BS EN 60143-2:2013

BSI Standards Publication

Series capacitors for power systems

Part 2: Protective equipment for series capacitor banks

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National foreword

This British Standard is the UK implementation of EN 60143-2:2013. It is identical to IEC 60143-2:2012. It supersedes BS EN 60143-2:1995 which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee PEL/33, Power capacitors.

A list of organizations represented on this committee can be obtained on request to its secretary.

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

Published by BSI Standards Limited 2013

ISBN 978 0 580 75148 6
ICS 29.240.99; 31.060.70

Compliance with a British Standard cannot confer immunity from legal obligations.

This British Standard was published under the authority of the Standards Policy and Strategy Committee on 31 July 2013.

Amendments/corrigenda issued since publication

Date	Text affected

EUROPEAN STANDARD

NORME EUROPÉENNE

EUROPÄISCHE NORM

EN 60143-2

June 2013

ICS 29.240.99; 31.060.70

Supersedes EN 60143-2:1994

English version

Series capacitors for power systems -
Part 2: Protective equipment for series capacitor banks
(IEC 60143-2:2012)

Condensateurs série destinés
à être installés sur des réseaux -
Partie 2: Matériel de protection pour les
batteries de condensateurs série
(CEI 60143-2:2012)

Reihenkondensatoren für
Starkstromanlagen -
Teil 2: Schutzeinrichtungen für
Reihenkondensatorbatterien
(IEC 60143-2:2012)

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Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the CEN-CENELEC Management Centre or to any CENELEC member.

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CENELEC
European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
Europäisches Komitee für Elektrotechnische Normung

Management Centre: Avenue Marnix 17, B - 1000 Brussels

Foreword

The text of document 33/517/FDIS, future edition 2 of IEC 60143-2, prepared by IEC/TC 33 "Power capacitors and their applications" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 60143-2:2013.

The following dates are fixed:

• latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2013-12-14
• latest date by which the national standards conflicting with the document have to be withdrawn	(dow)	2016-01-15

This document supersedes EN 60143-2:1994.

EN 60143-2:2013 includes the following significant technical changes with respect to EN 60143-2:1994:

- updated with respect to new and revised component standards;
- updates with respect to technology changes. Outdated technologies have been removed, i.e. series capacitors with dual self-triggered gaps. New technologies have been added, i.e. current sensors instead of current transformers;
- the testing of spark gaps has been updated to more clearly specify requirements and testing procedures. A new bypass making current test replaces the old discharge current test;
- Clause 5, Guide, has been expanded with more information about different damping circuits and series capacitor protections.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CENELEC [and/or CEN] shall not be held responsible for identifying any or all such patent rights.

This standard covers the Principle Elements of the Safety Objectives for Electrical Equipment Designed for Use within Certain Voltage Limits (LVD - 2006/95/EC).

Endorsement notice

The text of the International Standard IEC 60143-2:2012 was approved by CENELEC as a European Standard without any modification.

In the official version, for Bibliography, the following notes have to be added for the standards indicated:

IEC 60068-1	NOTE	Harmonised as EN 60068-1.
IEC 60068-2-2	NOTE	Harmonised as EN 60068-2-2.
IEC 60068-2-78	NOTE	Harmonised as EN 60068-2-78.
IEC 60068-2-30	NOTE	Harmonised as EN 60068-2-30.
IEC 60071-1	NOTE	Harmonised as EN 60071-1.
IEC 60071-2	NOTE	Harmonised as EN 60071-2.
IEC 60143-3	NOTE	Harmonised as EN 60143-3.
IEC 60255-1	NOTE	Harmonised as EN 60255-1.
IEC 60383-1	NOTE	Harmonised as EN 60383-1.

IEC 60383-2	NOTE	Harmonised as EN 60383-2.
IEC 60507	NOTE	Harmonised as EN 60507.
IEC 60549	NOTE	Harmonised as EN 60549.
IEC 60654-1	NOTE	Harmonised as EN 60654-1.
IEC 60654-4	NOTE	Harmonised as EN 60654-4.
IEC 60871-1	NOTE	Harmonised as EN 60871-1.
IEC 60909 Series	NOTE	Harmonised as EN 60909 Series (not modified).
IEC 61000-4-2	NOTE	Harmonised as EN 61000-4-2.
IEC 61000-4-11	NOTE	Harmonised as EN 61000-4-11.
IEC 62217	NOTE	Harmonised as EN 62217.
IEC 62271-100	NOTE	Harmonised as EN 62271-100.
IEC 62223	NOTE	Harmonised as EN 62223.

Annex ZA
(normative)

Normative references to international publications with their corresponding European publications

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.

NOTE When an international publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

Publication	Year	Title	EN/HD	Year
IEC 60044	Series	Instrument transformers	EN 60044	Series
IEC 60044-1	-	Instrument transformers - Part 1: Current transformers	EN 60044-1	-
IEC 60044-8	-	Instrument transformers - Part 8: Electronic current transformers	EN 60044-8	-
IEC 60060	Series	High-voltage test techniques	EN 60060	Series
IEC 60076-1	-	Power transformers - Part 1: General	EN 60076-1	-
IEC 60076-6	2007	Power transformers - Part 6: Reactors	EN 60076-6	2008
IEC 60099-4 (mod) + A1 + A2	2004 2006 2009	Surge arresters - Part 4: Metal-oxide surge arresters without gaps for a.c. systems	EN 60099-4 +A1 +A2	2004 2006 2009
IEC 60143-1	2004	Series capacitors for power systems - Part 1: General	EN 60143-1	2004
IEC 60255-5	-	Electrical relays - Part 5: Insulation coordination for measuring relays and protection equipment - Requirements and tests	EN 60255-5	-
IEC 60255-21-1	-	Electrical relays - Part 21: Vibration, shock, bump and seismic tests on measuring relays and protection equipment - Section 1: Vibration tests (sinusoidal)	EN 60255-21-1	-
IEC 60270	-	High-voltage test techniques - Partial discharge measurements	EN 60270	-
IEC 60358-1	-	Coupling capacitors and capacitor dividers - Part 1: General rules	EN 60358-1	-
IEC 60358-2	-	Coupling capacitors and capacitor dividers - Part 2: AC or DC single-phase coupling capacitor connected between line and ground for power line carrier-frequency (PLC) application	EN 60358-2	-
IEC 60794-1-1	-	Optical fibre cables - Part 1-1: Generic specification - General	EN 60794-1-1	-
IEC 60794-2	-	Optical fibre cables - Part 2: Indoor cables - Sectional specification	EN 60794-2	-

Publication	Year	Title	EN/HD	Year
IEC 61000-4-29	-	Electromagnetic compatibility (EMC) - Part 4-29: Testing and measurement techniques - Voltage dips, short interruptions and voltage variations on d.c. input power port immunity tests	EN 61000-4-29	-
IEC 61109	-	Insulators for overhead lines - Composite suspension and tension insulators for a.c. systems with a nominal voltage greater than 1 000 V - Definitions, test methods and acceptance criteria	EN 61109	-
IEC 61300-3-4	-	Fibre optic interconnecting devices and passive components - Basic test and measurement procedures - Part 3-4: Examinations and measurements - Attenuation	EN 61300-3-4	-
IEC 61869-3	-	Instrument transformers - Part 3: Additional requirements for inductive voltage transformers	EN 61869-3	-
IEC 61869-5	-	Instrument transformers - Part 5: Additional Requirements for capacitor voltage transformers	EN 61869-5	-
IEC 62271-1	-	High-voltage switchgear and controlgear - Part 1: Common specifications	EN 62271-1	-
IEC 62271-102 + corr. April + corr. May + corr. February	2001 2002 2003 2005	High-voltage switchgear and controlgear - Part 102: Alternating current disconnectors and earthing switches	EN 62271-102 + corr. March + corr. July	2002 2005 2008
IEC 62271-109	2008	High-voltage switchgear and controlgear - Part 109: Alternating-current series capacitor by-pass switches	EN 62271-109	2009

CONTENTS

1 Scope 6
2 Normative references 7
3 Terms and definitions 9
4 Quality requirements and tests 15
  4.1 Overvoltage protector 15
  4.2 Protective spark gap 16
    4.2.1 Purpose 16
    4.2.2 Classification of triggering principles 16
    4.2.3 Tests 16
  4.3 Varistor 21
    4.3.1 Purpose 21
    4.3.2 Classification 21
    4.3.3 Tests 22
  4.4 Bypass switch 26
  4.5 Disconnectors and earthing switches 26
    4.5.1 Purpose 26
    4.5.2 Classification 27
    4.5.3 Tests 27
  4.6 Discharge current-limiting and damping equipment (DCLDE) 28
    4.6.1 Purpose 28
    4.6.2 Classification 28
    4.6.3 Tests 28
  4.7 Voltage transformer 32
    4.7.1 Purpose 32
    4.7.2 Classification 32
    4.7.3 Tests 32
  4.8 Current sensors 33
    4.8.1 Purpose 33
    4.8.2 Classification 33
    4.8.3 Current transformer tests 33
    4.8.4 Electronic transformer tests 33
    4.8.5 Optical transducer tests 33
  4.9 Coupling capacitor 34
    4.9.1 Purpose 34
    4.9.2 Tests 34
  4.10 Signal column 34
    4.10.1 Purpose 34
    4.10.2 Tests 34
  4.11 Fibre optical platform links 34
    4.11.1 Purpose 34
    4.11.2 Tests 35
  4.12 Relay protection, control equipment and platform-to-ground communication equipment 35
    4.12.1 Purpose 35
    4.12.2 Classification 35

4.12.3 Tests 35
5 Guide 36
5.1 General 36
5.2 Specification data for series capacitors 36
5.3 Protective spark gap 37
5.4 Varistor 38
5.4.1 General 38
5.4.2 Varistor voltage-current characteristic 39
5.4.3 Varistor current and voltage waveforms during a system fault 40
5.4.4 Comments on varistor definitions and type tests 41
5.5 Bypass switch 44
5.6 Disconnectors 44
5.7 Discharge current-limiting and damping equipment 44
5.7.1 Purpose of the Discharge Current-Limiting and Damping Equipment 44
5.7.2 Location of the DCLDE 45
5.7.3 Configuration of the DCLDE 47
5.7.4 Miscellaneous comments regarding the DCLDE 48
5.8 Voltage transformer 49
5.9 Current transformer 49
5.10 Relay protection, control equipment and platform-to-ground communication equipment 49
5.11 Protection redundancy 51
5.12 Commissioning tests 52
5.13 Energization tests 52
Bibliography 54

Figure 1 – Typical nomenclature of a series capacitor installation 7
Figure 2 – Classification of overvoltage protection 16
Figure 3 – Illustration of waveforms in recovery voltage test 19
Figure 4 – Typical voltage-current characteristics of one specific metal oxide varistor element (95 mm diameter) 40
Figure 5 – Current, voltage and energy waveforms for a phase-to-earth fault 41
Figure 6 – Conventional location in the bypass branch 45
Figure 7 – DCLDE in series with the capacitor and the parallel connected MOV 45
Figure 8 – DCLDE in series with the capacitor and parallel to the MOV 45
Figure 9 – Only a discharge current-limiting reactor 47
Figure 10 – Discharge current-limiting reactor connected in parallel with a damping resistor. A varistor is connected in series with the resistor 47
Figure 11 – Discharge current-limiting reactor connected in parallel with a damping resistor. A small spark gap is connected in series with the resistor 47
Figure 12 – Current-limiting and damping equipment with and without damping resistor 48

Table 1 – Summary of varistor energy absorption design criteria (example) 38
Table 2 – Overview of typical series capacitor bank protections 51

SERIES CAPACITORS FOR POWER SYSTEMS –

Part 2: Protective equipment for series capacitor banks

1 Scope

This part of IEC 60143 covers protective equipment for series capacitor banks, with a size larger than 10 Mvar per phase. Protective equipment is defined as the main circuit apparatus and ancillary equipment, which are part of a series capacitor installation, but which are external to the capacitor part itself. The recommendations for the capacitor part are given in IEC 60143-1:2004. The protective equipment is mentioned in Clause 3 and 10.6 of IEC 60143-1:2004.

The protective equipment, treated in this standard, comprises the following items listed below:

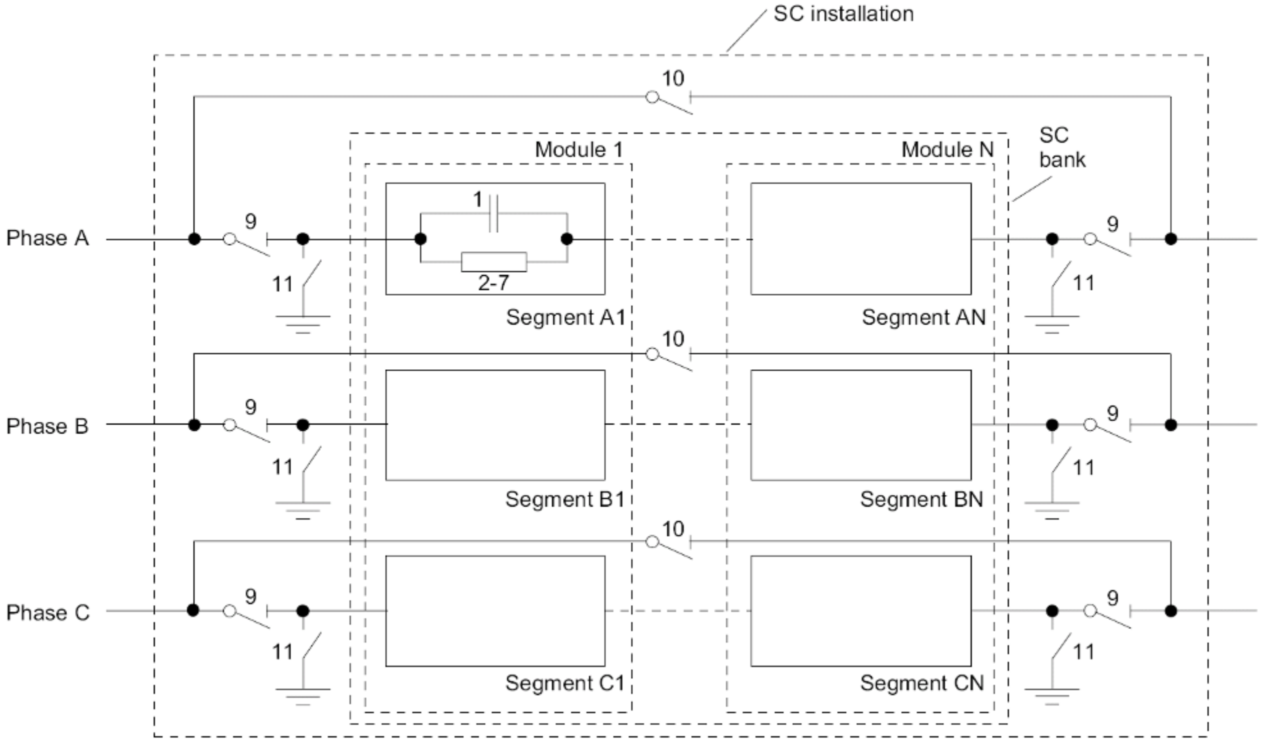
- overvoltage protector,
- protective spark gap,
- varistor,
- bypass switch,
- disconnectors and earthing switches,
- discharge current-limiting and damping equipment,
- voltage transformer,
- current sensors,
- coupling capacitor,
- signal column,
- fibre optical platform links,
- relay protection, control equipment and platform-to-ground communication equipment.

