maximum phase-to-phase (line-to-line) voltage, and in a single-phase system the fuse rated voltage should be equal to or greater than the maximum single phase voltage.

The rated voltage of expulsion fuses may exceed the system voltage by any desired amount, as these non-current-limiting fuses do not generate any significant over-voltages during interruption. While over voltages are present across the fuse during the interrupting process, these are primarily due to the inherent circuit TRV; therefore the voltage rating of the fuse does not have a significant effect on the magnitude of the switching voltage.

While the most commonly used testing method requires fuses to be tested at rated maximum interrupting current (Test Duty 1 or I_1) and rated voltage U_r, if a fuse is to be used only in three phase circuits IEC 60282-2:2008 permits an alternative testing method to be used. It should be pointed out, however, that in practice this has an effect on very few applications. This alternative method allows Test Duty 1 to be performed as two separate tests. The first is at 100 % rated voltage but only 87 % of I_1 and the second test is at 100 % I_1 but only 87 % U_r. This assumes that the first fuse to clear under conditions of a three-phase unearthed fault will only see a voltage of 87 % of the phase-to-phase voltage (phase-neutral voltage multiplied by a first phase to clear factor of 1,5), but at the full three-phase prospective current. The second fuse to clear a three-phase unearthed fault (or the first fuse to clear a phase-to-phase fault) will see full phase-to-phase voltage, but at a reduced fault current of 87 % of the normal three-phase prospective current. Fuses tested in this manner may be used in a single phase circuit providing that:

- the single-phase circuit voltage is not higher than 87 % of the rated voltage of the fuse, or
- the single-phase circuit prospective fault-current is not higher than 87 % of the rated maximum breaking capacity of the fuse.

In the case of North American practice (IEEE standards) the alternative testing method is the "preferred" test method, although only for Class B, "power-class" expulsion fuses (and for power-class current-limiting fuses). In practice, the two tests are normally combined (the "preferred" IEC method), since this results in less testing for the manufacturer.

Not recognized in IEC standards, but common in many parts of the world, are "slant-voltage-rated" distribution fuse-cutouts (e.g. 15/27 kV). These are cutouts intended primarily for use on three-phase star connected systems with solid earthing (effectively grounded wye systems). IEEE Standard C37.41 [6] includes special testing for these devices. The principle is that a single cutout is tested with full line-to-line voltage at lower currents (below approximately 25 % of I_1), and at line-to-earth voltage at higher currents. An additional test requirement is that two cutouts in series must interrupt I_1 at line-to-line voltage. This test simulates the situation of a line-to-line fault not involving earth, with a cutout in each line performing the interruption. Certain assumptions regarding system conditions are needed for this application, and rules for voltage rating selection with circuits other than solidly earthed neutral systems are required. The manufacturer should therefore be consulted for advice on fuse voltage selection.

Cutouts having a rated voltage equal or greater than the system phase-to-neutral voltage are also used in some solidly earthed neutral systems where multiphase faults not involving earth cannot occur, or are unlikely. Again the manufacturer should be consulted, since additional protection techniques may be needed for such applications.

5.1.3.3 Current-limiting fuses

Testing in accordance with IEC 60282-1:2009 assumes that current-limiting fuses will be used in three-phase circuits. Consequently it requires that interrupting current type tests, where the fuse is in its current-limiting mode, are performed at a voltage equal to 87 % of the rated voltage of the fuse-link. The value of 87 % represents the recovery voltage across the first fuse to clear with an unearthed three-phase fault. It is assumed that the remaining two fuse-links will then share the line-to-line recovery voltage (and the interruption duty), and thus each will be exposed to less than 87 % of the line-to-line voltage. In the case of a line-to-line fault, not involving earth, again two fuses will share the duty when the fuse-links are in their current-limiting mode (see 5.1.6).

In a three-phase solidly earthed neutral system or low impedance or low resistance-earthed neutral system, the rated voltage of the fuse-link should be at least equal to the highest line-to-line voltage.

In a single-phase application, the rated voltage of the fuse-link should be at least equal to 115 % of the highest single-phase circuit voltage.

Because fuses are tested in a single phase circuit, the requirements of IEC 60282-1:2009 mean that when they are used on a three phase circuit, the power-frequency recovery voltage is not higher than the values specified for the breaking current tests (which, in the case of Test Duty 1 and Test Duty 2, are less than the rated voltage of the fuse). It should therefore be noted that a special condition occurs if fuses are used on a three-phase isolated neutral system or a resonant earthed system. Because a double earth fault can occur, with one fault on the supply side and one fault on the load side of a fuse on another phase, the rated voltage of the fuse-link should be at least equal to 115 % of the highest line-to-line voltage of the system e.g. for a maximum system voltage up to 20,88 kV, a 24 kV fuse may be used. A fuse having a rated voltage less than 115 % of the highest line-to-line voltage of the system may be used provided that all breaking current tests have been performed at a value at least equal to the highest line-to-line value (for example, the most conservative approach is if fuses have been tested with I_1 and I_2 currents having a recovery voltage equal to the fuse rated voltage). In this case, the manufacturer should be consulted for further information as to the suitability of fuses for this application.

It may be noted that IEC fuse standards that have been modified for use in some countries (e.g. IEEE Std C37.41 [6]), particularly where single-phase applications are common, require that the interrupting tests of some types of current-limiting fuse-links to be at 100 % of the rated voltage of the fuse. For such fuses the requirements in 5.1.3.3 for selecting a fuse-link having a rated voltage of at least 115 % of the highest system voltage is replaced by a requirement that the rated voltage be at least 100 %. Other testing requirements may take account of the reduced prospective current that occurs with a line-to line fault versus a three-phase fault (see 5.1.3.2 for a discussion of the testing requirements for expulsion fuses in IEC 60282-2 that permits the use of this method of testing). The manufacturer's literature should be consulted for clarification.

A current-limiting fuse generates a high switching (peak arc) voltage during interruption in order to achieve current limitation. It is therefore advisable to select a fuse voltage rating not more than twice that of the system voltage, in order to limit the stress on the system insulation (see 4.2.3.1 and 4.2.4.5). For information on the switching voltage produced by a specific fuse and voltage combination, consult the manufacturer.

The possibility of interruption by current-limiting fuses of capacitive currents in the case of single phase-to-earth faults should also be considered. If fuse-links are used in such a network system, without having striker tripping of the associated switch, tests may be carried out by agreement between manufacturer and user, in accordance with the appropriate test conditions of IEC 62271-103 (switches 1 to 52 kV). The test currents should be agreed upon in relation to the fuse-link to be tested and the values of the currents in the healthy and faulty phases during earth fault.

In some countries, fuse-links having a rated voltage less than the phase-to-phase voltage are used to protect transformers that have an earthed star connection on both the high voltage and low voltage sides. Typically, these fuse-links are tested at a voltage equal to or greater than the phase-to-neutral voltage. Advantages of this method of protection include the use of physically smaller fuses and reduced switching voltages. However, the use of this technique requires that certain assumptions, concerning the types of possible faults and percentage of transformer earthed load, apply to this application. The manufacturer of the fuse-link should be consulted for more information. In many cases, these fuse-links are Back-Up fuses and are used in conjunction with another fault interrupting device in series. The series device is generally required to have a voltage rating equal to or greater than the phase-to-phase voltage. When the two devices are used together, the combination must be capable of interrupting and withstanding system recovery voltage. This may require some specific assumptions, requirements, and testing to assure proper coordination between the two devices. Therefore the manufactures of the fuse(s) should be consulted.

Care should be exercised when selecting fuses for applications in multi-phase circuits if the assumption has been made that, under fault conditions, two fuses will be effectively in series and will share the line-to-line voltage. For two fuses to share the voltage, they must arc simultaneously. Consequently, fuses in all phases should be of the same fuse rating, the same model and/or type of fuse, and be from the same manufacturer; consult the manufacturer for more information.

5.1.4 Coordination between fuses, and between fuses and other protective devices

5.1.4.1 General

For the fuses on an electric system to operate properly and provide the desired system protection, consideration of voltage, continuous current and interrupting ratings is not sufficient to select the proper fuse for a particular application. One must also ensure that the fuse being selected will operate correctly relative to the other series connected protective devices that are used in the system.

A discussion on the procedures necessary to achieve this with all possible series devices is beyond the scope of fuse standards. However the most common applications will be discussed here. For coordination information not covered in this report, consult the manufacturers of the fuses and/or devices that are connected in series.

When the series devices are two fuses, the procedure by which coordination is accomplished is called fuse-to-fuse coordination. The coordination information in this subclause applies to conventional fuses that use a current responsive fuse element for detecting and melting when a particular current and time occurs.

Two fuse characteristics are primarily used to select fuses that coordinate with one another, the Time-Current Characteristics (TCC) of a fuse and its I^2t characteristics. The primary method is to compare TCC curves for the pre-arcing (melting) and operating (clearing) characteristics of the fuses involved (see 4.2.4.2 and 4.3.5 for a discussion on the relationship between manufacturing tolerances and minimum, nominal, and maximum curves). The minimum pre-arcing time-current characteristic curve shows the minimum time, expressed in seconds, required to melt the fuse-element(s) and initiate arcing for a particular value of symmetrical power-frequency current. The operating TCC curve (total clearing TCC curve) shows the maximum time, expressed in seconds, to complete current interruption at a particular value of symmetrical current. Both curves take into account variations resulting from manufacturing tolerances and represent performance under specific conditions. If nominal curves are published, they must be shifted to take account of the manufacturer's tolerances.

For all types of fuses, both the minimum pre-arcing curves and operating curves are plotted on log-log scales with a lower time limit of 0,01 s. The upper limit of time depends on the type of fuse. As current increases, the melting time of a fuse decreases, and the actual pre-arcing time of a fuse can vary if the current is not symmetrical. However, the pre-arcing (melting) I^2t decreases towards a fixed value, which is a function of the fuse-element material and geometry. Therefore, I^2t (which varies much less with current asymmetry) is often used to assist with coordination. Also at high currents and very short pre-arcing times, the operating I^2t of current-limiting fuses (see 4.2.4.4) may be used in determining coordination with other devices.

For fuses that are not current-limiting, clearing cannot occur until a natural current zero occurs. For long melting times this may require several cycles of arcing, while at short melting times, it cannot occur before the first current zero. Time-current curves are generated using symmetrical currents because, with asymmetrical currents, each fuse would have an infinite number of curves depending on the current initiation closing angle and circuit power factor. However, for coordination purposes at high currents, the longest time that a fuse might take to clear is one asymmetrical loop, no matter how high the current. This value is approximately 0,013/0,016 s (0,8 of a cycle) for typical test power factor and 60/50 Hz. Consequently the operating time-current characteristic curve of a non-current-limiting fuse is drawn down to a time of approximately 0,013/0,016 s, at which time it becomes a horizontal line giving a constant clearing time for all higher currents. As a result, the operating curve of a non-current-limiting fuse will always cross the minimum pre-arcing curve of any larger fuse when these devices are compared for coordination purposes, resulting in special coordination considerations that will be discussed later.

When coordinating fuses (or fuses and other devices) in a system it is generally desired that the down-stream fuse (the fuse closest to the load) melts and then clears the circuit before the up-stream fuse (the fuse closest to the source) melts.

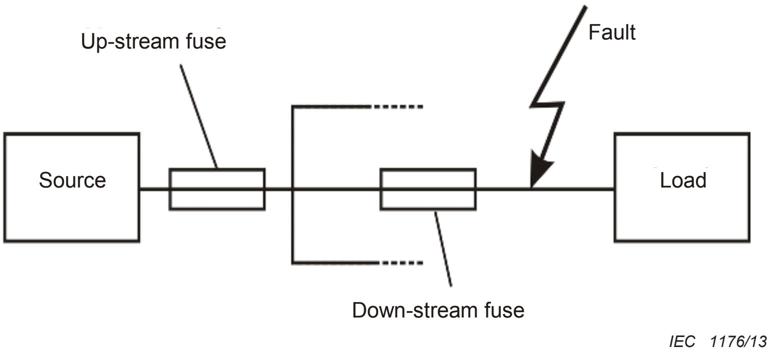


Figure 12 – Description of the terms "up-stream" and "down-stream" fuses

This method isolates the faulted portion of the circuit with a minimum of disruption to the remainder of the circuit.

NOTE In the following subclauses the terms "up-stream" and "down-stream" follow the preceding description as illustrated in Figure 12. In some literature the up-stream fuse is called the "protected" device, since the down-stream ("protecting") fuse operates and "protects" it from operating or from being damaged.

5.1.4.2 Fuse-to- fuse coordination procedures

5.1.4.2.1 General

Properly coordinating fuses in the area above 0,01 s is basically a matter of keeping the pre-arcing curve of the up-stream fuse above and to the right of the operating curve of the down-stream fuse within the range of fault current available at the down-stream fuse. To allow for variables such as preloading and ambient temperature variations the manufacturer may be consulted. In the absence of manufacturer's data, one of the following commonly used techniques may be used. A value of 75 % of the pre-arcing time of the up-stream fuse is generally used to make allowances for operating variables such as, preheating of the fuse element by the load current, normal variations in ambient temperature and preventing damage to the element of the up-stream fuse. To use this 75 % method, align the 4-second line of the up-stream fuse pre-arcing curve with the 3-second line of the down-stream fuse operating curve. Another method is to allow a 10 % safety-margin in current for any value of time.

In addition to limiting the area affected by a fault, coordination often seeks to minimize the risk of a correctly operating fuse exposing a series connected fuse to damage from that fault. In this sense, "damage" is where the partial, but not full, melting of a fuse’s element(s) occurs, which then changes its operating characteristics. Such a change might result in the damaged fuse melting at some later time, with a current that otherwise might not cause it to melt. If the fuse then interrupts correctly, it is classed as a "nuisance" operation. However, particularly in the case of current-limiting fuses, the fuse may be unable to interrupt the current (e.g. it may be a current below the minimum breaking current of a Back-Up fuse) leading to a failure. For this reason appropriate "safety-margins" are incorporated into the standard coordination procedures.

For Back-Up current-limiting fuses, currents that are less than the rated minimum breaking current, but will still melt the fuse element(s), are often shown as a dashed or broken line on the pre-arcing TCC curve. Currents less than the minimum current the fuse can interrupt are usually not shown on the operating curve since the fuse cannot reliably interrupt those currents, but they may be shown as a broken line on a maximum operating curve, when they represent the maximum pre-arcing TCC curve.

Other information provided by the fuse manufacturer, and needed for correct coordination in some cases, includes the rated maximum breaking current (rated maximum breaking capacity or rated maximum interrupting current) of the fuse. This rating should not be exceeded. Other characteristics such as minimum pre-arcing I^2t, maximum operating I^2t, and peak let-through current versus prospective current charts are also published and generally available.

5.1.4.2.2 Expulsion fuse to expulsion fuse

The down-stream fuse must clear the maximum fault current at its location before the up-stream fuse is damaged. To prevent damage to the up-stream fuse, the operating time of the down-stream fuse should be less than 75 % of the minimum pre-arcing time of the up-stream fuse for all current up to the maximum fault current where the down-stream fuse is located.

5.1.4.2.3 Current-limiting fuse to current-limiting fuse

As with expulsion fuse to expulsion fuse coordination, the down-stream fuse must clear the maximum fault current at its location before the upstream fuse is damaged. To prevent damage to the up-stream fuse, the operating time of the down-stream fuse should be less than 75 % of the minimum pre-arcing time of the upstream fuse for all current up to the maximum prospective current where the downstream fuse is located.

With higher fault currents, current-limiting fuses are capable of interrupting in less than 0,01 s, which is the shortest time shown on fuse TCC curves. If the TCC curves of the two fuses do not intersect above the 0,01 s line and the prospective current at the downstream fuse is of sufficient magnitude, i.e., to the right of where the up-stream fuse melt curve crosses the 0,01 s line, coordination in the current-limiting range must be confirmed. For this coordination, 75 % of the minimum pre-arcing I^2t for the upstream fuse should be greater than the operating (clearing) I^2t of the down-stream fuse. This is referred to as "I^2t coordination" The manufacturer's values for minimum pre-arcing (melt) I^2t and maximum operating (clearing) I^2t of current-limiting fuses should be published and readily available.

An example of current-limiting fuse/current-limiting fuse coordination is as follows: check the coordination between a 125 A Full-Range current-limiting fuse (CLF) and a 63 A General-Purpose CLF at point "A" as shown in Figure 13. Also, verify that the 125 A CLF will be able to operate correctly with faults between it and the 63 A fuse (i.e. in its zone of protection). This consideration is discussed in detail in 5.2.1.5 under the term "Reach".

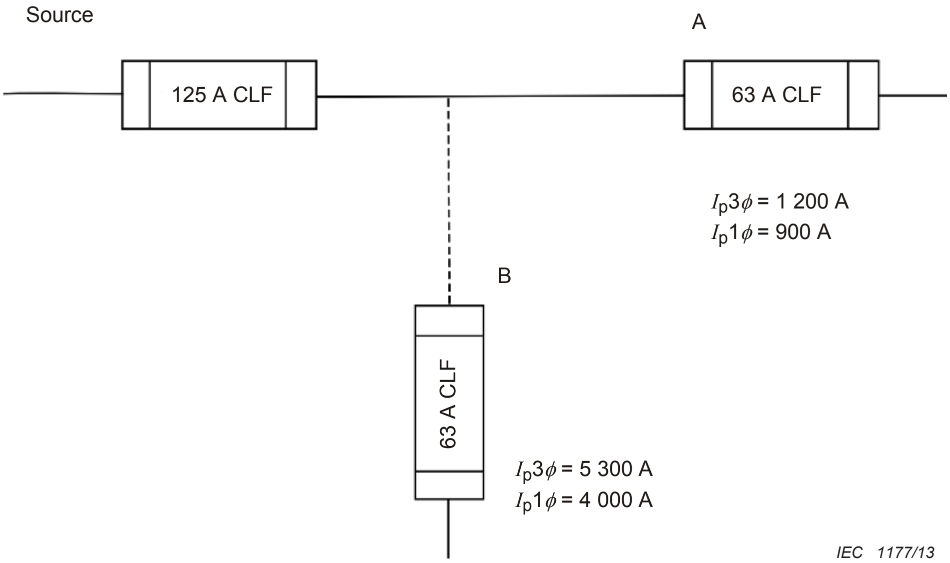


Figure 13 – Current-limiting fuse/Current-limiting fuse coordination example

The TCC curves for this combination are illustrated in Figure 14. Before comparing the fuse TCC curves, verify that the 125 A CLF has adequate reach (can operate with a fault at point "A"). At point "A", the phase to earth prospective current I_P is 900 A (assuming a bolted fault, that is a fault having no impedance). A Full-Range current-limiting fuse, can interrupt any current that causes it to melt, so it will operate with a current corresponding to the top of its published minimum pre-arcing TCC curve. However a fault persisting for hours would not be desirable so a utility will likely pick a shorter time for which they would like fuse operation. If a time of 300 s is chosen as a desirable maximum, the 300 s current for the 125 A fuse is 300 A. Since the phase-to-earth fault current at the 63 A fuse is 900 A, the fuse will melt in less than 300 s. However, another consideration is the fact that actual fault currents will be somewhat less than the calculated value, as a result of fault impedance. In this example, the current could be one third less (a "reach margin" of 3, see 5.2.1.5) and still operate the fuse in less than 300 s.

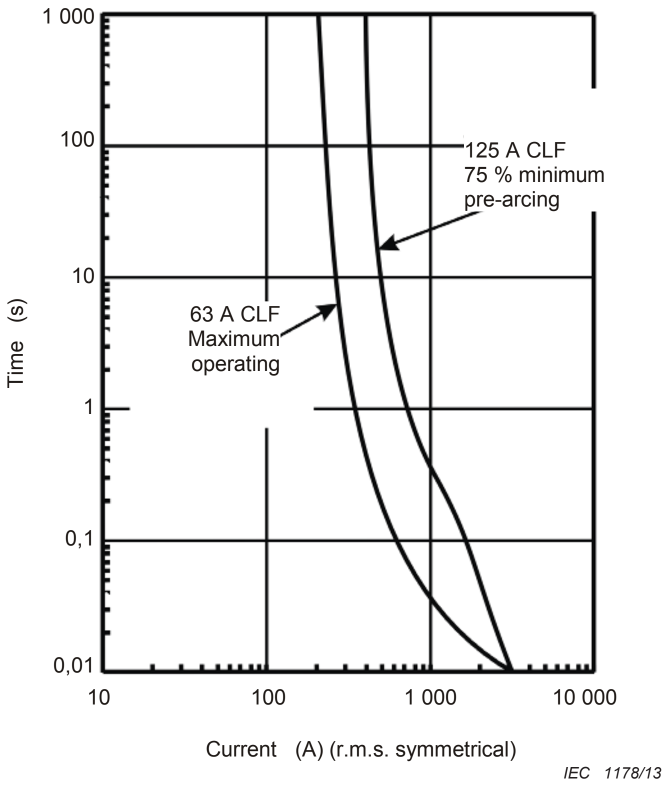


Figure 14 – Current-limiting fuse/Current-limiting fuse TCC curve example

To check TCC curve coordination between the 125 A and 63 A fuse, draw the 75 % minimum pre-arcing curve for the 125 A CLF and the maximum operating curve for the 63 A CLF. Note that the curves intersect at approximately 3 100 A, and at a time below 0,01 s. Therefore, since the maximum prospective current at the 63 A CLF does not exceed 3 100 A, time coordination exists. Because the prospective current is less than the point at which the 125 A TCC curve crosses the 0,01 s line, I^2t coordination does not need to be checked.

Had the prospective fault current at the 63 A fuse been higher, 4 000 A for example (position B in Figure 13), then I^2t coordination would have to be checked. The maximum operating I^2t for the 63 A fuse is 100 000 A^{2}s, while the minimum pre-arcing I^2t for the 125 A fuse is 100 800 A^{2}s. In this case, I^2t coordination at 4 000 A would not be achieved (100 000 A^{2}s $>$ 0,75 × 101 000 A^{2}s = 75 750 A^{2}s). If a 160 A fuse could be used instead of the 125 A fuse (with a pre-arcing I^2t of 136 000 A^{2}s) then this would be acceptable (100 000 A^{2}s $<$ 0,75 × 136 000 A^{2}s = 102 000 A^{2}s). Reach would still be acceptable because although the 300 s current would be higher (at 350 A) the prospective fault current is also higher. Coordination of the larger 160 A fuse with up-stream protection would also need to be checked.

5.1.4.2.4 Current-limiting fuse to expulsion fuse coordination

In this coordination, the current-limiting fuse is the up-stream device. Therefore, the maximum operating TCC curve of the expulsion (down-stream) fuse should be compared with the adjusted (reduced to 75 % in time) minimum pre-arcing TCC curve of the current-limiting (up-stream) fuse. As explained in 5.1.4.1, the operating TCC curve of the expulsion fuse becomes horizontal at a time of 0,8 of a cycle, so the curve will always cross the pre-arcing curve of the current-limiting fuse. Therefore, this fuse arrangement can only achieve coordination up to a certain current level, where the two curves cross.

An example of current-limiting fuse/expulsion fuse coordination is as follows: check coordination between a 100 A Full-Range current-limiting fuse and a 40 A expulsion fuse-link as shown in Figure 15. Also, verify that the 100 A current-limiting fuse has adequate "reach" (see 5.2.1.5 and 5.1.4.2.3) for its zone of protection. The TCC curves for this combination are illustrated in Figure 16.

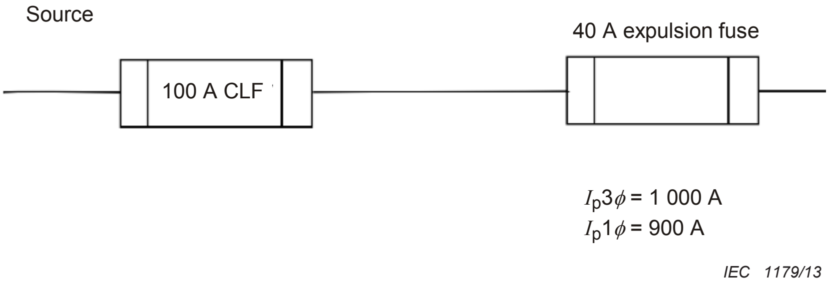


Figure 15 – Current-limiting fuse/Expulsion fuse example

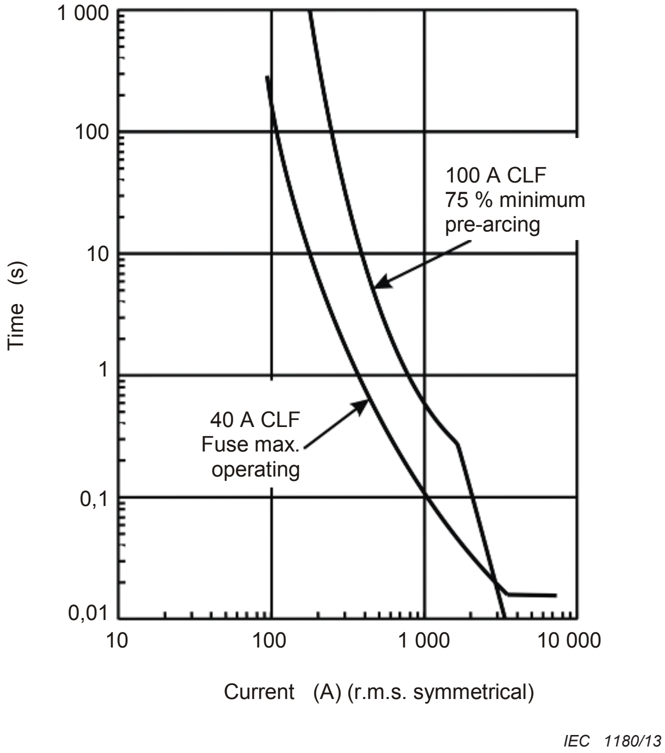


Figure 16 – Current limiting fuse/Expulsion fuse TCC curve example

Before comparing the fuse TCC curves, verify that the 100 A current-limiting fuse has adequate reach. The 100 A fuse must reach to the location of the 40 A fuse-link where the calculated fault current of 900 A is the lowest within its zone of protection. For a Full-Range current-limiting fuse, the fault current should be sufficient to melt the fuse in 300 s or less. The 100 A current-limiting fuse melts at approximately 220 A in 5 min. The ratio between the prospective current at the end of the zone protected by the 100 A current-limiting fuse and the 300 s fuse pre-arcing current is 900/220 = 4,1. This is higher than most normally used reach factors, so the 100 A current-limiting fuse has adequate reach.

To check coordination, draw the maximum operating TCC curve of the 40 A fuse-link and the 75 % minimum pre-arcing curve of the 100 A fuse. The curves intersect at approximately 2 800 A. Therefore, since the maximum fault current at the 40 A fuse-link, I_P, is 1 000 A, time coordination exists. Had the prospective current been over 2 800 A, coordination could not be guaranteed and operation of the expulsion fuse could damage the fuse elements of the current-limiting fuse.

5.1.4.2.5 Expulsion fuse to current-limiting fuse coordination

In this coordination, the expulsion fuse is the up-stream device.

For this case, the maximum operating TCC curve of the current-limiting (down-stream) fuse must lie to the left of the adjusted (typically downward to 75 % in time) minimum pre-arcing TCC curve of the expulsion (up-stream) fuse for all current values up to the maximum fault current available at the location of the current-limiting fuse. In addition, if the prospective current at the location of the current-limiting fuse is greater than the current where the current-limiting fuse maximum operating TCC curve crosses the 0,01 s line, the maximum operating I^2t of the current-limiting fuse must be verified to be less than the calculated minimum pre-arcing I^2t of the expulsion fuse, adjusted for preloading.

An approximation of the minimum pre-arcing I^2t for the expulsion fuse can be obtained by squaring the minimum pre-arcing current of the expulsion fuse at 0,015 s and multiplying this value by 0,015 s for 50 Hz (0,0125 s for 60 Hz). The adjusted value will be 75 % of this. Of course, if the manufacturer's I^2t data is available, it should be used.

An example of expulsion fuse/current-limiting fuse coordination is as follows: check coordination between a 160 A expulsion fuse and a General-Purpose 80 A CLF as shown in Figure 17. The TCC curves for this combination are illustrated in Figure 18.

