PD IEC/TS 60076-20:2017

BSI Standards Publication

Power transformers

Part 20: Energy efficiency

National foreword

This Published Document is the UK implementation of IEC/TS 60076-20:2017.

The UK participation in its preparation was entrusted to Technical Committee PEL/14, Power transformers.

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.

© The British Standards Institution 2017.
Published by BSI Standards Limited 2017

ISBN 978 0 580 85545 0
ICS 29.180

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

This Published Document was published under the authority of the Standards Policy and Strategy Committee on 28 February 2017.

Amendments/corrigenda issued since publication

Date	Text affected

IEC TS 60076-20

Edition 1.0 2017-01

TECHNICAL SPECIFICATION

colour
inside

Power transformers –
Part 20: Energy efficiency

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 29.180

ISBN 978-2-8322-3870-7

Warning! Make sure that you obtained this publication from an authorized distributor.

® Registered trademark of the International Electrotechnical Commission

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

POWER TRANSFORMERS –

Part 20: Energy efficiency

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as “IEC Publication(s)”). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.

2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.

3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.

4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.

5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.

6) All users should ensure that they have the latest edition of this publication.

7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.

8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.

9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

The main task of IEC technical committees is to prepare International Standards. In exceptional circumstances, a technical committee may propose the publication of a technical specification when

- the required support cannot be obtained for the publication of an International Standard, despite repeated efforts, or
- the subject is still under technical development or where, for any other reason, there is the future but no immediate possibility of an agreement on an International Standard.

Technical specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC TS 60076-20, which is a technical specification, has been prepared by IEC technical committee 14: Power transformers.

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

Enquiry draft	Report on voting
14/852/DTS	14/884/RVDTS

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

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

The reader's attention is drawn to the fact that Annex C lists all of the “in-some-country” clauses on differing practices of a less permanent nature relating to the subject of this standard.

A list of all the parts in the IEC 60076 series, under the general title *Power transformers*, can be found on the IEC website.

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

- transformed into an International standard,
- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

The reason prompting the preparation of this document is the need to save energy and to reduce the emission of greenhouse gases. The objective of this document is to promote a higher average level of energy performance for transformers.

It provides a basic model for national standards and, alternatively, a supplement to national standards that do not cover the whole range of transformers.

This part of IEC 60076 gives methods of specifying a transformer with an appropriate level of energy efficiency according to the loading and operating conditions applicable. It also gives minimum efficiency and maximum losses which lead to a generally acceptable balance between losses and use of other resources.

This document proposes two methods (A and B) of defining an energy efficiency index and introduces three methods of evaluating the energy performance of a transformer.

These are based on existing regional practices:

a) the Peak Efficiency Index (PEI) which should be used in conjunction with either a total cost of ownership (TCO) approach or any other mean of specifying the load factor.
b) the no-load and load losses at rated power for rationalization of transformer cores and coils for transformers generally produced in large volumes;
c) the efficiency at a defined power factor and particular load factor (typically at 50 %).

The appropriate method is chosen by agreement between purchasers and manufacturers or according to local regulations.

A transformer that does not comply with this document can still comply with the requirements of other standards in the IEC 60076 series.

Formulae for the calculation of efficiency are given to reflect different regional practices and purposes. The definition of rated power is given in IEC 60076-1.

Energy efficiency is not the sole basis for choosing a transformer. The total capital and estimated lifetime operating and maintenance costs (TCO) are also significant considerations in determining the most suitable transformer for the intended application, and may lead to the selection of more economical solutions when taking into account the lifetime of the transformers.

This document provides a standard method for evaluating the energy performance of power transformers through the use of the PEI, gives benchmark figures and the reasons why certain transformers may have efficiencies which are higher or lower than the benchmark.

Setting a reasonable value of minimum PEI will be effective in improving the overall energy performance of the installed transformer population by eliminating transformers with low efficiency, with the exception for some specific network limitations.

The use of a minimum value of PEI sets a floor for transformer energy performance, but the use of TCO evaluation for purchasing transformers is essential to select a transformer with the optimal economically justified level of efficiency.

POWER TRANSFORMERS –

Part 20: Energy efficiency

1 Scope

This part of IEC 60076 is applicable to transformers in the scope of IEC 60076-1.

The energy performance levels given in Clause 6 are not applicable to the following transformers:

- transformers for high current rectifiers as described in the IEC 61378 (all parts) and in the IEC 60146 (all parts);
- transformers for furnace applications;
- transformers for offshore applications;

NOTE 1 Transformer to be installed on fixed or floating offshore platforms, offshore wind turbines or on board of ships and all kind of vessels).

- transformers for emergency or temporary mobile installations;

NOTE 2 Transformers designed only to provide cover for a specific time limited situation when the normal power supply is interrupted either due to an unplanned occurrence such as failure or a station refurbishment, but not to permanently upgrade an existing substation.

- traction transformers;
- earthing transformers as described in 3.1.10 of IEC 60076-6:2007.
- phase shifting transformers;
- instrument transformers (IEC 61869-1);
- transformers and auto-transformers specifically designed for railway feeding systems, as defined in EN 50329;
- traction catenary supply transformer for 16,67 Hz;
- transformer for high current rectifiers (IEC 61869-1);

NOTE 3 These are transformers specifically designed and intended to supply power electronic or rectifier loads specified according to IEC 61378-1.