See Figure 1.

Principles involved in the application and operation of series capacitors are given in Clause 5.

Examples of fault scenarios are given in Clause 5.

Examples of protective schemes utilizing different overvoltage protectors are given in 4.1.



IEC 2904/03

Key

1	assembly of capacitor units
2-7	main protective equipment
9	isolating disconnector
10	bypass disconnector
11	earth switch

Figure 1 – Typical nomenclature of a series capacitor installation

NOTE Most series capacitors are configured with a single module, unless the reactance and current requirements result in a voltage across the bank that is impractical for the supplier to achieve with one module. Normally each module has its own bypass switch but a common bypass switch can be used for more than one module. See 10.2.3 of IEC 60143-1:2004 for additional details.

The object of this standard is:

- to formulate uniform rules regarding performance, testing and rating,
- to illustrate different kinds of overvoltage protectors,
- to provide a guide for installation and operation.

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 60044 (all parts), *Instrument transformers*

IEC 60044-1, *Instrument transformers – Part 1: Current transformers*

IEC 60044-8, *Instrument transformers – Part 8: Electronic current transformers*

IEC 60060 (all parts), *High-voltage test techniques*

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

IEC 60076-6:2007, *Power transformers – Part 6: Reactors*

IEC 60099-4:2009, *Surge arresters – Part 4: Metal-oxide surge arresters without gaps for a.c. systems*

IEC 60143-1:2004, *Series capacitors for power systems – Part 1: General*

IEC 60255-5, *Electrical relays – Part 5: Insulation coordination for measuring relays and protection equipment – Requirements and tests*

IEC 60255-21, *Electrical relays – Part 21: Vibration, shock, bump and seismic test on measuring relays and protection equipment – Section One – Vibration tests (sinusoidal)*

IEC 60270, *High-voltage test techniques – Partial discharge measurements*

IEC 60358-1, *Coupling capacitors and capacitor dividers – Part 1: General rules*

IEC 60358-2, *Coupling capacitors and capacitor dividers – Part 2: AC or DC single-phase coupling capacitor connected between line and ground for power line carrier frequency (PLC) application*[1]

IEC 60794-1-1, *Optical fibre cables - Part 1: Generic specification – General*

IEC 60794-2, *Optical fibre cables - Part 2: Indoor cables – Sectional specification*

IEC 61000-4-29, *Electromagnetic compatibility (EMC) – Part 4-29: Testing and measurement techniques – Voltage dips, short interruptions and voltage variations on d.c. input port immunity tests*

IEC 61109, *Insulators for overhead lines – Composite suspension and tension insulators for a.c. systems with a nominal voltage greater than 1 000 V – Definitions, test methods and acceptance criteria*

IEC 61300-3-4, *Fibre optic interconnecting devices and passive components – Basic test and measurement procedures – Part 3-4: Examinations and measurements – Attenuation*

IEC 61869-3, *Instrument transformers – Part 3: Additional requirements for inductive voltage transformers*

IEC 61869-5, *Instrument transformers – Part 5: Additional requirements for capacitor voltage transformers*

IEC 62271-1, *High-voltage switchgear and controlgear – Part 1: Common specifications*

IEC 62271-102:2001, *High-voltage switchgear and controlgear – Part 102: Alternating current disconnectors and earthing switches*

IEC 62271-109:2008, *High-voltage switchgear and controlgear – Part 109: Alternating current series capacitor bypass switches*

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[1] To be published.

NOTE No standard exists for varistors for series capacitors (SC). The relevant tests for series capacitors varistors are therefore dealt with in this standard.

3 Terms and definitions

For the purpose of this document, the following terms and definitions apply:

NOTE The definitions of capacitor parts and accessories in this standard are in accordance with IEC 60143-1:2004.

3.1
back-up gap
supplementary gap which may be set to spark over at a voltage level higher than the protective level of the primary protective device, and which is normally placed in parallel with the primary protective device

3.2
bank protection
general term for all protective equipment for a capacitor bank, or part thereof

3.3
bypass current
current flowing through the bypass switch or spark gap in parallel with the series capacitor

3.4
bypass switch
device such as a switch or a circuit-breaker used in parallel with a series capacitor and its overvoltage protector to shunt line current for a specified time, or continuously

Note 1 to entry: Besides bypassing the capacitor, this device may also have the capability of inserting the capacitor into a circuit and carrying a specified current.

Note 2 to entry: This device shall also have the capability of bypassing the capacitor during specified power system fault conditions. The operation of the device is initiated by the capacitor control, remote control or an operator. The device may be mounted on the platform or on the ground near the platform.

3.5
bypass disconnector
device to short-circuit the series capacitor after it is bypassed by the bypass switch

Note 1 to entry: Installed to keep the line in service while the bypass switch or series capacitor bank are maintained.

3.6
bypass fault current
current flowing through the bypassed series capacitor bank caused by a fault on the line

Note 1 to entry: See also “through fault current” and “partial fault current”.

3.7
bypass gap (protective gap)
gap, or system of gaps, to protect either the capacitor (type K) against overvoltage or the varistor (type M) against overload by carrying load or fault current around the protected parts for a specified time

3.8
bypass interlocking device
device that requires all three poles of the bypass switch to be in the same open or closed position

3.9
capacitor unbalance protection
device to detect unbalance in capacitance between capacitor groups within a phase, such as that caused by blown capacitor fuses or faulted capacitor elements, and to initiate an alarm or the closing of the bypass switch, or both

3.10
capacitor platform
structure that supports the capacitor/rack assemblies and all associated equipment and protective devices, and is supported on insulators compatible with phase-to-earth insulation requirements

3.11
continuous operating voltage
COV
MCOV of a varistor
(maximum) continuous operating voltage, COV is the designated permissible r.m.s. value of power frequency voltage that may be applied continuously between the varistor terminals

Note 1 to entry: COV of the series capacitor varistor is usually equal to the rated voltage of the series capacitor. This definition is different from the definition of COV (U_c) for a ZnO arrester according to IEC 60099-4:2009.

Note 2 to entry: In IEC 60099-4:2009 U_C is used to designate “continuous operating voltage”. However, in this standard, COV is used to designate “continuous operating voltage”. The reason is that U_C is used to designate “capacitor voltage” in the IEC 60143 series.

Note 3 to entry: Consideration of short-time overvoltages of the series capacitor, such as voltages produced by swing currents and overload currents, should be taken into account when the protective level of the varistor is determined.

3.12
discharge current-limiting and damping equipment
reactor or reactor with a parallel connected resistor to limit the current magnitude and frequency and to provide a sufficient damping of the oscillation of the discharge of the capacitors upon operation of the bypass gap or the bypass switch

3.13
external fault
line fault occurring outside the protected line section containing the series capacitor bank

3.14
fault-to-platform protection
device to detect insulation failure on the platform that results in current flowing from normal current-carrying circuit elements to the platform and to initiate the closing of the bypass switch

3.15
forced-triggered bypass gap
bypass gap that is designed to operate on external command on quantities such as MOV energy, current magnitude, or rate of change of such quantities

Note 1 to entry: The sparkover of the gap is initiated by a trigger circuit. After initiation, an arc is established in the power gap. Forced-triggered gaps typically operate only during internal faults.

3.16
insertion
opening of the bypass switch to place the series capacitor in service

3.17
insertion current
r.m.s. current that flows through the series capacitor bank after the bypass switch has opened

Note 1 to entry: This current may be at the specified continuous, overload or swing current magnitudes.

3.18
insertion voltage
peak voltage appearing across the series capacitor bank upon the interruption of the bypass current with the opening of the bypass switch

3.19
internal fault
line fault occurring within the protected line section containing the series capacitor bank

3.20
isolating disconnector
devices to connect or disconnect the bypassed series capacitor from the line

SEE: Figure 1.

3.21
leakage current (of a varistor)
continuous current flowing through the varistor when energized at a specified power-frequency voltage

Note 1 to entry: At COV, and at a varistor element temperature equal to normal ambient temperature, the leakage current is usually mainly capacitive.

3.22
limiting voltage
maximum peak of the power frequency voltage occurring between capacitor unit terminals immediately before or during operation of the overvoltage protector, divided by √2

Note 1 to entry: This voltage appears either during conduction of the varistor or immediately before ignition of the spark gap. See IEC 60143-1:2004 for details.

3.23
loss-of-control power protection
means to initiate the closing of the bypass switch upon the loss of normal control power

3.24
main gap
part of the protective spark gap, that shall carry the fault current during a specified time, comprising two or more heavy-duty electrodes

3.25
minimum reference voltage (of a varistor)
U_{MRef}
minimum permissible reference voltage for a complete varistor or varistor unit measured at a specified temperature, typically (20 ± 15) °C

Note 1 to entry: See Figure 4 and comments in Clause 5.

3.26
module
capacitor switching step
three-phase function unit, that consists of one capacitor segment (possibly several) per phase with provision for interlocked operation of the single-phase bypass switches

SEE: Figure 1.

Note 1 to entry: The bypass switch of a module is normally operated on a three-phase basis. However, in some applications for protection purposes, the bypass switch may be required to temporarily operate on an individual phase basis.

3.27
overvoltage protector
quick-acting device (usually MOV or voltage triggered spark gap) which limits the instantaneous voltage across the series capacitor to a permissible value at power-system faults or other abnormal network conditions

3.28
platform
structure that supports one or more segments of the bank and is supported on insulators compatible with phase-to-ground insulation requirements

3.29
platform control power
energy source(s) available at platform potential for performing operational and control functions

3.30
platform-to-ground communication equipment
devices to transmit operating, control and alarm signals between the platform and ground level, as a result of operation or protective actions

3.31
protective level
U_{pl}
maximum peak of the power frequency voltage appearing across the overvoltage protector during a power system fault

Note 1 to entry: The protective level may be expressed in terms of the actual peak voltage across a segment or in terms of the per unit of the peak of the rated voltage across the capacitor segment. This voltage appears either during conduction of the varistor or immediately before ignition of the spark gap.

3.32
rated short-time energy (of a varistor)
maximum energy the varistor can absorb within a short period of time, without being damaged due to thermal shock

Note 1 to entry: The short time energy is usually expressed in J, kJ or MJ.

3.33
reference current (of a varistor)
peak value of the resistive component of a power-frequency current used to determine the reference voltage of the varistor

Note 1 to entry: The reference current is chosen in the transition area between the leakage current and the conduction current region, typically in the range 1 mA to 20 mA for a single varistor column (see Figure 4).

3.34
reference voltage (of a varistor)
peak value of power-frequency voltage divided by $\sqrt{2}$ measured at the reference current of the varistor

Note 1 to entry: Measurement of the reference voltage is necessary for the selection of correct test samples in the type testing.

3.35
reinsertion
restoration of line current through the series capacitor from the bypass path

3.36
reinsertion current
transient current flowing through the series capacitor after the opening of the bypass path during reinsertion

3.37
reinsertion voltage
transient voltage appearing across the series capacitor after the opening of the bypass path during reinsertion

3.38
residual voltage (of a capacitor)
voltage remaining between terminals of a capacitor at a given time following disconnection of the supply

3.39
residual voltage (of a varistor)
peak value of voltage that appears between the terminals of a varistor during passage of current

3.40
section (of a varistor)
complete, suitably assembled part of a varistor necessary to represent the behaviour of a complete varistor with respect to a particular test

Note 1 to entry: A section of a varistor is not necessarily a unit of a varistor.

3.41
segment
single-phase assembly of groups of capacitors which has its own voltage-limiting devices and relays to protect the capacitors from overvoltages and overloads

SEE: Figure 1.

3.42
subharmonic protection
device that detects subharmonic current of specified frequency and duration and initiates an alarm signal or corrective action, usually bypassing the capacitor bank

3.43
sustained bypass current protection
means to detect prolonged current flow through the overvoltage protector and to initiate closing of the bypass switch

3.44
sustained overload protection
device that detects capacitor voltage above rating but below the operating level of the overvoltage protector and initiates an alarm signal or corrective action

3.45
swing current
highest value of the oscillatory portion of the current during the transient period following a large disturbance

Note 1 to entry: The swing current is measured in A r.m.s. and is characterized by a specified amplitude, frequency and decay time-constant. The swing current is propagated from electromechanical oscillations of the synchronous machines in the actual power system. The frequency of these oscillations is typically in the range 0,5 Hz to 2 Hz.

3.46
temporary overvoltage
temporary power-frequency voltage across the capacitor higher than the continuous rated voltage U_N of the series capacitor

3.47
thermal section (of a varistor)
section assembled in a suitable housing with the same heat transfer capability as the actual varistor

3.48
thermal runaway (of a varistor)
varistor condition when the sustained power losses of the varistor elements steadily increase due to increased temperature, while the varistor is energized

Note 1 to entry: The heat generated by the power losses of the varistor elements exceeds the cooling capability of the varistor housing, which causes further temperature rise and finally leads to a varistor failure if the process is not interrupted, e.g. the voltage is decreased or the varistor is bypassed.

3.49
thermal stability (of a varistor)
varistor condition after a temperature rise, due to an energy discharge and/or temporary overvoltage, when the varistor is energized at its COV under specified ambient conditions and the temperature of the varistor elements decreases with time

Note 1 to entry: This is the opposite of a "thermal runaway".

3.50
through fault current
partial fault current
component of the fault current that flows through the SC bank and not the total fault current (bus fault current)

Note 1 to entry: The component of the fault current which flows through the SC bank is called “through fault current” or “partial fault current”.

Note 2 to entry: See IEC 60909.

3.51
trigger circuit
device to ignite the main gap at a specified voltage level or by external command

3.52
varistor
metal oxide varistor
non-linear resistor
device to act as overvoltage protection of the capacitor consisting of resistors with a non-linear voltage-dependent resistance (normally metal-oxide varistors)

Note 1 to entry: The term varistor is used when it is not necessary to distinguish between varistor element, varistor unit or varistor group.

3.53
varistor element
metal-oxide varistor element
dense ceramic cylindrical body, with metallized parallel end surfaces, constituting the smallest active component used in larger varistor assemblies

3.54
varistor column
metal-oxide varistor column
column comprising "n" varistor elements connected in series

3.55
varistor unit
metal-oxide varistor unit

assembly of varistor elements, comprising one or several varistor columns mounted in a suitable housing

3.56
varistor group
metal-oxide varistor group

single-phase group of varistor units connected in parallel and/or in series, carefully matched together, to form an overvoltage-limiting device for a series capacitor

3.57
varistor coordinating current

magnitude of the maximum peak of power frequency varistor current associated with the protective level

Note 1 to entry: The varistor coordinating current waveform is considered to have a virtual front time of 30 μs to 50 μs. The tail of the waveform is not significant in establishing the protective level.