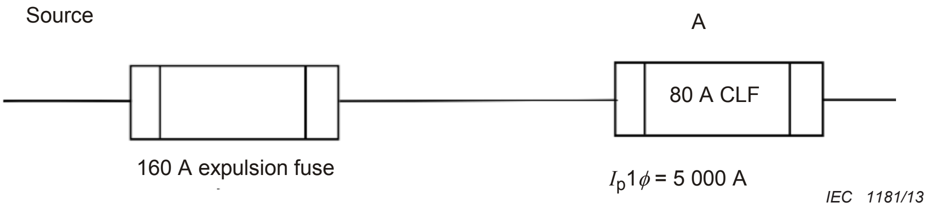


Figure 17 – Expulsion fuse/Current-limiting fuse example

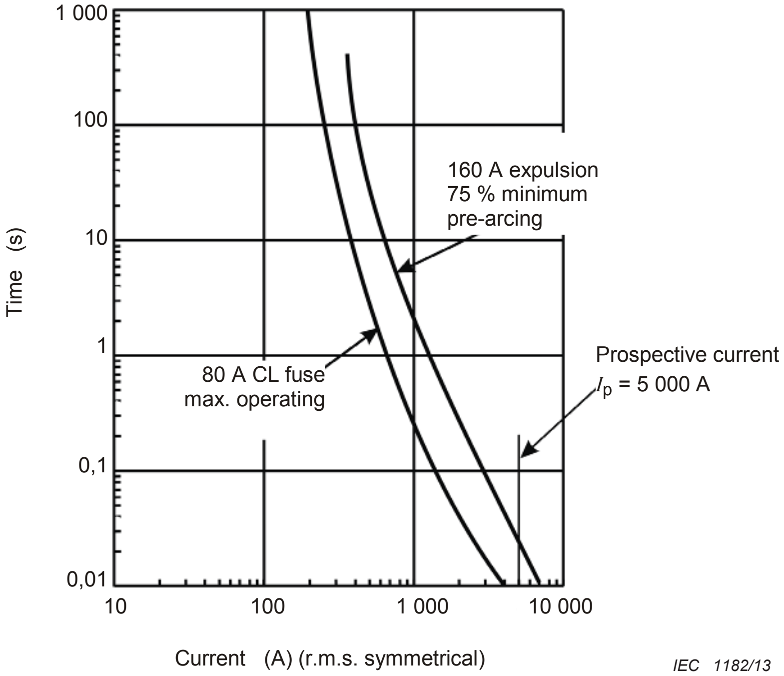


Figure 18 – Expulsion fuse/Current-limiting fuse TCC curve example

To check TCC curve coordination, draw the maximum operating TCC curve of the 80 A current-limiting fuse and the 75 % minimum pre-arcing TCC curve of the 160 A fuse-link. The curves do not intersect; therefore, TCC curve coordination exists.

Since the maximum available fault current I_P of 5 000 A is greater than the current value where the 80 A CLF maximum operating curve crosses the 0,01 s line, the maximum operating I^2t of the 80 A CLF is compared with 75 % of the minimum pre-arcing I^2t of the 160 A fuse-link; the maximum operating I^2t of the 80 A fuse is 181 000 A^2s, as specified by the manufacturer. The minimum pre-arcing curve for the 160 A fuse-link crosses the 0,015 s line at approximately 6 000 A; therefore,

$(6\,000)^2 \times (0{,}015) \times (0{,}75) = 405\,000\ A^2s$ and $181\,000\ A^2s < 405\,000\ A^2s$

Since the 80 A CLF maximum operating I^2t is less than the minimum pre-arcing I^2t of the 160 A fuse-link, reduced to 75 %, I^2t coordination exists.

5.1.4.2.6 Coordination with General-Purpose current-limiting fuses

A General-Purpose fuse is defined by standards as a device that can interrupt any fault current between a low value equal to a current that will cause the fuse to melt in one hour (here termed its "one-hour pre-arcing current") and its rated maximum breaking current. Typically, these fuses are used for transformer through-fault protection – see 5.2.2.1.1 b) – (for melting times less than about 1 hour), or to protect the system from the effects of a high current, low impedance fault.

General-Purpose current-limiting fuses may not require any series device to be used with them. However, care should be taken so that the fuse is not called upon to interrupt a continuous overload current that is less than its one hour pre-arcing current. In addition, general-purpose fuses should not be subjected to continuous currents between their rated current and their one-hour pre-arcing current, even if such a current does not result in melting. Operating a fuse in this zone can lead to fuse deterioration, which might later prevent the fuse from performing successfully at currents it could otherwise interrupt.

One method of ensuring that the General-Purpose fuse is not overloaded, or required to interrupt overload conditions, is to apply the fuse in conjunction with load or temperature sensing devices such as a secondary or primary breaker in liquid-filled distribution transformers. This prevents the fuse from melting open as a result of overloads or very long duration low current transformer through faults. Breakers must be selected so that they will interrupt the current going through the transformer before the General-Purpose fuse, mounted to the primary of the transformer, is damaged. A secondary breaker will not protect the transformer fuse from being damaged by a high impedance primary fault.

5.1.4.2.7 Coordination with Full-Range current-limiting fuses

A Full-Range current-limiting fuse, as defined by standards, can interrupt any continuous current between the minimum current that can cause melting of its elements, and its rated maximum breaking current. IEC 60282-1 allows two types of testing for Full-Range fuses depending on the surrounding temperature to which it will be subjected. Where the anticipated surrounding temperature is not expected to exceed 40 °C, the fuse must be shown to be capable of interrupting its rated current. The assumption is that use in an enclosure at moderate temperatures will not result in a de-rating sufficient to cause the fuse to melt with a current less than this value. For applications where it is known that the fuse will be subjected to severe temperatures (for example in a transformer) tests are performed with the fluid (air, gas, or liquid) surrounding the fuse at a temperature assigned by the manufacturer (Maximum Application Temperature – MAT). The fuse must interrupt a current, found from tests at the MAT, determined to be the lowest current that will cause it to melt.

A Full-Range current-limiting fuse does not require any other associated device to protect it from overloads or high-impedance faults, as long as the fuse is within its temperature limit. Full-Range fuses can be used to protect against both faults and overloads.

Manufacturer’s will often list the allowable continuous current of Full-Range fuses at various surrounding temperatures, as well as de-rating factors for common enclosures such as canisters surrounded by air, SF_6 and oil.

5.1.4.2.8 Coordination with Back-Up current-limiting fuses

It should be noted that when the CLF being coordinated is a Back-Up fuse, because these fuses have a minimum breaking current capability, special coordination rules apply as they must be used in conjunction with another device that will interrupt the currents below their rated minimum breaking current. For specific information on coordination between Back-Up fuses and expulsion fuses see 5.2.2.4.

5.1.4.3 Recloser and fuse coordination

When selecting fuses for reclosers or circuit-breaker by-pass switches, some desirable protection characteristics to be considered are as follows:

a) to protect the substation transformer from feeder faults in the zone from the bypassed device to the next main circuit down-stream overcurrent protective device, and coordinate with the next up-stream overcurrent protective device up to the maximum through-fault current available at the bypass fuse;

b) to permit loading of the feeder to the maximum loading practice of the user;

c) to properly coordinate with main circuit down-stream overcurrent protective devices.

With coordination of reclosers and down-stream (load-side) current-limiting fuses, the possibility of reclosing into a partially melted current-limiting fuse should be avoided, since the fuse may not satisfactorily interrupt if the element melts while picking up normal line current after a successful reclose. For a recloser that is protected by a fuse in overhead applications, the fast (A) curve of the recloser should be below and to the left of the 75 % minimum pre-arcing curve of the fuse for all possible fault currents, in order not to damage the fuse on a temporary fault (in this case it can be considered that the recloser is protecting the down-stream fuse).

To prevent an unnecessary time delay operation of the recloser, and possible fuse damage, there should be a 0,2 s margin required between the maximum operating curve of a "protecting" fuse and the time delay curve of the protected recloser.

On underground circuits, faults will most likely be permanent in nature. Therefore, it is unnecessary for the recloser to reach through the fuse and trip instantaneously for a fault on the load-side of the fuse. Typically, in these situations, the instantaneous trip of the recloser would be defeated.

For a fuse protected by a recloser (usually in a step-up or step-down transformer bank situation), the time delay curve of the recloser multiplied by the recloser "K" factor should be below and to the left of the 75 % minimum pre-arcing curve of the protected fuse when they are plotted on the same voltage base. No additional margin is required.

5.1.4.4 Coordinating current-limiting fuses with arresters

Since current-limiting fuses generate a substantial switching voltage during fault interruption, consideration has to be given to their coordination with source side arresters. While transformer and other equipment insulation does not appear to be adversely affected by the operation of current-limiting fuses, the peak arc voltage may be high enough to drive a source-side arrester into conduction. The energy from the system during the high switching voltage phase of the fuse clearing may, under certain rare circumstances, exceed the capability of the arrester. With the advent of Metal Oxide Varistor (MOV) arresters this situation is rare, since even if a fuse switching voltage causes an arrester to conduct (for example, with a low current rating wire element fuse) the peak of the switching voltage is brief and the MOV arrester quickly stops conducting.

An arrester on the load side of the current-limiting fuse is not vulnerable, i.e., it is neither exposed to the peak arc voltage generated by the fuse nor is it subject to the possibility of excessive energy from the system. Thus, it may be desirable to locate the current-limiting fuses on the source side of the arrester for a transformer installation, recognizing that other arresters on the source side of the fuse may remain vulnerable. The disadvantage of this arrangement is that lightning surges passing through the arrester also pass through the CL fuse (and expulsion fuse if a cutout/Back-Up fuse combination is used). Occasional lightning surges will be large enough to cause nuisance operation of the fuse(s) unless they are very large ratings (generally over 40 A).

5.1.5 Current rating and breaking capacity considerations for fuses in parallel

Fuse manufacturers supply both current-limiting and expulsion type multi-barrel fuse-links that are mounted in a parallel arrangement. Such "factory" paralleled arrangements are not the subject of this subclause.

Configurations of two or more fuses have been successfully used in parallel for many years. This has been accomplished by installing two or more fuse-links and/or their fuse-mounts (supports) connected in parallel. This may be done by a user, a third party assembler, or by a manufacturer supplying a device that holds two or more fuses in a single fuse-mount. This provides for increased current ratings. The continuous current carrying capability of the combination will usually be somewhat less than the sum of the current ratings of the individual parallel fuses due to variations in path resistances and proximity heating effects. The fuse manufacturer should be consulted to determine the appropriate de-rating factor; in many cases, a 10 % de-rating factor for two fuses and a 15 % de-rating factor when three or more fuses are used in parallel have been used.

Before a user places fuse-links and their bases in parallel, the manufacturer should be consulted to verify that the fuse and the fuse-base would function correctly when used together and for guidelines on how to connect the fuses so they have equal current paths. Only fuses from the same manufacturer and having the same type reference and rating should be connected in parallel.

In such cases the following should be noted:

a) the fuse manufacturer should be consulted to determine the suitability of a given fuse design for connection in parallel;

b) the current rating of the combination will usually be somewhat less than the sum of the individual fuse current ratings, e.g. due to proximity heating effects;

c) the I^2t values of the combination during operation will be approximately equal to $n^2 \times I^2t$ of a single fuse-link, where n is the number of fuse-links connected in parallel;

d) the cut-off current value of the combination during operation at a current of I_P will be approximately equal to n × cut-off current value of a single fuse-link at a prospective current of I_P/n, where I_P is the value of prospective current of the combination and n the number of fuse-links connected in parallel;

e) unless otherwise advised by the manufacturer, the maximum breaking current of the parallel combination of fuses cannot be assumed to be greater than that for a single fuse;

f) unless otherwise advised by the manufacturer, the minimum breaking current of the combination is no lower than n times that for a single fuse of the same given type, where n is the number of parallel fuses;

g) the pre-arcing TCC curve of n fuse-links connected in parallel will consist, approximately, of a curve having a current I_P at any particular time, t, equal to $n \times I_\mathrm{s}$, where I_s is the current at time t on the TCC curve for a single fuse. At long times (over about 100 s) this approximation may become less accurate as adjacent fuses can affect heat flow from each other. This will depend on a number of factors; consult the manufacturer for more information. For an approximation of the maximum operating TCC curve, a similar technique can be used. It should be noted that a manufacturer who approves the use of their fuses in parallel will normally supply TCC curves drawn for the fuse-links mounted in parallel. For longer pre-arcing times, there is the danger of current unbalance between the parallel fuses, causing the combination to melt at a lower current than anticipated. Care is therefore needed with back-up fuses that they do not melt at a current below the minimum breaking current of the combination.

The fuse-links and the fuse-base(s), or the manufacturer’s device to hold multiple fuse-links, form a resistive current divider that divides the current flowing through each fuse-link according to the resistance of each current path. Adequate sharing is normally achieved if the resistance of the current path for each fuse-link lies within approximately 2 % to 3 % of the other fuse-link(s) current path(s). This assures that each of the fuses will experience approximately the same current under both steady state and fault interrupting conditions. If the current path of any given fuse has a significantly lower resistance than the other(s), more current will flow through that path, increasing the duty on that fuse-link. In some cases, the duty may cause damage to the fuse-link and it may not successfully carry its share of the load current or interrupt a faulted circuit.

Fuse-links that are paralleled need to be tested in their fuse-base(s), or with an equivalent mounting arrangement, as both the fuse-link resistance and the impedance of the current path through the fuse base(s) control the current distribution through the fuse-links. Generally, the manufacturer can provide information as to how the fuse-links have been tested, to verify performance, particularly for continuous current and circuit interruption tests. These tests are specified in the fuse standards.

When very large current ratings are achieved by paralleling current-limiting fuses, these parallel combinations may not provide any current limiting action (that is reduce the peak current value) even at current levels as high as the typical interrupting ratings of 50 kA or 63 kA.

5.1.6 Voltage considerations of fuses in series

The voltage rating of a combination of two or more fuses in series cannot be guaranteed to be higher than the individual voltage rating of each of the separate fuses. In order to achieve a higher voltage than either fuse alone, the combination in question should be subject to separate tests to verify this. In some cases, a manufacturer will supply such fuses either as matched pairs, or permanently joined together in series.

In some cases, it is assumed that series connected current-limiting fuses will share voltage and be able to interrupt fault current at a voltage higher than the voltage with which they were tested. Traditionally this has only been considered to occur when fuses are in their current-limiting mode (but see 5.2.6). This is part of the basis for I_1 and I_2 tests in IEC 60282-1 being conducted at 87 % of the rated voltage of the fuse. In a three phase faulted circuit the assumption is that the second and third fuses to clear will share line-to-line voltage. Some North American type transformer applications use current-limiting fuses having a voltage rating equal to or greater than the system phase-to-neutral voltage (with earthed star-earthed star systems and with matched-melt coordinated Back-Up fuses/expulsion fuses combinations protecting delta connected transformers (see 5.2.2.6.2)). It is assumed that with a line-to-line fault (not involving earth) a fuse in each phase will share line-to-line voltage at high fault currents.

Care should be exercised when selecting and replacing fuses for applications in multi-phase circuits if the assumption has been made that, under fault conditions, two fuses will be effectively in series and will share the line-to-line voltage. For two fuses to share the voltage, they must arc simultaneously. Consequently, fuses in all phases should be of the same fuse rating, the same model and/or type of fuse, and be from the same manufacturer; consult the manufacturer for more information.

5.1.7 Fuse recovery voltage withstand

Most fuses are designed to withstand recovery voltage across a blown fuse indefinitely. In addition, outdoor fuses have creepage, and materials or coatings, designed to withstand voltage stress and contamination. However, distribution fuse-cutouts and other drop-out fuses are designed to incorporate a drop-open action following an interrupting operation. This action quickly removes all voltage stress across the fuse holder. There are, therefore, some types of non-drop-out fuses, such as some Back-Up current-limiting types, that are intended to be used with a series expulsion fuse, or other device, coordinated to provide isolation means. Also, many capacitor unit fuses have a built in disconnector that removes any long-term voltage stress from a blown fuse. Isolation of a blown fuse then prevents possible dielectric breakdown of a, possibly contaminated, non-drop-open fuse if it is subjected to long-time voltage stress. This enables the fuse to be made shorter (with less creepage) than would otherwise be required.

For those special applications where long-time voltage stress can occur across a blown fuse, and dielectric breakdown would permit resumption of current flow, the fuse manufacturer should be consulted as to the adequacy of the proposed fuse for this application.

5.1.8 Partial discharge

See 5.2.5.5.

5.2 Typical applications

5.2.1 Protection of cables and overhead lines

5.2.1.1 General

5.2.1.1.1 Inrush considerations

Inrush current into a distribution circuit for the first few cycles can be very high due to magnetizing current for transformers that have high residual magnetic flux in the core and maximum energizing flux. This coupled with incandescent lighting inrush and locked-rotor inrush into motors (plus some out-of-phase residual flux) should be considered by the user. Transformer magnetizing current may be quite high for an individual transformer, but when the transformer is only one of many in the circuit being energized, one would expect the total magnetizing inrush current in the circuit to be less than the sum of each transformer's maximum magnetizing inrush current . Also, inrush currents that are quite high could result in a voltage drop that would act to reduce the inrush currents.

For example, if ten 50 kVA transformers were being energized simultaneously for a total of 500 kVA, an inrush current of 20 times transformer rated current would represent a connected load of 10 000 kVA at that instant. Some distribution circuits would experience appreciable voltage dip during this period, and thus significantly reduce the inrush magnitude. However, since it may be difficult to determine which circuits are capable of producing and sustaining the higher inrush currents for varying numbers of transformers being applied, the conservative approach would be to utilize the connected kVA and the multipliers discussed in 5.2.2.1.2 (25/12 times at 0,01/0,1 s) for single transformers.

Experience has shown that if a distribution sectionalising fuse was carrying no more than 30 % of its rated current at the time of a power failure, power has not been off for more than one hour, and no significant changes in the load have taken place, then there should be no problem with inrush currents.

A fuse operation may result when the connected load current is between 30 % and 50 % of the fuse rating. Above 50 %, the circuit should be sectionalised to pick up only a part of the load. It is not recommended that a fuse be bypassed (by use of a low impedance "jumper", cable for example) to avoid sectionalising the circuit.

5.2.1.1.2 Load pick-up considerations

A more important factor for selecting a sectionalising fuse is often that of cold-load pick up. After an extended outage period, many applied loads are ready to start up as soon as the transformers are re-energized. Some of these loads, such as motors, can have current requirements of 5 to 10 times the normal running current for a period of time ranging into seconds. Published literature (see the bibliography) on this subject indicates that the sectionalising fuse should be capable of handling about 6 times the peak load current prior to the outages for one second, three times the peak load current prior to the outages for 10 s, and 2 times this value for 15 min.

5.2.1.1.3 Fault considerations

The rated maximum breaking current of the fuse should be higher than the prospective (available) fault current. The fuse manufacturer specifies maximum breaking current for a device. A sectionalising fuse typically would be required to interrupt high fault currents since the transformer fuse or protective device would sense and interrupt transformer secondary faults and abnormally high overload currents. When the transformer fuse is expected to respond to low-level overcurrents, it must be capable of interrupting those currents.

5.2.1.2 Fuses for reclosers or circuit-breaker bypass switches

Some desirable protection characteristics to be considered in selecting fuses in these applications are as follows:

a) to protect the substation transformer from feeder faults in the zone from the bypassed device to the next main circuit down-stream overcurrent protective device, and coordinate with the next up-stream overcurrent protective device up to the maximum through-fault current available at the bypass fuse;
b) to permit loading of the feeder to the maximum loading practice of the user;
c) to properly coordinate with main circuit downstream overcurrent protective devices.

5.2.1.3 Fuses for sectionalising

Some desirable protection characteristics to be considered in selecting fuses for these applications are as follows:

a) to protect conductors from thermal failure or extreme heating in the zone from the sectionalizing fuse to the next main circuit downstream overcurrent protective device, and coordinate with the next upstream overcurrent protective device up to the maximum fault current available at the sectionalizing fuse;
b) to permit loading of the circuit to be maximum loading practice of the user;
c) to properly coordinate with main circuit downstream overcurrent protective devices.

5.2.1.4 Fuse applications on subtransmission systems

Some desirable protection characteristics to be considered in selecting fuses for these applications are as follows:

a) to protect the substation bus from faults at or within the distribution substation transformer, and coordinate with all upstream overcurrent protective devices up to the maximum fault current available on the substation bus;
b) to provide maximum protection to the transformer from through-faults. The degree of transformer protection is determined by comparing the maximum operating time-current characteristic curve for the selected fuse with the appropriate transformer short-time loading curve. Both curves need to be properly adjusted to reflect differences between primary and secondary phase currents and winding currents associated with specific transformer connection involved and the types of possible faults in the secondary circuit;
c) to provide detection and isolation of internal transformer faults and reduce the possibility of a transformer case rupture;
d) to permit loading the transformer to the maximum loading practice of the user;
e) to withstand combined transformer magnetizing inrush and load pickup current after short-time (up to 1 min) voltage interruption on the substation bus;
f) to properly coordinate with overcurrent protective devices on the secondary of transformer.

5.2.1.5 Determining the zone of protection for fuses (reach)

Fuses melt and clear overcurrent conditions according to their TCC curves. The minimum current that produces successful fuse melting and interrupting should be less than the minimum fault current that might develop from a fault at the end of the zone to be protected (the end of the line or the next down-stream protection device). The minimum fault current must therefore be determined at each sectionalising point and at the end of each zone of protection.

A term used in coordination and overcurrent protection work is "reach". Reach is a measure of the ability of a protective device to sense a fault condition within its zone of protection. It was developed in the context of devices, such as reclosers, that have a clearly defined pick-up value – if a sufficient current is not available the device will not operate. The word was originally used to describe the ability of a recloser to "reach" beyond the next fuse and operate without the fuse melting (see 5.1.4.3). However it is now also used for fuses, and has particular relevance for those fuses having a defined minimum interrupting capability. Such fuses include General-Purpose current-limiting fuses and type "B" expulsion fuses (boric acid fuses). General-Purpose fuses should not generally be subjected to currents between their rated current and their one-hour pre-arcing current, and boric acid fuses can be damaged by prolonged overloading.

In order to clarify the concept of reach, refer to Figure 19. Consider device A as the device for which a calculation of the reach is desired. Fault current calculation methods are described in IEEE Std 141 [4], IEEE Std 399[5] and IEC 60909-0.

The zone of protection of device "A" is shown by the dotted line. It terminates at other protective devices ("B", "C", etc.) and the end of the radial taps (spurs). Assume that the desired operating current (minimum pick up value) of device "A" is 100 A. This is a current that gives a required operating time – for a general-purpose fuse it might be the minimum one hour pre-arcing current. While a fuse may be capable of melting in several hours (e.g. a full-range current-limiting fuse) it is not normally desirable to permit a fault to exist for that long. An appropriate maximum time may therefore be chosen for the minimum device operating current, e.g. 300 s (all fuses have TCC curves drawn to 300 s) or a user might want a shorter maximum fault time. The current is calculated for various points within the zone of protection of the fuse. In the example the lowest prospective current in the zone is at point 10, which produces 300 A flowing through fuse "A".

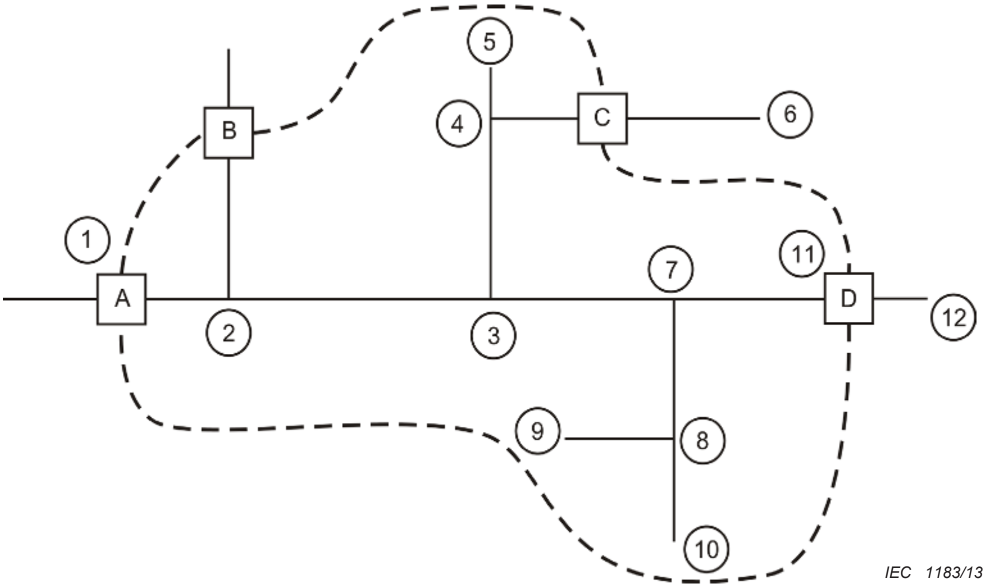


Figure 19 – Reach example

Clearly 300 A would cause the fuse to operate in less than the maximum desired time (for this example 300 s). However, typically, fault currents on distribution circuits are calculated for bolted faults (relatively low resistance faults). In actuality, upwards of 90 % of all faults encountered on overhead distribution circuits are temporary in nature (e.g., tree limbs brushing conductors), and many such faults have high resistance, thereby significantly reducing the magnitude of fault current. The possibility of reduced values of fault current must be taken into account when sizing a protective device to reach to the end of its zone of protection. A user can therefore use their experience to determine how much less current there can be, and incorporate a "safety factor" into the calculation. Typically factors of 3 or less are used. In the above example, the "reach" margin is:

$$\text{Reach margin} = \frac{\text{(minimum fault current through device within zone of protection)}}{\text{(minimum current to operate protective device)}}$$

which, in this example, would equal

$$\frac{300\ \text{A}}{100\ \text{A}} \quad \text{or} \quad \frac{3}{1}$$

This is normally an acceptable margin (it also allows for some errors in calculating the prospective current).

Experience shows that faults are normally either of low impedance, giving currents similar to calculated values, or are of such high impedance that it is very difficult to detect with upstream fuses. Utilities with this experience therefore tend to use lower reach margins.

5.2.1.6 Current-limiting fuses

5.2.1.6.1 Selecting minimum fuse current ratings

Fuses should be sized based on total connected nameplate kVA, magnetizing inrush, and the anticipated peak load conditions as discussed in 5.2.1.1.

Since magnetizing inrush is a high current for a short duration, if the fuse-link is not chosen correctly, one or more fuse elements may melt open at a minimal cross-sectional area. Partial melting of a fuse element, or full melting of a partial number of parallel elements, may reduce the continuous current capability of the fuse and its ability to withstand additional surges. For fuses fitted with a striker, which trips a series switch, this can result in nuisance operation. However for other designs of fuse the result could be overheating, and eventual fuse failure, or the fuse may be melted by a current that does not allow it to clear successfully. Because of this, sizing a current-limiting fuse properly to withstand magnetizing inrush is extremely important.

To evaluate the loading capability of fuses used for line protection, each fuse's minimum pre-arcing curve should be compared with the magnetizing inrush and the cold-load pick up characteristics of the circuit it is protecting. The value of current at which the fuse's minimum pre-arcing curve lies completely to the right of each of these points for each case, i.e. cold-load pick up and magnetizing inrush, can be tabulated.

Since the shape of the minimum pre-arcing curve for each fuse varies, some fuses are more suitable for withstanding cold-load pick up than magnetizing inrush and vice versa. This necessitates looking at each fuse individually instead of using a rule-of-thumb such as sizing a fuse for 1,5 times to 2 times the connected load current.

5.2.1.6.2 Zone of protection considerations

For many years, current-limiting fuses have been used for radial tap line (spur-line or branch) protection of overhead and underground distribution circuits. In addition to the current-limiting aspects of these fuses, they are used because of their effectively noiseless operation and their high interrupting capabilities. Applying current-limiting fuses as spur-line protection requires considerations not typically encountered with other overcurrent protective devices. With most overcurrent protection devices, miscoordination only results in the nuisance operation of a source-side device. Miscoordination of current-limiting fuses, however, may not only result in the nuisance operation of the fuse but also may result in the failure of the fuse. Subclause 5.2.1.6.2 outlines the special considerations needed for current-limiting fuses applied as spur-line protection.

a) General-Purpose current-limiting fuses

   It is clear that a General-Purpose fuse will be subjected to a fault current at the end of its zone of protection; however it should also be able to interrupt the lowest value of fault current anticipated. Some General-Purpose current-limiting fuses can be damaged if they are subjected to a continuous current above their rated current and below their one-hour pre-arcing current (given by manufacturer). Either the fuse may melt at a current too low for it to interrupt, or the overload current heats up the fuse causing damage to the fuse components or its holder before the fuse can melt and interrupt the current. Therefore, the reach capability of a General-Purpose fuse is largely dependent on its design. Any limitation on overloading must be considered when determining the reach for these fuses.