3.58
voltage triggered bypass gap

bypass gap that is designed to spark over on the voltage that appears across the gap terminals

Note 1 to entry: The spark over of the gap is normally initiated by a trigger circuit set at a specified voltage level. A voltage-triggered bypass gap may be used for the primary protection of the capacitor and may spark over during external as well as internal faults.

4 Quality requirements and tests

4.1 Overvoltage protector

The purpose and classification of an overvoltage protector are as follows.

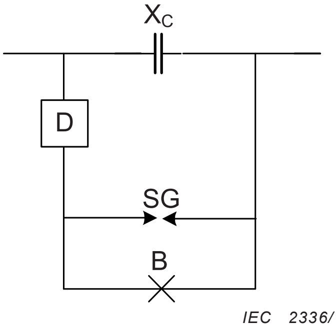
a) Purpose

The overvoltage protector is a quick-acting device which limits the instantaneous voltage across the series capacitor to a permissible value when that value would otherwise be exceeded as a result of a power-system fault or other abnormal network condition.

b) Classification

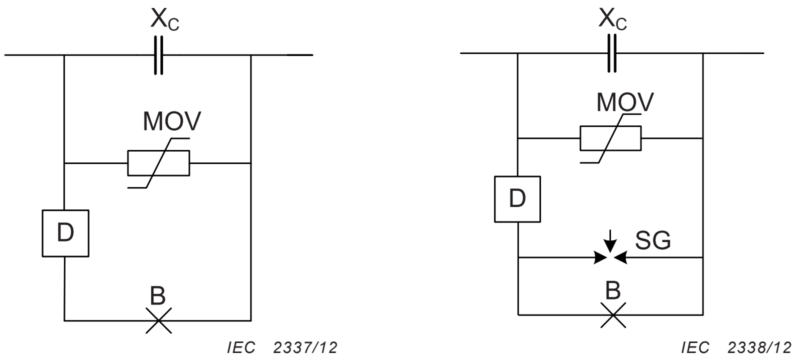
Three common alternatives of overvoltage protectors are listed below:

- single-protective spark gap (type K1). See Figure 2a).
- varistor (gapless) (type M1). See Figure 2b).
- varistor with bypass gap (type M2). See Figure 2c).



IEC 2336/12

2a) Single gap (type K1)



2b) MOV (type M1)

2c) MOV + bypass gap (type M2)

Key

X_C	Capacitor
SG	Spark gap
D	Current-limiting damping circuit
B	Bypass switch

Figure 2 – Classification of overvoltage protection

4.2 Protective spark gap

4.2.1 Purpose

The purpose of the protective spark gap is to act as overvoltage protector for the capacitor (protection scheme K1) or as protection for the varistor (protection scheme M2), see also 5.3.

4.2.2 Classification of triggering principles

The protective spark gaps can be classified as follows:

- self-triggering (used in type K1)
- forced triggering (used in type M2)

4.2.3 Tests

4.2.3.1 General

For practical reasons, certain tests could be performed on the main gap and trigger circuit separately.

For forced triggered spark gaps, a type test on the total gap assembly is required. The test shall verify that the overvoltage protector comprising the main gap, trigger circuit and varistor overload protection operate correctly. See 4.2.3.4.2 below.

4.2.3.2 Main gap

4.2.3.2.1 Routine tests

Routine tests are as follows.

a) dimensional inspection;
b) routine test and inspection of spark-gap components.

Examples of components are electrodes, porcelain housings, grading components, bushings and support insulators, according to relevant IEC standards.

4.2.3.2.2 Type tests

Type tests are as follows.

a) Fault current test

A fault current test shall be performed to demonstrate that the main gap will withstand the rated power frequency bypass through fault current. The magnitude of the test current shall correspond to the maximum specified bypass through fault current (partial fault current) at the location of the series capacitor. The first peak of the applied test current shall correspond to the specified short-circuit current value including peak asymmetrical.

The duration of the test current shall conform with the maximum specified duration of the through fault current at the series capacitor bank location. Fault scenarios and maximum back-up line circuit breaker fault-clearing time shall be taken into account. Typical fault scenarios are given in Clause 5.

The test shall be performed once.

Criteria for acceptance of the test:

Self-triggered spark gap

No significant mechanical damage or excessive erosion, nor significant change in spark over voltage of the gap shall occur. This shall be verified by a power frequency spark over voltage test. The power frequency spark over voltage test shall be performed before and after the bypass making current test. The mean value of at least 10 subsequent tests shall be calculated and the ratio of single and mean values shall not exceed ±10 %.

Forced triggered spark gap

No significant mechanical damage or excessive erosion, nor significant change in spark over voltage of the gap shall occur. This shall be verified by:

1) A power frequency voltage withstand test with a voltage peak corresponding to 1,2 times the protective level voltage. The voltage wave form shall be purely sinusoidal with a duration of 60 seconds. This test is not needed if the bypass making current test is performed on the same test object after the fault current test. If the spark gap design contains auxiliary gaps the test is limited to the main gap only. Auxiliary gaps shall not be mounted to avoid self-triggering.
2) Functional test to verify correct triggering within claimed limits.

b) Bypass making current test

A test shall be performed to demonstrate that the main gap will withstand the combination of the capacitor discharge current and the power frequency fault current the gap will be exposed to during normal bypassing of the capacitor.

The magnitude of test current first peak shall be equal to the simulated maximum instantaneous sum of the capacitor discharge current at the maximum protective level and the power frequency fault current including offset. The simulation shall be performed on a power system model of the actual power system including a model of the actual series capacitor.

For each application the current peak shall not be less than 95 % of the required magnitude and the average of the peaks for all 20 applications shall not be less than the required magnitude. For each application the mean value of the symmetrical current during the specified test duration shall not be less than the maximum symmetrical series capacitor through the fault current.

The duration of the test current shall conform with the normal line circuit breaker fault clearing time.

The test current may be either a combination of a 50 Hz (60 Hz) current and a high frequency capacitor discharge current or a pure 50 Hz (60 Hz) current.

- If a combined test current is used then the damping of the capacitor discharge current shall correspond to the minimum expected damping in installation.
- If a pure 50 Hz (60 Hz) current is used, then the required magnitude of the first peak may be obtained by using an unsymmetrical current.

The test shall be performed 20 times.

Criteria for acceptance of the test:

Self-triggered spark gap

No significant mechanical damage or excessive erosion, nor significant change in spark over voltage of the gap shall occur. This shall be verified by a power frequency spark over voltage test. The power frequency spark over voltage test shall be performed before and after the bypass making current test. The mean value of at least 10 subsequent tests shall be calculated and the ratio between single and mean values shall not exceed ±10 %.

Forced triggered spark gap

No significant mechanical damage or excessive erosion, nor significant change in spark over voltage of the gap shall occur. This shall be verified by:

1) Either a recovery voltage test or a power frequency voltage withstand test with a peak corresponding to 1,2 times the protective level voltage. The voltage wave form shall be purely sinusoidal with a duration of 60 seconds. If the spark gap design contains auxiliary gaps the test is limited to the main gap only. Auxiliary gaps shall not be mounted to avoid self-triggering.
2) Functional test to verify correct triggering within claimed limits.

c) Recovery voltage test (forced triggered gaps only)

The test shall demonstrate that the gap has sufficient recovery voltage withstand taking into account the trigger circuit, to allow the capacitor to be reinserted after a successful line auto reclosure.

The test shall be performed on a test object that has been exposed to at least 10 applications in the bypass making current test.

The gap shall be exposed to the current described in the bypass making current test, followed by a test voltage which is applied, after the current is disconnected, for a time equal to the specified series capacitor reinsertion time.

The prospective 50 Hz (60 Hz) test voltage shall have a peak value of 1,5 times the protective level voltage of the series capacitor. The actual voltage across the gap shall be limited to not less than the protective level voltage by a varistor giving the appropriate voltage wave form (see Figure 3).

The duration of the test voltage shall be 100 ms.

Criteria for acceptance of the test: 1 out of 1 or 2 out of 3 successful applications.

In order to verify different combinations of protective levels and reinsertion times, the test may be combined with the bypass making current test. However, at least 10 applications in the bypass making current test shall be performed before verification of the recovery voltage.

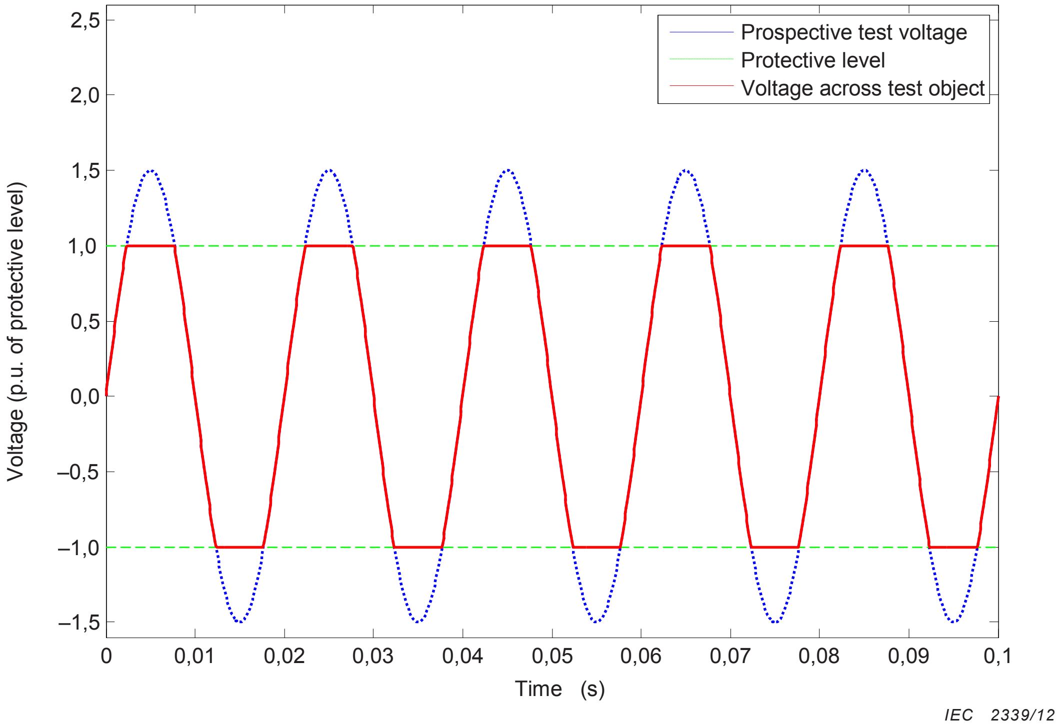


Figure 3 – Illustration of waveforms in recovery voltage test

d) Recovery voltage test (self-triggered gaps only)

The test shall demonstrate that the gap has sufficient recovery voltage withstand, taking into account the trigger circuit, to allow the capacitor to be reinserted after a successful line auto reclosure.

The test shall be performed on a test object that has been exposed to at least 10 applications in the bypass making current test.

The gap shall be exposed to the current described in the bypass making current test, followed by a test voltage which is applied when a time equal to the specified series capacitor reinsertion time has passed after the test current.

The 50 Hz (60 Hz) prospective test voltage shall have a peak value corresponding to the maximum expected series capacitor voltage (including offset) at reinsertion.

The test shall be carried out once.

Criteria for acceptance of the test: 1 out of 1 or 2 out of 3 successful applications.

e) Mechanical endurance test

This test is only applicable for designs that contain moving parts. The test shall be made at the ambient air temperature of the test location. The ambient air temperature shall be recorded in the test report. Auxiliary equipment forming part of the operating devices shall be included.

The test shall consist of 500 operating sequences where each sequence consists of a close operation followed by an open operation.

The operating times and the contact resistance (if applicable) shall be recorded before and after the test.

Criteria for acceptance of the test:

- The contact resistance (if applicable) measured before and after the test shall not exceed a value claimed by the manufacturer.
- The closing time, measured at the first and last application shall not exceed a value claimed by the manufacturer.

4.2.3.3 Trigger circuit

4.2.3.3.1 Self-triggered circuit routine test

Routine tests and type tests for a trigger circuit are as follows.

a) Power-frequency spark over voltage test or power-frequency reference voltage test, whichever is applicable.
b) Measurement of grading current or leakage current (if applicable).
c) Check of internal corona (if applicable).
d) For trigger units with sealed housings a leakage test shall be made on each unit by any sensitive method adopted by the manufacturer.

4.2.3.3.2 Self-triggered circuit type tests

A routine test shall be performed before the type test is carried out.

a) Spark over voltage test

   The test shall demonstrate that spark over occurs within the specified tolerance range.

b) Environmental test

   The test shall demonstrate that spark-over of the main gap occurs within the specified tolerance range, for the specified ambient conditions, such as temperature, air pressure, etc. (see IEC 60060-1).

4.2.3.3.3 Forced-triggered circuit routine test

Routine tests for a forced-triggered circuit are as follows.

a) Functional test (can be performed at commissioning).
b) Spark over voltage test of precision gap (if applicable).
c) Measurement of grading current or leakage current (if applicable).
d) Check of internal corona (if applicable).
e) For trigger units with sealed housings a leakage test shall be made on each unit by any sensitive method adopted by the manufacturer.
f) Measurement of component values.

4.2.3.3.4 Forced-triggered circuit type test

See 4.2.3.4.2.

4.2.3.4 Special tests (type test)

4.2.3.4.1 Complete gap test of self-triggered gap (optional)

The test shall verify that the complete gap, comprising the main gap and the trigger gap operates correctly. The test circuit shall comprise the complete gap. Oscillographic recordings shall be made.

4.2.3.4.2 Complete gap test of forced-triggered gap

The complete test sequence is as follows.

a) Test of total bypass time at 0,95 times the protective level

   The purpose of the test is to verify the total delay time from the instant when the varistor current reaches the high current threshold until gap conduction is not longer than claimed by the manufacturer. The test circuit shall comprise the main gap, trigger circuit and varistor overload protection.

A d.c. voltage with a magnitude not exceeding 0,95 times the protective level voltage is applied across the equipment. A bypass order is generated by subjecting the varistor overload protection to a current with a magnitude (considering CT ratios) that exceeds the threshold. The test shall be performed with any redundant system disabled.

The test shall be performed 5 times for both polarities of the applied d.c. voltage.

Criteria for acceptance of the test: Triggering of the main gap shall occur for all applications and the maximum delay time shall not exceed the time claimed by the manufacturer.

b) Verification of triggering and bypass time at minimum voltage

The purpose of the test is to verify the minimum voltage for triggering and the associated delay time from the instant a bypass is ordered until gap conduction. The test circuit shall comprise the main gap and trigger circuit.

An a.c. voltage with a crest value equal to the guaranteed minimum voltage for triggering is applied across the equipment. The test shall be performed with any redundant system disabled. The bypass order shall be generated in a cyclic manner at phase position 0, 30, 60 … 330 with respect to the applied voltage.

Criteria for acceptance of the test: Bypass for all applications shall occur within the time specified by the manufacturer.

NOTE 1 This test is only applicable if the gap is able to bypass the series capacitor via an external bypass order, for example to mitigate high TRV on line circuit breakers.

c) Power frequency voltage withstand test

The test shall demonstrate that the complete gap including trigger circuits has sufficient voltage strength to withstand external faults without bypassing the series capacitor under the specified ambient conditions, such as temperature, air pressure, etc.

The test circuit shall comprise the complete overvoltage protector consisting of the main gap, the forced trigger circuit, and a varistor.

The gap shall be exposed to a 50 Hz (60 Hz) voltage that is limited by a varistor. The prospective test voltage shall have a peak value of at least 1,5 times the protective level voltage. The varistor shall limit the voltage across the equipment to the protective level voltage.

The duration of the test voltage shall be 0,5 seconds.

The test shall be carried out once.

NOTE 2 The test is applicable for forced triggered gaps only.

NOTE 3 The test voltage and the varistor protective level are adjusted to consider the influence of ambient conditions such as air pressure, altitude etc.

NOTE 4 The test duration is based on the transmission line fault clearing time and limited to 0,5 seconds in order to avoid excessive varistor energy.

4.3 Varistor

4.3.1 Purpose

The main purpose of the varistor is to act as overvoltage protector for the capacitor (type M1 and M2).

4.3.2 Classification

The varistors can be classified as follows, with regard to the working principle:

- varistor without a bypass gap (type M1);
- varistor with a bypass gap (type M2).

The tests for the two types are the same.

4.3.3 Tests

4.3.3.1 Routine tests

4.3.3.1.1 General

The routine tests are not described in detail, since many different test methods can ensure the same energy capability, protection performance and service reliability. The test programme given here, therefore, shall be seen as an example.

4.3.3.1.2 Energy withstand test

All varistor elements shall be subjected to an energy withstand test including repeated sequences of energy injections with cooling time in between. Each test sequence shall expose the varistor element to an energy injection higher than or equal to the rated short-time energy.

4.3.3.1.3 Residual voltage test

In order to verify that a given protective level is fulfilled a residual voltage test shall be performed on all individual varistor elements or complete assembled varistor units. The test should preferably be performed with a current amplitude of the same order of magnitude as the maximum prospective fault current for the varistor taking the current scale factor, n_{c}, into account. The waveshape may have any front time from μs to ms.

The protective level for the varistor group at the actual current waveshape and amplitude is then determined by the type test and the ratio between the residual voltage at routine test current and the residual voltage of the type test sections at the same current wave.

4.3.3.1.4 Leakage test

Completely assembled units with sealed housings shall be subjected to a suitable leakage test.

4.3.3.1.5 Reference voltage test

The reference voltage shall be measured on each varistor unit. The measured values shall be within a range specified by the manufacturer.

4.3.3.1.6 Measurement of power losses

The power losses shall be measured at a power-frequency voltage equal to the COV for each varistor unit and the power losses shall be within limits specified by the manufacturer.

A power-frequency voltage equal to the COV for each varistor unit shall be applied and the leakage current checked to be within guaranteed data. (At this voltage level the leakage current is almost purely capacitive.)

4.3.3.1.7 Partial discharge test

A satisfactory absence from internal partial discharges shall be demonstrated in all assembled varistor units by a sensitive method. The test shall be performed with an applied power-frequency voltage equal to at least 1,05 times the COV of the varistor unit. The measured value for the internal partial discharge shall not exceed 10 pC.

4.3.3.1.8 Current-sharing test

A maximum accepted deviation in current sharing between parallel columns of varistor elements within a complete varistor has to be specified by the manufacturer. Further, the manufacturer shall present the routine test procedure to demonstrate that the current sharing will be within given tolerances.

4.3.3.2 Type tests

4.3.3.2.1 Test samples

Unless otherwise stated all type tests shall be performed on three sections of new varistor elements which have not been subjected to any previous tests except for evaluation purposes.

The scale factors in voltage, current and energy used to determine representative stresses to be applied on the test samples are further described in Clause 5.

4.3.3.2.2 Residual voltage test

The purpose of the measurement of residual voltage is to obtain the maximum residual voltage for a given design for all specified currents. This is derived from type test data and from the maximum residual voltage at an impulse current used for routine tests as specified and published by the manufacturer.

The maximum residual voltage of a given varistor design for any current amplitude is calculated from the residual voltage of sections tested during type tests multiplied by a specific scale factor. This scale factor is equal to the ratio of the declared maximum residual voltage, as checked during routine tests, to the measured residual voltage of the sections at the same current and waveshape.

4.3.3.2.3 Switching impulse residual voltage test

The test shall be performed on sections with a reference voltage of at least 3 kV. The sections shall consist of one single column of varistor elements, which need not be encapsulated in any form and shall be exposed to open air at an ambient temperature of (20 ± 15) °C.

The sections are subjected to a switching current impulse as per IEC 60099-4:2009 with a virtual front time greater than 30 µs but less than 100 µs and a virtual time to half-value on the tail of roughly twice the virtual front time. The current amplitude is chosen to approximately 0,5, 1,0 and 1,5 times the maximum prospective current of the varistor group divided by the current scale factor n_{c}. The residual voltage for the complete varistor is determined according to 4.3.3.2.2 for the section with highest residual voltage.

If the current magnitudes are the same and the virtual front time of the routine test waveform within 30 µs to 100 µs the routine test is sufficient and the type test is not required.

4.3.3.2.4 Accelerated ageing procedure

The test shall be performed in accordance with 8.5.2 of IEC 60099-4:2009 to determine if a correction factor has to be applied to continuous operating voltage COV in the energy withstand and power-frequency voltage stability test of 4.3.3.2.6.

4.3.3.2.5 Repeated energy withstand test

The purpose of this test is to verify that the varistor can withstand the current and energy duties for which it is designed, keeping any possible changes of the characteristic within tolerable limits.

The test shall be performed on varistor elements of each height and diameter of a design.

The energy withstand test shall be made on three new samples of sections which have not been subjected previously to any test except that specified above for evaluation purposes.

The sections shall consist of individual varistor elements either in still air or in the actual surrounding medium of the design (the choice is up to the manufacturer) and shall be exposed to open air at an ambient temperature of (20 ± 15) °C.

A long-duration current impulse of approximately (2 to 4) ms virtual duration shall be applied to the section giving an energy injection equal to maximum prescribed varistor energy taking into account the energy scale factor, n_W.

The test shall be performed 20 times with a time interval between operations sufficiently long to permit the section to cool to ambient temperature.

Prior to the repeated energy withstand test the following measurements shall be made:

- reference voltage measurement;
- residual voltage measurement with current amplitude 500 A and waveshape 30/60 μs.

These measurements shall be repeated after the test and it shall be demonstrated that no significant changes have occurred. The reference voltage shall not have decreased by more than 5 % and the residual voltage shall not have changed by more than 5 %.

Furthermore there shall be no indication of mechanical damage (puncture, flashover or cracking).

NOTE Work performed and published by Cigré WG A3.17 has shown that the energy capability of varistor elements for events in the time range 200 μs to 10 s practically is independent of the application time. Therefore, in order to simplify the test procedure, rectangular current impulses have been selected for the energy application.

4.3.3.2.6 Energy withstand and power-frequency voltage stability test (thermal recovery test)

The purpose of this test is to verify that the varistor is able to withstand the maximum specified energy, followed by a possible temporary overvoltage sequence and thereafter show thermal stability energized at COV and at the highest ambient temperature.

The test shall be made on three new samples of sections which have not been subjected previously to any test except that specified above for evaluation purposes. The sections shall consist of varistor elements encapsulated in such a way that the section represents a true thermal model of the varistor group.

If the varistor group contains units with several parallel columns of varistor elements the prorated sections shall have the same number of parallel columns.

Further, if the reference voltage in the repeated energy withstand test in 4.3.3.2.5 has decreased for any of the test samples, the same varistor elements shall be used in this test. Otherwise new varistor elements shall be selected.

Prior to the test the following measurements shall be made:

- reference voltage measurement;
- residual voltage measurement with current amplitude 500 A and waveshape 30/60 μs.

These measurements shall be repeated after the test and it shall be demonstrated that no significant changes have occurred. The reference voltage shall not have decreased by more than 5 % and the residual voltage shall not have changed by more than 5 %.

The energy withstand and power-frequency voltage stability test starts with a preheating of the test sections to (60 ± 3) °C in an oven.

Within 5 min after removing the test section from the heat source the test shall be performed with the start temperature of the active parts at (60 ± 3) °C, measured by a temperature sensor. The energy shall be injected within 3 min by one or more long-duration current impulses with (2 to 4) ms virtual duration (number not specified). The current amplitude and number of the impulses shall be chosen such that the total energy discharged is not less than the maximum prescribed varistor energy taking into account the energy scale factor, n_W.

As soon as possible and in less than 5 s after the energy injection a power-frequency voltage equal to continuous operating voltage of the varistor group taking into account the voltage scale factor, n_V, shall be applied and maintained for 30 min. During the 30 min thermal stability shall be demonstrated i.e. resistive component of the leakage current and/or the temperature of the varistor elements and/or the power losses shall be measured and show a steady decrease.

If a temporary overvoltage sequence is specified for the varistor group after an energy absorption, the same or equivalent sequence shall be applied to the test sections taking the voltage scale factor into account.

If the temporary overvoltage is very high, the temperature may increase during this period. However, when the voltage is reduced to continuous operating voltage or a level which can be maintained during hours thermal stability shall be proved. For example after a fault sequence the capacitor voltage can be 35 % higher than continuous operating voltage for 30 min followed by an overload of 17 % for an additional 24 h. The varistor shall then be thermally stable after maximum energy and 35 % overload during 30 min. i.e. the varistor shall be able to cool down when subjected to the 24 h overload voltage.

NOTE 1 The COV can, if necessary, be adjusted according to the result of the accelerated ageing procedure of 4.3.3.2.4.

NOTE 2 If the same varistor elements as in the energy withstand test are used due to decreased reference voltage the voltage scale factor will be calculated from the initial measurement of reference voltage i.e. before the energy withstand test.

4.3.3.2.7 Verification of thermal sections

The test shall be performed in accordance with Annex B of IEC 60099-4:2009. In order to prove that the section is a true thermal model of the varistor group, the cooling curve of the section shall be compared to the cooling curve of the longest unit in the varistor.

The cooling curves shall be determined either as mean value or by checking the temperature of single varistor elements.

If it is chosen to check the temperature of one single varistor element, an element located between 1/2 to 1/3 of the unit length from the top shall be chosen.

Finally to prove thermal equivalency, the test section shall for all instants during the cooling period have a higher or equal temperature than the varistor unit.

NOTE Differences between the cooling curve of the thermal model and that of the real varistor (faster cooling of the thermal model) during the first 15 minutes are acceptable but can be compensated by a higher start temperature in the tests. The increase of the start temperature corresponds to the biggest temperature difference between the thermal model and the real varistor during the first 15 minutes.

4.3.3.2.8 Short-circuit test

The test is applicable for all varistors, i.e. also for designs that do not have a pressure relief device. In IEC 60099-4:2009 short-circuit (pressure relief) test procedures valid for conventional arresters are prescribed. The intention of these tests is to show that an internal short-circuit of the arrester will not cause explosive shattering of the housing which might cause accidental damage to surrounding or personnel equipment.

Since the varistor is connected across the capacitor bank, due regard has to be taken, that the test also covers the discharge of the capacitor bank from the protective level, i.e. that the capacitor will discharge through the varistor.

In the absence of an alternative procedure, pressure-relief tests with both high and low current shall be performed as per IEC 60099-4:2009.

For varistor units of the same type differing from each other only in insulator length, a successful test on the longest unit is regarded as valid also for all the shorter ones.

4.4 Bypass switch

The purpose of the bypass switch is to bypass and insert the series capacitor. Capacitor insertion is accomplished by opening of the bypass switch. It may also be used for automatic bypassing in case of faults and disturbances. Due regard shall be taken to the high-frequency inrush current when the capacitor is being bypassed. In some cases the bypass switch is connected in series with a protective spark gap, and used for insertion only (type K with two gaps). See IEC 60143-1:2004, 5.1.3.The bypass switch shall fulfil the requirements in IEC 62271-109:2008.

It is important to observe, that the breaking element(s) shall be rated to switch the actual capacitor segment, while the insulation to earth shall correspond to that of the power system.

The operation cycle shall be reversed, for example (O)-C-O-C and it is recommended that the bypass switch be equipped with two closing coils.

With regard to the required mechanical duty, IEC 62271-109:2008 defines two classes.

- Bypass switch class M1: Bypass switch with normal mechanical endurance (mechanically type tested for 2 000 operating sequences). This is the normal case.
- Bypass switch class M2: Frequently operated bypass switch for special service requirements and designed so as to require only limited maintenance as demonstrated by specific type tests (bypass switch with extended mechanical endurance, mechanically type tested for 10 000 operating sequences). This type of bypass switch is normally used on multi-segmented series capacitors where the control of the capacitor reactance is a frequent duty. This is the extended case.

4.5 Disconnectors and earthing switches

4.5.1 Purpose

4.5.1.1 Bypass disconnector

The purpose of the bypass disconnector is to bypass the series capacitor bank, provided that the series capacitor bank is already bypassed by the bypass switch. The purpose of the bypass disconnector is also to connect the series capacitor bank into the transmission system by opening the bypass disconnector. The isolating disconnectors and the bypass switch shall be closed when opening the bypass disconnector.

The opening of the bypass disconnector is difficult especially if the current-limiting damping circuit is connected in parallel with the capacitor and the reactor´s inductance is high, see 5.7.

4.5.1.2 Isolating disconnector

The purpose of the isolating disconnector is to deliberately disconnect the series capacitor bank from the line.

Both bypass and isolating disconnectors enable the disconnection of the series capacitor bank without interrupting the operation of the line, for example at maintenance of the SC bank.

4.5.2 Classification

Disconnectors can be classified in different ways.

a) With regard to their operating principle: centre-break, double-break, horizontal break, vertical break, pantograph, semi-pantograph, etc.

b) With regard to operating mechanism: motor-driven, pneumatic, hydraulic, etc.

4.5.3 Tests

4.5.3.1 General

The following tests shall be performed. Coordination shall be made with IEC 62271-102:2001 and IEC 62271-1.

4.5.3.2 Routine tests

The routine test sequence is as follows:

a) Dielectric test on the main circuit

7.1 of IEC 62271-102:2001 is applicable.

b) Dielectric test on auxiliary and control circuits

7.2 of IEC 62271-102:2001 is applicable.

c) Measurement of the resistance of the main circuit

7.3 of IEC 62271-102:2001 is applicable.

d) Tightness test

7.4 of IEC 62271-102:2001 is applicable.

e) Design and visual checks

7.5 of IEC 62271-102:2001 is applicable.

f) Mechanical operating tests

7.101 of IEC 62271-102:2001 is applicable.