   For example, one manufacturer of a General-Purpose current-limiting fuse states that the fuse will carry 100 % of the current rating continuously without damage. However, in order to melt and clear properly, the over- current must be at least 220 % of the fuse's rating. If this fuse is subjected to a continuous current in excess of its rating (up to 220 %), it may sustain damage to its fuse body and possibly fail before the fuse element can melt and clear. Therefore, the minimum allowable fault current at the end of the zone of protection to obtain a 3/1 reach with this General-Purpose current-limiting fuse would be: $I_r \times 2{,}2 \times 3{,}0$ or $I_r \times 6{,}6$, I_r. being the fuse current rating

b) Full-Range current-limiting fuses

The concept of reach (5.2.1.5), in the case of Full-Range current-limiting fuses, becomes almost arbitrary considering the low-current interrupting capability of the fuse. However, consideration should be given to whether the fuse will interrupt the low values of fault current before other devices in the system are adversely affected.

To determine reach, the current at which the fuse melts in an acceptable time (e.g. 300 s or less) must be determined. From the minimum pre-arcing TCC curve for one manufacturer's 100 A fuse it can be shown that a current of approximately 220 A will melt the fuse in 300 s. Therefore, to obtain a 3/1 reach, the minimum allowable fault current at the end of the zone protected by this fuse would be as follows: 220 A (current to melt at 300 s) times 3 meaning 660 A. Again, the Full-Range fuse will satisfactorily interrupt lower currents; however, the above criterion will limit the pre-arcing time.

5.2.1.7 Expulsion fuses

The most common type of fuse for line protection and sectionalising applications are expulsion fuses. They are normally drop-out fuses so that it is easy to see when a fuse has operated. Fuses should be sized based on total connected nameplate kVA, magnetizing inrush, and the anticipated peak load conditions as discussed in 5.2.1.1.

Since magnetizing inrush is a high current for a short duration, the fuse element may melt open where the fuse element has a minimal cross-sectional area. Partial melting of a fuse element may reduce the continuous current capability of the fuse and its ability to withstand additional surges. This can lead to nuisance operation.

Consideration of the zone of protection (reach) of an expulsion fuse is covered in 5.2.1.5.

5.2.1.8 Combination of Expulsion and current-limiting fuses

If the available fault current at the location of an expulsion fuse is higher than the fuse's rated maximum breaking current, then one of three options are available. The first is to replace the expulsion fuse with one having a higher maximum breaking current. If the device is a distribution fuse-cutout, this may require a different fuse-carrier or a different fuse-holder (fuse-carrier and fuse-base, i.e. the whole fuse except for the fuse-link). Alternatively, a Class B expulsion fuse may be needed, as they tend to have higher interrupting ratings. The second option is to replace the expulsion fuse with a current-limiting fuse. However this may make coordination with source side (up-stream) fuses and breakers harder since current-limiting fuses tend to have different TCC curves. Also, fewer current-limiting fuses having a drop-out action are available (usually desirable for overhead circuits for both isolation and visibility). The third option is to add a current-limiting fuse to the expulsion fuse and make a fuse combination (sometimes termed the "two-fuse" method). The current-limiting fuse in this case is usually a Back-Up fuse. When this is done, correct coordination between the two fuses is needed (see 5.2.2.5 and 5.2.2.6.2). The advantage of this method is that, if fault currents have increased beyond the capability of an economical expulsion fuse, it is often possible to retro-fit existing fuse installations with the current-limiting fuses. Adding a current-limiting fuse also helps with discrimination, that is minimizing the extent of an outage. This is because the relatively fixed current-limiting fuse I^2t makes it easier to coordinate with up-stream (source side) fuses and circuit breakers than an expulsion fuse. Of course the combination approach is also used extensively for new installations as a cost-effective solution to circuits having a high fault current and/or low power factor (high X/R). When considering the zone of protection (5.2.1.5), since it is the expulsion fuse that provides low current operation, it is the expulsion fuse characteristics that are considered.

5.2.2 Distribution transformer applications

5.2.2.1 General

5.2.2.1.1 Purpose of fuses

It should be remembered that the primary purpose of a transformer fuse is to remove a faulted transformer from the power system and minimize the risk of an eventful failure. Protection of the system, and minimization of the extent of the area affected by a fault, is therefore a significant concern. An "eventful" transformer failure, is one that results in external damage that might be a risk to persons or property. In addition to these primary benefits, fuses can, under certain circumstances, also provide overload or secondary short-circuit protection for the transformer. While this is normally provided by secondary protection, it is sometimes required from the primary fuses (sometimes as "back up" to the secondary protection). Some desirable protection characteristics to be considered in selecting fuses for transformer applications are listed; however, it should be borne in mind that some of these requirements may be contradictory, in which case the user’s priorities should be taken into account:

a) to protect the distribution system from the effect of faults at or within the transformer, and coordinate with the next upstream overcurrent protective device up to the maximum fault current available at the transformer fuse;
b) to provide the best possible protection to the transformer from damaging through-faults (the current flowing through the transformer from a secondary fault, outside the transformer). The degree of transformer protection is determined by comparing the operating time-current curve for the selected fuse with the appropriate transformer short-time loading curve. Both curves need to be properly adjusted to reflect differences between primary- and secondary-phase currents and winding currents associated with the specific transformer connection involved and the types of possible faults in the secondary circuit, see 5.2.2.1.5;
c) to provide detection and isolation of internal transformer faults and reduce the possibility of transformer case rupture;
d) to permit loading the transformer to the maximum loading practice of the user;
e) to withstand combined transformer magnetizing inrush and load pickup current after short-time (up to 1 min) service interruption, and combined transformer magnetizing inrush and load pickup current after extended (30 min and longer) outages;
f) to properly coordinate with overcurrent protection devices on the secondary side of the transformer;
g) to withstand surge discharges through a transformer with an earthed primary winding that experiences saturation of its magnetic circuit by a lightning-induced surge voltage with a long time wave shape (primarily with small transformers 25 kVA and lower);
h) to withstand surge currents that may be discharged through an arrester located on the load side of the fuse and ahead of the protected transformer. This surge may be in addition to that referred to in 5.2.2.1.1 g).

5.2.2.1.2 Inrush considerations

Fuses may be subject to damage if inrush currents cause partial melting of the fuse element(s). Inrush currents due to energizing a transformer can be high and require checking as part of the normal selection and coordination procedure.

When a transformer is energized, relatively high inrush currents may occur, depending upon the residual flux in the core and the voltage at the instant of closing the circuit. Tests with typical transformers, as well as many years of experience in applying both current-limiting and expulsion fuses for transformer applications, have produced a generally accepted set of guidelines for fuse selection. These guidelines consider the typical first loop current value, as well as the r.m.s. value over the duration of a typical inrush current. The guidelines are in the form of two time-current points, and are expressed as multiples of transformer rated full-load current. The transformer manufacturer's guidelines should be followed if available, but typically the values used are 25 times rated current for 0,01 s (North American practice) and/or 12 times rated current for 0,1 s (universal practice). Different values may be applied based on transformer size and design. These points are compared to the fuse’s minimum pre-arcing TCC. If at these points, the fuse characteristic lies above and to the right, then the fuse is considered to be capable of properly withstanding the magnetizing-current inrush of the transformer.

5.2.2.1.3 Pick-up considerations

Cold-load pick up is a transient current condition that occurs upon energizing a circuit after it has been de-energized for 2 min or longer. Fuses used in certain applications, such as protecting pumps, can experience elevated currents after outage times as short as 6 s. Tests have shown that large fans can draw six times rated current for 60 s. On residential circuits, cold-load currents can cause problems because load diversity has been lost. Refrigerators, air circulating fans, air conditioner compressors and/or heat pumps, water pumps, etc., are all ready to cycle on. The combined starting currents of these devices could also contribute to an inrush current problem known as cold-load pick up. Since compressors have little or no head pressure, their motors are able to come up to speed rapidly enough to mitigate this problem.

Another problem, commonly referred to as sympathetic tripping, arises on a momentary dip in voltage, due to a fault on another part of the system, which is then cleared in a matter of cycles, allowing the subject area voltage to be restored to normal. During the voltage dip, voltage in parts of the system drop to a point that compressor motors stall. When full voltage is restored, the large compressor motors cannot come up to speed due to high head pressure. Locked rotor currents exist until the thermal overload on the compressor motor trips. Tests on circuits subject to this phenomenon indicate approximately 2,7 times pre-fault current for about 7 s. The 2,7 multiplier results from all motors being instantaneously energized (some contactors have not had a chance to open), with a loss of diversity. Low power factor locked rotor conditions combine with the inductance in the secondary, the transformer, the lateral, the main feeder, and the substation to cause low voltage on the motor terminals and the overcurrent. Seven seconds is the approximate time it takes for the thermal overloads on motors with locked rotor currents to trip open.

The distinction between sympathetic operation and cold-load pick up arises in part from the operating time of control relays and contactors. In most cases, there is enough randomness in closing to allow the relatively small, single-phase air conditioning motors to come up to speed, at normal voltage, in much less than one second, since there is no head pressure.

No standardized values have existed in IEC fuse standards as these pick-up requirements clearly depend on the user's practices. Furthermore, because these requirements may be in conflict with the desire that fuse operation in the 2 to 10 s region be with as low a current as possible (see 5.2.2.1.4), pickup requirements should be by agreement between manufacturer and user. However, in the absence of specific information, a commonly used rule of thumb in many parts of the world is that the fuse should be selected so that the minimum pre-arcing TCC curve lies to the right of the points corresponding to six times rated full-load current for one second, three times rated full-load current for 10 s, and 2 times rated full-load current for 15 min. These requirements can often be reduced for larger sized transformers.

Repeated starting currents from heavily loaded motors can cause unusual stresses on a current-limiting fuse element; special designs for motor-starter applications have been produced to handle this special application. This is discussed in 5.2.3.

5.2.2.1.4 Transformer loading and overloading considerations

IEC 60076-7 and IEC 60076-12 define the safe loading for transformers. These standards detail the potential loss of transformer life for various load levels and durations. The information is given in a series of equations and in tabular form. The data in the tables can also be graphed and expressed as a safe loading curve. The fuse's operating TCCs should lie to the left of the safe loading curve to provide adequate protection. In many cases, transformer overload protection is provided by secondary devices (fuses or circuit breakers). However, particularly with smaller sized transformers using the North American approach (see 5.2.2.4) primary fuses may have to provide overload protection.

Generally, a transformer or fuse manufacturer will recommend fuse sizes to handle full-load and some overload currents without fuse operation or damage. The surrounding temperature that the fuse encounters during the overloading will depend on where the fuse is located.

5.2.2.1.5 Through-fault considerations

The current flowing through a transformer due to a fault on the secondary side is often termed a "through fault". The highest current occurs when the fault is on the secondary terminals of the transformer (also then called a "bolted secondary" fault), when it is limited only by the transformer impedance (and also to a small extent by up-stream system impedance). IEC 60076-1 requires that a transformer have a thermal ability to withstand a short circuit for 2 s (with transformers up to 2 500 kVA neglecting system impedance if it is equal to or less than 5 % of the short-circuit impedance of the transformer). The primary fuse clearing TCC curves are required to lie to the left of the 2 s point. Other transformer standards recognize a mechanical component in the damage from through faults, and may have more stringent requirements. Fuse clearing TCC curves may then be required to lie to the left of an additional characteristic drawn for times longer than 2 s and based on constant I^2t values from the 2 s short-circuit point. Secondary faults, when reflected to the primary winding that the current-limiting fuse would be protecting, are typically of magnitudes to operate the fuse in 0,02 s to 1,0 s; thus, little or no current-limiting action would occur. Therefore, the fuse must have low-current interrupting ability to handle this duty. It should be noted that, under fault conditions, the transformer-winding arrangement will affect the current in the primary lines (and therefore the fuses) compared to current in a secondary phase. Thus for an earthed star – earthed star connected transformer, one per-unit current in a secondary phase is supplied by one per-unit current in a primary line. However, for a delta – earthed star transformer, one per-unit current in a secondary phase, experiencing a phase to ground fault, is supplied by only 58 % per-unit primary line current.

The through-fault condition may be disregarded under some conditions when using a switch-fuse combination (see 5.2.7.2)

5.2.2.2 Current-limiting fuses

5.2.2.2.1 General

Current-limiting fuses are commonly used to protect transformers for reasons covered in 4.1.5. There are two common methods of protecting transformers based loosely on "European" practice and "North American" practice, although there are many parts of the world that use one, or both, of these practices. IEC standards recognize "European practice" and "North American practice" in terms of preferred voltages and insulation levels; therefore these terms will also be used in relation to transformer protection practices, while recognizing that such practice is not unique to either area.

While there are many reasons why one or the other practice is adopted, one of the driving forces is the density of utilization. Where many customers are concentrated in a particular area, larger sized transformers used with ring main units (incorporating switch-fuse combinations, with the switch tripped by the back-up fuse striker, or circuit-breakers) are often more economical. This is "European" practice. Where customers tend to be more spread out, it is more common to provide a small number of households (often one) with an individual transformer. This makes the switch-fuse combination impracticable. Instead, either a Full-Range fuse is employed, or a combination of back-up fuse and expulsion fuse provides the full-range capability. This is "North American" practice, and such a combination of fuses poses special coordination requirements, which will be covered in 5.2.2.4.

5.2.2.2.2 Fuse-link time-current characteristics

The time-current characteristics of HV fuse-links for transformer circuit applications should have the following features:

a) relatively high operating current in the 0,1 s region so as to withstand transformer inrush current and give good coordination with protection devices on the secondary side (where fitted), see 5.2.2.1.2;

b) relatively low operating current in the 10 s region so as to:

- ensure rapid clearance of transformer winding faults, secondary side faults (see 5.2.2.1.5) and, if applicable, primary side earth faults;
- give good coordination with up-stream overcurrent protective devices (source side).

Therefore, the pre-arcing time-current characteristics of fuse-links for transformer circuit applications should preferably be within the following limits:

$$I_{\text{f10}} / I_{\text{r}} \leq 6$$

- to fulfil condition b)

$$I_{\text{f0,1}} / I_{\text{r}} \geq 7(I_{\text{r}} / 100)^{0,25}$$

- to fulfil condition a)

where, all current values being expressed in amperes,

I_{r}	is the rated current of the fuse-link;
I_{f10} and $I_{\text{f0,1}}$	is the pre-arcing currents corresponding to 10 s and 0,1 s respectively, expressed as mean values with the tolerances specified in 4.11 of IEC 60282-1:2009.

The term $(I_{\text{r}} / 100)^{0,25}$ is introduced to take account of the fact that the pre-arcing time-current characteristics for a range of fuse-links diverge as they approach the short-time region.

5.2.2.2.3 Coordination

Figure 20 illustrates a typical transformer application involving a high-voltage fuse-link (or fuse-links), a transformer and possible protective devices on both source and load sides.

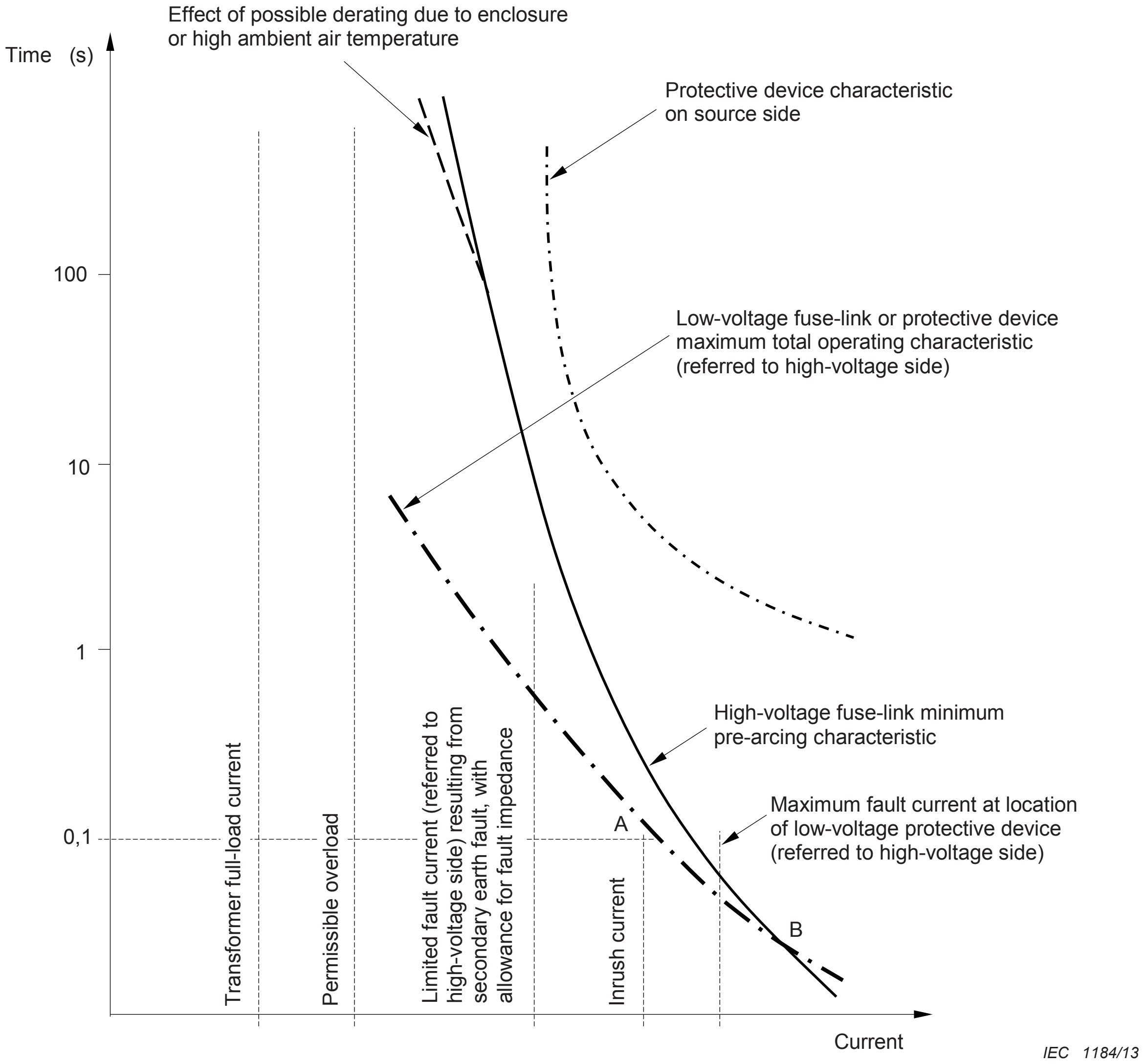


Figure 20 – Characteristics relating to the protection of the HV/LV transformer circuit

The transformer will be chosen first for its particular duty. This establishes the value of the rated current of the transformer, the value of the permissible overload current (where applicable) and also by inference, the inrush current. The HV fuse-link(s) are then chosen so as to give optimum protection to the circuit, bearing in mind the factors of Items a) to d) listed below.

With reference to Figure 20, the following should be noted:

a) the primary side HV fuse-link minimum pre-arcing time-current characteristic should be to the right of point A defining the transformer inrush characteristic. For practical purposes this may be taken as approximately 12 times the transformer rated current for a duration of 0,1 s;

b) the rated current of the primary side HV fuse-link should exceed the rated current of the transformer:

   1) by an amount sufficient to allow for permissible overloading of the transformer under service conditions (refer to IEC 60076-7 and IEC 60076-12);

   2) by a further amount where the fuse-link(s) are mounted in an enclosure so as to ensure that the specified temperature limits for fuse-links are not exceeded and so that excessive fuse element temperature does not lead to premature fuse operation. See Annex A;

   3) by a further amount where the ambient air temperature is likely to exceed that specified in Clause 2 of IEC 60282-1:2009;

c) the pre-arcing current of the primary side HV fuse-link should be as low as possible in the 10 s region of the fuse time-current characteristic in order to ensure the maximum protection of the transformer (see 5.2.2.1.5);

d) for complete coordination between primary side and secondary side fuse-links or other protective devices on the load side, the intersection B of the primary side time-current characteristic (minimum pre-arcing) and the secondary side device characteristic (maximum operating) (as referred to the primary side taking into account the appropriate ratio) should occur at a value of current greater than that of the maximum fault current on the load side of the secondary side protective device.

Finally, where it is seen that the desired degree of coordination has not been achieved, the selection or setting of the source side overcurrent protective device may be re-examined. Similarly, the maximum rating of the secondary side fuse-link(s) may need to be reduced for the same reasons.

5.2.2.2.4 Rated voltage

Switching voltage (peak arc voltage) requirements for current-limiting fuse-links (see 4.2.4.5) are specified in IEC 60282-1, and are set at values that should not cause problems with transformer or system insulation levels. In some countries it is the practice to use "dual voltage" transformers, i.e. transformers that contain internal switching arrangements that enable them to be used with more than one standard primary voltage. The current-limiting fuse must have a voltage rating equal to or greater than the selected voltage. If the current-limiting fuse will not be changed depending on the actual service voltage, or if the typically North American practice of an internally mounted fuse that cannot easily be replaced is employed (see 5.2.2.4), then the fuse must be chosen based on a current rating suitable for the lower voltage setting, and a voltage rating suitable for the higher voltage setting. In this case, if the lower voltage is less than about 50 % of the fuse rated voltage, the switching voltage (suitably adjusted for the lower system voltage) should be checked to ensure that there will be no system insulation breakdown issues. In addition, the use of a single current-limiting fuse for both voltages, unless it is intended only to provide high-voltage short-circuit protection, may result in other transformer protection requirements being compromised.

5.2.2.2.5 Fuse class and rated minimum breaking current:

Back-Up fuse-links should be selected so that the value of minimum breaking current is appropriate to the particular application concerned. It should be stressed that use of a fuse-link having too high a value of minimum breaking current could, under certain circumstances, result in disruptive failure of the fuse-link and consequent damage (see 4.2.3.4). In the case of General-Purpose fuses, they should not be exposed to overload currents below a current that causes them to melt in one hour (see 4.1.2.1).

5.2.2.2.6 Back-Up fuses used in combination or association with other switching devices

When a Back-Up fuse is used in conjunction with a series switching device having a low current interrupting ability (switch, circuit breaker, or other fuse), its minimum breaking current need only be low enough to ensure correct coordination with the series switching device. Note that the term "combination" when applied to a fuse and series connected mechanical switching device refers to devices specifically covered by IEC 62271-105; in this report, the relationship between fuses and switching devices that are not covered by IEC 62271-105 is termed an "association" (see 5.2.7 for a full explanation of this).

a) Use in switch-fuse combinations (striker tripped):

   In applications where operation of the fuse striker ensures operation of the combination tripping mechanism, automatic transfer of interrupting duty under low fault conditions from the fuse to the combination switch is assured. Back-up fuses can be used for this application where it is necessary to ensure that the duty transferred to the combination switch is within its maximum breaking capacity (transfer current criteria, see 5.2.7).

In the case of intentional delay of the tripping mechanism of the switch (see IEC 62271-105:2012, 3.7.119) it is the responsibility of the manufacturer of the switch-fuse combination to ensure that the arcing time of the fuse (consisting of the fuse initiated opening time plus the arcing time of the switch) remains below its demonstrated arcing withstand time, which is at least 100 ms; see also 5.2.7.2.4.

b) Use in relay-operated switchgear:

In such applications back-up fuses may be used where it is necessary to ensure that the time-current characteristics of fuse and associated switchgear relay intersect at a value of current above the minimum breaking current of the fuse and under the maximum breaking capacity of the associated switchgear (maximum take-over current for a combination).

c) Use with series expulsion fuse: (see 5.2.2.4)

For standardized applications of a) and b) above, refer to IEC 62271-105, *Alternating current switch-fuse combinations*, to IEC 62271-107, *Alternating current fused circuit-switchers for rated voltages above 1 kV up to and including 52 kV*, and to IEC 62271-106, *High-voltage alternating current contactors, contactor-based controllers and motor-starters*.

In principle, the guidance of a) and b) applies also to fuses used in other forms of association with switching devices not covered by IEC standards (see 5.2.7).

5.2.2.2.7 Current-limiting fuses used as the only protection on the HV side of the transformer

In European practice, for applications where it can be shown by calculation or by service experience that low fault levels are unlikely to occur, then suitable Back-Up fuses may be used. In this case it is necessary to ascertain that the rated minimum breaking current of the fuse-link is less than the smallest HV fault current likely to occur due to a fault located between the HV fuses and the low-voltage protecting device(s). This method is seldom used in North American practice, both because secondary protection may be some distance from the transformer, leading to lower potential fault currents, and because current-limiting fuses are often mounted in the transformer liquid, so that a fuse melting below its minimum breaking current could lead to a serious failure.

For applications where experience or calculation indicates there is a possibility of very low values of overcurrents (i.e. below the minimum breaking current of Back-Up fuses) then if a single fuse is desired, general-purpose or full-range fuses should be employed.

The latter class of fuse is especially recommended for applications where overcurrents can occur at values as low as the fuse minimum melting current or where the fuse has to be de-rated for use in an enclosure.

It should be checked that for a general-purpose fuse the 1 hour melting current (or the minimum breaking current if rated by the manufacturer), and for a Full-Range fuse the minimum melting current, of the selected fuse is not above the value of the overcurrent to be considered.

5.2.2.2.8 Current-limiting fuses used to provide short-circuit protection in combination with expulsion fuse-links

Minimum breaking current need only be lower than the cross-over current of the series combination. Values of minimum breaking current vary widely depending on the design of the combination. Back-up fuses are normally used for this application. See 5.2.2.4.

5.2.2.2.9 Selection of rated currents of fuse-links for transformer circuit applications

The manufacturer of fuse-links intended for transformer circuit protection should make available recommendations for rated currents of fuse-links for given kVA ratings of transformers. In most cases, the rated current of the fuse-link is significantly higher than the rated current of the transformer, due to the need to choose a fuse primarily by its TCC and meet the criteria in 5.2.2.2.2.

NOTE Existing selection tables generally do not cover the application with associated switchgear.

Manufacturing tolerances and variations between cold and hot characteristics of the various components of the circuit should be taken into considerations.

5.2.2.3 Expulsion fuses

Expulsion fuses are frequently used to protect pole type transformers (smaller units mounted on distribution power poles, normally single phase but often three phase). Often a combination of expulsion and current-limiting fuses are used (see 5.2.2.4). The expulsion fuses in this case are normally distribution fuse-cutouts, although liquid-filled expulsion fuses are quite common. Most of these are the "liquid-submerged" type (cartridge fuses, see 4.3.2.1.5), but external "liquid fuses" (see 4.3.2.1.6) have been used, particularly in areas where fire is a hazard. External liquid fuses are, however, tending to be replaced by full-range fuses for this application, in part due to the low maximum breaking current of the former. Also pad-mounted transformers using "North American" practice will often use internally mounted liquid-submerged expulsion fuses. While many units will use only an expulsion fuse (normally where prospective currents are quite low) it is becoming increasingly common to use a combination of expulsion fuse and back-up current-limiting fuse for these applications.

The selection procedures for expulsion fuses are very similar to those for current-limiting fuses outlined in 5.2.2.2. The main difference with under-oil fuses is that the effect of the transformer oil temperature on the pre-arcing TCC of the fuse becomes particularly important. If a high temperature fuse element material is used (e.g. copper or a copper alloy are quite common), then oil temperature will have little effect on the long time melting characteristic (generally less than 5 %). However, quite low melting point materials are often employed in order to make the fuse sensitive to oil temperature and thus transformer overload. If the user desires overload protection, then this can be provided by selecting an appropriate fuse-link element material. Overload protection is determined by examining the minimum fusing current of the fuse-link at 20 °C or 25 °C (published curve for IEC 60282-2 or IEEE C37.41 [6]) and applying a "shift" in the characteristic based on oil temperature. For example, an oil temperature of 120 °C can reduce a minimum pre-arcing current at a long melting time by as much as 60 %. By a combination of knowing how much overload current will produce a particular oil temperature, and how much current it takes to melt a particular fuse under substantially "steady state" conditions, it becomes possible to determine how much overload a particular fuse will permit. The transformer manufacturer and/or the fuse manufacturer must do this calculation, so application tables are normally provided to enable users to pick the correct fusing to meet their needs.

When distribution fuse-cutouts are used with pole-type transformers, it is important that lightning surges that pass through the fuse do not cause nuisance operation (see 5.1.4.4). Starting with Edition 3 of IEC 60282-2:2008, a "lightning surge impulse withstand test" is included in the "special tests" clause. Any type of link can be qualified – the test involves subjecting three samples to a standard 8/20 current impulse having a 15 kA peak value. The links must not be damaged. Small current rating links are available that will still meet this impulse withstand for fusing low kVA transformers.