4.5.3.3 Type tests

6.1 of IEC 62271-102:2001 is applicable.

a) Dielectric tests
6.2 of IEC 62271-102:2001 is applicable.

b) Radio interference voltage (r.i.v.) tests
6.3 of IEC 62271-102:2001 is applicable.

c) Measurement of the resistance of circuits
6.4 of IEC 62271-102:2001 is applicable.

d) Temperature-rise tests
6.5 of IEC 62271-102:2001 is applicable.

e) Short-time withstand current and peak withstand current tests

   6.6 of IEC 62271-102:2001 is applicable.

f) Verification of the protection

   6.7 of IEC 62271-102:2001 is applicable.

g) Tightness test

   6.8 of IEC 62271-102:2001 is applicable.

h) Electromagnetic compatibility test (EMC)

   6.9 of IEC 62271-102:2001 is applicable.

i) Test to prove the short-circuit making performance of earthing switches

   6.101 of IEC 62271-102:2001 is applicable.

j) Operating and mechanical endurance tests

   6.102 of IEC 62271-102:2001 is applicable.

k) Operation under severe ice conditions

   This test may only be made on special request by the user. 6.103 of IEC 62271-102:2001 is applicable.

l) Operation at the temperature limits

   6.104 of IEC 62271-102:2001 is applicable.

m) Test to verify the proper functioning of the position indicating device

   6.105 of IEC 62271-102:2001 is applicable.

n) Bus-transfer current switching tests

   6.106 and Annex B of IEC 62271-102:2001 are applicable.

o) Induced current switching tests

   6.107 and Annex C of IEC 62271-102:2001 are applicable.

4.6 Discharge current-limiting and damping equipment (DCLDE)

4.6.1 Purpose

The purpose of the discharge current-limiting and damping equipment is to limit the current magnitude and frequency and to provide a sufficient damping of the capacitor discharge oscillations upon operation of the protective spark gap or closing of the bypass switch.

4.6.2 Classification

The damping equipment consists of a discharge current-limiting reactor and in some applications it may also include a damping resistor connected in parallel with the reactor. The reactor is almost exclusively of a dry type air core design. The resistor is also almost exclusively of a dry type design. The damping resistor may be connected continuously into the circuit or may be connected only during the operation of the bypass device.

The discharge current-limiting and damping equipment may be located in the bypass branch of the capacitor bank or in the capacitor branch. See 5.7.

4.6.3 Tests

4.6.3.1 General

Tests shall be performed on the reactor and the resistor separately.

4.6.3.2 Discharge current-limiting reactor

4.6.3.2.1 General

The routine, type and optional tests for the discharge current-limiting reactor shall be carried out in accordance with Clause 9 of the reactor standard IEC 60076-6:2007.

4.6.3.2.2 Routine tests

The following routine tests shall be performed:

a) Measurement of winding resistance.

   The d.c. and a.c. resistance (at 50 Hz or 60 Hz) shall be measured. IEC 60076-6:2007, 9.10.2 and IEC 60076-1 are applicable

b) Measurement of inductance

   IEC 60076-6:2007, 9.10.5 is applicable

c) Measurement of loss and quality factor

   IEC 60076-6:2007, 9.10.6 is applicable

d) Winding overvoltage test

   IEC 60076-6:2007, 9.10.7 is applicable. The test shall be performed three (3) times.

The impulse voltage test value shall be determined taking the protective voltage level into account. See IEC 60143-1:2004, 6.1.3.4.

A power frequency withstand voltage test can normally not be carried out on a discharge current-limiting reactor due to the low impedance of the reactor. A corresponding impulse voltage test is therefore used. Due to the low inductance value of the discharge current-limiting reactor, the wave shape of the impulse may be shorter than 1,2/50 μs and the wave may be distorted. This should be accepted.

4.6.3.2.3 Mandatory type tests

Mandatory type tests are as follows.

a) Short-circuit current test

   A short-circuit current test shall be performed to demonstrate that the discharge current-limiting reactor will withstand the rated power frequency bypass through fault current (existing/future fault current). The magnitude of the test current shall correspond to the maximum specified bypass through fault current (partial fault current) at the location of the series capacitor. The first peak of the applied test current shall correspond to the specified mechanical short-circuit current value.

   The duration of the test current shall conform with the maximum specified duration of the through fault current at the series capacitor bank location. Fault scenarios and maximum back-up line circuit breaker fault-clearing time shall be taken into account. Typical fault scenarios are given in Clause 5. The test shall be performed twice.

   IEC 60076-6:2007, 9.10.10 is applicable.

b) Bypass making current test

   A bypass making current test shall be performed to demonstrate that the discharge current limiting reactor will withstand the combination of the capacitor discharge currents and the power frequency fault currents the reactor will be exposed to during bypassing of the capacitor.

   The magnitude of the test current shall be the simulated maximum instantaneous sum of the capacitor discharge current at maximum protective level and the power frequency fault current including offset. The simulation shall be performed on a power system model of the actual power system including a model of the actual SC.

The frequency of the test current shall correspond to the discharge current frequency of the actual series capacitor bank. However, a 50 Hz or 60 Hz half-cycle current wave with the same amplitude supplied from a short- circuit generator may also be used.

The duration of the test current shall be selected in order to give the same thermal stress on the reactor as expected during service conditions. Consideration shall be taken to whether the reactor may be exposed to multiple capacitor discharges within a few seconds time due to high speed auto-reclosing of the transmission line.

The bypass making current test shall be performed 20 times.

Criteria for acceptance of the test: there shall not be any evidence of excessive heating, nor mechanical nor electrical damage.

c) Temperature rise test

During the temperature rise test, the damping resistor, if any, shall also be installed in its place, if it is located inside the reactor.

IEC 60076-6:2007, 9.10.8 is applicable.

4.6.3.2.4 Mandatory type tests, where applicable.

The following special tests shall be performed when specifically requested by the purchaser.

a) Modified short-circuit/bypass making current test

As an alternative to the tests in items a) and b) of 4.6.3.2.3, a modified short-circuit/bypass making current test may be performed. This test will include both the requirements in the bypass making current test and the fault current test.

IEC 60076-6:2007, 9.10.15 is applicable.

b) Mechanical resonance test

IEC 60076-6:2007, 9.10.16 is applicable.

c) Measurement of winding resistance and inductance versus frequency

Measurement of the winding resistance and inductance as a function of frequency, in a specified frequency interval above power frequency, shall be carried out with an approved bridge method at reduced voltage. The frequency range shall be the frequency interval specified by the series capacitor manufacturer.

4.6.3.3 Damping resistor

4.6.3.3.1 Routine tests

Routine tests to be carried out are as follows.

a) Resistance measurement

The resistance shall be measured at a.c. at the discharge frequency as well as at d.c.

A low-voltage d.c. measurement is sufficient, if the ratio between this d.c. measurement and the actual a.c. resistance is known from the discharge type test at high voltage.

b) Leakage test

If applicable to the actual resistor design.

c) Reference voltage test

If the resistor contains a series varistor, a reference voltage test shall be carried out.

d) Sparkover voltage test

The auxiliary spark gap, if any, shall be subjected to a spark over voltage test.

e) Partial discharge test (internal corona test)

The test shall be carried out in accordance with IEC 60270. The test is only relevant to the part of the damping resistor which contains a varistor if applicable.

4.6.3.3.2 Type tests

The resistor shall be tested to verify that the energy withstand, the high-frequency current withstand and the power-frequency fault current withstand are according to the specification.

For practical reasons, the test can be carried out on a smaller model of the damping resistor. The design of the model shall be similar to the design of the actual resistor.

a) Energy absorption capability test

   The energy absorption capability of the resistor shall be tested by discharging a capacitor bank through the resistor. The energy shall be based on the expected resistor short time energy accumulation during in service conditions also considering multiple capacitor discharges within a short period of time due to high speed auto-reclosing of the transmission line (see Clause 5). The test shall be performed 10 times. The test sample shall be allowed to cool down to ambient temperature between the tests.

   Before and after the test the resistance of the test sample shall be checked. It shall be demonstrated that no significant changes have occurred. The resistance shall not have changed by more than ± 5 %.

   Furthermore there shall be no indication of mechanical damage (puncture, flashover or cracking).

b) Discharge current test

   A discharge current withstand test shall be performed to demonstrate that the resistor will withstand the discharge current that the resistor will be exposed to during bypassing operations of the capacitor. Injection of current with the correct amplitude into the resistor shall be made from a charged capacitor bank. The current amplitude shall not be less than 1,05 times the maximum discharge current in service and the time to current crest shall not be less than in actual service. The test shall be performed 2 times. The test sample shall be allowed to cool down to ambient temperature between the tests.

   Before and after the test the resistance of the test sample shall be checked. It shall be demonstrated that no significant changes have occurred. The resistance shall not have changed by more than ± 5 %.

   Furthermore there shall be no indication of mechanical damage (puncture, flashover or cracking).

c) Power-frequency fault current withstand test

   The test shall verify that the resistor can withstand the power-frequency current which follows after the high-frequency capacitor discharge current (if applicable). A power-frequency current with correct magnitude and duration shall be injected into the resistor. The test shall be performed once.

   Before and after the test the resistance of the test sample shall be checked. It shall be demonstrated that no significant changes have occurred. The resistance shall not have changed by more than ± 5 %. Since the resistance is related to the temperature of the resistor element, it shall be taken into account in the evaluation of results.

   Furthermore there shall be no indication of mechanical damage (puncture, flashover or cracking).

   NOTE If the resistor includes a series varistor this test is not applicable, since the varistor will prevent power frequency currents to flow.

d) Impulse voltage test of enclosure

   The resistor enclosure shall be subjected to an impulse voltage test. The impulse voltage amplitude shall be calculated based on the protective voltage level and applying a safety factor of 1,2. See IEC 60143-1:2004, 6.1.3.4.

   15 impulses of both polarities shall be applied. A maximum of 2 external flashovers are allowed for each polarity.

The impulse generators of high voltage laboratories may not be able to provide 1,2 /50 μs impulse voltage with correct wave shape due to the low resistance of the damping resistor. The 'tail' may be shorter than 50 μs.

e) Extinguishing of the spark gap of the damping resistor

   In some cases there is a small spark gap connected in series with the damping resistor, which connects the resistor into the circuit only during the discharge oscillation. The extinguishing of the spark-gap current, against the power frequency voltage across the parallel connected reactor, after the high frequency discharge current has ceased, shall be demonstrated by testing, otherwise the power-frequency test according to c) shall be performed and the resistor be rated for continuous power losses.

4.7 Voltage transformer

4.7.1 Purpose

Voltage transformers in series capacitor banks may have different purposes:

- For series capacitors connected to low-voltage systems, magnetic voltage transformers may be used to measure the voltage across the capacitor segment (two high-voltage terminals) or the phase-to-earth voltage, (one high-voltage terminal and one low-voltage or earthed terminal). Magnetic voltage transformers may also be used as a discharge device.
- For series capacitors connected to high-voltage systems, capacitive voltage transformers (CVTs) may be used to measure phase-to-earth voltage. CVTs can also be used to supply auxiliary power to protection and control equipment located on the platform (inverted CVT). See Clause 5.

4.7.2 Classification

Voltage transformers can be classified in different ways.

a) With regard to where they are located:
   - voltage transformer placed at earth potential. The insulation level shall correspond to the power-system voltage;
   - voltage transformers placed on platform potential. The insulation level shall be according to Clause 6 of IEC 60143-1:2004.

b) With regard to design:
   - inductive (magnetic) voltage transformers. Inductive voltage transformers are generally oil insulated and equipped with an iron core;
   - capacitor voltage transformers (CVT). A CVT consists of a capacitive voltage divider (CVD) and an inductive (magnetic) output transformer.

4.7.3 Tests

4.7.3.1 General

Tests (routine/type) of the voltage transformer, shall be made in accordance with IEC 61869-3 or IEC 61869-5.

4.7.3.2 Additional type tests for inductive voltage transformers

If the service conditions are such, that an inductive voltage transformer forms a closed circuit with a capacitor, the following type tests shall be carried out.

a) Discharge current test

   The purpose of the test is to verify, that the voltage transformer can electrically and mechanically, withstand the dynamic current at a capacitor discharge.

The test shall preferably be carried out by charging a capacitor with a d.c. voltage, and then discharging the capacitor through the voltage transformer. The amplitude of the discharge current shall be 110 % of the actual discharge current of the installation, when the capacitor is charged to at least the protective level. The test shall be performed 10 times.

No damage to the winding and the terminals of the voltage transformer shall occur.

b) Energy dissipation capability test

The purpose of the test is to verify, that the voltage transformer can absorb the specified energy at consecutive capacitor discharges. The energy per discharge and the number of consecutive capacitor discharges shall be specified. See further clarifications in Clause 5.

The test shall preferably be carried out by charging a capacitor with d.c. voltage, and then discharging the capacitor through the voltage transformer. Each shot shall have an energy which is the sum of the energies of the specified number of the consecutive capacitor discharges. The test shall be performed five times with a cooling period in between tests consistent with actual operating practice.

No excessive temperature rise nor any damage to the voltage transformer shall occur.

4.8 Current sensors

4.8.1 Purpose

The main purpose of current sensors, is to supply measurements for protection, see Clause 5.

Current transformers may also be used to supply auxiliary power to protection and control equipment located on the platform.

4.8.2 Classification

Three types of sensors can be used to measure current flow on the platform. These sensors include iron core current transformers, electronic transformers which integrate electronics with the current transformer, and optical current transducers.

Current sensors may be classified with regard to the potential where they are located:

- current sensors placed on ground potential. The insulation level shall correspond to the power-system voltage;
- current sensors placed on platform potential. The insulation level shall be according to Clause 6 of IEC 60143-1:2004.

Information about different CTs feeding the different SC protections is given in Clause 5 and IEC 60143-1:2004.

4.8.3 Current transformer tests

Routine and type tests of the current transformers shall be made in accordance with IEC 60044-1.

4.8.4 Electronic transformer tests

Routine and type tests of the current transformers shall be made in accordance with IEC 60044-8.

4.8.5 Optical transducer tests

Routine and type tests of the current transformers shall be made in accordance with applicable parts of the IEC 60044 series.

4.9 Coupling capacitor

4.9.1 Purpose

The purpose of a coupling capacitor in a series capacitor installation is to supply auxiliary power to protection and control equipment located on the platform.

The insulation level shall correspond to the system voltage.

4.9.2 Tests

Tests (routine/type) of coupling capacitors shall be made in accordance with IEC 60358-1 and IEC 60358-2.

4.10 Signal column

4.10.1 Purpose

The purpose of the signal transmission system is to feed information and/or commands from the platform level down to the control cabinet inside the control building. Also the commands from the control cabinet up to the platform level (for instance forced triggering command) are sent through the signal transmission system.

The signal transmission system typically consists of three main sub-components: platform electronics, fibre optic signal column and fibre optic cable. The platform electronics is treated in 4.12. Optical fibre cables are covered by IEC 60794-1-1 and IEC 60794-2.

The signal column to which 4.10 refers is specifically a high voltage insulated fibre optic link which may be subject to operational voltages greater than 1 000V.

4.10.2 Tests

The signal column has both insulation and optical test requirements.

Dielectric tests

For the purpose of electrical testing and visual insulation checks the signal column shall be tested in accordance with IEC 61109, and to this end, as well as in this standard, it is defined as a “hybrid” insulator, which is not normally designed to support mechanical loads.

The type test voltage withstand levels shall match those of the platform, and the signal column may be tested in such a way as to simulate its position under or next to the platform.

Optical tests

For the purpose of optical testing the signal column shall be tested in accordance with IEC 61300-3-4. Exactly which method from this standard is to be employed shall be determined between the customer and the supplier, based on the length of the fibres, fibre type and the optical connectors (if any) used.

4.11 Fibre optical platform links

4.11.1 Purpose

The purpose of the fibre optical platform links is to provide a path for transmission of optical signals between the current sensors located at different locations on the platform and the fibre optical signal column. In addition the fibre optical platform links provide insulation between the current sensors and the platform.

4.11.2 Tests

4.11.2.1 General

The dielectric tests shall be carried out in general accordance with IEC 61109 and IEC 60143-1:2004.

4.11.2.2 Routine tests

Routine tests are as follows.

a) visual inspection;

b) continuity test and light attenuation test of each optical fiber.

4.11.2.3 Type tests

Dielectric tests, wet.

4.12 Relay protection, control equipment and platform-to-ground communication equipment

4.12.1 Purpose

The purpose of the relay protection equipment is to supervise all functions of the series capacitor installation as well as self-supervision methods for signal transmission from platform to earth and provide protective action in the event of faults such as capacitor unbalance, sustained gap arcing, flashover to platform etc. The protections normally initiate bypassing of the series capacitor, by closing the bypass switch and/or by triggering a spark gap followed by closing of the bypass switch.

The purpose of the control equipment is to provide control functions for the series capacitor installation, such as insertion and bypassing.

The purpose of the platform-to-ground communication equipment is to provide communication between the equipment mounted on the platform and the equipment located on the ground and vice versa.

The communication can be accomplished by mechanic, pneumatic, magnetic or optic signal transfer. At present, optic signal transfer by means of optical fibres is the predominant method in use.

4.12.2 Classification

Information about different protections and control functions is provided in Clause 5.

4.12.3 Tests

4.12.3.1 General

Testing of the SC protection and control system consists of routine tests, type tests and operational tests. The purpose of the type tests is to verify proper design of the equipment that it is capable of operating in specified ambient conditions and meet the specified performance and electromagnetic compatibility requirements.

Coordination shall be made with IEC 60068-2 for environmental conditions, IEC 60255-21 for mechanical tests, IEC 60255-5 for dielectric tests, IEC 61000-4-11 and IEC 61000-4-29 for auxiliary power voltage variations and IEC 61000-4 for electromagnetic compatibility requirements unless otherwise stated.

4.12.3.2 Routine tests

4.12.3.2.1 General

The following tests shall be carried out as a minimum. The listed tests shall apply to the platform located part of the equipment, to the platform-to-earth communication equipment and to the ground located part of the equipment.

a) Visual examination.
b) Dielectric withstand test (IEC 60255-5).
c) 100 h burn-in test.
d) Operational test (4.12.3.2.2).

The objective of the tests is to verify the manufacturing quality of all components and of the complete assembly.

4.12.3.2.2 Operational test

The procedure consists of injecting signals that simulate conditions requiring protective action into each control input. Each output is monitored during these tests. All hardware and software settings are verified. Software settings may be verified by software techniques.

If optical platform-to-ground communication is used, the output power of the transmitters shall be checked.

An optical loss test shall be performed on each fibre of the platform-to-ground communication insulators.

4.12.3.3 Type tests

The following type tests shall be carried out as a minimum.

a) Environmental tests: Dry heat test and Damp heat test (IEC 60068-2).
b) Dielectric test (IEC 60255-5).
c) Electromagnetic compatibility tests (IEC 61000-4).
d) Mechanical test (IEC 60255-21).

The listed test shall apply to the platform located part of the equipment, to the platform-to-ground communication equipment and to the ground located part of the equipment.

NOTE The pre-commissioning tests at site, on relay protection, control equipment and platform-to-earth communication equipment, are normally specified. These tests are performed before the bank is energized to the high-voltage network. See Clause 5.

5 Guide

5.1 General

A brief summary of some principles involved in the application and operation of series capacitors is presented here.

5.2 Specification data for series capacitors

The following data should be supplied to the manufacturer by the purchaser:

- initial and ultimate capacitive reactance per phase (Ω/phase);
- initial and ultimate rated current per phase (A/phase);
- maximum emergency current magnitude (A) and duration (s, min, h);

- swing current (A, s);
- maximum protective voltage level (kV peak);
- minimum protective voltage level (kV peak);
- maximum reinsertion current (A);
- maximum fault current through the series capacitor bypass circuit, with the series capacitor bypassed (initial/ultimate) (kA). Note that this current is smaller than the total fault current to earth;
- speed of reinsertion following clearing of system fault (external) when a gap is used (ms);
- line length (km);
- line parameters (r/km, x/km, b/km) (positive and zero sequence components);
- series capacitor location[2];
- type of line protection relays;
- normal and highest phase-to-phase voltage of system (kV);
- insulation level between capacitor platform and ground: LIWL, SIWL, short-duration power-frequency withstand voltage (kV peak-kV peak-kV r.m.s. respectively);
- altitude above sea level (m);
- maximum wind speed (m/s);
- maximum ice load (N/m^2);
- seismic requirements;
- ambient temperature range (°C);
- station supply voltages available at ground level (V a.c., V d.c.);
- maximum permissible fault-current duration (ms);
- minimum permissible line circuit-breaker reclosing time after clearing fault and number of reclosing operation (ms);
- required number and function of control and alarm channels required to ground level;
- minimum number and functions of operation signals to be monitored, if requested.

5.3 Protective spark gap

Spark gaps are used in series capacitor banks in order to protect the capacitor units against overvoltages (self-triggered gaps) or to protect the metal oxide varistor against overload (forced-triggered gaps).

The spark gaps can be self-triggered or forced-triggered.

Self-triggered spark gap

The spark gap used for the conventional series capacitor without varistors, is the self-triggered (voltage triggered) type spark gap. It sparks over when the voltage across its terminals reaches the spark over setting.

The self-triggered spark gap shall have an accurate spark over voltage tolerance in the order of ± 3 % to ± 6 %.

Forced triggered spark gap

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[2] One line diagram of the actual power system is preferable.

In the varistor scheme, the self-triggering voltage of the spark gap is adjusted to be higher than the protective level voltage U_{PL}. The spark gap is triggered by a forced triggering control circuit in case the thermal capability of the metal oxide varistor is exceeded.

5.4 Varistor

5.4.1 General

The purpose of the varistor is to limit the transient overvoltage across the capacitor by conducting the excess transmission line current, usually due to power-system faults, that would otherwise cause excessive capacitor voltage. This condition occurs on each half-cycle during the duration of the overcurrent condition. See Figure 5. The maximum voltage that results across the series capacitor is dependent upon the non-linear voltage-current characteristics of the varistor and the magnitude of the excess-current. Because the varistor voltage increases with current, the maximum protective level is usually defined at the maximum expected varistor current during a power-system fault. See Figure 4

Selection of the protective level of the varistor shall consider the voltages associated with non-fault currents through the series capacitor such as:

– normal and rated current

– emergency currents (magnitude/duration)

– swing currents

The varistor shall withstand these voltages, after having been exposed to rated short-time energy injection. Maximum ambient temperature shall be considered.

The varistor shall be designed for the maximum energy it will be exposed to during a defined fault situation in the network. The fault-situations for which the varistor shall be designed is usually specified in a fault duty cycle stating types of faults, fault duration and pause time between successive faults. The length of the pause time may be a decisive factor on the design of the varistor. An example of a fault duty cycle is shown in Table 1.

Table 1 – Summary of varistor energy absorption design criteria (example)

Fault type	Time duration
External phase-to-earth	5 cycles, 0,5 s open – 12 cycles
Phase to phase	5 cycles, 0,5 s open – 12 cycles
Three-phase	12 cycles
Internal phase-to-earth	5 cycles[a], 0,5 s open – 12 cycles [a]
Phase to phase	5 cycles [a], 0,5 s open – 12 cycles [a]
Three-phase	12 cycles [a]
NOTE It is most common to study single-phase and three-phase faults.	
[a] The varistor may be bypassed by the back-up gap during the 5 cycles and 12 cycles period of internal faults.	

The energy which is developed during a specified fault duty cycle in a varistor protecting a series capacitor depends mainly on the factors listed below:

- varistor current magnitude;
- voltage-current characteristics of the varistor;
- total fault duration;
- instant of fault inception.

The energy development process is illustrated in the waveforms shown in Figure 5.

Current, voltage and energy waveforms for an internal phase-to-earth fault are shown.

A commonly used philosophy to reduce the energy requirements and hence the cost of a varistor is to allow fast bypassing of the varistor by means of the triggered gap for faults on the compensated line section (internal faults). However, the varistor shall be designed to withstand the energy from specified fault duty cycles outside the compensated line section (external faults) without fast bypassing. See Table 1.

An electromagnetic transients computer study based on system short-circuit equivalents, transmission line parameters (positive and zero sequence) and varistor characteristics is generally required to determine the proper size and ratings of the varistors. The energy absorption shall correspond to the worst possible combination of fault type, fault duration and reclosing practices for example two phase-to-earth faults or one three-phase fault.

Required system information

- equivalent system positive and zero-sequence impedances;
- system load flows;
- maximum primary fault-clearing time;
- reclosing time after primary fault clearing;
- number of reclosures;
- maximum total back-up clearing time;
- reclosing time after back-up clearing.

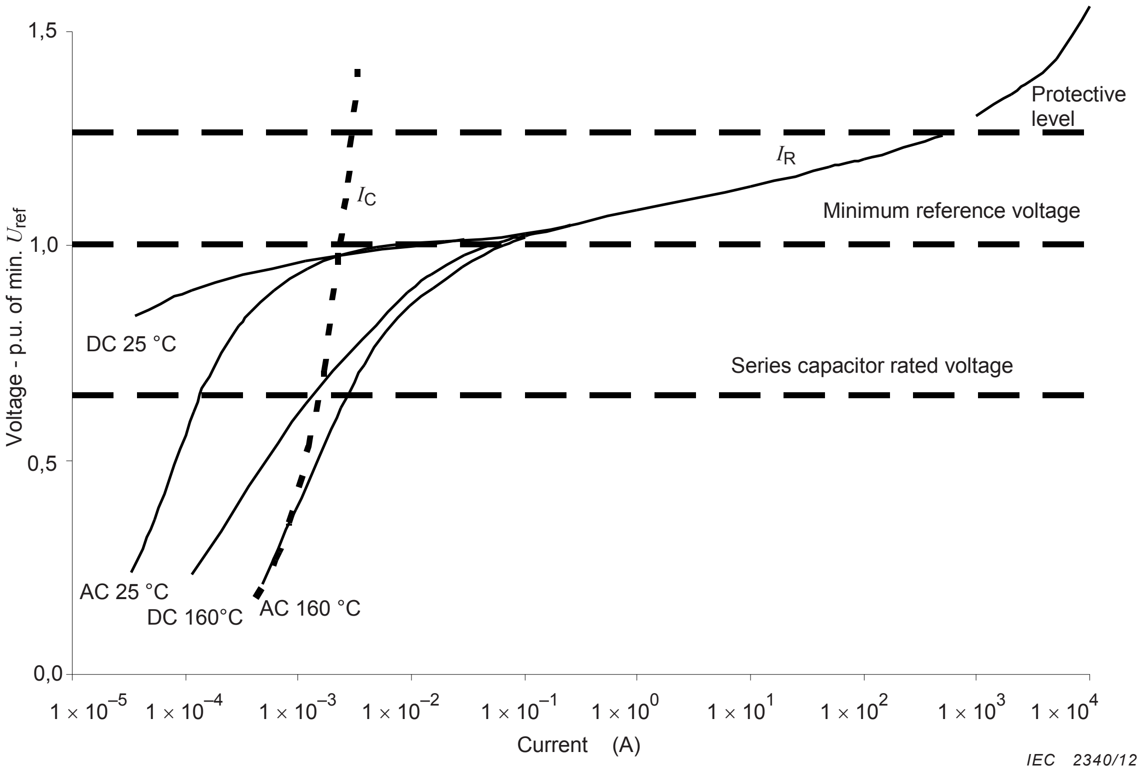
5.4.2 Varistor voltage-current characteristic

Typical voltage-current characteristics of one specific metal-oxide varistor element is shown in Figure 4. Series capacitor rated voltage, reference voltage and protective level of the varistor are indicated.

Historically, the U-I-characteristics of a varistor have been described by a formula

$$I = \mathrm{k}U^{\alpha}$$

where k and α are constants for a specific material. If such a formula is used for the resistive component of the current through metal oxide discs, it shall be emphasized that a single exponent cannot describe the complete characteristic. The applicable exponents depend on the conduction region and can vary between 3 and 50. Even in a specific region generalized numbers are not applicable and the actual varistor characteristic shall be used for the determination of the constants.



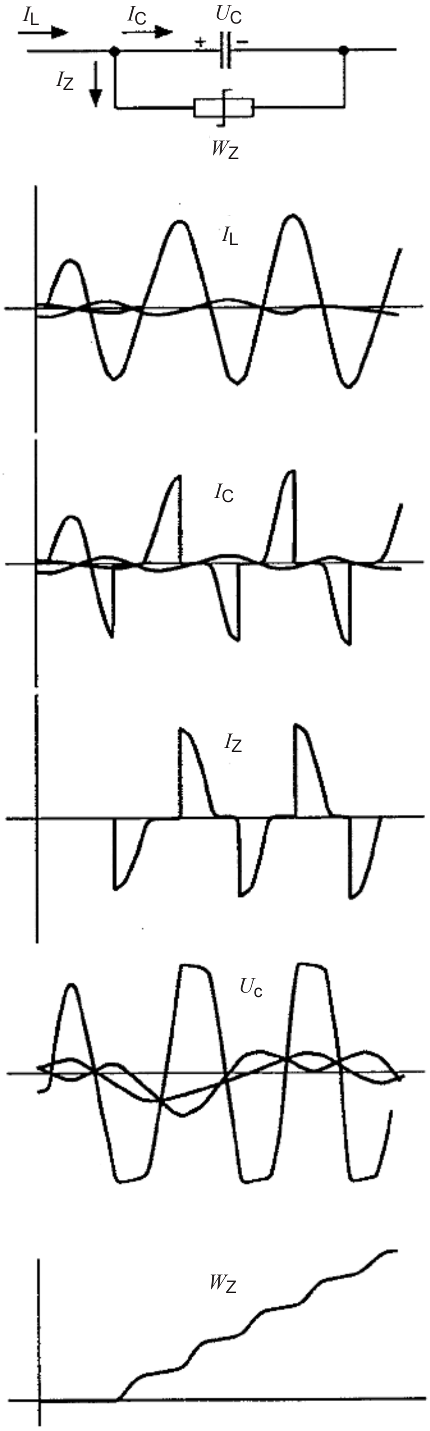
I_R = Resistive component

I_C = Capacitive component

Figure 4 – Typical voltage-current characteristics of one specific metal oxide varistor element (95 mm diameter)

5.4.3 Varistor current and voltage waveforms during a system fault

Current, voltage and energy waveforms for a phase-to-earth fault are shown in the diagrams in Figure 5.



IEC 2341/12

Figure 5 – Current, voltage and energy waveforms for a phase-to-earth fault

5.4.4 Comments on varistor definitions and type tests

5.4.4.1 General

Hereafter important clarifications and comments to the varistor definitions and type tests of Clause 2 are given.