The rated maximum breaking current of an expulsion fuse selected for use with a transformer should be equal to or higher than the prospective fault current that can occur at the transformer’s location. Because expulsion fuses have lower rated maximum breaking currents than current-limiting fuses (sometimes much less) it is quite common to add a Back-Up fuse to the expulsion fuse for transformer applications (see 5.2.2.4).

5.2.2.4 Current-limiting fuses combined with expulsion fuses

As has been discussed in 5.2.2.3, while expulsion fuses are commonly used for transformer protection using "North American" practice, their limited maximum breaking current and lack of current-limiting action results in them frequently being "paired" with back-up current-limiting fuses. The characteristic of back-up fuses having a minimum breaking current (see 4.2.3.4) makes them a natural partner for expulsion fuses (and indeed some types of Full-Range current-limiting fuse make this pairing in the same body). The general coordination principle therefore becomes that each fuse must protect the other in its area of non-operation, i.e. the expulsion fuse must operate for currents below the back-up fuse's rated minimum breaking current, while the back-up fuse must operate at currents above the expulsion fuse's rated maximum breaking current. Detailed coordination information will be given for typical transformer applications; however the basic coordination principles will apply to other applications, including the common back-up current-limiting fuse/expulsion fuse combination used for line protection. Also, although expulsion fuses are the most common devices used with back-up fuses for the transformer application, HV circuit breakers are also available for mounting in the transformer oil. However the same coordination principles apply.

5.2.2.5 Coordination of a current-limiting fuse and a distribution fuse-cutout

A back-up fuse used out-of-doors in series with a distribution fuse-cutout presents a special case of coordination. Typically, back-up fuses used in this application are rated by the largest expulsion fuse-link with which they may be used while still meeting coordination rules. For instance, one type of back-up fuse that can be used with a 12 A type K expulsion fuse-link is designated as being a 12K coordinating fuse. The coordination method is "matched melt coordination", discussed in 5.2.2.6.2. This ensures that the fuse-cutout will drop open even if it is the back-up fuse that is responsible for the current interruption. The drop-out action provides two benefits. The first, and obvious, is that it can be seen that the fuse has operated. The second is that voltage stress is removed from the operated back-up fuse. This gives users the option of choosing particularly compact back-up fuses for this application that are not suitable for long-time exposure to severe outdoor conditions (e.g. pollution) while energized after operation. In most cases, fuses are not left energized for long periods due to fast user response; however there are applications (capacitor banks for example) where fuse operation can go unreported for long periods. While a distribution fuse-cutout is the most common paring for outdoor use, current-limiting back-up fuses are also used with type "B" expulsion fuses, usually in higher current ratings.

5.2.2.6 Coordination of a current-limiting fuse and a liquid-submerged expulsion fuse

5.2.2.6.1 Basic coordination

The first step in selecting appropriate fusing is to choose the expulsion fuse, based on the application information in 5.2.2.3. The choice of the back-up fuse is then addressed by considering four fundamental areas, to ensure that proper coordination exists between a back-up fuse and a series-connected expulsion fuse:

a) each fuse must protect the other in its area of non-operation;

b) unless the back-up fuse is to be replaced after each expulsion fuse operation it must not be damaged by such an operation;

c) overload currents must not damage the back-up fuse;

d) the back-up fuse, like the expulsion fuse, must not be damaged by surges: the same rules that are used to select an expulsion fuse for this requirement also apply to the Back-Up fuse, and so this area will not be discussed further. However, it may be noted that if the expulsion fuse has been correctly chosen, a back-up fuse that coordinates correctly with it usually meets those same surge requirements.

Primary coordination between the series expulsion fuse and the back-up current-limiting fuse (item a) above) ensures that the two will work together to clear all currents from the lowest current that will cause the expulsion fuse's element to melt up to the current corresponding to the rated maximum breaking current of the current-limiting fuse. Achieving this primary coordination requires that when the appropriate time-current characteristic curves for the two devices are overlaid, the expulsion fuse maximum operating TCC curve crosses the minimum pre-arcing TCC curve of the back-up fuse at a current equal to, or higher than, the Back-Up fuse's rated minimum breaking current, and less than, or equal to, the rated maximum breaking current of the expulsion fuse. The two series devices then provide "full-range" protection and each fuse protects the other fuse in its zone of "vulnerability." This second criteria (crossover occurring below an expulsion fuse's rated maximum breaking current) is sometimes relaxed for large transformer applications, when certain operating and coordination conditions apply. This coordination is seen in Figure 21.

Depending upon the relative location of the two curves, one of two different types of coordination will exist. These two methods of coordination are commonly referred to as "matched melt" coordination and "time-current curve crossover" coordination, although matched melt coordination should in fact be considered a form of time-current curve crossover coordination with some additional requirements. Figure 21 and Figure 22 illustrate the principles involved.

5.2.2.6.2 Matched melt coordination

For this method of coordination, in addition to the basic coordination rules described in 5.2.2.6.1, another criterion must be met. This is to ensure that the expulsion fuse melts open any time the two-fuse combination clears an overload or fault. In general, matched melt coordination will result in the minimum pre-arcing time-current characteristic of the expulsion fuse lying to the left of the minimum pre-arcing TCC of the back-up fuse for all times longer than 0,01 s, as shown in Figure 21. However, this is not a reliable method of ensuring that the expulsion fuse will melt at times shorter than 0,01 s. To be certain that the expulsion fuse will always melt open at any current which causes the current-limiting fuse to operate, the minimum operating I^2t let through by the current-limiting fuse should be equal to, or greater than, the maximum pre-arcing I^2t of the series expulsion fuse, at 0,01 s and less. It is this criterion from which the method's name is derived.

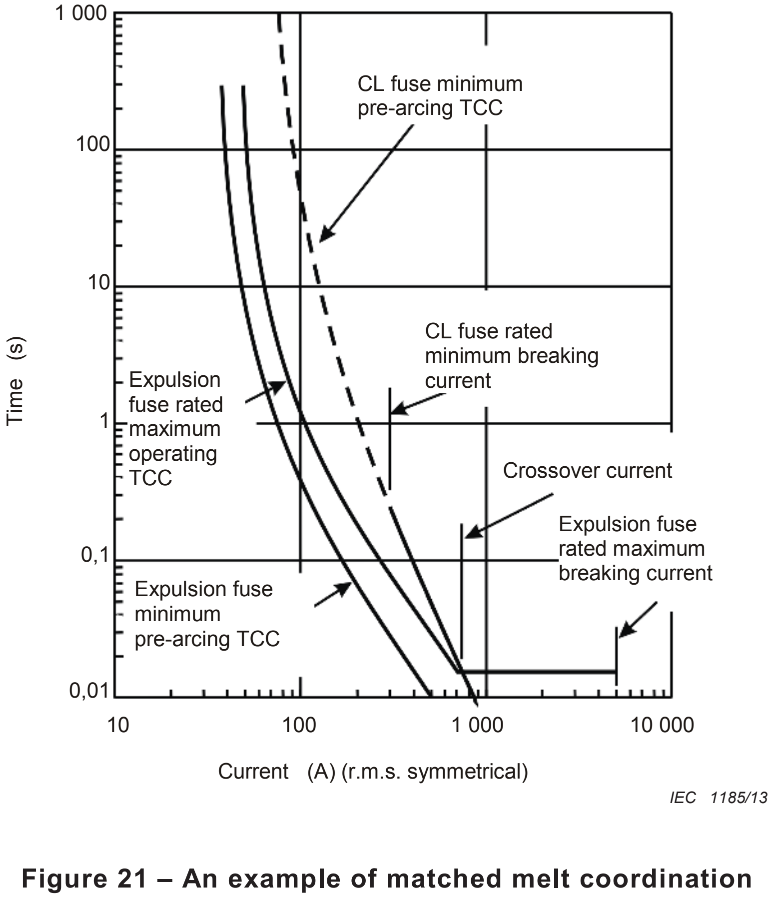


Figure 21 – An example of matched melt coordination

One conservative approach to ensuring that the current-limiting fuse will let through sufficient energy to melt open the expulsion fuse is to choose a current-limiting fuse having a minimum pre-arcing I^2t greater than the maximum pre-arcing I^2t of the expulsion fuse used in series with it. However, a more practical approach is to take into account the fact that the current-limiting fuse will, under almost all practical circumstances, let through more I^2t than its minimum pre-arcing I^2t. Minimum pre-arcing I^2t values correspond to very short fuse pre-arcing times, and worst-case manufacturing tolerances. Therefore, not only will the actual I^2t that causes pre-arcing likely be higher than the published minimum values, additional I^2t will be let through as a result of the current during the arcing that occurs after melting, and which continues until the fuse has cleared. Experience has shown that excellent coordination can be realized as long as the maximum pre-arcing I^2t of the expulsion fuse does not exceed approximately twice the minimum pre-arcing I^2t of the current-limiting fuse. The only circumstances under which such an approach could result in the failure of the expulsion fuse to melt open is if a very short duration surge of current (e.g. a lightning surge) were to occur and its magnitude just happened to be such that the I^2t of the surge exceeded the pre-arcing I^2t of the current-limiting fuse, but was less than the pre-arcing I^2t of the expulsion fuse. Obviously, such a situation would very rarely develop, and thus need not be a significant consideration in selecting the best current-limiting fuse for a particular application.

As is obvious from the preceding discussion, in order to use the matched-melt method of coordination, one must know the values of the short-time maximum pre-arcing I^2t for the expulsion fuse and the minimum pre-arcing I^2t for the current-limiting fuse. Although the latter is usually published by the current-limiting fuse manufacturer, the expulsion fuse manufacturer does not normally publish the former. However, it can be readily calculated from the expulsion fuse's minimum pre-arcing time-current characteristic curve. One method of calculation involves first determining the current corresponding to the value of time representing the fewest whole number of quarter-cycles. For many published curves this might be the current corresponding to three (3) quarter cycles (0,0125/0,015 s for 60/50 Hz). Once the current has been determined from the expulsion fuse's minimum pre-arcing curve, it should be increased by an appropriate factor to take into account variations resulting from manufacturing tolerances. In the case of expulsion fuses having silver fuse elements, this factor is 10 %. For fuses with elements made from other materials, this factor could be as high as 20 %. After the current has been corrected to allow for manufacturing tolerances, the maximum pre-arcing I^2t of the expulsion fuse can be calculated by first squaring this current and then multiplying that value by the time (expressed in seconds) that was the basis for determining the current. Obviously, should the expulsion fuse manufacturer publish a value for the fuse's maximum pre-arcing I^2t, that value should be used rather than the value that one would obtain from the previously described procedure.

The principal advantage of the matched-melt method is that the expulsion fuse will melt open even if the current-limiting fuse does the actual clearing. This is the method used with fuse-cutouts (see 5.2.2.5).

Another advantage of this coordination method is that in certain non-effectively earthed three-phase applications, the voltage rating of the back-up current-limiting fuse need only be equal to the system's line-to-neutral voltage as long as the voltage rating of the expulsion fuse is equal to the system's line-to-line voltage. Because this requires certain assumptions to be made regarding possible fault scenarios, in practice this is not usually done if a line-to-line rated fuse is available. However, there have been applications in which it was the only fusing option available and is the main reason why this coordination method is sometimes used with the under-oil back-up current-limiting fuse.

5.2.2.6.3 Time-current curve crossover coordination

The second method for coordinating back-up current-limiting fuses is referred to as time-current curve-crossover coordination. This method of coordination is frequently used with under-oil back-up current-limiting fuses, and is illustrated in Figure 22. In the example shown, the minimum pre-arcing TCC curve of the expulsion fuses crosses the minimum pre-arcing TCC curve of the expulsion fuse at a time longer than 0,01 s, making it less likely that the combination would meet the requirements for matched melt coordination. When a fault current is higher than this crossover point, the current-limiting fuse may melt and clear without letting through sufficient energy to melt the expulsion fuse. Time-current crossover curve coordination is rarely used in applying outdoor back-up current-limiting fuses, since there is no assurance that a series distribution fuse-cutout would melt and drop open using this method. If the distribution fuse-cutout does not open, full voltage can be impressed on a weathered outdoor Back-Up fuse that may no longer have full voltage withstand capability.

Because of the location of the intersection or crossover point of the expulsion fuse's operating TCC curve and the back-up fuse's minimum pre-arcing TCC curve, one need not be concerned with the melt I^2t values of the two fuses when using this method of coordination. The principal criterion to be satisfied is that the previously discussed crossover point must correspond to a current which is greater than the rated minimum interrupting current of the current-limiting fuse, but less than the rated maximum interrupting current of the expulsion fuse. The manufacturers of the expulsion fuse and the current-limiting fuse are required to publish values for these performance characteristics.

The principal advantage of the time-current curve crossover method, compared to matched melt coordination, is that it normally permits the use of a current-limiting fuse having a smaller current rating. This can be significant in several regards.

Firstly, the lower the current-limiting fuse's current rating is, the less energy it is apt to let through under fault conditions. Obviously, the lower the energy that is let through by the current-limiting fuse, the better the protection will be against eventful failure anywhere on the system, that is protected by the current-limiting fuse. In addition, the fault will have less effect on the rest of the distribution system as voltage drops are minimized.

Secondly, the lower the current rating of the current-limiting fuse, the smaller it is apt to be and the less space it is apt to require for installation.

Thirdly, when this method of coordination is used rather than matched melt coordination, often the largest available back-up fuse rating can then be used to protect larger transformers.

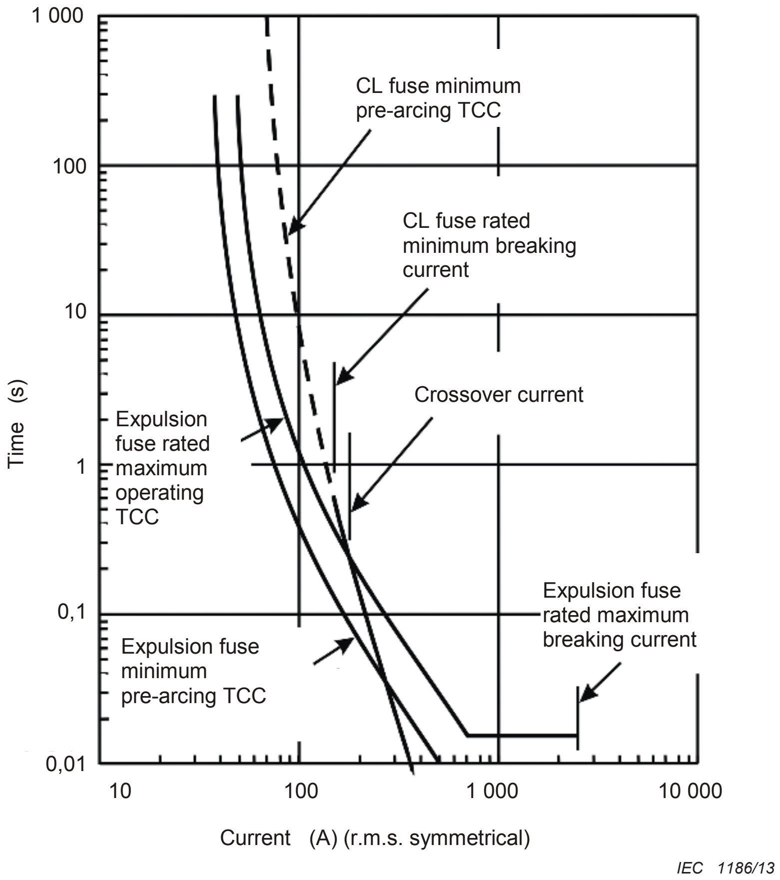


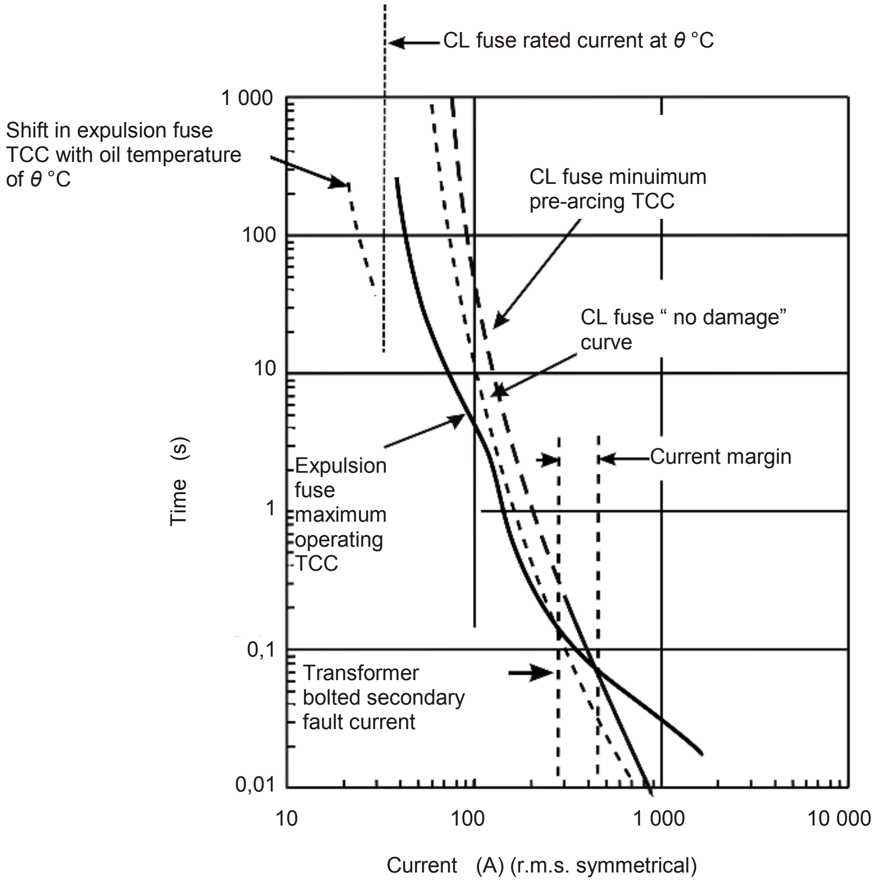
Figure 22 – An example of time-current crossover coordination

5.2.2.6.4 Prevention of damage to the back-up current-limiting fuse

For applications of back-up current-limiting fuses with expulsion fuses on the primaries of transformers, there is another selection criterion that is particularly important in practice. When the current-limiting back-up fuse is inside the transformer it is possible to arrange the coordination such it will only operate in the event of an internal transformer fault. In this way the back-up fuse does not have to be replaceable. The concepts to be discussed are illustrated in Figure 23, and involve currents up to the value corresponding to a fault at the secondary terminals of the transformer (that is a fault limited only by the transformer’s impedance – often termed "bolted secondary fault current" or in the case of transformer testing "short-circuit current"). A current-limiting fuse should be chosen such that this current is less than the current corresponding to the crossover point of the expulsion fuse’s maximum operating curve and the back-up fuse’s minimum pre-arcing curve by an appropriate margin. This ensures that the back-up fuse does not melt with, and more importantly is not damaged by, a fault external to the transformer. "Damage" in this case refers to a partial melting of the fuse elements and/or, at longer melting times, deterioration of other components by fuse overheating. A damaged back-up fuse could later melt at a current below its minimum breaking current and fail to interrupt this current. The "appropriate margin" will therefore now be discussed.

Although not published by the fuse manufacturer, one can envision a "no-damage" characteristic curve, which lies slightly below and to the left of the minimum pre-arcing curve of a back-up current-limiting fuse. The separation between the published minimum pre-arcing curve and the imaginary no-damage curve represents a margin of safety and is intended to compensate for various factors associated with real life (practical) applications. Some factors affect the accuracy of the calculation of the bolted secondary fault current. These include the tolerances on the transformer impedance, system line voltage fluctuations, and the use of taps. Other factors involve actual damage to the fuse element(s), caused by partial melting and mechanical stress, which can occur prior to the complete severing of the element. Only after the element(s) completely melt open can arcing be initiated, and it is this time that is used to plot the TCC curve.

If the fuse manufacturer has a recommended margin, this should be used. In the absence of this information, a commonly used method involves setting the no-damage current equal to 80 % of the current shown on the minimum pre-arcing curve for any particular pre-arcing time. Since proper coordination between the back-up current-limiting fuse and the series expulsion fuse requires that the current-limiting fuse not be damaged by any current equal to or less than the bolted secondary fault current, this method requires that the calculated bolted secondary fault current be no greater than 80 % of the current-limiting fuse minimum pre-arcing current at a time corresponding to the maximum operating time of the expulsion fuse (with a current equal to the bolted secondary fault current). Conversely, the Back-Up fuse's minimum pre-arcing current must equal at least 125 % of the calculated bolted secondary fault current at a time corresponding to the expulsion fuse's maximum operating time at that current.



IEC 1187/13

Figure 23 – Fuse "no-damage" margin

When a back-up current-limiting fuse has been chosen using appropriate bolted secondary fault current coordination, it is not necessary to provide access to permit a current-limiting fuse located inside the transformer to be replaced "in the field". If bolted secondary fault coordination is not achieved, then the back-up fuse must also be replaced any time the expulsion fuse operates.

5.2.2.6.5 Overload protection for the back-up current-limiting fuse

There is another aspect of coordination that must be considered before one can be sure that a back-up fuse is properly coordinated. This requires that checks be made to show that the back-up current-limiting fuse will not melt or be damaged as a result of overloads. This is also illustrated in Figure 23. First, when the back-up fuse is used for transformer protection, the maximum operating curve of the expulsion fuse should not cross the no-damage curve, discussed in 5.2.2.6.4, for all currents below the bolted secondary fault current of the transformer. In other words, for all expulsion fuse operating times from the value corresponding to the operating time at the bolted secondary fault current up to 1 000 seconds or more, the corresponding current on the expulsion fuse's maximum operating curve should be no more than 80 % of the corresponding current on the current-limiting fuse’s minimum pre-arcing curve (unless the fuse manufacturer specifies a different no-damage criterion). Preloading should not affect this coordination as any shifting to the left of the characteristic curves due to Joule (I^2R) heating of the fuse elements, or surrounding liquid temperature rise will be as much or more for the expulsion fuse as for the current-limiting fuse.

The second condition to be satisfied is that under pre-loaded conditions, the maximum current that the expulsion fuse can carry without melting for a relatively long period of time (i.e. greater than five minutes) must be less than the current rating of the current-limiting fuse. When the expulsion fuse is located inside equipment, such as a transformer, any shifting of the curve caused by temperatures produced by overload conditions should be taken into account when this criterion is examined. For example, some types of expulsion fuses experience a significant shift in their maximum operating TCC curve at elevated temperatures. A "dual" element type fuse in oil at 120 °C can have its long time pre-arcing characteristic shifted, in terms of current, to about 40 % of the values published at 20 °C. Overload protection for the back-up fuse can also be provided by secondary protection.

See 5.2.2.6.4 for coordination techniques to prevent back-up fuse damage, and 5.3.5.5 for a discussion of fuse damage caused by the operation of a series device.

5.2.3 Motor-circuit applications

5.2.3.1 General

Fuses for motor circuit applications are primarily used with motors started direct-on-line on alternating current systems of 50 Hz and 60 Hz. They are typically back-up current-limiting fuses designed specifically for the application and are normally used in conjunction with a contactor that interrupts currents below their minimum breaking current. Their function is to provide short-circuit protection for the supply system from faults at or within the motor, and from cable faults between the motor and the motor starter, that are above the "takeover" point from the associated device that provides low overcurrent protection. The primary characteristic of the fuses is their ability to withstand repeated motor starting currents due to their specially designed fuse elements. For this purpose, the manufacturer may state a "K" factor (see 5.2.3.3), which will indicate to the user the degree to which the fuse-link is capable of withstanding cyclic overloads without deterioration. The "K" factor is based on test requirements specified in IEC 60644 and the manufacturer will state if the K factor is related to the minimum or the mean pre-arcing time-current characteristic.

5.2.3.2 Fuse-link time-current characteristics

Fuse-links complying with IEC 60644 will have characteristics as detailed below.

Relatively high operating current (slow operation) is desirable in the 10 s region of the pre-arcing time-current characteristic to give maximum withstand against motor starting current.

Relatively low operating current (fast operation) is desirable in the region below 0,1 s to give maximum short-circuit protection to associated switching devices, cables and motors and their terminal boxes.

The pre-arcing time-current characteristics of fuse-links for motor circuit applications are therefore within the following limits:

$I_{f10}/I_r \geq 3$ for $I_r \leq 100$ A

$I_{f10}/I_r \geq 4$ for $I_r > 100$ A

$I_{f0.1}/I_r \leq 20(I_r/100)^{0,25}$ for all current ratings

where:

I_r	current rating of the fuse-link;
I_{f10} and $I_{f0,1}$	pre-arcing currents corresponding to 10 s and 0,1 s respectively expressed as mean values with the tolerances specified in IEC 60282-1:2009, 4.11.

The term $(I_r/100)^{0,25}$ is introduced to take account of the fact that the pre-arcing time-current characteristics for a range of fuse-links diverge as they approach the short-time region.

5.2.3.3 *K* Factor

5.2.3.3.1 General

This is a factor that defines an overload characteristic to which the fuse-link may be repeatedly subjected under specified motor starting conditions, and other specified motor-operating overloads, without deterioration.

For the purpose of IEC 60644, the value of K is chosen at 10 s. Unless otherwise stated by the fuse-link manufacturer, it is valid from 5 s to 60 s, for a frequency of starts up to six per hour and for not more than two consecutive starts. For conditions different from those specified above, for example where service conditions involve inching, plugging or more frequent starts, the manufacturer should be consulted.

The overload characteristic is obtained by multiplying the current on the pre-arcing characteristic by K (less than unity). This then defines the boundary of the overload curve for a given number of motor starts per hour.

5.2.3.3.2 Withstand requirements

The performance of a fuse-link for motor circuit applications is in general determined by the following criteria:

- to withstand without deterioration starting pulses in rapid succession due for example to abnormal conditions, such as those occurring during commissioning of the equipment;
- to withstand without deterioration a large number of motor starts in normal service conditions.

IEC 60644 therefore specifies two sequences of tests representative of these conditions: 100 cycles corresponding to abnormal service conditions, and 2 000 cycles corresponding to normal service conditions. It is expected that a fuse-link that passes these tests will have a good behaviour during a satisfactory life duration.

5.2.3.4 Selection of fuse-links for motor circuit applications and correlation of fuse-link characteristics with those of other components of the circuit

5.2.3.4.1 Selection of fuse-links

The fuse-link is inserted in the motor circuit that the fuse-link is intended to protect. Some ratings of the fuse-links (e.g. rated voltage and rated maximum breaking current) are therefore dependent on the system and others (e.g. rated current) are dependent on the motor.

The rated maximum breaking current of motor-starter fuses should equal or exceed the maximum available short-circuit duty at the point in the system where the fuses are installed. In general, the rated minimum breaking current need only be low enough to ensure correct coordination with the switching device over-current relay. However, where additional safety is required, the fuse-link minimum breaking current should be at least as low as the stalled rotor current of the protected motor.

The ability to withstand repetitive starting conditions is an important factor. When selecting a fuse-link for a given motor circuit application, due regard should be paid to the K factor, which should be applied to the pre-arcing time-current characteristic of the fuse-link to take account of these starting conditions.

The usual concept of rated current, based upon the ability of a fuse-link to carry a given current continuously without exceeding a specified temperature rise, is usually of secondary importance where the motor is started direct-on-line. The fuse-link for such applications is normally chosen by reference to the paragraphs above.

However, it should be verified that the rated current of the fuse-link exceeds the running current of the motor in the service conditions by an amount sufficient to take account of the effects of the temperature of the surrounding air when the fuse-links are enclosed in starting motor control equipment.

Where assisted starting is used and thereby starting currents are reduced, the above method of selection is generally applicable, but allowance may have to be made for the high transient currents which, with some methods of starting, flow during transition from one connection to the succeeding connection. Further, since assisted starting in general allows the use of fuse-links of lower current-rating, the temperature-rise under running conditions is likely to be of primary importance.

Some motor-starter fuses, using "North American" practice are not assigned a rated current but rather are identified by an "R" rating (e.g. 2R, 4R, etc.). IEEE C37.46 [8] specifies that an "R" rated fuse should melt in a range of 15 to 35 seconds at a value of current equal to 100 times the R number. IEEE C37.46 [8] also specifies minimum values for the allowable continuous current (see 5.1.1.1.3) rating of R rated fuses at surrounding temperatures of 40 °C and 55 °C (e.g. currents for a 2R fuse are 70 A and 63 A and for a 4R fuse 130 A and 115 A at 40 °C and 55 °C respectively). It should be noted that this TCC requirement is approximately in line with the requirements given in 5.2.3.2. As an historical note, the "R" number originally referred to the number of parallel "ribbons" (fuse elements) in a motor-starter fuse, but this is not necessarily the case with modern fuses.