5.4.4.2 Comment on minimum reference voltage (U_{MRef})

U_{MRef} is used in the designation of the varistor. In the routine test of all assembled varistor units it should be checked that the reference voltage is equal to or higher than U_{MRef} in order to secure that no varistor unit with too high power losses is accepted.

NOTE 1 The ratio $U_{\mathrm{Ref}}/U_{\mathrm{MRef}}$ is used to determine the scale factor of a section used for type testing. U_{Ref} is the reference voltage of the section and U_{Mref} is the minimum permissible reference voltage given for the complete varistor.

NOTE 2 This definition of U_{MRef} means, depending on the choice of reference current, that U_{MRef} will almost be equal to the term "duty cycle voltage rating" (ANSI[3]) or "rated voltage" (IEC) for surge arresters. However, these definitions are not straightforward and defined by test procedures. As the "rated voltage" of a varistor intended for the protection of an EHV series capacitor could easily be mixed up with the rated voltage of the series capacitor, this term has been avoided here.

5.4.4.3 Selection of test samples for type tests

Unless otherwise stated all type tests shall be performed on three sections of new varistor elements which have not been subjected to any previous tests except for evaluation purposes.

The scale factors in voltage, current and energy used to determine representative stresses to be applied on the test samples shall be determined as follows:

a) *The voltage scale factor* n_{v}

   The ratio between the minimum-volume of the varistor elements used in the complete varistor for the same number of parallel columns as in the test sample and the volume of the varistor elements used as test samples, is defined as n_{v}.

   The reference voltage of the test section U_{Ref} should be equal to $U_{\mathrm{MRef}}/n_{\mathrm{v}}$. In case $U_{\mathrm{Ref}} > U_{\mathrm{MRef}}/n_{\mathrm{v}}$ for an available test sample the factor n_{v} has to be reduced correspondingly.

b) *The current scale factor* n_{c}

   is determined as the ratio between the total number of parallel columns of the complete varistor and the number of parallel columns of the test sample.

c) *The energy scale factor* n_{w}

   It is determined as $n_{\mathrm{v}} \times n_{\mathrm{c}} \times$ the maximum permissible tolerance in current sharing between parallel columns.

5.4.4.4 Comment on residual voltage type test

The purpose of the measurement of the residual voltage is to obtain the maximum residual voltage for a given design for all specified currents, i.e. to verify that a given protective level is fulfilled.

The routine test procedure to control residual voltage shall allow for measurements of residual voltage on complete varistors, varistor units or individual varistor elements. In the latter case the sum of the residual voltages measured on units (if several units in series) or on elements shall be added to constitute the residual voltage for the complete varistor.

The maximum residual voltage at an impulse current used for routine tests shall be specified and published in the manufacturer's type test data.

The measured residual voltages of the test sections at any specified current and waveshape are then multiplied by the ratio of the maximum residual voltage at the routine test current to the measured residual voltage for the section at the same current to obtain maximum residual voltages for the complete varistor.

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[3] American National Standards Institute.

Example

All varistor elements for a specific varistor are classified at 500 A with a current pulse of 8/20 µs (virtual front time 8 µs, time to half value 20 µs). A specified number of varistor elements are then stacked in series. As many stacks of elements as required to obtain the number of parallel column of the varistor are built. The maximum residual voltage at the routine test current of 500 A to 8/20 µs for any column, given by the sum of the residual voltages of the individual varistor elements, is prescribed to a certain value (U_M).

A test section chosen for residual voltage tests is at first tested at the same current of 500 A to 8/20 µs, giving a residual voltage of U_{TM}.

The ratio U_M/U_{TM} is then used to recalculate the measured residual voltages of the test section at specified currents and waveshapes to representative figures for the complete metal oxide varistor.

5.4.4.5 Comment on accelerated ageing procedure

Regarding the accelerated ageing procedure there is an agreement between the IEC and IEEE[4] working groups preparing standards for the testing of a.c. arresters, about the main principles of the testing procedure. Since there are no other essential differences these main principles can also be applied for varistors in series capacitor applications. For a.c. arresters the voltage distribution along the arresters due to stray capacitances to earth is considered. This is done by using a formula in which the height of the arrester is included. However, most of the varistors for series capacitors are short. Further, the great number of parallel units will secure a linear voltage distribution. Therefore this consideration of arrester height is omitted for metal oxide varistors.

5.4.4.6 Comment on current sharing

To meet high energy requirements parallel columns of varistor elements may have to be used in surge arresters. For the application as protection of series capacitors this is the usual case. Metal oxide varistors with as many as 400 parallel columns have been commissioned. Of greatest importance is to secure a good current and energy sharing to avoid an uneconomical design. Taking into account the extreme non-linearity of the material, even rather small differences in residual voltages between parallel columns may prevent almost completely a satisfactory current sharing.

Due to production tolerances a typical maximum spread in residual voltage to a current of 100 A to 1 000 A per varistor element is about 5 %. With a factor of non-linearity α equal to 30 in the equation $I = kU^{\alpha}$, this will correspond to a current ratio of 1:4.

The required energy capability for varistors usually means that the decisive currents per varistor element will fall within this interval. For higher currents due to lightning, which have to be considered for surge arresters, the factor α is smaller, about 11 at a current of 10 kA. Because the residual voltage is usually routinely measured at this current, the spread is smaller, about 1 % to 2 %, and thus the current sharing is better even if no special steps are undertaken. With α equal to 11 and a 2 % difference in discharge voltages a current ratio of 1:1,24 is obtained.

5.4.4.7 Spare varistor units

Another conclusion which shall be drawn from the current-sharing tests is that considering the extreme non-linearity even small changes in residual voltages within normal measuring tolerances may affect the current distribution between parallel columns. It is therefore recommended to always install and energize possible spare varistor units right from the

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[4] Institute of Electrical and Electronics Engineers.

commissioning date among the other units. This will assure uniform ageing of all varistor units including the spare units, and the current-sharing tolerances will be maintained. Note that each phase will have its own electrical history, and therefore it is not recommended to mix spare units from different phases. Each phase shall have its own spare units.

Due to the reasons stated in 5.4.4.7, it is not recommended to upgrade existing varistor banks by adding newly manufactured varistor columns.

5.5 Bypass switch

The bypass switch is normally ground mounted on its own support structure with each breaking unit in parallel with the series capacitor and protective equipment in each phase or segment.

The bypass switch shall be capable of opening to insert the capacitors in the circuits when the system conditions are such that the capacitors would load to their emergency 1/2 h overload rating and when these loadings may result in a transient insertion voltage across the poles equal to the protective level.

The bypass switch shall be restrike free and shall withstand inrush current from frequent capacitor discharges from rated voltage (crest value) and rare discharges from a voltage equal to the protective level.

The bypass switch shall be able to perform this duty at a frequency no less than the frequency determined by the capacitance discharge current-limiting damping equipment (e.g. 500 Hz to 1 500 Hz).

Further information is given in IEC 62271-109:2008.

5.6 Disconnectors

Upon energizing the capacitor, for example after maintenance, the isolating disconnectors are closed, the bypass disconnector is opened and finally the bypass switch is opened.

Upon de-energizing the capacitor, the opposite switching sequence is followed.

When opening the bypass disconnector the current has to commutate to the bypassed capacitor bank (see Figure 1). Opposite to the usual use of a disconnector (i.e. opening of a line which means interrupting a capacitive current), in this case an inductive current has to be switched off.

The bypass disconnector shall have sufficient interrupting capability to perform this duty at high-line loading and possibly several segments.

In addition to the normal function, the bypass disconnector may be used as an emergency closing device, as back-up for the bypass switch. Due to the fact that disconnectors usually are closing slowly, pre-arcing and heavy welding of the contacts is to be expected. Especially chosen contact materials may minimize damages.

5.7 Discharge current-limiting and damping equipment

5.7.1 Purpose of the Discharge Current-Limiting and Damping Equipment

The purpose of the Discharge Current-Limiting and Damping Equipment (DCLDE) is to limit and damp the high frequency discharge current which is produced at spark-over of the protective spark gap or closure of the bypass switch. The amplitude (particularly the first current peak) as well as the frequency of the high frequency current, produced at a capacitor discharge, shall be limited. The amplitude, frequency and damping of the capacitor discharge current shall be limited to acceptable values for the fused capacitor units, the bypass switch and the spark gap.

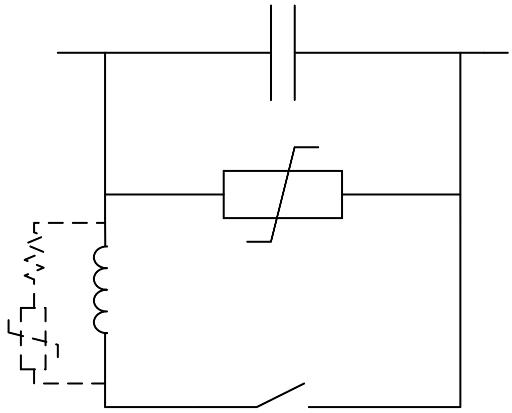
5.7.2 Location of the DCLDE

5.7.2.1 General

The location of the DCLDE is determined by the specified requirements.

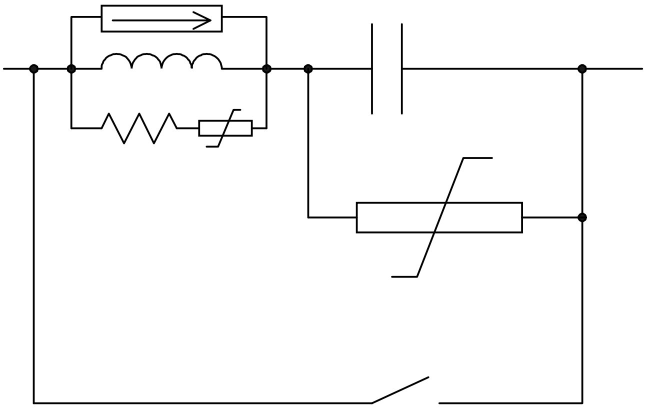
The present praxes for the location of the DCLDE are listed below:

- conventional location in the bypass branch according to Figure 6;
- location in series with the capacitor according to Figure 7 or Figure 8.



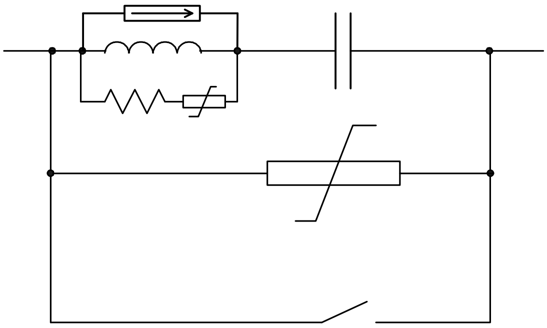
IEC 2342/12

Figure 6 – Conventional location in the bypass branch



IEC 2343/12

Figure 7 – DCLDE in series with the capacitor and the parallel connected MOV



IEC 2344/12

Figure 8 – DCLDE in series with the capacitor and parallel to the MOV

If no requirements on the location of the DCLDE are specified, the DCLDE may be located in the conventional way according to Figure 6. If there is a requirement that the voltage across the capacitor shall be very low, when the series capacitor is operated with the bypass switch in the closed position, the DCLDE should be located in series with the capacitor according to Figure 7 or Figure 8. Note that series connected DCLDE will increase the total losses of the SC installation, due to the fact that the reactor is continuously exposed to the line current when the SC is in service, i.e. not bypassed.

With the DCLDE in series with the capacitor according to Figure 7 and Figure 8, a parallel damping resistor is required also in the case when a damping resistor is not specified in the customer specification. The reason is, that the reactor shall be designed with low continuous losses because it is exposed to the service current when the SC is in operation. The low losses correspond to a high q-value of the reactor which means that the damping of the capacitor discharge current will be very low. To improve the damping of the capacitor discharge current a parallel damping resistor should be installed.

With the DCLDE located according to Figure 7 and Figure 8, the reactance of the capacitor has to be increased in order to compensate for the series connected reactor.

NOTE 1 When the DCLDE is located according to Figure 7 and Figure 8, it will attenuate carrier-frequency transmission over the line. In some cases, the associated coupling devices of the carrier-frequency transmission are installed on the line side of the series capacitors (line end located series capacitors).

5.7.2.2 Location of the DCLDE in parallel with the capacitor

The advantage with the location of the DCLDE in parallel according to Figure 6 is that continuous reactor losses are avoided when the SC is in service, i.e. not bypassed. This means that the reactor can be designed with a low q-value in order to obtain the required damping of the capacitor discharge current. The consequence is that the damping resistor can be omitted in many cases, e.g. if strong requirements on the damping are not specified. .

The disadvantages with the location of the DCLDE in parallel according to Figure 6 are:

a) When the bypass switch of a series capacitor is in the closed position, the capacitor and the reactor will form a parallel-resonant circuit. If the bypass switch is in the closed position and if there is significant harmonic current in the transmission line, a high circulating harmonic current can result in the reactor/capacitor circuit. It is possible that this harmonic current can overheat the reactor.

   The inductance of the reactor must be selected in such a way, that the resonance frequency of the parallel-resonant circuit does not coincidence with harmonic frequencies of the following orders:

   (i) $6 \times n \pm 1$, $n = 1, 2, 3, \ldots$(converter harmonics)

   (ii) $3 \times k$, $k = 1, 3, 5, \ldots$

b) When the bypass disconnector is opened (bypass switch in the closed position) a voltage appears across the reactor. The magnitude of the reactor voltage depends on the inductance of the reactor and the actual magnitude of the line current at opening of the bypass disconnector. The bypass disconnector shall be capable of opening against the reactor voltage.

5.7.2.3 Location of the DCLDE is series with the capacitor

The advantages with the location of the DCLDE in series according to Figure 7 and Figure 8 are:

a) The voltage across the SC at opening of the bypass disconnector (bypass switch in the closed position) is very low. This fact puts low requirements on the opening capability of the bypass disconnector. The bypass disconnector can be opened without problems, independently of the magnitude of the actual line current.

b) There is no risk of a parallel resonant condition for harmonic frequencies if the reactor is connected in series with the capacitor.

The disadvantages with the location of the DCLDE according to Figure 7 and Figure 8 are:

a) The total losses of the SC installation with the SC in service will be higher compared to the losses with the location according to Figure 6.

b) The installation cost for a damping resistor in parallel to the reactor has to be added.

c) The attenuation of the carrier frequency transmission over the transmission line will be increased.

d) The reactance of the capacitor has to be increased to compensate for the inductive reactance of the reactor.

e) With the location of the DCLDE located according to Figure 7 and Figure 8, an additional surge arrester may have to be installed across the reactor in order to protect the reactor from overvoltages caused by travelling waves travelling along the transmission line, unless the damping resistor resistance is low enough to limit the maximum reactor overvoltage.

f) With the location of the DCLDE located according to Figure 8, the capacitor shall be designed for a higher protective level compared to a location of the DCLDE according to Figure 6 and Figure 7. The reason is that voltage spikes will appear across the capacitor during line fault conditions when the line current is commutated between the MOV and the capacitor. See IEC 60143-1:2004, 10.5.2.

5.7.3 Configuration of the DCLDE

The configuration and design of the DCLDE depends on the specified requirements. The following standard configurations are in use:

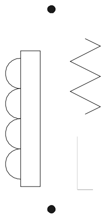
a) Only a discharge current-limiting reactor. See Figure 9.

b) A discharge current-limiting reactor connected in parallel with a damping resistor. A varistor is connected in series with the resistor. Figure 10.

c) A discharge current-limiting reactor connected in parallel with a damping resistor. A small spark gap is connected in series with the resistor. See Figure 11.

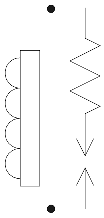
IEC 2345/12

Figure 9 – Only a discharge current-limiting reactor



IEC 2346/12

Figure 10 – Discharge current-limiting reactor connected in parallel with a damping resistor. A varistor is connected in series with the resistor



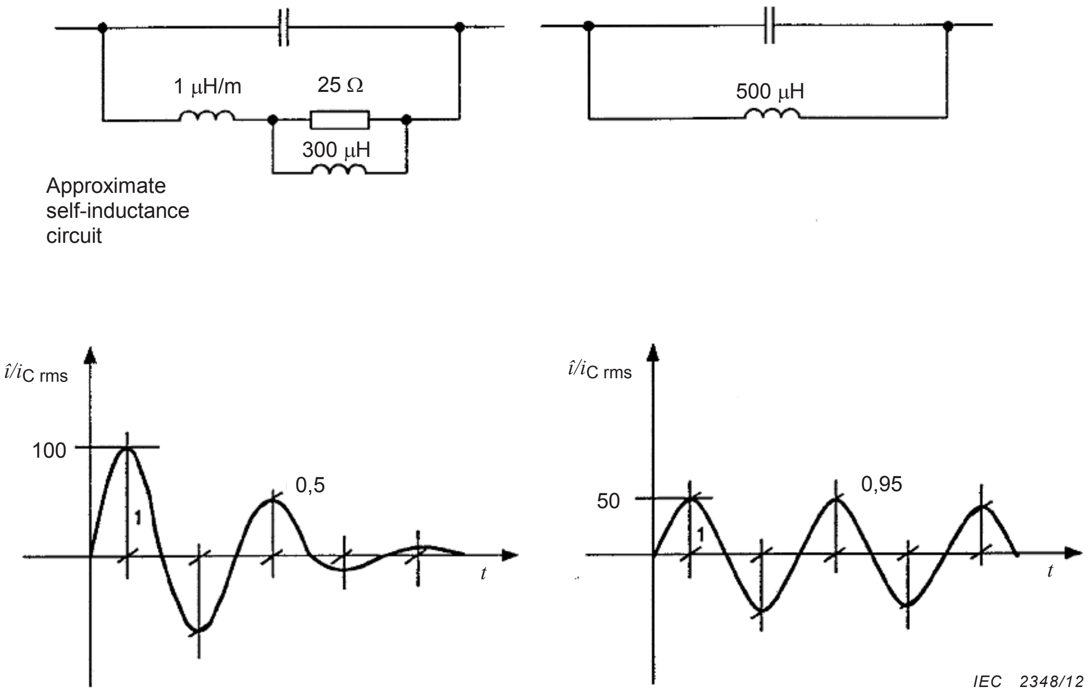
IEC 2347/12

Figure 11 – Discharge current-limiting reactor connected in parallel with a damping resistor. A small spark gap is connected in series with the resistor

The parallel connected damping resistor is needed when the DCLDE is located in series with the capacitor according to Figure 7 and Figure 8. The parallel connected damping resistor is also needed when the specified damping requirement is < 0,9 pu, i.e. if a heavy damping of the capacitor discharge current is required. This is valid for all locations according to Figure 6 through Figure 8.

The purpose of having a varistor or a spark gap connected in series with the damping resistor is to avoid continuous losses in the resistor during steady state operation of the SC bank. The arrangement implies that the damping resistor is in operation and exposed to high voltage and high current only during transient discharge oscillations of the capacitor.

Examples of waveforms of capacitor – DCLDE discharge oscillations are shown in Figure 12 for two different configurations of the DCLDE.



IEC 2348/12

Figure 12 – Current-limiting and damping equipment with and without damping resistor

5.7.4 Miscellaneous comments regarding the DCLDE

As the discharge current limit damping equipment is in series with the line, when the capacitor bank is bypassed, it shall be designed to carry regular and overload line currents, and withstand the thermal and mechanical stresses at discharge and short-circuit currents.

Since the discharge frequency usually lies between 500 Hz and 1 500 Hz it is generally not possible to provide such current values for testing the device (except if a whole segment of the capacitor bank is erected).

In practice the performance of the discharge current-limiting damping equipment with regard to electromagnetic forces is proven by a 50 Hz or 60 Hz short-circuit test, provided that the equipment is free from mechanical resonances when exposed to current at discharge frequency. This is of particular concern for the current-limiting reactor without a damping resistor.

The number of consecutive discharges during the tests is determined in connection with the fault scenarios, so that the discharge current-limiting damping equipment is able to withstand the total energy applied to it at the worst case of the faults.

The measurement of the losses of a current-limiting damping reactor requires special care due to the low-power factor. It is customary to require measurement of the reactor loss resistance at the fundamental power-frequency and at the discharge frequency, for example at 500 Hz to 1 500 Hz. An appropriate method (wattmeter, bridge or other) shall be adopted by the manufacturer. Since these reactors usually do not contain any magnetic material the measurement may be made at any current and corrected to rated continuous current. For temperature corrections refer to IEC 60076-1.

As an alternative the losses may be calculated from the a.c. resistance.

An unshielded air core reactor generates a magnetic stray field which occupies a space around the reactor. This alternating magnetic field can induce currents in nearby metallic geometries, causing heating effects during continuous current loading and forces on them during discharge current or short-circuit current flow.

There are some simple rules of thumb for estimating magnetic clearances around the reactor:

Clearance to small metallic parts not forming closed loops should be at least one half the coil diameter from the edges of the reactor. Larger geometries or closed loops should be located at least one coil diameter from all the surfaces of the reactor. For more detailed information it is advisable to consult the manufacturer of the reactors.

The insulation level on the platform of a segment is determined by both the maximum voltage during normal operation and the maximum overvoltages limited by the overvoltage protection during line fault conditions. The platform-to-earth insulation level corresponds to the phase-to-earth insulation. As is stated for the bypass switch the insulation level of the discharge current-limiting damping equipment corresponds to that of the actual capacitor segment, if it is mounted on the platform (which is usually done). Otherwise the phase-to-earth insulation level shall be considered for this equipment.

The reactor shall be designed in such a way that mechanical resonance at 2× f_0 is avoided.

5.8 Voltage transformer

It is essential, that the voltage transformer (magnetic type) is designed to withstand the mechanical and thermal stresses that occur during a series capacitor discharge. The insulation level of the voltage transformer shall be coordinated with that of the series capacitor installation.

5.9 Current transformer

Each current transformer in the series capacitor installation (see Annex B in IEC 60143-1:2004) shall be specified and designed for its individual duty. It is important to consider not only the fault current (thermal stress) but also the large surge current stresses (dynamic stress) that may occur during series capacitor discharges. For instance, the platform transformer shall be designed to withstand the high-amplitude, high-frequency discharge current resulting from a flashover to the platform.

The insulation level of the current transformer shall be coordinated with that of the series capacitor installation.

5.10 Relay protection, control equipment and platform-to-ground communication equipment

Protection and control functions that should be considered for a fixed series capacitor include the following.

Protection of SC equipment against overstress from system conditions:

a) Capacitor overload – the purpose of the capacitor overload protection is to protect the capacitor units against excessive overload caused by overcurrent through the series capacitor.

b) Varistor overload – the purpose of the varistor overload protection is to protect the varistor against high temperature and high short time energy exceeding the rated values.

c) Subharmonic protection (optional) – the purpose of the subharmonic protection is to detect sub-harmonic oscillations on the line current and bypass the series capacitor to avoid possible disturbances on the network.

d) Subsynchronous resonance (SSR) protection (optional) – the purpose of the subsynchrounous resonance protection is to detect subharmonic currents of specified frequencies and prevent the SSR phenomenon.

e) Line current supervision – the purpose of this protection is to block the insertion of the series capacitor when there is a fault current on the line. Typically the insertion of the series capacitor under line fault current could occur when high-speed auto-reclosing of the line circuit breakers is activated.

f) SSR are torsional interactions of the rotor shaft of turbine-generators together with the electrical transmission system that may fatigue or damage of the rotor shaft. SSR does not present a risk to series capacitors and therefore the series capacitor does not need to be protected against SSR. Due to the complexity of the SSR-phenomenon as well as its dependency on the grid topology and system operating conditions a common approach is to conduct a screening study in order to evaluate whether certain turbine generators in a power system are at risk of experiencing SSR. A detailed study will inform at what system and operating conditions SSR occur, whether or not they cause fatigue or damage to the rotor shaft and what protection measures are required to efficiently prevent the phenomenon (SSR frequencies and magnitude, protection strategy, time delays for protection reaction). The screening study shall be agreed upon between purchaser and manufacturer.

Protection functions associated with SC equipment failure:

a) Capacitor unbalance – the purpose of the capacitor unbalance protection is to detect element failures leading to harmful stress within the capacitor units.

b) Flashover to platform – the purpose of the flashover to platform protection is to detect current through the platform due to breakdown of the insulation of any platform mounted equipment.

c) Varistor failure – the purpose of the varistor failure protection is to detect failure within a varistor unit.

d) Bypass gap failure – the purpose of the bypass gap protection is to detect unintended conduction of the bypass gap (applicable only to forced triggered gaps) and mis-operation of the bypass gap: i) fail to conduct when a bypass order has been sent; ii) prolonged conduction time when conduction was supposed to be extinguished

e) Bypass switch failure – the purpose of the bypass switch failure protection is to detect failure to close after a bypass order and failure to open after an open order.

f) Pole disagreement – the purpose of the pole disagreement protection is to detect discrepancy between the phases of the bypass switch.

g) Protection and control system failure – the purpose of the protection and control system protection is to supervise the operational status of protection and control systems of the series capacitor.

NOTE Bypass switch failure protection is usually based on the position indicating auxiliary contacts of the bypass switch.

SC control functions:

a) Capacitor discharge function – the purpose of the capacitor discharge function is to discharge the series capacitor via the bypass circuit when the transmission line circuit breakers are opened.

b) Bypassing – bypassing of the series capacitor due to protective operation and manual action.

c) Insertion (automatic or manual) and reinsertion – insertion of the series capacitor by operation action, expiring of temporary block insertion and high speed auto-reclosing function.

d) Lockout – permanent lockout caused by corresponding protective operation.

e) Temporary block insertion – temporary lockout caused by corresponding protective operation.

f) Operation of disconnect switches – the disconnect switches are commanded by operation action.

g) Interlocking – disconnect switches and bypass switch commands are executed as long as the interlocking conditions are fulfilled.

Table 2 presents an overview of typical series capacitor bank protections and corresponding actions during their operation.

Table 2 – Overview of typical series capacitor bank protections

Function	Alarm level	Bypass	Lockout	Temporary block insertion	Reinsertion
Capacitor overload	X	X		X	X
Varistor overload		X		X	X
Sub-harmonic protection	X	X		X	X
SSR protection	X	X			
Line current supervision				X	
Capacitor unbalance	X	X	X		
Flashover to platform protection		X	X		
Varistor failure		X	X		
Bypass gap failure		X	X		
Bypass switch failure protection: close failure		X	X		
Bypass switch failure protection: open failure		X	X		
Bypass switch pole disagreement protection		X	X		
Disconnector pole disagreement protection		X	X		
Protection and control system failure		X	X		
Flashover to platform		X	X		

5.11 Protection redundancy

The amount of redundancy is usually specified indirectly in the form of overall reliability and availability requirements for the series capacitor. The purchaser may however specify those items that have redundancy, see examples from the following list. It may also be specified by the purchaser that the two protection systems be physically separate, each in its own cabinet. The purchaser may specify if the protection system is to be operated from one or two station batteries and the degree of separation between the supplies that is required within the series capacitor bank protection and control system.

- Digital protection system and relays.
- Digital control system.
- I/O modules and relays.
- Power supplies.
- Platform-to-ground signal columns.
- Current transformers and current sensors.
- Circuits to trigger the forced –triggered bypass gap.
- Closing coils for the bypass switch.

5.12 Commissioning tests

When the series capacitor is installed, but before it is energized, the following procedure is recommended:

- capacitance measurement of capacitor groups;
- balance check at low voltage test;
- spark gap measurement and adjustment if necessary;
- triggering test of forced triggered spark gaps;
- impedance measurement of damping reactors and resistors;
- functional tests of relay protection, control equipment and platform-to-ground communication equipment;
- attenuation test of fibre optic system;
- functional test of bypass switch;
- functional test of disconnectors.

5.13 Energization tests

When a series capacitor bank is energized, some field tests are to be made before the bank is put into commercial operation:

- Energization of platform: the platform is energized for a 1/2 hour with the bypass switch closed. The currents are measured.
- Low-load test: the line is energized from one end, with the other end open. The bank is connected to the line for a 1/2 hour. Line current and voltage are measured.
- High-load test: the series capacitor is inserted with the line loaded to 50 % to 100 % of the rated line current during a 1/2 hour. Transient and stationary capacitor current and voltage are recorded, at opening and closing of the bypass switch.

  Additional tests indicated below may be agreed upon between the manufacturer and the purchaser:

  - Thermovision control: temperatures of connections of capacitor units and apparatus are observed by a thermovision camera, at as high line current as possible.
  - Sub-harmonic test: the line, with the series capacitor included, is energized from one end. A reactor or an unloaded power transformer is connected to the other end. Line current and voltage are recorded by an oscillograph, and content of sub-harmonic components is observed.
  - Line fault test: it may be useful to perform a staged fault test (phase-to-earth fault) to prove that the series capacitor protective equipment and the line protection relays operate correctly.

- Energization of a parallel or adjacent line: to take out and place in service a parallel or adjacent line to the series capacitor bank and observe the behaviour of the series capacitor bank following the power swing.
- Fault to provoke a bypass of the SC bank: the SC banks can be placed in service initially and faulted. The objective of this test is to verify the complete response and operation from the detection/measurement to the bypass of the SC bank in presence of a fault. The test shall help to validate the speed of operation including the time when the transmission system is energized and the closing of the bypass switch from the detection of the disturbance. Examples of this test are a platform insulation fault or a capacitor unbalance. This test could include the shorting of a capacitor unit prior to insertion of the series capacitor bank.
- Opening and closing of disconnector: the objective of this test is to verify the series capacitor control immunity to the noise that is created by the operation of a disconnector. A disconnector near the SC bank should be selected for this test. The risk associated to this test is limited to an immediate bypass of the SC bank.

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Cigré-Publication 411, *Protection, Control and Monitoring of Series Compensated Networks. ISBN: 978-2-85873-098-8. Cigré Working Group B5-10*

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