5.2.3.4.2 Coordination with other circuit components

Figure 24 illustrates a typical motor circuit application involving a motor, relay or relays (providing one or more of the following: inverse overcurrent protection, instantaneous overcurrent protection, instantaneous earth fault protection), contactor or other mechanical switching device, the cable and the fuse-link itself.

The motor will be chosen for its particular duty, thus fixing the values of the full load current and the starting current. The duration and frequency of the starts will also be fixed. The characteristic of the associated inverse overcurrent relay will then be chosen to give adequate thermal protection to the motor. The switching device is selected in conjunction with fuse-link to co-ordinate with the already selected motor.

In particular:

a) the pre-arcing time-current characteristic of the fuse-link, when multiplied by the appropriate K factor, should lie to the right of the motor starting current at point A;
b) the mechanical switching device should be capable of withstanding the conditions defined by the combined operating characteristics dBCE;

c) the rated current of the fuse-link should be chosen such that when the fuse-link is mounted in its service position it is capable of carrying continuously the running current of the motor without overheating. This is of particular importance where assisted starting is used;

d) the current corresponding to the point of intersection B of the curves of the fuse-link and the overcurrent relay should be less than the maximum breaking current of the mechanical switching device;

e) the minimum breaking current of the fuse-link should not exceed the minimum takeover current, "B";

f) in the event of instantaneous protection being provided, the takeover point will move from B to C. Due regard should be paid to the possibility that the mechanical switching device might open at a current greater than its rated maximum breaking current;

g) the cut-off current of the fuse-link at the maximum fault current of the system should not exceed the through-fault current withstand of the mechanical switching device for the operating time of the fuse, typically one half cycle or less;

h) it is desirable that the minimum breaking current of the fuse-link should be as low as possible and preferably should be at least as low as the stalled rotor current of the motor;

i) as shown in Figure 24, the whole of the withstand curve of the cable should lie to the right of the operating characteristic dBCE. Where high ratings of fuse-link are necessary due to the nature of the motor starting duty (for example, long starting times and frequent starts), the section BCE moves to the right and may necessitate an appropriate increase of cable size.

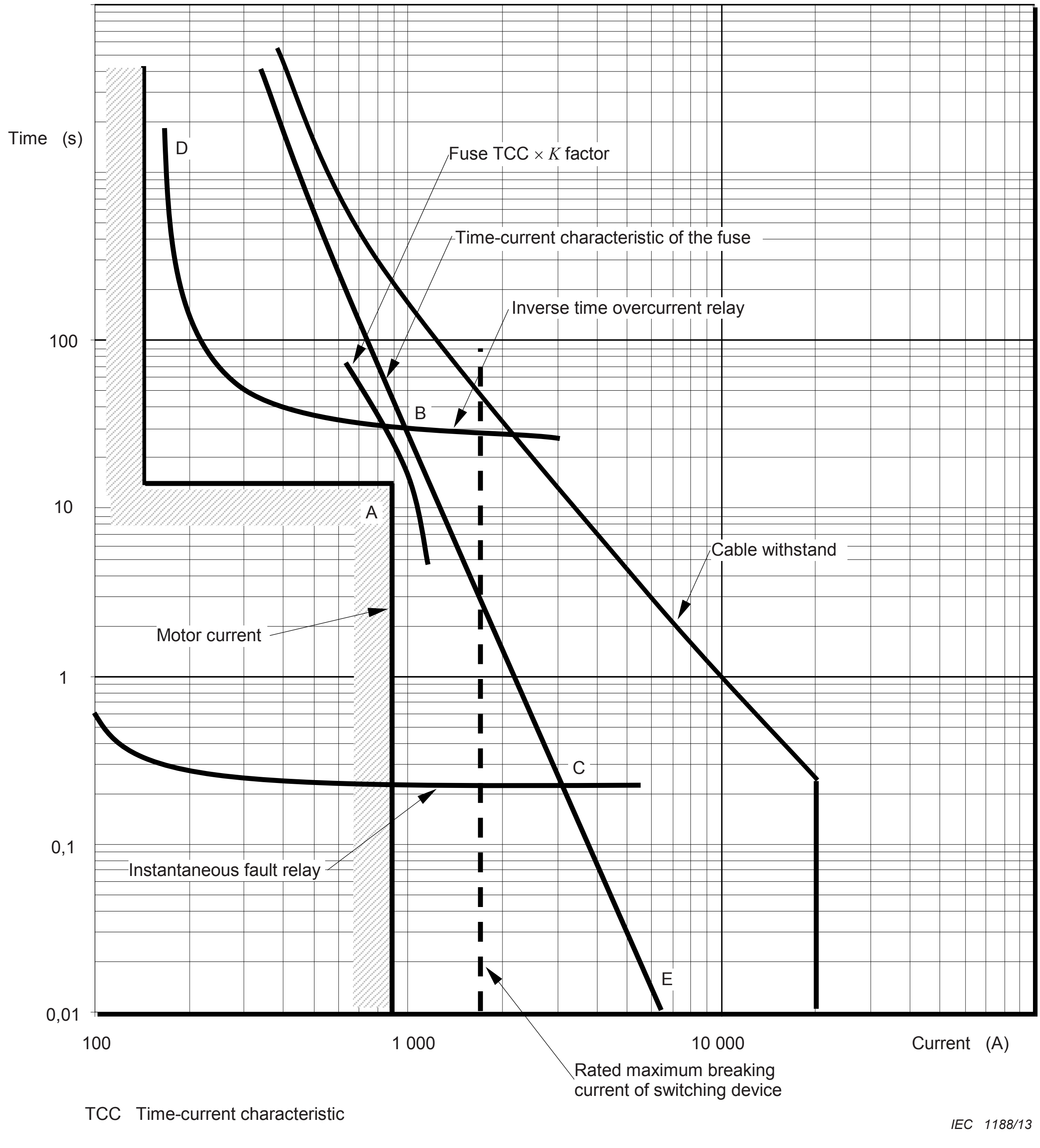


Figure 24 – Characteristics relating to the protection of a motor circuit

5.2.4 Capacitor protection applications

5.2.4.1 General application information for external fuses for shunt capacitor banks

Subclause 5.2.4 provides application guidelines for fuses that are mounted external to the capacitor(s), and that are intended for the overcurrent protection of the capacitor(s). Capacitor fuses are typically tested to IEC 60549 or IEEE C37.41 [6]. While, at the time this report was produced, these standards show differences in testing methods, their differences were in the process of being resolved with changes to both standards.

An external fuse used for shunt capacitor-bank protection, within the limits of its ratings, minimizes damage to the system and to the capacitor bank or capacitor unit resulting from a fault. The capacitor fuse cannot prevent a capacitor from failing. For many installations, reducing the risk of capacitor tank rupture is a primary concern. Ideally the fuse should also clear before upstream protective devices operate or are damaged. Proper fuse performance will depend upon the correctness of the application.

There are two kinds of external capacitor fuses: capacitor line fuses and capacitor unit fuses. Capacitor line fuses (also commonly referred to as "group" fuses) are used for the protection of the entire capacitor bank installation, whereas capacitor unit fuses (often referred to as "individual" fusing) are used for the protection of individual capacitor units. Some installations incorporate both capacitor line fuses and capacitor unit fuses. The types of fault current seen by the two types of fuse tend to be different, so different breaking tests are specified for each. In most cases, different fuse designs are used for the two types of fuse, while in other cases the same fuse can be used as a line fuse or a unit fuse, but it will have been shown to be capable of interrupting fault currents associated with the two types of application. Often, small distribution capacitor banks are just protected by capacitor line fuses.

Typically, the melting of the fuse is initiated by power-frequency overcurrent and/or, for capacitor unit fuses, from stored capacitor energy that is discharged through the fuse.

Power-frequency current and stored energy factors that should be considered when determining the proper protection for a capacitor bank are: the system fault current available at the capacitor bank location, the type of capacitor bank connection (such as delta or star (wye), neutral earthed (grounded) or unearthed (ungrounded), the rating of the capacitor unit or capacitor bank in terms of volt-amperes reactive (usually divided by 1 000 and expressed as kVAr), and the number of capacitor units in parallel.

An unbalance protection scheme is frequently used for capacitor bank protection. The setting of the unbalance protection may affect the voltage across an individual capacitor unit fuse when it clears, and should be considered in determining the fuse voltage rating. Some earthed star capacitor banks on earthed star systems and some delta connected capacitors banks (regardless of system earthing), that use only one series connected string of capacitor units (no parallel strings), may not require unbalance protection for reliable capacitor bank protection.

For applications where capacitor line or capacitor unit fuses are used in enclosures or vaults, expulsion fuses that have controlled venting or current-limiting fuses should be considered.

Where fuse-links are used to protect capacitor units, very low minimum breaking current values may be desirable in order to take account of the small increases in current that occur when one or more series connected capacitor elements break down. In the case of fuse-links used only for line protection (where individual units are separately protected by other means) then fuse-links with an appropriately higher value of minimum breaking current may be employed (see IEC 60549).

While capacitors are considered constant current devices, they are subject to overcurrents in actual operation on a system. These are caused by over-capacitance (manufacturing tolerance), operation at higher than rated voltage, and system harmonic currents.

Overvoltage increases the current into a capacitor linearly with voltage change. Excessive voltage may also cause an increase in third harmonic current from over-excited transformers. Some standards allow operation at 10 % overvoltage and a 15 % over-capacitance. Harmonic currents depend on system conditions and are difficult to predict. Allowance for such increases in service current are termed "allowance factor", and are discussed in 5.2.4.5.1.

5.2.4.2 Capacitor fuse application aims

5.2.4.2.1 Capacitor line (group) fuses

Typically, when small star connected or single series group delta connected distribution capacitor banks are protected by fuses, only capacitor line fuses are employed. For larger banks a line fuse may be used to protect the bank along with unit fuses for protection of each capacitor unit.

Some desirable characteristics for capacitor line fuses may be to:

a) protect the distribution system or substation bus from major faults at, or within, the capacitor bank, and coordinate with the next upstream overcurrent protective device up to the maximum fault current available at the capacitor bank;
b) provide earliest possible isolation of one or more phases of a capacitor bank having a faulted capacitor unit, if no capacitor unit fuses are used;
c) permit higher current loading associated with: plus-side tolerance of capacitance in capacitor units, operating voltage in excess of nameplate rating, and the presence of harmonic currents (a fuse is often chosen to have an allowable continuous current of 135 % of the nominal capacitor current, see 5.2.4.5.1);
d) Operate, when one phase of an unearthed-star bank becomes faulted to neutral, within a time span that will minimize the probability of damaging the capacitor units in the unfaulted phases due to overvoltage.
e) withstand the transient energizing current from the system and from other nearby energized capacitor banks;
f) withstand or operate (user's choice) on discharge current from the capacitor bank into a fault on the system near the capacitor bank. It may be noted that a fuse pre-arcing characteristic that would be required if the bank is to remain connected during such a fault may provide less desirable bank protection than that obtained with a fuse having a characteristic that would result in operation with a fault close to the bank.

Some considerations where only capacitor line fuses are used:

a) it is important that the fuse have a maximum operating time-current characteristic consistent with the degree of risk associated with capacitor unit rupture that is acceptable for the type of installation and location contemplated for the capacitor bank;
b) where line fuses are used on an unearthed star connected bank the capacitor units on the unfaulted phases are subjected to overvoltages up to 1,73 per unit until the fault is cleared by the line fuse;
c) where line fuses are connected outside of the delta on a delta-connected bank, a faulted capacitor unit is not disconnected from the circuit if only one fuse operates.

5.2.4.2.2 Capacitor unit (individual) fuses

Some desirable characteristics for capacitor unit fuses may be to:

a) provide earliest possible isolation of a faulted capacitor unit;
b) permit maximum normal loading associated with:
    1) capacitance of the capacitor unit larger than nominal;
    2) voltage across the capacitor unit higher than nominal, due to system operating voltage above nominal and/or increased voltage across the remaining capacitor units in a group resulting when parallel capacitor units are isolated;
    3) the presence of harmonics in the capacitor current;
c) withstand the discharge transient "outrush" current from an individual capacitor unit into a faulted capacitor unit within the same series group.

5.2.4.3 Capacitor inrush considerations for line fuses

While being energized, capacitor banks may initially appear as a short-circuit. The capacitor bank charging current (or inrush current) will be limited by the circuits' impedance and depend on the system voltage phase angle at which the bank is initially energized.

The fuse's minimum pre-arcing I^2t must be larger than the inrush I^2t. The I^2t of the inrush current can be estimated with good accuracy. The initial magnitude of the inrush current, I without any consideration for damping due to system resistance can be calculated, using Equation (1):

$$I = U(C/L)^{1/2} \tag{1}$$

which is based on the relationship $(L/2)I^2 = (C/2)U^2$

where

U is the peak voltage,
C is the capacitance,
L is the source circuit inductance.

The inrush energy enters the capacitor by way of a high-frequency damped sinusoidal current, whose initial magnitude is determined by the system voltage, inductance, and surge impedance. The high-frequency resistance, a value much greater than the 60 Hz circuit resistance, and one that can only be empirically determined, causes damping of the high-frequency inrush current. A typically severe, and therefore conservative, inrush current is one having a first peak that is 90 % of that for an undamped current, with subsequent 1/2 cycle peaks that should be 81 % of each preceding peak. Equation 2 describes the I^2t that results from that current:

$$I^2t = 3{,}74\ E^2C^{3/2}L^{-1/2}\ \mathrm{A^2s} \tag{2}$$

where:

E is the phase to ground peak voltage in volts,
C is the phase capacitance of bank in farads,
L is the source circuit inductance in henries.

A capacitor with no initial charge (has not been energized in the previous 5 min) results in an initial instantaneous inrush current unaffected by an existing charge. This transient current diminishes as the capacitor charges until eventually the current is equal to $V\omega C$ (ω is equal to 2π times the power frequency). The transient current has a frequency, f, proportional to the reciprocal of the square root of the product of capacitance and the short-circuit inductance (Equation 3).

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{3}$$

Excessive switching may degrade the characteristics of a fuse-link as repeated inrush currents can cause localized heating and movement of the fuse element(s). Considerations for inrush conditions in single bank applications are as follows:

a) energizing a capacitor during recloser/breaker operations with short (measured in cycles) "open" time may result in higher inrush currents if the charge trapped on the capacitor is of a polarity opposite to the circuit voltage at the moment of energizing;

b) energizing a capacitor bank on a circuit that has an energized bank already in service causes the instantaneous current to be a function of the impedance between the two banks as well as the short- circuit current from the source. The frequency of the inrush current has two components, one resulting from the inrush characteristics of the bank and the other from the short-circuit characteristics of the circuit. The following equations express these relationships:

$$f_{\text{inrush}} \text{ is proportional to } \{(L_{\text{betweenbanks}}) \times [(C1C2)/(C1 + C2)]\}^{-1/2} \tag{4}$$

$$f_{\text{short-circuit component}} \text{ is proportional to } \{(L_{\text{short-circuit}}) \times (C1 + C2)\}^{-1/2} \tag{5}$$

5.2.4.4 Selection of fuse rated voltage

5.2.4.4.1 General

The rated voltage U_r of the fuse is its rated maximum voltage, i.e. the maximum power-frequency r.m.s. voltage (including any system overvoltage or unbalance) at which it is intended to be applied.

The selection of the fuse voltage rating is based on achieving proper fuse operation at the maximum continuous system operating voltage. This basis for voltage rating selection does not include provision for operation during transient or short-time overvoltages associated with restriking circuit breakers, system faults, etc.

The rated voltage of expulsion fuses may exceed that required by the application by any desired amount.

When a shunt capacitor is used in a power system, the leading (capacitive) current it draws has the effect of increasing system voltage at the point where it is connected. This is because the current produces a voltage rise as it flows through the circuit reactance. While this is usually desirable for maintaining a satisfactory operating voltage level (and often the reason that shunt capacitors are used), excessive capacitive current can cause an unwanted voltage increase. Excessive capacitive current usually occurs due to the failure of capacitor elements or units that are in series with other capacitor elements or units (and/or the operation of unit fuses). A failure produces a significant increase in voltage across the remaining series elements or units, resulting in increased capacitive current flow through them. This higher than normal current can produce an increase in system voltage. Capacitors are usually required to operate satisfactorily at up to 10 % above their rated voltage, so capacitor banks normally use protection that limits overvoltage to 10 %. Testing to IEC 60549 limits the permissible rise in circuit voltage, due to the switching of the capacitance that produces the desired capacitive prospective current. This limit is set at 10 % above test circuit recovery voltage. There is no guarantee, however, that a given fuse has been tested in a circuit that gives a 10 % voltage rise (it may have been less). Therefore the "capacitive voltage rating" is set no higher than the power frequency recovery voltage (the same voltage as if the test had been with an inductive current). Because of this, the maximum circuit voltage, or internal bank voltage, that a fuse must be able to interrupt against, even under conditions of capacitor failure, must be known in order to choose the correct capacitor fuse rated voltage. The fuse rated voltage must be equal to or higher than this maximum voltage. IEC 60549 calls for a fuse to be rated at 1,1 times the rated voltage of the capacitor. However this is only the correct fuse rated voltage if the maximum fault current produced by failing capacitors can only result in a 10 % voltage rise above the nominal capacitor voltage rating before the capacitor bank protection operates.

5.2.4.4.2 Capacitor line fuses

Current-limiting fuses may produce switching voltages that are substantially higher than normal system peak power-frequency voltage. Selection of current-limiting fuses having a rated maximum voltage that is considerably higher than system power-frequency voltage may result in switching voltages that may cause insulation damage or surge arrester failure. The lowest available voltage rated current-limiting fuse that meets the application voltage requirement is therefore recommended. If higher voltage rated current-limiting fuses are to be used, consult the manufacturer.

For unearthed capacitor banks (unearthed-star or delta-connected) the voltage across the second line fuse to clear is system line-to-line voltage, regardless of the system grounding at the capacitor bank (unearthed systems, including uni-grounded systems, or earthed star systems, including impedance earthed systems). For unearthed star or delta connected capacitor banks, fuses should have been tested at a voltage equal to, or exceeding, the maximum system line-to-line voltage. This may require a fuse having a rated maximum voltage equal to at least 115 % of the maximum line-to-line voltage (see 5.1.3).

For earthed-neutral star connected capacitor banks applied on effectively earthed (multi-earthed four wire) systems, fuses tested at 100 % of their maximum rated voltage should have a maximum rated voltage equal to, or exceeding, the maximum system line-to-ground voltage. Some Class B expulsion fuses and current-limiting fuses may be tested as three phase devices, with some tests at reduced voltage. This may require a fuse having a rated maximum voltage equal to at least 115 % of the maximum line-to-ground voltage (see 5.1.3). This application information is based on the usual application where the fuses are located close to the capacitor bank and a three-phase fault not involving ground is not likely to occur. For applications where the fuses are located remote from the capacitor bank, or the capacitor bank construction is such that a three phase fault not involving ground needs to be considered, the recovery conditions for this fault should be used to select the appropriate fuse. For these applications fuses having all test voltages equal to, or exceeding, the maximum system line-to-line voltage should be used.

It may be noted that, in the event of a three-phase unearthed fault, the first capacitor line fuse to clear would see a recovery voltage of 1,5 times the line-to-ground voltage after clearing the fault current in its phase. The probability of the occurrence of such faults will have an effect, as indicated above, on the determination of the fuse voltage rating selected for the application.

The insulation withstand voltage level (BIL, power frequency voltages and creepage) of the mounting used for the line fuse should be consistent with the system insulation level.

5.2.4.4.3 Capacitor unit fuses

An expulsion fuse or a current-limiting fuse should have a rated maximum voltage equal to or exceeding the maximum power frequency voltage that will appear across the fuse following its operation. Higher than nominal capacitor bank voltages can result from higher than nominal system voltages or from voltage unbalance within the bank. Formulae are available in IEEE Std C37.99 [10] for calculating the voltage across a capacitor group as a function of the number of isolated capacitor units, the number of series groups and the capacitor bank connection. For example, for a small bank operating at rated voltage, the operation of the first fuse may result in 109 % voltage across the affected series group (with an alarm), the operation of the second fuse may result in 120 % voltage across the affected series group until the unbalance voltage protection trips and operates. In this case the fuse rated voltage should be at least 1,2 times nameplate rating of the capacitor unit. If the capacitor bank will be operated at above rated voltage, the fuse rating may need to be even higher.

The unbalance protection in a capacitor bank should be fast enough to avoid the last fuse in a series group ever having to operate without a capacitor in parallel and with a very high recovery voltage. Refer to IEEE Std C37.99 [10] for information on unbalance protection.

An expulsion fuse can have a rated maximum voltage that exceeds the power frequency system voltage by any amount. If the bank is fused with current-limiting fuses and a fuse could be subjected to an inductive current fault, care should be taken in applying fuses with voltage ratings much greater than the maximum system voltage. The fuse manufacturer should be consulted in this regard.

5.2.4.5 Selection of fuse current rating

5.2.4.5.1 Allowance factor

In general, a capacitor fuse should be selected based on the highest anticipated capacitor bank or unit current. Specifically, the fuse selected should have an allowable maximum continuous current-carrying capability, as differentiated from its nominal ampere rating, which is greater than this highest anticipated current level.

It follows, then, that this maximum capacitor bank or unit current should be accurately known. This maximum current can be estimated by, first calculating the nominal current, and then applying correction factors.

The nominal capacitor line or unit current (I_{nominal}) for single-phase capacitor banks or units can be calculated using Equation (6):

$$I_{\text{nominal}} = \frac{kVAr}{kV}\ \text{A} \tag{6}$$

where

$kVAr$ is the nominal single-phase rating of the capacitor bank or unit (in kVAr), and

kV is the nominal single-phase voltage rating of the capacitor bank or unit (in kilovolts).

The nominal capacitor line fuse current is equal to the nominal capacitor bank phase current. This nominal phase current (I_{nominal}) for three phase capacitor banks can be calculated using Equation (7):

$$I_{\text{nominal}} = \frac{kVAr_{3\phi}}{\sqrt{3}\,kV_{\phi-\phi}}\ \text{A} \tag{7}$$

where

$kVAr_{3\Phi}$ is the nominal three-phase rating of the capacitor bank or unit, measured in volt-amperes reactive divided by 1 000 (kVAr), and

$kV_{\Phi\text{-}\Phi}$ is the nominal phase-to-phase voltage rating of the capacitor bank or unit in kilovolts

Equations (6) and (7) provide a method for calculating the nominal phase current for single phase or 3-phase capacitor banks or nominal current for capacitor units when the expected operating voltage is equal to the nominal voltage rating of the capacitor bank or unit. When fusing the individual legs of a delta-connected capacitor bank, the current in each leg (i.e., the current seen by the capacitor line fuse) may be determined by multiplying the nominal capacitor bank phase current by 0,58. For systems operating at an expected voltage below their nominal rated voltage, the adjusted bank phase current (I'_{nominal}) can be determined by using Equation (8):

$$I'_{\text{nominal}} = I_{\text{nominal}} \frac{kV_{\text{system}}}{kV_{\text{nominal}}}\ \text{A} \tag{8}$$

where

I_{nominal} is the nominal capacitor bank phase current,

kV_{system} is the nominal system voltage in kilovolts, and

kV_{nominal} is the nominal voltage rating of the capacitor bank in kilovolts.

For capacitor units operating at an expected voltage below their nominal rated voltage, the adjusted capacitor unit current (I'_{nominal}) can be determined by using Equation (9):

$$I'_{\text{nominal}} = I_{\text{nominal}} \frac{kV_{\text{operating}}}{kV_{\text{nominal}}} \text{A} \tag{9}$$

where

I_{nominal} is the nominal capacitor unit current,

$kV_{\text{operating}}$ is the expected operating voltage of the capacitor unit (in kilovolts), and

kV_{nominal} is the nominal rated voltage of the capacitor unit (in kilovolts).

The same base reference is used for all voltage parameters (e.g., either a phase-to-phase or phase-to-ground voltage reference).

Once the nominal capacitor bank current has been calculated from the system voltage, capacitor bank voltage and capacitor bank kVAr rating, the highest anticipated capacitor bank current is then determined by considering the possibility of a system voltage higher than nominal, capacitor manufacturing tolerances, and the presence of harmonics. Past capacitor standards allowed a 6 % higher system voltage (excluding harmonics), a +15 % capacitance tolerance, and a +10 % higher current due to harmonic content. These factors, taken together, would require that the nominal capacitor bank current, calculated based on rated voltage and kVAr, be increased by an allowance as high as 34 % (1,06 × 1,15 × 1,1 = 1,34). This was typically rounded to an allowance of 35 % when conservatively selecting a capacitor line fuse. Recent capacitor standards, have changed the allowable variations listed earlier. This new tolerance results in an allowance of 29 % (1,06 × 1,10 × 1,1 = 1,29). Since the age of the capacitors to be used in an installation is not generally known, the use of the older allowance of 35 % is usually prudent.

When estimating the highest anticipated capacitor unit current, it may operate for some extended time at a voltage 10 % higher than its nominal voltage rating. Allowing for capacitor tolerance and harmonics, the nominal capacitor unit current, calculated based on rated voltage and kVAr, may be increased by an allowance as high as 39 % (1,1 × 1,15 × 1,1 = 1,39).

In practice, however, the operating variables described above rarely attain the maximum values listed, and it is even less likely that they will all be at their maximum value at the same time. Consequently, some presently used line fuse allowances are as low as 17 % for unearthed banks and 25 % for earthed banks. When applying expulsion type fuses, use of such allowances will typically result in the selection of a fuse ampere rating that can withstand inrush currents which result during switching of the capacitor bank even when other energized banks are nearby. For unit fuses, some presently used allowances are as low as 22 % for unearthed banks and 31 % for earthed banks. Capacitor banks for certain types of industrial users, on the other hand, may have currents of high harmonic content. Sufficient allowance must be factored in for these cases.

For small rated current expulsion fuses (less than 25 A), or for current-limiting type fuses, a slower speed ratio and/or a larger current rating may be required because of system transients caused by lightning, nearby faults, or switching of back-to-back banks.

When applying current-limiting type fuses, greater allowances may be required even with higher current rated fuses so the fuse can withstand these transient currents. For these types of applications, it is recommended that the manufacturer of the selected capacitor line fuse be consulted.

In addition, capacitor banks for certain types of industrial users may have currents of high harmonic content. Sufficient allowance must be made for these cases.

5.2.4.5.2 Unit fuse additional considerations

A further factor needs to be considered while selecting the current rating of a capacitor unit fuse. When capacitor units are paralleled within a capacitor bank and a full-fault occurs in one of the capacitor units, there is an energy discharge out of the other parallel-connected capacitor unit into the faulted capacitor unit. The discharge consists of a damped high frequency current whose characteristics depend upon such factors as capacitor bank construction (number, rating and spacing of capacitor units) and the location of the faulted capacitor unit. The capacitor unit fuses of capacitor units connected in parallel with the faulted capacitor should be capable of withstanding this "outrush" current without melting and without damage that would alter their time-current-characteristics (TCC). Some manufacturers may limit the application of certain fuses to avoid this type of damage.

For some current-limiting fuses the current rating may be dictated by the level of inrush and "outrush" currents occurring during operation of the capacitor bank, and to how frequently the capacitor bank is switched. Consult the application data of the fuse manufacturer for the selection of fuses for frequently switched back-to-back capacitor bank applications, or capacitor bank applications where a large number of nearby faults are expected.

5.2.4.5.3 Adjustment for ambient temperature

Some manufacturers publish a maximum allowable continuous current for each fuse ampere rating (higher than the rated current) when it is operating in a 25 °C or 30 °C ambient temperature. Peak load capabilities should be reduced according to manufacturers' recommendations to reflect operation in ambient temperatures as high as 40 °C (higher, if the installation warrants). Correction for a higher ambient recognizes that power-factor correction and voltage regulation provided by shunt capacitor banks is most crucial on those days when the load is highest. This condition may be coincident with summer peak loads and/or heat storms.

5.2.4.5.4 Maximum rated current of selected fuse

The above considerations guide the selection of the minimum rated current of a suitable fuse. The maximum rated current of a fuse for the application is determined by case rupture considerations.

For unearthed star connected banks, the ability of the capacitor units in the unfaulted phases to withstand the overvoltage described in 5.2.4.2.1 until the fault is cleared should be considered.

The smallest rated current fuse that meets the guidelines in 5.2.4.5.1, 5.2.4.5.2 and 5.2.4.5.3 is usually preferred for case rupture considerations and to minimize the time that the capacitors in the unfaulted phases of an unearthed neutral capacitor bank are exposed to overvoltage.

5.2.4.6 Selection of maximum breaking current

5.2.4.6.1 Capacitor line fuses

Generally, capacitor line fuses used for the protection of small capacitor banks must be capable of interrupting both capacitive type fault currents and inductive type fault currents. The capacitive and inductive fault current interrupting ratings for capacitor line fuses should be equal to or greater than the maximum fault current of each type that is available at the bank's location. Both types of fault current interrupting ratings are specified in symmetrical amperes and are directly comparable to calculated fault current values of each type that are available at the capacitor bank location.

Capacitive current faults occur when there is some amount of capacitance that remains in series with the fuse as it is interrupting the circuit. A typical minimum capacitive type current the fuse may be required to interrupt can occur when there is progressive pack failures within the capacitor unit and the fuse is sized to respond prior to complete capacitor unit failure. A typical maximum capacitive type current the fuse may be required to interrupt can occur with a capacitor bank that has an unearthed-neutral and only one series group of capacitors per phase. This current is three times the normal bank current and occurs if one phase is fully faulted.

For some larger capacitor banks, a line fuse may be used to protect the bank along with capacitor unit fuses for protection of each individual capacitor unit. Depending on the application and capacitor bank configuration, the line fuse may not need to meet the capacitive current interrupting requirements associated with a capacitor line fuse. For example in a earthed-star bank with a single series group, the individual capacitor unit fuses will normally respond to failures within a capacitor unit thereby preventing the operation of the line fuse. As each individual capacitor unit is removed by its capacitor unit fuse, the line fuse sees decreasing current, and should only operate in the event of a catastrophic failure or fault external to the bank. In this case, the line fuse will see the full available inductive-type fault current. Another example where a line fuse may not need to meet the capacitive current interrupting requirements for a capacitor line fuse is an earthed-star capacitor bank with multiple series groups protected by a switch and associated fuse. As successive individual capacitor units in a series group are isolated from the bank by their respective fuses, the surviving units are protected against overvoltage stress by the capacitor unbalance protection. In this selective coordination scheme, the line fuse will only respond in cases where a line-to-ground, line-to-line, or three-phase inductive-type fault occurs. Other examples, including delta-connected banks with a single series group, illustrate this point. A capacitor line fuse, rated for capacitive current interruption, must be used for the protection of banks where the configuration of the bank is such that interruption of capacitive currents by the line fuse cannot be ruled out.

Inductive fault currents are always possible in capacitor banks protected by capacitor line fuses since inductive fault currents can occur in the leads to the capacitor bank, in equipment between the fuses and the capacitor bank (switches, arresters, etc.), for some types of capacitor unit failure, or in the case of a major fault within the bank.

If the prospective inductive fault current at the capacitor bank exceeds the interrupting rating of an expulsion type capacitor line fuse, or the capability of the connected equipment, a current-limiting fuse may be used. This can be a general-purpose or full-range fuse to replace the expulsion fuse or the addition of a back-up current-limiting fuse in series with the expulsion fuse. The let-through current of the current-limiting line fuse should be less than the withstand capability of the associated switch(es), expulsion fuse(s) and capacitor unit(s).

For applications where capacitor line fuses are used in enclosures or vaults, expulsion fuses that have controlled venting or current-limiting fuses should be used.

5.2.4.6.2 Capacitor unit fuses

Capacitor unit fuses may be required to interrupt capacitive type fault currents. With some bank configurations and some fault conditions they may also be required to interrupt inductive type fault currents. The capacitive and inductive fault current interrupting ratings for capacitor unit fuses should be equal to or greater than the maximum fault current of each type that is available at the fuse location. Both types of fault current interrupting ratings are specified in symmetrical amperes and are directly comparable to the calculated values of each type that is available at the capacitor fuse location.

Capacitive current faults occur when there is some amount of capacitance that remains in series with the fuse as it is interrupting the circuit. A typical minimum capacitive type current the fuse may be required to interrupt can occur when there is progressive pack failures within the capacitor unit and the fuse is sized to respond prior to complete capacitor unit failure. A typical maximum capacitive type current the fuse may be required to interrupt can occur with a capacitor bank that has an unearthed-neutral and only one series group of many parallel connected capacitors per phase. This current is three times the normal bank current and occurs if the failing capacitor unit is fully faulted. This maximum capacitive current to be interrupted could be as high as 50 times the normal capacitor unit current if it is a large bank with many parallel capacitor units.

On systems where inductive fault currents can occur (such as star connected single series group capacitor banks with a earthed neutral and/or a earthed capacitor bank frame, or single series group delta connected banks) the maximum inductive fault current available at the bank location requires consideration. For the star connected banks listed above the fault current will be the available phase-to-neutral fault current and for the delta bank it will be the available phase-to-phase fault current. Fuses are rated for their interrupting capability in symmetrical amperes.

If the available inductive-fault current at the capacitor fuse location exceeds the interrupting rating of an expulsion type unit fuse, a current-limiting unit fuse may be used.

For applications where capacitor units are used in enclosures or vaults, and capacitor unit fuses are required, current-limiting fuses should be used.

5.2.4.7 Capacitor unit rupture protection

5.2.4.7.1 General

In addition to consideration for the fuse's rated maximum interrupting current, proper capacitor line fuse and unit fuse selection will also consider the maximum fault current that the capacitor unit can withstand without rupturing.

Capacitor units consist of series and parallel packs within a metal case that is filled with a dielectric fluid. These packs usually consist of a metal foil electrode and a film dielectric. Capacitor unit failure typically begins with the failure of a single pack. When this pack fails and shorts out, the voltage across and the current through the remaining packs increases. This increased stress causes additional packs to fail and, if the failure process is allowed to continue, it will result in all of the capacitor unit series packs being shorted. Other capacitor unit failures may be caused by improper internal connections or dielectric failure to the case. Capacitor failure may lead to case rupture.

To determine case rupture protection, the maximum operating TCC curve for the fuse or fuse-link is compared to the capacitor unit's case rupture curve. For typical case rupture curves, see Figure 25. The currents for both of these curves are expressed in symmetrical values. The degree of case rupture protection will be dependent on the fuse's current rating and the shape of its time-current characteristic curve. Protection is obtained if the maximum operating TCC curve of the fuse is to the left of and below the capacitor unit's case rupture curve.

For expulsion or other types of non-current-limiting fuses the lower part of the maximum operating TCC curve turns and becomes asymptotic with the 0,8 cycle (0,16 s for 50 Hz, 0,013 s for 60 Hz) line. Therefore, a fuse curve that is otherwise to the left of the capacitor case rupture curve will always intersect with the case rupture curve at this time. This intersection delineates the highest equivalent available symmetric fault current for which the fuse will protect the capacitor unit from case rupture. To avoid case rupture when using these types of fuses, the capacitive current or inductive current available at the bank location should be less than this value.

For inductive fault currents, the symmetrical current available at the bank should be used, instead of the asymmetrical current available. This is an acceptable practice for rupture protection comparisons since capacitors usually will degenerate into a total unit failure at or near a peak voltage, thereby producing a symmetrical current fault.

Capacitor manufacturers should be able to provide the case rupture curves mentioned above and/or provide additional information or assistance regarding the protection of their capacitor units. The maximum operating TCC curves are available from the fuse manufacturer.

5.2.4.7.2 Banks protected by line fuses only

If the prospective inductive fault current at the bank location exceeds the capacitor unit's withstand level, the system fault current may be limited by the use of general-purpose, full-range or back-up type current-limiting fuses. When an expulsion fuse/back-up current-limiting fuse combination is used as a capacitor line fuse, the series expulsion fuse should coordinate with the current-limiting fuse such that all currents below the rated minimum interrupting current of the Back-Up fuse are cleared by the expulsion fuse before the back-up fuse melts open.

On these systems with high inductive faults the use of a current-limiting fuse will reduce the probability of case rupture. Protection in the area where the operating time of the current-limiting fuse is greater than 0,010 s is determined by comparing the maximum operating TCC curve of the fuse to the capacitor unit's case rupture curve. Protection is obtained in this area if the maximum operating TCC curve of the fuse is to the left of and below the capacitor unit's case rupture curve. Generally when a current-limiting fuse is properly selected for capacitor case rupture protection for current levels below the current-limiting fuse’s 0,010 s maximum operating current, the current limiting action of the current-limiting fuse will also provide adequate case rupture protection at higher currents. In the event that extrapolation of the curves up to the maximum short-circuit current available at the capacitor bank location indicates possible intersection, consult the capacitor and fuse manufacturers. An example of a capacitor case rupture curve characteristics is shown in Figure 25.

As capacitor bank size is increased by the use of multiple parallel capacitor units, the size of the capacitor line fuse will also increase. As the fuse size increases its total operating curve will move towards the right while the case rupture curve remains constant. As a result, the bank size that can be protected with a line fuse is limited. If the system requires that amount of capacitance in that location, one solution is to use larger (kVAR) capacitor units in the bank since larger units may have greater withstand capabilities. Another solution may be to use multiple smaller banks in the same basic location spacing them some number of poles apart.

5.2.4.7.3 Capacitor banks protected by capacitor unit fuses

When the capacitor unit is completely shorted the power-frequency current through it depends upon various factors. For example, in a single series group earthed star bank applied on an effectively earthed system or a single series group delta bank, this will be the system inductive fault current that is available at the bank location. With multiple series group capacitor banks or unearthed star connected banks the power-frequency current will be the available capacitive current that is allowed by the capacitors that remain in the circuit.

If the bank can be subjected to inductive type fault currents and these fault currents exceed the capacitor unit withstand level, the system fault current can be limited by the use of current-limiting fuses. Protection in the area where the operating time of the current-limiting fuse is greater than 0,010 s is determined by comparing the maximum operating TCC curve of the fuse to the capacitor unit's case rupture curve. Protection is obtained in this area if the maximum operating TCC curve of the fuse is to the left of and below the capacitor unit's case rupture curve. Generally when a current-limiting fuse is properly selected for capacitor case rupture protection for current levels below the current-limiting fuse’s 0,010 s maximum operating TCC current, the current limiting action of the current-limiting fuse will also provide adequate case rupture protection at higher currents. In the event that extrapolation of the curves up to the maximum short circuit current available at the capacitor bank location indicates possible intersection, the capacitor and fuse manufacturers should be consulted. An example of a capacitor case rupture curve characteristics is shown in Figure 25.

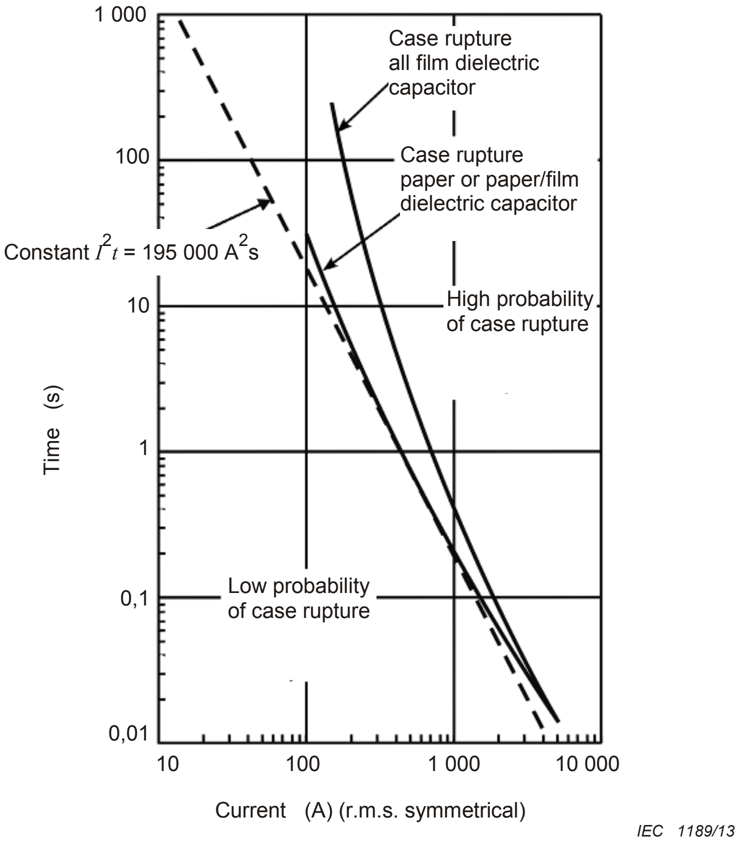
Many station banks have multiple series groups or other configurations such that capacitance remains in the circuit when a single capacitor unit fails. Since these fault currents are relatively small as compared to inductive system faults a current-limiting fuse is not normally required to limit available fault current.

The use of current-limiting fuses as a capacitor unit fuse is normally limited to:

a) star connected single series group capacitor banks with a earthed neutral and/or a earthed capacitor bank frame, or a single series group delta connected bank;

b) metal enclosed banks because of their non-gassing operation;

c) applications where the discharge from many parallel units has enough energy that it exceeds the discharge interrupting capability of expulsion fuses or the withstand ability of the capacitor unit cases.



NOTE Typical case rupture characteristics for two types of capacitors. Curves vary by manufacturer and unit construction; refer to manufacturer for actual curves.

Figure 25 – An example of capacitor case rupture curve characteristics

5.2.4.8 Selection of the capacitor unit fuse for discharge-energy withstand

If a capacitor unit failure occurs in a capacitor bank, where the capacitor units are protected by unit fuses, the energy stored in the parallel connected unfaulted capacitors will discharge through the unit fuses on these units and into the failed capacitor unit and its fuse. The energy stored in a capacitor, or group of capacitors, measured in Joules, at a given instantaneous value of voltage is:

$$E = CU^2/2$$

where

E is energy in Joules,

C is the capacitance in microfarads,

U is the instantaneous voltage in kilovolts.

The capacitor unit fuse of a fully-faulted capacitor unit which is part of a parallel-group of other capacitors units must be able to operate and withstand, without bursting during operation, the "outrush" current from the healthy parallel capacitors as they discharge into the faulted capacitor unit. The energy stored in the parallel connected capacitor units is available to be absorbed by the fuse and the faulted capacitor unit. While the fuse itself may absorb only a portion of the total energy available in the parallel-connected capacitor units, the withstand requirement for the fuse is determined by the total energy that is available for this discharge.

Capacitor units also have a discharge-energy withstand capability that is related to their construction. If the capacitor bank design can produce a total discharge-energy that is equal to or less than the withstand capability of the capacitor units, then the fuse is not required to limit the discharge. A fuse with a discharge-energy rating equal to or exceeding this total discharge-energy should be selected without regard to current limitation.

If a capacitor bank design has the capability to discharge more energy than the capacitor units can withstand, then the use of current-limiting fuses should be considered. Current-limiting fuses are capable of limiting the discharge energy from adjacent parallel connected capacitor units into the faulted capacitor unit. For proper protection of the capacitor unit from the discharge energy of the parallel capacitor units, the maximum operating I^2t of the fuse should be less than the withstand I^2t of the capacitor unit. For specific guidelines in this area the capacitor and fuse manufacturers should be consulted.

Other methods that can be used to eliminate excessive discharge energy are:

a) to use more series groups and less parallel units;
b) to use two smaller parallel capacitor banks.

The discharge-energy rating for a capacitor unit fuse is the maximum stored energy at rated voltage with which the fuse will be required to operate and successfully interrupt the circuit. Typical discharge-energy ratings for expulsion type capacitor unit fuses range from 10 to 30 kJ. The application of these fuses may be limited to less than the maximum discharge energy rating of the fuse by the withstand capability of the capacitor unit. The rating for current-limiting capacitor unit fuses are usually 40 kJ or higher.

5.2.4.9 Types of fuses used for capacitor applications

5.2.4.9.1 Current-limiting fuses

Current-limiting fuses can be used for all of the applications discussed. Where low current interruption is necessary, a Full-Range fuse (or under some circumstances a General-Purpose fuse) should be used. Fuses should be suitable for withstanding the repeated inrush currents where applicable, and fuses with specially designed elements for this purpose have been used. Capacitor unit fuses are available having a disconnecting action. In some cases this takes the form of a pigtail attached to the bottom of the fuse, disconnected by a small pyrotechnic charge. This is "fired" when the main elements interrupt the current. The disconnecting action removes voltage from across the fuse body. This allows a shorter fuse to be used than would be required if the fuse had to withstand voltage indefinitely in an outdoor environment. The loss of one capacitor in a large bank may not warrant immediate replacement. The advantages to using current-limiting fuses for capacitor protection are their high maximum breaking current and significant reduction in fault I^2t, reducing the possibility of capacitor can failure. Also there is no expulsion action, which can lead to a reduction in clearances.

5.2.4.9.2 Expulsion Fuses

Expulsion fuses are commonly used for both capacitor line fuses and capacitor unit fuses. Distribution fuse-cutouts, tested for capacitive interruption are often used as line fuses, particularly on small distribution circuit pole-top capacitor banks. Expulsion fuses, in the form of a fixed fuse-carrier with the fuse-link pigtail tensioned by a spring contact arm, are often used for capacitor unit fuses.

5.2.4.9.3 Combination Fuses

Some types of Full-Range fuse use a combination of a Back-Up style fuse element in series with an expulsion style fuse element. However, these fuses are not normally considered to be "combination" fuses. A fuse that is normally classed as a "combination fuse" is where a Back-Up fuse-link has an expulsion fuse attached to one end. It is possible to replace the expulsion fuse-link without replacing the current-limiting fuse-link. Because the expulsion part only has to interrupt low currents, the expulsion tube can be made shorter than with a typical distribution fuse-cutout (typically 75 mm long or less). In addition to providing for low current interruption, the expulsion fuse normally has its lower contact in the form of a flexible pigtail. This is attached to a spring, and provides a method of isolation after operation. Such fuses are used as capacitor unit fuses. The fuse must be sized to ensure that the Back-Up part of the fuse cannot be damaged by operation of the series expulsion fuse.

Where the available fault current is high, a method of providing capacitor protection is a combination of a fuse-cutout and Back-Up fuse. While not a "combination" fuse per standard, this "two-fuse" approach is common for capacitor line applications. Since the Back-Up fuse only operates in the event of a line-to-ground or line-to-line fault, it only has to interrupt high inductive currents, not capacitive currents. Such fuses therefore require no additional capacitive testing. Capacitive currents are interrupted by the fuse-cutout, which must be tested as a capacitor fuse.

5.2.5 Voltage transformer applications

5.2.5.1 General

Current-limiting fuses are normally used to protect the power system by isolating failed voltage transformers from the system. Since voltage transformers can be installed at the substation bus and their kVA ratings are lower than power or distribution transformers, they require fuses that combine low continuous current ratings with high rated maximum breaking current.

NOTE Some documents (e.g. IEEE standards) use the wording "potential transformer" for voltage transformers.

5.2.5.2 Voltage rating

Some manufacturers recommend the fuse’s rated voltage be 100 % to 140 % of the maximum system line-to-line voltage to which the fuse is to be applied. This range of application voltage is recommended because the current-limiting action of the fuse is characterized by the generation of a switching voltage that should coordinate with system and circuit insulation levels. Since the current ratings are low, and often use wire fuse elements (see 4.2.4.5), for some designs switching voltages can be high. Other manufacturers feel that application at lower system voltage is acceptable for their design of fuse. The maximum voltage permitted for each fuse rating is based on its rated voltage, assigned by the manufacturer, and the system grounding (see 5.1.3.3).

For separately mounted fuses where higher voltage insulation than would normally be specified is required, the fuse is selected on the basis of actual service voltage. The fuse can be mounted with insulators of a higher voltage rating, providing additional insulation to ground.

5.2.5.3 Current rating

To provide maximum protection against damage to other equipment in the event of a failure of the voltage transformer, it is usually necessary to select the fuse with the smallest rating that will not result in nuisance fuse operations. The selected fuse should withstand magnetizing inrush currents to preclude nuisance fuse operation or damage to the fuse element(s) that could result in failure of the fuse. Since voltage transformer burdens are lower and the construction of these transformers is different from power transformers, fuses selected solely on the basis of inrush considerations will seldom protect voltage transformers from overloads.

The inrush withstand capability of the fuse is readily available from the manufacturer in the form of minimum pre-arcing I^2t values. The inrush current of the voltage transformer can be recorded with appropriate data capture electronics, and the I^2t calculated, or the I^2t value can be obtained from the voltage transformer manufacturer. For satisfactory fuse application and for preventing nuisance fuse operations, it is clear that the fuse's melt I^2t should exceed the transformer magnetizing inrush I^2t, with a reasonable margin of safety. This safety-margin, expressed as a multiplying factor, is dependent on the method used to connect the voltage transformer to the system bus. Empirically, for delta-connected transformers with three line fuses, or for open delta transformers with three line fuses (where three-phase voltage is obtained from only two voltage transformers), the multiplying factor is 4,5. That is, the I^2t of the fuse should be equal to or greater than 4,5 times the transformer's inrush I^2t. For single-phase units, open delta units with four fuses, or delta units with six fuses, this multiplying factor is 1,5. The inrush I^2t of the voltage transformer increases rapidly with an increase in applied voltage. In requesting I^2t values from transformer manufacturers, the voltage specified should be the maximum expected in service.

In some applications, particularly in underground cable circuits, there is a possibility that the inherent capacitance of the circuit will give rise to a discharge current through the primary windings of the voltage transformer connected to the bus. The magnitude and duration of the discharge currents may be calculated from the circuit constants. Caution should be used to ensure that the fuse will not operate under these conditions.

5.2.5.4 Maximum Breaking current

The fuse's rated maximum breaking current should be equal to or greater than the maximum short-circuit current from the system at the point of fuse installation.

5.2.5.5 Partial discharge

One concern with voltage transformer fuses is the possibility of partial discharge on the fuse elements, in this case commonly termed "corona". Partial discharge occurs from the sharp edges of energized apparatus parts. In the case of a voltage transformer fuse, the "sharp edge" is the very small diameter fuse element that is usually used, and the insulation is the air in the voids of the filler material. Radio influence voltage (RIV) measurements are made to determine the extent of radio interference generated by this corona. Normally the concern with corona (other than radio interference) is the damaging effect it can have on non-restorable insulation. In the case of a voltage transformer fuse, however, the insulation is self-restoring, so there is no damage but what is of concern is the effect on the fuse element itself. Because of the delicate nature of the elements used in the very low current rating fuses needed for voltage transformers (often less than one ampere) any appreciable partial discharge will lead to the element being damaged (the element material is removed, ion by ion, and deposited on the fuse filler and body). Such damage could lead to nuisance (or even incorrect) operation of the fuse. Suitable fuse mounting, to avoid the onset of partial discharge, is therefore important; primarily of concern is the location of earth-connected components near to the fuse.

5.2.6 Wind power generation applications

5.2.6.1 Introduction

The generation of electricity using renewable energy sources other than hydro-electric is becoming more common. One of the most developed methods is wind power, and this provides some opportunities, and challenges, for the use of fuse protection. The use of step-up distribution transformers to connect wind power generators to the network ("wind farm transformers") is normal, and the increasing power requirements has led to the use of innovative fusing schemes and the development of higher rated fuses. There are several technologies of wind power generators but fuse selection is not, in general, affected by these different technologies.

The step-up transformers used for this application can be liquid filled (oil or other insulating liquids) or cast-resin types. The transformers may be installed inside or outside the tower but cast-resin and "less-flammable" or "non-flammable" liquid filled transformers, that minimize the fire risk, are more commonly used inside (in the nacelle or at the bottom of the tower) while oil-filled transformers are more commonly used outside. Liquid filled transformers have lower losses than cast-resin types, and are easier to use with liquid-immersed fuses. The preferred transformer connection on the HV side is usually delta, and the typical voltages range from about 20 kV to 36 kV, depending on utility practices at the location of the wind farm.

There are several methods used to protect the wind farm transformers on the HV side. Most methods use current-limiting fuses due to the high fault currents that can occur, particularly when multiple wind generators are used in a "wind farm". One common method is based on a switch-fuse combination according to IEC 62271-105. This method is, in general, well adapted to protect smaller wind farm transformers, generally lower than 2 MVA. In this case, operation of the CL fuse releases a striker that causes the series switch to open, isolating the transformer (see 5.2.7).

CL fuses are also used in association with other types of switches or interrupters. For these applications, the series switch or interrupter is not tripped by a fuse striker. They typically use coordinated Vacuum Interrupters, which are available to protect transformers, up to about 3 MVA for dry type transformers and 3,8 MVA for liquid-filled transformers. In this case, the series switch, or interrupter, uses a thermal or electronic trigger to cause the switch to open.

The use of interlinked switches or interrupters placed in series with CL fuses results in all three-phases being opened, effectively simultaneously, which may be advantageous. Protection schemes that use switches can therefore avoid putting the generator in a bi-phase or mono-phase supply, and isolate the step-up transformer from the fault currents coming from the network. In any case, the two devices used together must always result in interruption of the current when they operate.

Another approach to the protection of wind farm transformers involves the use of liquid-submerged expulsion fuses in series with liquid immersible current-limiting Back-Up fuse (as discussed in 5.2.2.6). At the time of writing, transformers up to about 3,8 MVA at 34,5 kV delta can be protected in this way.

Which of the two basic methods used for transformer protection is chosen, switch-fuse or fuse-fuse, depends on a variety of considerations. Liquid-submerged expulsion fuses are relatively inexpensive, but their use is normally limited to liquid-filled transformers. For applications up to 23 kV, expulsion fuses that are easily replaced from outside the transformer (often termed "bayonet" type fuses) are available. However, for higher voltages, the liquid-submerged expulsion fuses normally require replacement through a transformer hand-hole. Therefore, if frequent expulsion fuse operation occurs, the more expensive approach of using a switch rather than an expulsion fuse may be preferred.

5.2.6.2 Fuse selection for wind farm transformers

In general, the rules for choosing fuses for wind farm transformers follow those for normal transformer applications (see 5.2.2). While there are differences from conventional transformer applications, these relate primarily to the additional protection requirements that occur as a result of the transformer being "fed" from both the high voltage and low voltage sides. These aspects will be discussed in 5.2.6.3. The sizing of fuses for transformer magnetizing inrush is the same as conventionally fed transformers (i.e. transformers fed from the HV side), but of course "cold-load pick-up" has no meaning in this application. However, experience has shown that, in general, good results are achieved if the pre-arcing TCC curve of the fuse-link coordinates with the commonly used transformer cold load pick-up points (see 5.2.1.1.2). That is, the element of the fuse will not be melted open by the current at conventional cold load pick-up current and time points (normally the expulsion fuse in the case of a combination expulsion fuse and back-up CL fuse). What the fuses are actually subjected to are surges associated with generator speed variations and fluctuations in power flow. These fluctuations may have peak values higher than the normal full-load current, depending on the level of load control achieved for the wind turbine and associated control equipment. Such variations may be much more common than typical load pick-up variations, and therefore the fuse manufacturer should be consulted before their fuses are used for this application. For example, experience shows that expulsion fuses, usually available in a variety of element materials, should be chosen to use an element type less susceptible to fatigue resulting from the current cycling.

Phase-to-phase rated fuses are normally used for three-phase delta fusing applications (see 5.1.3 including the cautions involving isolated and resonant earthed systems). However, phase-to-ground rated current-limiting fuses that are "matched-melt" coordinated (see 5.2.2.6.2) with a series line-to-line rated expulsion fuse have also been used for wind farm applications, particularly at the higher voltages. The key consideration is that a combination of the current-limiting fuse applied in series with an expulsion fuse must be capable of interrupting any current that produces melting, and after current interruption the fuses must withstand the system recovery voltage. However, because using this technique requires various assumptions regarding the power system, and may require special testing of the fuses, the fuse manufacturer should be consulted for information before using this technique. While this technique permits the use of lower voltage rating fuses, it generally requires the use of higher current ratings to achieve matched melt coordination, (and higher values of I^2t let through).

5.2.6.3 Additional aspects of wind farm protection

A further aspect of wind farm applications that must be understood is that fuses on the HV side can only isolate the transformer from the power system. An internal transformer fault will continue to be fed from the LV (generator) side until the generator is also isolated from the circuit. Protection on the LV side must also quickly remove the generator if an eventful failure of the transformer is to be avoided.

An internal transformer failure on the system side of the HV coils will not produce a very high HV current fed from the LV side (having a maximum value equivalent to the normal bolted secondary "through fault" current, when fed from the HV side).However, arcing will continue to feed energy into the transformer until the LV protection operates. Commonly used over-voltage, under-voltage, over-current, and under-current relays that cause the low voltage circuit-breaker to trip may provide this protection.

It is important that the LV protection operate very quickly for another reason. If the transformer is isolated from the HV circuit by the operation of the fuse protection, a condition known as "islanding" may occur (i.e. the generator and transformer become an isolated power system). It has been shown that for some applications, the generator output can move out of phase with the system within a few cycles. This may result in higher than normal recovery voltages across the fuses, if there is no combined/associated switching device, theoretically approaching as much as twice the nominal voltage. However, this can only occur if the transformer continues to operate almost normally (that is it does not have a permanent internal fault). While this would be the case if the fuses operated as the result of an overload, overloads should be prevented by devices that limit the generator output to the rated power value. There is another way that loss of voltage synchronization across the primary protection could occur. This is a transient primary fault within the transformer, which causes the primary fuse combination to operate but leaves the HV transformer winding energized at the same voltage, but fed from the LV generator. Providing the low-voltage protection responds during the transient fault (when the fault is also fed from the generator), this will not happen. In the case of the higher voltage wind farm applications (36 kV), transient faults should be rare since a free arc in oil will not self-extinguish at this voltage.

In the case of a switch-fuse combination according to IEC 62271-105, an overvoltage produced by islanding may be withstood by the combination of the two different protection devices, the switch in the open position and the fuse itself. In the case of current-limiting fuses with no combination switch or similar device, the CL fuse must be able to withstand this voltage. Although the voltage is higher than the voltage the CL fuse had to interrupt against, once the CL fuse cools after interrupting a high current, even for a very short time, experience has shown that the CL fuse has a withstand voltage that is also higher than the voltage the fuse interrupted against. If matched-melt coordination is used with a series connected under-oil expulsion fuse, a large, under oil, isolation gap always results even if the line-to-ground rated current-limiting fuses perform the interrupting function. After operation at currents not causing a current-limiting action, some types of Full-Range fuse may not be able to withstand a voltage significantly higher than the voltage against which they have operated, so they should not be exposed to an "islanding" condition for any significant duration. Careful consideration of the LV protection is therefore very important.

5.2.7 Current-limiting fuses used in conjunction with mechanical switching devices

5.2.7.1 General

Current-limiting fuses and mechanical switching devices are commonly used together in a variety of ways. A very common application uses a fuse with a striker (normally a Back-Up fuse) in series with a switch. Such arrangements, which are the subject of IEC 62271-105, are termed "switch-fuse combinations". By definition, this consists of a three-pole switch with three fuses provided with strikers, the operation of any striker causing all three poles of the switch to open. It includes fuse-switch combinations in which the fuses form the moving contacts. The arrangement of switches and fuses constitute a functional assembly. In this report, when fuses are used in conjunction with other mechanical switching devices (e.g. circuit-switchers, circuit-breakers, vacuum interrupters, contactors, etc.) or without striker tripping, the term "association" will be used, since the term "combination" is used by the switchgear standards only for their type of association covered by IEC 62271-105.

The use of current-limiting fuses and series connected mechanical switchgear combines the positive capabilities of the two types of device, while essentially eliminating any negative properties each may possess individually. The main positive property of a current-limiting fuse is its unsurpassed ability to interrupt high short- circuit currents so quickly, in fact within a few milliseconds, that the asymmetrical peak current and hence the hazardous effects of a potential short-circuit fault, will be significantly reduced. No mechanical switchgear is able to achieve that effect. This current-limiting effect, together with the very high maximum breaking current capability of the CL fuse, which increases the breaking capacity of the combination, are the main reasons for including them with switchgear. While various types of switchgear differ widely in their breaking capabilities, almost all current-limiting fuses have a rated maximum breaking current high enough as to virtually eliminate concern over what value the prospective fault current might be at any point in the system.

When back-up fuses are employed, protection for currents below their minimum breaking current is required. With the use of striker tripping, or appropriate relaying/sensing, the switching device can interrupt currents that the back-up fuse cannot. Normally, the fuse minimum breaking current therefore only needs to be low enough to ensure correct coordination with the switching device. An additional, and often important, feature of the association, that cannot be supplied by the single-pole fuse alone, is the ability to isolate all phases – faulty or not – downstream from the fuses.

The association of fuses and switchgear usually, but not necessarily, makes use of the tripping of the latter by the action of the striker of the first fuse to melt. The time-current characteristic of the fuse – extremely fast operation at high current to slow operation at low current – can thus be used in place of inverse time-current relay tripping of the switchgear. In the case of "release-operated" switching device, an overcurrent or shunt release is used to trip the device, either in addition to, or instead of, the fuse striker tripping. When both the switch and fuse have operating time-current characteristics (e.g. a fuse and a release-operated switch), a "take-over" current exists. This is the current at which the two TCC intersect, with fuse operation occurring above the take-over current and the switching device interrupting below the take-over current. This take-over point is used for coordination purposes. If the switching device is not tripped by a striker, the take-over current must be higher than the fuse’s rated minimum breaking current.

There is a "hierarchy" of switching device capability (see IEC 62271-107 for a discussion of this). Switches tend to have limited breaking capability in terms of both current and TRV, circuit-switchers come next with a higher capability and finally circuit-breakers tend to have the highest breaking capability. Because of the differing capabilities of the series devices, some different application considerations apply to each of them.

5.2.7.2 Switch-fuse combinations (IEC 62271-105)

5.2.7.2.1 General

Switch-fuse combinations are the subject of IEC 62271-105, which does not apply to fuse-circuit breakers, fuse-contactors, combinations for motor circuits or combinations including capacitor bank switches. Although they are most commonly used for transformer applications, they are subject to some application restrictions because of transformer fault TRV characteristics. The primary function of the fuses is to increase the short-circuit breaking rating of the combination beyond that of the switch alone, and to significantly reduce the I^2t permitted into the fault (see 4.1.5.2). The high voltage fuse may be mounted on the source side of the switch or be on the load side (when forming part of the actual switch mechanism it is termed a fuse-switch) so that when the switch is opened the fuses are electrically isolated making replacement more convenient. The fuses are fitted with a striker that ejects in the first few milliseconds after the fuse elements have melted, or in the case of thermally-operated strikers, when the temperature has reached a pre-determined value. The striker operates a tripping mechanism in the switch unit, designed to open the switch contacts. This performs two important functions:

a) it ensures that even if only one or two fuses melt, all three phases are disconnected;
b) if the fuse melts with a current less than its minimum breaking current, the striker trips the switch, interrupting the current and isolating the fuse from the supply.

IEC 60282-1:2009, 4.15, contains special testing for back-up fuses for switch-fuse combinations. It shows that they can arc for sufficient time (a minimum of 0.1 s), at a current that they cannot interrupt, to allow the switch to be released, open, and interrupt the current, without the fuse suffering external damage. The 0.1 s arcing time is derived from the sum of 0.05 s (the maximum time permitted for a striker to be released) and 0.05 s for the typical operating time of a striker released switch. This fuse testing is not required for full-range fuses, or fuses that use a thermally released striker (where it can be shown that the thermal release of the fuse striker, at currents below I_3, operates before fuse arcing can occur).

The main and general requirement for the coordination of fuses and switches is that the transfer current for striker operation is less than the relevant breaking capacity of the switch. The transfer current is the current at which the fuses and switches exchange breaking duties – above this current only the fuses interrupt, while immediately below this current the fuse in the first pole to clear interrupts, but the current in the other two poles is interrupted by either the switch or the fuses, depending on fuse TCC tolerances. Refer to Annex B of IEC 62271-105:2012 for a fuller explanation. The combination is therefore assigned a "rated transfer current" based on testing specified in IEC 62271-105 (a fuse interrupts in one pole while the other two poles are fitted with solid links in place of fuses, requiring the switches to interrupt the current). IEC 62271-105:2012, Annex B, provides a method to determine the transfer current for a particular switch-fuse combination based on the fuse's TCC curve shape and tolerances, and the fuse-initiated opening time of the switch. This transfer current then has to be less than the rated transfer current for the switch. The transfer current calculation is complex, and users are advised to consult the fuse and/or switch manufacturer for advice on the correct application of switch-fuse combinations.

For a switch-fuse combination that uses a release-operated switch, tests at the maximum take-over current (taking into account tolerances, etc.) is required. If the maximum take-over current is equal to or higher than the transfer current, then the transfer current test is not required.

Fuses that are used in a switch-fuse combination should be adequately de-rated in terms of current to allow, if applicable, for the heating effects of the enclosure (see Annex A);

The following additional issues need to be considered in the interdependent coordination between fuse and switch:

5.2.7.2.2 Fuse-link current withstand

Fuses are susceptible to the transient current associated with transformer inrush. This needs particular consideration, since one or more transients passing through an incorrectly rated fuse may lead to local deterioration or melting of one or more fuse elements, a situation absolutely to be avoided. Such damage could lead to melting under normal operating conditions. See 5.2.2.1.2 for guidance on fuse selection for transformer applications. Transient current considerations often limit how low the fuse rating can be for a given application. However, a fuse that has a higher current rating than necessary will give less protection, and may lead to problems with the transfer current and the solid (bolted) secondary short circuit current (see 5.2.7.2.3).

5.2.7.2.3 Transformer applications

The widest application of switch-fuse combinations is in the protection of distribution transformers. However, the load/fault breaking capability of switches used in switch-fuse combinations is restricted not only in magnitude but also in the circuit conditions of power factor and TRV. A switch tested to IEC 62271-103 is not specified for and may not be capable of interrupting a solid short circuit (bolted fault) on the secondary terminals of a transformer, due to the high TRV conditions. The primary fuse is therefore required to interrupt such a current. The transfer current for the chosen fuse current rating (the current at which interrupting duty is transferred to the switch) must therefore not only be lower than the (tested) rated transfer current of the switch-fuse combination, but also less than the solid short-circuit current of the transformer. In cases where a system provider considers that the design of the LV connections between transformer and LV switchgear (e.g. inside prefabricated substations according IEC 62271-202) prevents a solid short-circuit on the secondary transformer terminals, the above fault condition need not be considered in the selection of the fuse-links. However, if no suitable switch-fuse combination exists, a different type of switching device should be used, e.g. a fused circuit-switcher (see IEC 62271-107) or fuse and circuit breaker. In critical cases, contact the fuse and/or the switchgear manufacturer.

5.2.7.2.4 Switch operating speed

A further point to be considered in the coordination context is that modern SF_6 and vacuum switches, due to their extremely short contact movement, inherently have correspondingly very short operating times. Such speed is not usually required for their operation in the combination, but may create conflicting situations with the slower operation of fuses at moderate currents. This exacerbates the concerns discussed in 5.2.7.2.3. At currents that are between the breaking capacity of the switch and the rated maximum breaking current of the fuse, the tolerance in operating time between the fuses of a multi-phase system may be such that the tripping of fast switches, initiated by the first fuse to melt, may result in switch contacts opening before the other fuses have had time to clear the fault current. This would expose the switches to currents that they are not capable of interrupting. Using a fuse having a smaller current rating helps this situation, but fuses must be able to withstand current surges such as transformer inrush (see 5.2.7.2.2). In this case a larger fuse can be used if a slight intentional delay is included in the tripping of the switch, sufficient to ensure that the last-operating fuses take over the fault clearance in all poles before contact separation in the switch occurs. However any delay introduced into tripping should not extend the time beyond the 0,05 s assumed in the fuse testing requirements (see 5.2.7.2.1), unless a Full-Range fuse or thermally released striker is used, or a Back-Up fuse with a longer arcing withstand time is available.

5.2.7.3 Fused circuit-switchers

Limitations in switch-fuse combinations discussed in 5.2.7.2 sometimes require the use of switching devices having a higher current interrupting ability. A circuit-switcher is such a device and the association of a circuit-switcher and fuse is covered by IEC 62271-107 (again intended primarily for transformer applications). In addition to generally having a higher breaking capacity than switches, circuit-switchers are tested with a higher TRV. Since release-operation, not striker-tripping is a requirement, no transfer current test is specified but the switch must demonstrate successful interruption at a current greater than the maximum take-over current. This current corresponds to the maximum pre-arcing (melting) current of the maximum fuse to be used with the association, at a time equal to the minimum opening time of the switch. Obviously, this take-over current must also be higher than the rated minimum breaking current of the fuse. Any fuse used with the circuit-switcher must have a TCC that crosses the circuit-switcher TCC at a current higher than the fuse's rated minimum breaking current, unless the circuit-switcher is also released by a striker. A fused circuit-switcher may have tripping only initiated by a fuse striker (in effect substituting a circuit-switcher for a switch in a switch-fuse combination). However a fused circuit-switcher tested to IEC 62271-107 requires no additional "transfer current" testing for this application.

Although Circuit-switchers are tested with a higher TRV at the take-over current than switch-fuse combinations tested to IEC 62271-105, IEC 62271-107 still states that "The TRV specified for the take-over current type test may not cover the situation of a bolted short-circuit on the secondary side of a MV-LV transformer, if the type of transformer and the MV connections provide a very low capacitance." In this case, more severe TRV testing of the circuit-switcher, according to IEC 62271-100:2012, Annex M, is required (or a different type of switching device should be used).

5.2.7.4 Additional fuse and mechanical switching device associations

Fuses can also be used with circuit breakers. No IEC standard discusses this application, but the basic coordination rules of circuit-switchers apply – the take-over current should be above the fuse's rated minimum breaking current and less that the circuit breakers maximum breaking capacity. If a full-range fuse is used in conjunction with any series switching device, only the requirement for a take-over current less than the switching device's rated breaking capacity is needed, as the fuse can interrupt any current that causes it to melt.

In the association with circuit-breakers, only the current-limiting feature of the fuses is made use of (low I^2t and peak current) plus their higher breaking capacity to increase that of the series device. All classes of fuses are applicable in these associations.

Fuses used with mechanical switching devices, but not employing striker tripping, may need to be general-purpose or full-range type fuses in order to ensure clearance of low values of fault current unless other tripping devices are employed. Where a protection relay and switching device is used, refer to 5.2.2.2.6 and 5.2.3.

5.3 Installation, operation, maintenance and replacement considerations

5.3.1 General

A fuse in an electric circuit stands guard at all times to protect the circuit and the equipment connected to it from damage within the limits of its ratings. How well this fuse will perform depends not only upon the accuracy with which it was manufactured, but also upon the correctness of the application and the attention it receives before and after it is installed. If a fuse is damaged at any time, it may not be able to interrupt a current that causes it to melt. Therefore, if it is not properly applied, installed and maintained, considerable damage may occur to costly equipment. As an example, drop-out fuse-carriers that remain in the open position for prolonged periods of time, may accumulate water and pollution in their internal parts, which may result in the degradation of their operational properties (see 5.3.3.3).

High-voltage fuse-links should be handled with at least the same degree of care as any other precision-made item of equipment (such as a relay). Fuse-links should be stored in their protective packaging until required for use. If a fuse-link is dropped or otherwise subjected to severe mechanical shock, the manufacturer should be consulted as to the proper procedures to be followed to determine if the fuse is suitable for use.

It cannot be stressed too strongly that prescribed safety rules should be observed at all times when manipulating or maintaining fuses near energised equipment or conductors.

Fuses should be installed in accordance with the manufacturer's instructions. For multipole arrangements of fuses, when the distance between poles is not fixed by the construction, the poles should be mounted with clearances not less than those specified by the manufacturer.

When applicable, the manufacturer should provide information concerning the disposal of fuses with due regard to environmental considerations.

It is the responsibility of the user to consider and comply with all local relevant regulations concerning disposal.

For all application purposes, the ratings of a given fuse (current, voltage, maximum breaking current, etc.) are to be considered the maximum values, which should not be exceeded in service. The only exception is the minimum breaking current of a Back-Up fuse, which should be considered a minimum value.

Normal operation of current-limiting fuses: a normal operation of a current-limiting fuse will not produce excessive external forces on the mounting or surrounding parts. In addition, there is comparatively little noise or reaction when a current-limiting fuse operates.

Precautions should be taken concerning the selection of the site of installation of expulsion type fuses, due to the high level of noise and emission of hot gases during operation that are inherent in some types. They should be applied with adequate clearance in the direction or directions in which they are vented, and facilities should be provided to ensure that operators are not exposed to fuse discharges either during replacement or when working in the area. When this is not possible, the circuit should first be de-energized.

It should be noted that, when fuse-links are subjected to the effect of severe solar radiation, or are used in an enclosure that subjects the fuse-link to a surrounding temperature above 40 °C, certain aspects of the performance of these fuse-links may be significantly affected. Depending on the fuse design, aspects affected may include current rating, time-current characteristics and current interrupting ability. Some fuse types have to be specifically designed and tested for such an application (for example some organic fuse-links, see IEC 60282-1 for definition). The effect on the fuse's current rating and time-current characteristics is covered in 5.1.1.2 and 5.1.1.3. Additional testing requirements for certain fuse-links intended for use in a surrounding temperature above 40 °C are covered in IEC 60282-1.

5.3.2 Installation guidelines

The manufacturers guidelines concerning fuse installation should be followed. During installation and replacement of fuses, careless handling can result in a damaged fuse being installed. Current-limiting fuses are particularly sensitive to careless handling. While damage may be clearly visible, such as denting of the fuse cap or cracking or breakage of the fuse tube, there may be invisible damage – such as breakage of a fuse element inside the fuse or disruption of a seal in an under-oil fuse. This damage can interfere with key performance requirements placed on the fuse, that is a damaged fuse may not be able to carry its rated current or it may not be able to interrupt a faulted circuit. If the latter occurs, damage to associated equipment or even injury to personnel could result. While expulsion fuses tend to be more robust than current-limiting fuses, they can also have delicate elements and be damaged by dropping.

Some typical causes of damage include, but are not limited, to the following:

- dropping or mishandling a fuse;
- excessive force in closing a fuse into its mounting;

- improper alignment of the fuse with its base during insertion or removal;
- over-tightening or under-tightening of connection points;
- excessive lead size or weight causing too high a cantilever force being placed on a fuse;
- using a fuse in a thermal environment beyond its rating.

The manufacturer should be consulted as to proper installation force and acceptable mountings as well as correct handling guidelines. If damage is suspected, the fuse should be removed from service.

5.3.3 Operation guidelines

5.3.3.1 Installation of non-expendable cap on expendable-cap distribution fuse-cutouts

This results in a reduction of the expendable-cap cutout interrupting capability. Refer to manufacturers' instructions concerning the reduction in the rating.

5.3.3.2 Locking or latching of fuse-links, blades, or fuse-carriers in closed position

Special care should be taken to see that the fuse-link, blade, or fuse carrier is securely locked, latched, or held fast in the closed position as recommended by the manufacturer.

5.3.3.3 Fuse-carrier position

Certain types of outdoor fuses should not be left hanging in the open position as a means of isolating the equipment from the system since rain water may collect in the fuse tube and cause swelling or other damage, thus impairing the interrupting capability of the fuse. If an equipment installation or a circuit is to be left out of service the fuse-carriers may be hung upright from a pin or hook on the pole.

5.3.3.4 Operation of energized fuses

A fuse or piece of fused equipment not equipped with a means of breaking load should not be used to open a circuit unless it is known that no current is flowing (either because the fuse has blown or the circuit has been de-energized). When a fuse or piece of fused equipment equipped with a means of breaking load is used (e.g. see 4.3.2.3), it should not be opened immediately after the circuit has been energized. The time delay before opening will vary considerably, depending upon the current rating of the fuse, but should be adequate to allow the fuse to interrupt any existing fault current that might exceed the load-break rating of the device. For large-sized fuse-links above 100 amperes, this time delay could be as long as 10 min. Switch-fuse combinations according to IEC 62271-105 are not under the scope of Subclause 5.3.3.

5.3.3.5 Liquid-submerged expulsion fuses in enclosures

The liquid is an integral part of the equipment design and the fuse performance, and manufacturer's recommendations should be followed. The operation of the fuse may cause carbon to form in the liquid. The degree to which this will affect the equipment characteristics depends upon the number of operations as well as their magnitude and duration. Operating experience will usually be the best basis for establishing a maintenance schedule.

5.3.3.6 Electromagnetic compatibility (EMC)

Fuses within the scope of this report are not sensitive to electromagnetic disturbances and therefore no immunity tests are necessary. Any electromagnetic disturbance which may be generated by a fuse is limited to the instant of its operation.

5.3.4 Maintenance considerations

5.3.4.1 General

Under normal operating conditions, internal components of high-voltage fuses that have been correctly sized for their particular application are not normally subject to influences that could reduce their reliability. However, external effects may damage the outside casing and contact area of a fuse-link, and the contacts and insulators of a fuse-base particularly in outdoor applications. If the manufacturer of the fuses specifies maintenance requirements, then these should be followed. In the absence of specific guidelines, general maintenance information appears in 5.3.4.3. Since the time-scale of environmental damage varies greatly depending on the conditions (indoor in a clean environment or outdoor in a polluted environment being the two extremes) no guidance is possible as to the frequency of maintenance. For some users, maintenance may only occur during the replacement of a "blown" fuse-link, while for others, severe environmental conditions may call for frequent inspections.

When one or two current-limiting fuses in a three-phase arrangement are replaced, in addition to replacing the "blown" fuse(s), all fuse bases should be examined and the fuses in other phases should normally be replaced (see 5.3.5.5). Fuses of all types should always be replaced by identical fuse-links to those originally installed, unless the protection scheme is examined to ensure the replacement fuses will perform the same function. In a two or three phase arrangement, all fuses should be of the same current rating, be from the same manufacturer, and have the same manufacturer’s type designation.

5.3.4.2 Precautions to be observed

Examination and maintenance of equipment that is connected to an energized circuit should be done at a safe distance from any exposed energized parts of equipment or conductors, or the circuit and equipment should be de-energized. In the case of equipment on capacitor installations, precautions should be taken to discharge and connect to ground the capacitors after de-energisation. Alternatively, live line techniques may be employed if they are adequate to ensure safety to personnel.

A very important precaution is that personnel should take special care when approaching equipment that may contain an active fault (usually evidenced by a hissing or buzzing noise) since it may be highly dangerous to do so. In such a case the supply should be disconnected upstream before proceeding further.

5.3.4.3 Inspection of fuse or switching device

Equipment within the scope of this report usually consists of several parts, some current-carrying and some non-current-carrying, all subject to atmospheric and other environmental conditions. The equipment is also subject to the normal and abnormal operating conditions of the system in which it is connected. The frequency and completeness of inspection will necessarily be a function of the service reliability required and the conditions at the specific equipment location and so can only be determined by the user, taking into account manufacturer’s instructions. Some of the items that might be considered are as follows:

a) general examination for obvious defects and to ensure that bolts, nuts, washers, pins, and terminal connectors are securely in place/tightened and in good condition;
b) inspection of insulators and other porcelain or plastic parts for breaks, cracks, burns, or contamination. Cleaning of Insulators and other insulating surfaces of any excessive contamination, such as salt deposits and cement or road dust, to avoid flashover as a result of the accumulation of foreign substances on their surfaces. Cracked or broken insulators and other insulating parts should be replaced. To prevent flashover, consideration should be given to replacing badly burned insulating parts;
c) Examination of current-contact surfaces for pitting, burning, alignment, and to ensure that the contacts when closed are held together with adequate pressure. Replacement and adjustment may be required

d) vent holes on equipment so equipped should be examined to ensure the holes are not plugged with dirt or other foreign substances, and cleaned if necessary;

e) if applicable to the equipment, the fuse unit or fuse tube and renewable fuse element should be examined for corrosion of the fuse element or connecting conductors, excessive erosion or delamination of the inside of fuse tubes, tracking and dirt on the outside of the fuse tube, and improper assembly that may prevent proper operation. Components showing significant signs of deterioration should be replaced. Fuse tubes made of organic material may be refinished according to manufacturer's specifications;

f) current-carrying parts, such as blades or fuse-links, should be examined for thermal damage resulting from heavy short-circuit currents or overloads. Damaged fuse-links and other parts significantly deformed should be replaced;

g) the mechanical operation should be checked per manufacturer's recommendations.

5.3.4.4 Inspection of fuse-links in distribution fuse-cutouts

Fuse-links in fuse-cutouts may require periodic replacement since corrosion of the lower terminal of the fuse-link (generally a flexible cable) at the lower open-end of the fuse holder may cause breakage or melting at this point rather than at the current-responsive fuse element. Link-break cutouts are more susceptible to this problem because of the mechanical strain placed upon the fuse-link by the link-break mechanism.

5.3.4.5 Additional maintenance guidelines for specific devices

5.3.4.5.1 Capacitor fuses

Care should be taken to discharge and ground capacitors before maintenance is performed. See 5.3.5 for further information.

5.3.4.5.2 Liquid-submerged expulsion fuses in enclosures

Liquid: The level and quality of the liquid in the equipment may affect the performance of the expulsion fuse. All gasketed joints and seals should be properly maintained. Inspection should include checking the tank for liquid leakage and for indications of any external damage or deterioration. The level of the liquid should be checked to see that it is in accordance with the switchgear manufacturer's recommendation. Liquid should not be withdrawn from, or added to, the switchgear while it is energized unless there is a suitable means or procedure for this function.

Component inspection: Manufacturer's recommendations and requirements for inspection and maintenance of fuse components should be followed. Replacement fuses should be those recommended by the switchgear manufacturer. Many users have established procedures to allow inspection and maintenance of energized equipment. In the absence of such procedures, the equipment should be de-energized before performing any inspection or maintenance.

The following are some general guidelines for inspecting and maintaining fuse components:

a) all current-carrying components of a fuse carrier or bayonet assembly should be inspected. Any components showing indication of excessive heating or damage from arcing should be replaced. Excessive arc damage or heating of contact surfaces may indicate the need to inspect internal contacts. This generally requires removing the unit from service;

b) any fuse carrier or cartridge showing signs of cracks, erosion, tracking, or excessive wear should be replaced;

c) all seals and gaskets should be checked and any that are deteriorated or deformed should be replaced. Manufacturer-approved replacements should be used;

d) electrical connections should be checked to determine that they are clean and tightly secured;

e) satisfactory condition of the fuse should be verified, as recommended by the manufacturer.

5.3.4.5.3 Infrared testing

One way of evaluating current-limiting fuses, and higher ampere rated expulsion fuses while they are in service, and observable, is to use infrared test equipment. This approach is becoming more common.

Since fuses are. of necessity, heat producing devices and may often run hotter than other surrounding equipment, the following factors are appropriate to consider when using this equipment:

a) a temperature reading of 30 °C above ambient temperature is common;
b) in some cases total measured temperatures as high as 105 °C may be normal;
c) on three-phase installations, readings on all three phases should be close if the loading is equal on all three phases.
d) The focus of infrared measurement should be on fuse contact temperatures as element temperatures above 105 °C may be observed if the fuse body is included in temperature scans.

5.3.5 Replacement considerations

5.3.5.1 General

Replacement of fuses should be done with the circuit de-energized, unless their design, testing, and the manufacturer's recommendations permit replacement while energized. In the case of fuses that are under the control of a utility, fuse replacement should be done using utility practices developed in conjunction with the fuse's manufacturer. However, expulsion fuses should never be replaced from within the venting area with the circuit energized.

Replacement fuses should be those recommended by the manufacturer. Care is particularly required in certain applications (i.e. any time a fuse is coordinated with other devices, see below) Testing is performed in accordance with IEC standards that cover only the performance of fuses as tested, when the fuse consists of a particular combination of fuse-base, fuse-carrier, and/or fuse-link. Successful performance of other combinations of components from different manufacturers cannot be implied from such tests.

Particular caution should be exercised when replacing a back-up fuse, or the series device with which it is coordinated (e.g. see 5.2.2.5), after either, or both, have operated. Coordination between the two devices is critical to preventing damage to them and the associated equipment. Therefore, replacement of either protective device with one of a different rating or supplied by a different manufacturer should be done only after a careful review of the total protection scheme to be sure that coordination is maintained. Because Back-Up fuses are always coordinated with another device, care is often necessary when the series device has operated.

It is advisable to locate and correct the situation that caused the fuse to operate before re-energizing. The operator should be aware that a potential hazard may exist if the circuit is re-energized with the fault condition still present.

The exhaust-control device on expulsion fuses so equipped may be suitable for reuse after a fuse operation. This is dependent upon the fault magnitudes, and numbers of fault-current interruptions it has experienced. It is advisable, after the operation of a fuse, to inspect the exhaust-control device and follow carefully the manufacturer's instructions for determining the suitability of the device for further service.

5.3.5.2 Storing spare fuse-links and replaceable parts

Spare fuse-links, refill units. and replaceable parts of fuses should be stored in such a manner that they will not be damaged, and will be available when needed. Boric acid expulsion fuses are particularly sensitive to moisture ingress and should be stored in their original packaging in a dry environment. If several types and ratings of fuses are used in a given location the spare parts should be suitably marked, coded, or indexed to show the mountings, circuits, or equipment with which they are to be used. This will minimize the possibility of improper use. Consult the manufacturer for recommendations.

5.3.5.3 Capacitor fuse replacement

Care should be taken to discharge the capacitors after de-energisation, and to ground the entire capacitor bank before any maintenance is performed. Fuses used on capacitor units should not be handled, removed or replaced unless due precautions are taken beforehand to de-energize, discharge and ground the capacitor units. The entire capacitor bank should be de-energized and earthed while replacing capacitor-unit fuses. Capacitor line fuses may be handled using live-line tools.

Capacitor units used in power applications usually have a discharge resistor to reduce the capacitor unit voltage to a specified value in a specified time after being de-energized. This internal-discharge device should not be considered as a substitute for the recommended safety practice of manually discharging the residual stored energy before working on capacitor units. Capacitor units may be damaged if discharged too soon after being de-energized. It is recommended that at least 5 minutes be allowed for adequate discharge through the discharge resistor, and then the capacitor terminals should be shorted together and connected to ground.

When installing or removing capacitor unit fuses using fuse-links having a flexible tail or leader, the leader should first be disconnected from the capacitor bushing to avoid twisting of the fusible element.

When replacing a capacitor unit fuse it may be desirable to check the continuity and the condition of the fuses or fuse-links on adjacent parallel capacitor units.

5.3.5.4 Liquid-submerged expulsion fuses in enclosures

During removal and replacement of fuses, it should be considered that a sealed enclosure (tank) may have a pressure greater than atmospheric. This internal pressure should be returned to atmospheric pressure prior to removing fuses

5.3.5.5 Three-phase applications/series fuse operation

Under certain circumstances, fuses may be damaged or experience partial element melting by a current that is not of sufficient magnitude and duration to cause total melting and operation of the fuse.

Considerations regarding fuse replacement after one or two fuse operation on two or three-phase applications include the following:

a) if not all fuses of a two or three-phase group operates, there is a possibility that another phase was involved and, while it did not operate, its fuse may be damaged. Unless the user can positively rule out this possibility, then all fuses in a two or three-phase set should be replaced when any have operated;
b) an example of a situation in which a multi-phase fault can be ruled out is in the case in which the fault location can be positively identified and only the phase(s) with the operated fuse(s) was involved with the fault;
c) for capacitor banks that use capacitor line fuses (group fuses) the following conditions apply. On a earthed-star capacitor bank, if one fuse operates there is no need to replace

the other two fuses. On an unearthed-star capacitor bank, if one fuse operates the other two fuses may be damaged since they have been subjected to 3 times normal current when the capacitor shorted (which caused the first fuse to operate). On delta-connected banks, usually two fuses operate simultaneously and there is no need to replace the third. If a second fuse did not operate, then after the faulted capacitor is identified (and isolated), the second fuse, on the other line bushing of the faulted capacitor unit, should be replaced.

In applications where fuses are used in series with other fuses or interrupting devices in the same phase in such a manner that their pre-arcing or operating curves cross one another, it is advisable after an operation to follow carefully the manufacturer's instructions for determining the suitability of the other fuse(s) for continued service.

Care should be exercised when replacing fuses in multi-phase circuits if the assumption has been made that, under fault conditions, two fuses will be effectively in series and will share the line-to-line voltage. For two fuses to share the voltage, they must arc simultaneously. Consequently, fuses in all phases should be of the same fuse rating, the same model and/or type of fuse, and be from the same manufacturer; consult the manufacturer for more information.

5.4 Recycling

When applicable, the manufacturer should provide information concerning the disposal of fuses with due regard to environmental considerations.

It is the responsibility of the user to consider and comply with all local relevant regulations concerning disposal.

Reuse of current-limiting fuses after interruption: current-limiting fuse-links should not be reused or rebuilt (unless the work is performed by the fuse manufacturer or their authorized agent).

Annex A
(informative)

Practical guidelines for thermal de-rating of current-limiting fuses

A.1 Object

The object of this annex is to provide guidance on the determination of thermal de-rating of a fuse when the temperature around the fuse exceeds 40 °C. This may be caused by higher ambient temperature in a non-enclosed situation or by use in an enclosure.

Hence methods are given for the following cases:

a) de-rating for use in ambient air temperature above 40 °C (type 1CL see 5.1.1.2.2);
b) de-rating for use in relatively large enclosures (type 1CL see 5.1.1.2.2);
c) de-rating for use in relatively small enclosures(type 2CL see 5.1.1.2.2);
d) de-rating for use in enclosures with insulating liquid surrounding the fuse-links (type 3CL see 5.1.1.2.2).

In addition, method e) may be used as an alternative to methods a), b), c) and d).

NOTE Other methods of de-rating are used in certain countries; see the bibliography.

A.2 General

Guidance on the use of current limiting fuses in elevated surrounding temperatures is covered in 5.1.1. IEEE standards have used the term "allowable continuous current" to describe a current higher or lower than rated current that a fuse can carry without deterioration and without exceeding permitted temperatures in a particular surrounding temperature (or in a given enclosure having a particular surrounding temperature). Annex A, uses the term "maximum permissible continuous current I_{encl}" to indicate the modified rated current caused by an enclosure and the two terms are approximately equivalent.

Subclause 5.1.1.2.1 further advises that the suitability for a specific application of the fuse-link in an enclosure is the responsibility of the supplier of the fuse enclosure package (FEP).

NOTE FEP means the combination of the fuse in its enclosure.

The results of the power-dissipation tests (see 4.2.4.6 and 6.5 of IEC 60282-1:2009), along with a method for determining enclosure temperature, may enable the FEP manufacturer to assess the maximum permissible continuous current which may be carried by any FEP, prior to confirmation by tests. However, often specific advice from the fuse manufacturer is required as to the suitability of a particular design for use in an enclosure, and the method to be used to determine appropriate de-rating.

Many HV fuse-links are used for transformer circuit application, for which 5.2.2 gives guidance for the selection of fuse-links. As stated in 5.2.2.2.2 item a), these fuse-links should have relatively high operating currents in the 0,1 s region of the time-current characteristics. To meet this requirement, the fuse-link rated current is generally in excess of circuit full-load current and, therefore, de-rating as determined using this annex will usually already be met for Back-Up fuses, although General-Purpose and Full-Range fuses frequently need de-rating.

The need for de-rating the fuse-link arises for one or other of the following reasons:

- to limit the internal hot-spot temperature to a value which will not cause deterioration. This value is dependent upon the specific fuse-link design;

– to ensure that contact temperatures do not exceed maximum values as given in IEC 60282-1.

It is often the first of these requirements that determines the fuse-link rating. However, as cooling become more restrictive and current de-rating increases, the temperature drop from the fuse element to the exterior of the fuse barrel decreases. This leads to a shift from having the maximum load current determined by the hot-spot temperature of the fuse elements to having it determined by the contact temperature.

a) De-rating for use in ambient air temperatures above 40 °C

   A conservative method of calculating a current that will result in the same contact temperatures in a higher surrounding temperature assumes that heat loss from the fuse is proportional to the difference between contact temperature and ambient temperature. Figure A.1 uses this approach to provide the percentage de-rating required as a function of surrounding temperature for values of maximum temperature of contacts and terminals as specified in Table 6 of IEC 60282-1:2009 (and reminded in Table A.1). This is conservative for several reasons. Firstly it assumes that at rated current a fuse has the maximum temperature rise permitted. This is not always true for maximum current ratings and seldom true for lower ratings. Additionally it assumes the same fuse element temperature at the de-rated current while in practice the average temperature will generally drop (as explained in the previous paragraph). De-rating based on maximum hot-spot temperatures will generally give a de-rating factor that allows a higher percentage of the rated current than given in Fig A.1, so the values from Fig A.1 err on the safe side, and are intended to be used where more precise information is not available from the fuse-link manufacturer. Where such information is available, less onerous de-rating factors may be applicable. This method is also applicable to fuses in vaults or large enclosures where the heat generated by the fuse is an insignificant contribution to the heat generated in the enclosure.

b) De-rating for use in relatively large enclosures

   Within this category are typically three-phase box-type enclosures with significant heat dissipation from the fuse-links by convection. Although not necessarily constructed from metal, the clearances to the sides (and partitions, if any) of the box will be consistent with clearances required for electrical purposes appropriate to the medium immediately surrounding the fuse-links for non-shrouded metal-type enclosures.

   For such enclosures, Figure A.1 may be used to assist in determining the de-rated current (I_{encl}) value for the fuse-links when used in a given enclosure. If the temperature of the medium surrounding the fuses is known, then Figure A.1 is used to verify whether the I_{encl} is correct. However, the difficulty to be overcome is that the heat produced by the fuse-link has a direct effect on the temperature within the enclosure.

   IEC 60890 gives a method for calculation of the temperature rise of air inside enclosures, and the same principles may be applied to enclosures containing HV fuse-links.

   Consider the example shown in Figure A.2, and assume 100 A fuse-links with power dissipation of 85 W at rated current.

   NOTE Actual power-dissipation values are obtained from the fuse-link manufacturer in accordance with 6.5.3. of IEC 60282-1:2009

   Complete the table shown in Figure A.3 (a full explanation of the procedure is given in IEC 60890).

   The completed table is shown in Figure A.4, and an I_{encl} value of 80 A has been assumed. The first section results in a value for effective cooling surface A_{e}. Constants K, d, × and c are obtained from IEC 60890. The effective power dissipation P requires some explanation.

   It is necessary to assume an I_{encl} value and obtain the appropriate power dissipation. For the initial assessment in this example, an I_{encl} value of 80 A has been assumed giving a power dissipation of $(80/100)^2 \times 85 = 54{,}4$ W. The resultant temperature rise of the enclosure at the upper end is determined to be 37,5 K.

   If Figure A.1 is now examined for a de-rating factor on bolted contacts (105 °C) and at an ambient temperature of 40 °C + 37,5 °C = 77,5 °C, the de-rating factor is seen to be 65 %.

Hence, since the selected rated current of 100 A exceeds the rated current × derating factor (i.e. 100 A × 0,65 = 65 A) an I_{encl} value of 80 A is seen to be excessive.

The exercise must now be repeated, using a lower current. Hence consider 70 A, where power dissipation $(70 \times 100)^2 \times 85$ = 41,6 W. This in turn leads to a temperature rise of the enclosure at the upper end of 30,3 K. Now if we examine Figure A.1 for an ambient temperature of 40 °C + 30,3 °C = 70,3 °C, the de-rating factor is seen to be 73 %. Hence the permissible rating of 0,73 × 100 A = 73 A now exceeds the proposed I_{encl} value of 70 A and thus the latter is assessed as acceptable.

This example shows how the information available in Figure A.1, and in IEC 60890 can be used to assess an acceptable I_{encl} value for an FEP. Where there are other items of equipment or connections within the enclosure that produce appreciable power dissipation, then these values should be added to the power dissipation of the fuse-links.

c) De-rating for use in relatively small enclosures or canisters

The main characteristics of a canister, seen in the context of the de-rating of fuse-links are as follows.

The canister is typically a single-phase enclosure.

- The distance between the outer surface of the fuse-link and the inner wall of the canister is small, typically 10 % to 25 % of the fuse-link diameter.
- Due to the narrow space, cooling by convection is of little significance, whereas radiation and conduction may dominate. The fuse-link and canister form an integrated assembly, and de-rating may often be based on the maximum power dissipation the assembly can withstand.
- Depending upon canister construction and materials used, the temperature of the interior of the canister may, in some cases, be the determining factor for the de-rating.

Because of the close interaction of the canister and fuse-link, the de-rating of this combination can normally only be determined by measurement.

d) De-rating for use in enclosures with insulating liquid surrounding the fuse-links

The rated currents of fuse-links intended for use under insulating liquid are determined by tests under relatively restricted conditions, designed to simulate service conditions (see 6.5.1.2 of IEC 60282-1:2009). Hence de-rating, if any, within an enclosure is usually minimal. However, due account should be taken of external ambient temperatures above 40 °C, particularly in the case of Full-Range fuses and with transformer applications (see 5.2.2.2).

Methods a) to d) provide a means of assessment and are not a substitute for actual tests expected to be carried out by the FEP manufacturer. When tests are conducted by the FEP manufacturer, then the results of those tests override any assessment made by use of this annex.

e) Alternative method for establishing de-rating

Where it is possible for the FEP manufacturer or end-user to make tests on the equipment complete with relevant fuses, the following method may be adopted for establishing the I_{encl} value for the FEP:

1) obtain from the fuse manufacturer the value of watts dissipation (W_{r}) at rated current (I_{r}) of the fuse under the normal test conditions. From this value, calculate the maximum permissible hot resistance of the fuse-link ($W_{\text{r}} / I_{\text{r}}^2$);
2) install a set of three fuses as in service. Apply a gradually increasing value of test current until:
   - the hot resistance (as given by dividing the voltage drop across each fuse-link by the current) reaches the value calculated in 1) above, or
   - the temperature rise on the fuse contacts and terminals reaches the permissible limits specified by the fuse manufacturer or in Table A.1;
3) the I_{encl} value for the fuse-link will be the lower of the following:
   - that value which results in the maximum permissible hot resistance;

– that value which results in the appropriate maximum temperature rise specified in 4.7 of IEC 60282-1:2009.

It should also be noted that this annex is concerned with continuous full-load current requirements of associated and/or protected equipment such as transformers or motors. Use under cyclic overload conditions should be subject to agreement between manufacturer and user.

Table A.1 – Contact Temperature limits extracted from Table 6 of IEC 60282-1:2009

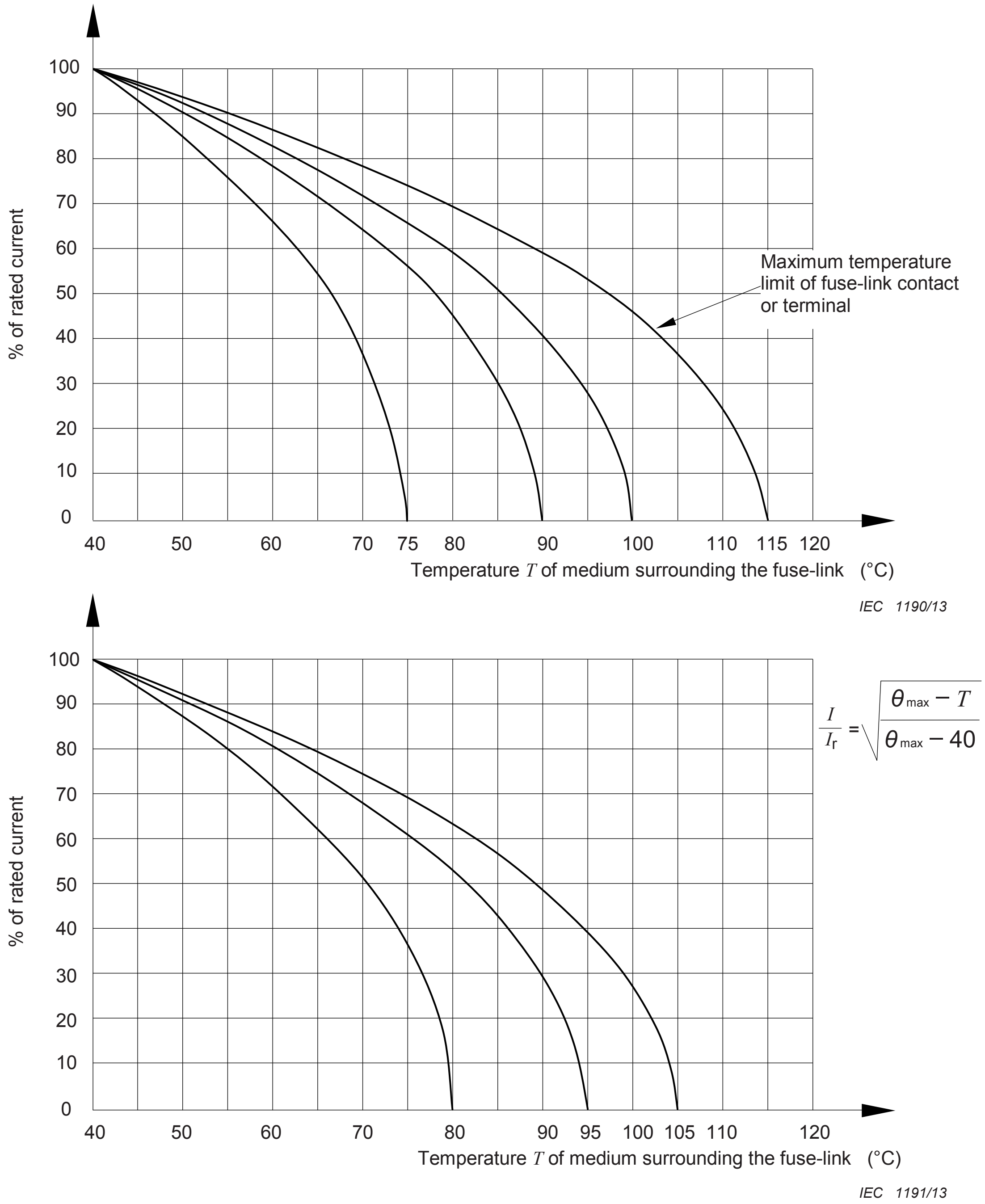


Figure A.1 – Derating curves for some allowed temperature limits

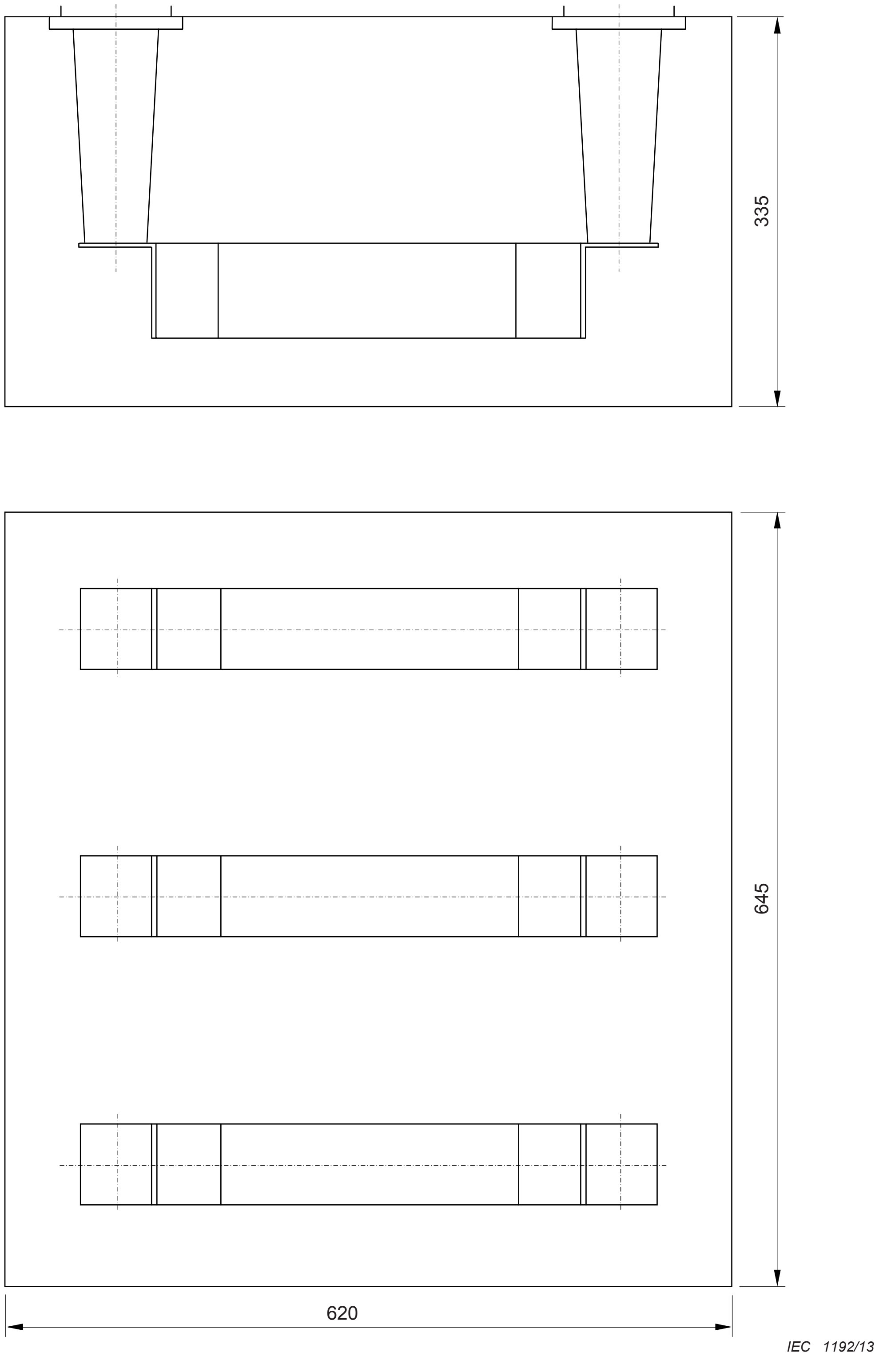
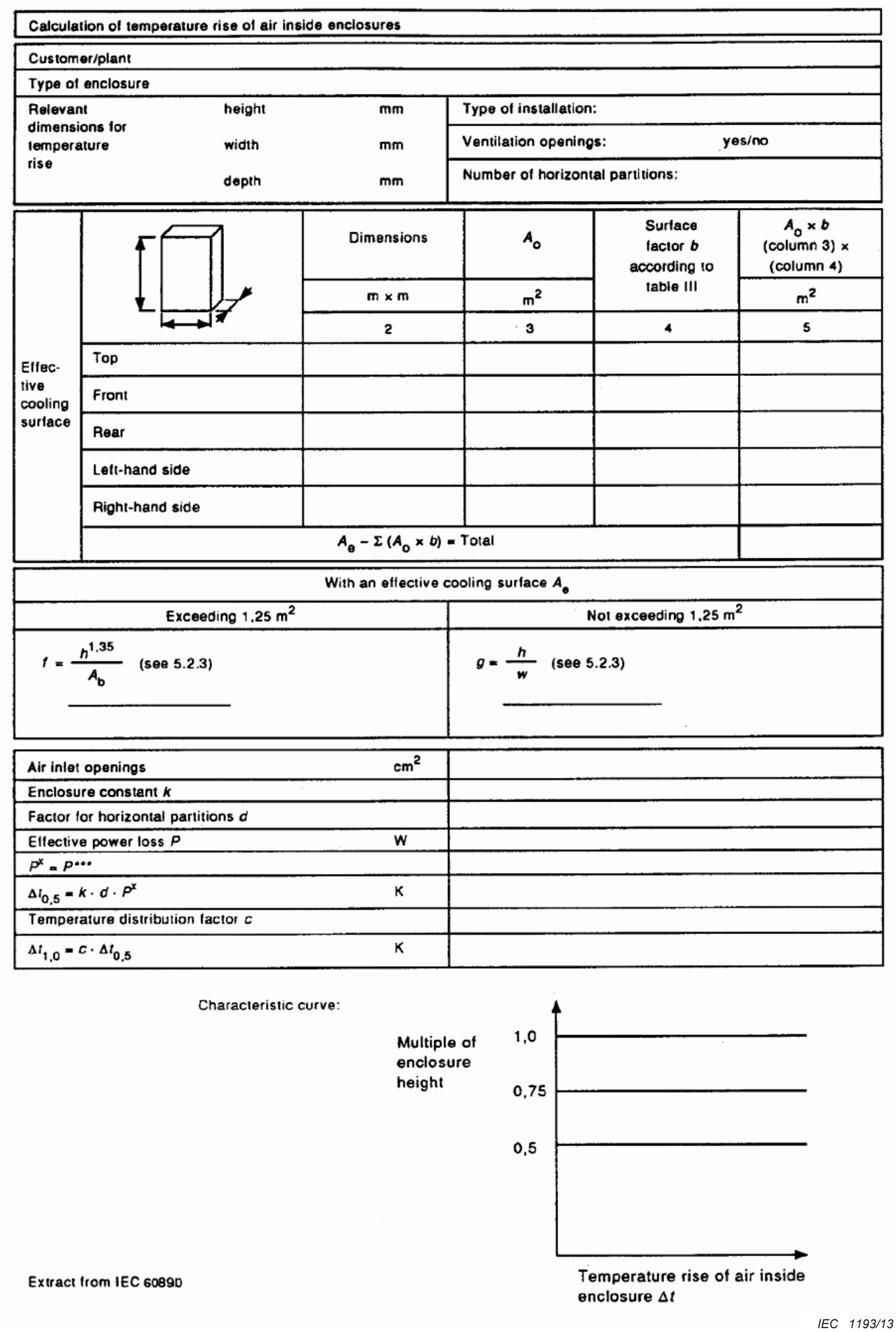


Figure A.2 – Practical example: dimensions



Calculation of temperature rise of air inside enclosures

Customer/plant				
Type of enclosure				
Relevant dimensions for temperature rise	height	mm	**Type of installation:**	
	width	mm	**Ventilation openings:**	yes/no
	depth	mm	**Number of horizontal partitions:**	

		Dimensions	A_o	Surface factor b according to table III	$A_o \times b$ (column 3) × (column 4)
		m × m	m²		m²
		2	3	4	5
Effective cooling surface	**Top**				
	Front				
	Rear				
	Left-hand side				
	Right-hand side				
	$A_e - \Sigma (A_o \times b) =$ Total				

With an effective cooling surface A_e	
Exceeding 1,25 m²	Not exceeding 1,25 m²
$f = \dfrac{h^{1,35}}{A_b}$ (see 5.2.3)	$g = \dfrac{h}{w}$ (see 5.2.3)

Air inlet openings	cm²	
Enclosure constant k		
Factor for horizontal partitions d		
Effective power loss P	W	
$P^x = P^{***}$		
$\Delta t_{0,5} = k \cdot d \cdot P^x$	K	
Temperature distribution factor c		
$\Delta t_{1,0} = c \cdot \Delta t_{0,5}$	K	

Characteristic curve:

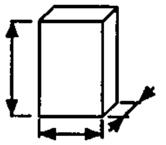
Extract from IEC 60890

IEC 1193/13

Figure A.3 – Extract from IEC 60890

Calculation of temperature rise of air inside enclosures

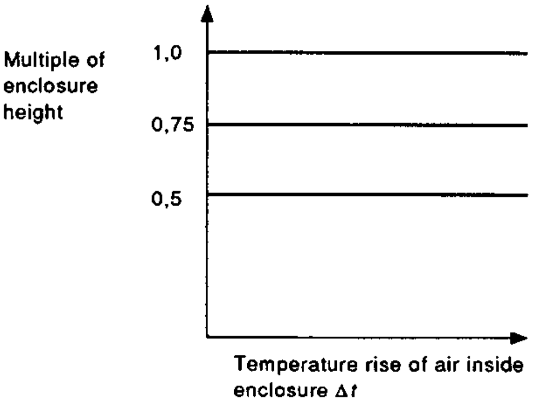
Customer/plant	Example only (see figure 2)				
Type of enclosure	three-phase				
Relevant dimensions for temperature rise	height	620	mm	Type of installation:	
	width	645	mm	Ventilation openings: yes/no	no
	depth	335	mm	Number of horizontal partitions:	None

		Dimensions m × m	A_0 m²	Surface factor b according to table III	$A_0 \times b$ (column 3) × (column 4) m²
Effective cooling surface		2	3	4	5
	Top	0,645 × 0,335	0,216	1,4	0,3024
	Front	0,645 × 0,620	0,400	0,9	0,3600
	Rear	0,645 × 0,620	0,400	0,9	0,3600
	Left-hand side	0,335 × 0,620	0,208	0,9	0,1869
	Right-hand side	0,335 × 0,620	0,208	0,9	0,1869
	$A_e = \Sigma (A_0 \times b)$ = Total				1,396

With an effective cooling surface A_e		
Exceeding 1,25 m²	Not exceeding 1,25 m²	
$f = \frac{h^{1,35}}{A_b}$ (see 5.2.3 of IEC 60890) $\frac{0,620^{1,35}}{0,645 \times 0,335} = 2,43$	$g = \frac{h}{w}$ (see 5.2.3 of IEC 60890) 1st trial	Final

		1st trial	Final
Air inlet openings	cm²	–	–
Enclosure constant k		0,48	0,48
Factor for horizontal partitions d		1	1
Effective power loss P	W	54,4 × 3 = 163	41,6 × 3 = 124,8
$P^x = P^{0,804}$		60,1	48,5
$\Delta t_{0,5} = k \cdot d \cdot P^x$	K	28,85	23,3
Temperature distribution factor c		1,3	1,3
$\Delta t_{1,0} = c \cdot \Delta t_{0,5}$	K	37,5	30,3
		at 80A	at 70A

Characteristic curve:



Example of application

IEC 1194/13

Figure A.4 – Practical example of application

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The bibliographic entries are either documents referred to in the body of the report or are references to information concerning fuses that may be of help to those using fuses.

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