NOTE 4 This exclusion does not apply to transformers intended to provide AC power from DC sources such as transformers for wind turbine and photo voltaic applications as well as transformers designed for DC transmission and distribution applications."

- transformers for railway feeding systems (EN 50329);
- subsea transformers;
- starting-, testing- and welding transformers;
- starting transformers, specifically designed for starting three-phase induction motors so as to eliminate supply voltage dips;

NOTE 5 Examples are transformers that are de-energised during normal operation, used for the purpose of starting a rotating machine).

- transformers specifically designed for explosion-proof and underground mining applications;
- transformers which cannot fulfil the energy performance requirements due to unavoidable size and weight limitations.

NOTE 6 Due to the unavoidable weight and size limitation for a rolling stock application, this definition includes all traction transformers for rolling stock, irrespective of the frequency (e.g. 16,7 Hz, 25 Hz, 50 Hz, 60 Hz).

In this document, "transformers" includes both separate winding transformers and autotransformers.

NOTE 7 Transformers intended to provide AC power from DC sources such as transformers for wind turbine and photo voltaic applications as well as transformers designed for DC transmission and distribution applications are included in the Scope of this document.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

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

IEC 60076-2, *Power transformers – Part 2: Temperature rise for liquid-immersed transformers*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
efficiency
ratio of output active power to input active power

Note 1 to entry: This is an apparent power

3.2
electrical losses
electrical power consumed by the transformer at a particular value of transmitted apparent power excluding the power consumed by the cooling system

3.3
efficiency index method A
EI_A
ratio of the transmitted apparent power of a transformer minus electrical losses including the power consumed by the cooling to the transmitted apparent power of the transformer for a given load factor

3.4
efficiency index method B
EI_B
ratio of the transmitted apparent power of a transformer to the transmitted apparent power of the transformer plus electrical losses for a given load factor

Note 1 to entry: This method is only applicable for naturally cooled transformers.

3.5
peak efficiency index
PEI
highest value of efficiency index method A that can be achieved at the optimum value of load factor

Note 1 to entry: To characterize the energy performance of power transformers, it is useful to define an index that is relevant to the transformer design applicable to a wide range of uses rather than a figure that varies from second to second depending on system conditions. For this reason, a metric, the peak efficiency index, has been developed and used, which is based on active power losses and total apparent power transmitted and is independent of load phase angle, load factor and rated power.

3.6
input apparent power
S_{input}
input voltage multiplied by the input current

Note 1 to entry: This is an apparent power.

Note 2 to entry: For three phase transformers, a factor √3 shall be added.

3.7
output apparent power
S_{output}
output voltage multiplied by the output current

Note 1 to entry: This is an apparent power.

Note 2 to entry: For three phase transformers, a factor √3 shall be added.

3.8
transformer load factor
k
ratio of the actual input current to the rated current of the transformer

3.9
load factor of peak efficiency index
k_{PEI}
load factor at which the peak efficiency index (3.5) occurs

3.10
transmitted apparent power
kS_{r}
product of the load factor and the rated power

4 Efficiency and efficiency index calculation

4.1 General

Transformer efficiency is based on the apparent power, this is equivalent to assuming that the power factor is one. For transformers, the efficiency is expressed as follows:

$$\text{Efficiency} = \frac{S_{\mathrm{input}} - L}{S_{\mathrm{input}}} = \frac{S_{\mathrm{output}}}{S_{\mathrm{output}} + L} \qquad (1)$$

The defined power can be either input apparent power or output apparent power resulting in two methods for the calculation of efficiency (Method A and Method B), and historically both methods have been used.

Method A $$\text{Efficiency} = \frac{S-L}{S} \tag{2}$$

Method B $$\text{Efficiency} = \frac{S}{S+L} \tag{3}$$

where

S is the defined power;

L is the sum of no-load loss and load loss including loss for cooling equipment.

NOTE S is defined as input apparent power in method A and S is defined as output apparent power in method B.

The formula for calculating efficiency index with method B is limited to transformers without cooling losses.

For the scope of this document and for the sake of simplicity, it is conventionally assumed that:

- the voltage and load current systems are symmetrical and sinusoidal;
- the line voltage is equal to the rated voltage.

4.2 Methods of evaluating energy performance

For the purposes of this document, to consider energy efficiency in a practical manner, the power factor is assumed to be unity, and efficiency can be defined in terms of an efficiency index at a specific power.

This document defines two methods of calculating the efficiency index, method A and method B.

This document introduces three methods of evaluating the energy performance of a transformer:

a) the peak efficiency index (PEI);
b) the no-load and load losses at rated power or at a particular reference power;
c) the efficiency at a defined power factor and particular load factor (typically at 50 %).

The appropriate method shall be chosen by agreement between purchasers and manufacturers or according to local regulations.

The general definition of efficiency raises some complications, such as whether the electrical consumption of the cooling equipment of the transformer at no-load or at a particular load shall be included in the calculation.

The PEI includes the losses associated with only that part of the cooling system that is in service at k_{PEI}.

At k_{PEI} loading, sufficient cooling shall be in service to ensure that the rise in temperature of the transformer does not exceed the requirements of IEC 60076-2 or the customer's specification.

NOTE 1 The advantage of the PEI is that it does not impose a particular load factor that can vary greatly depending on the application, and because it does not depend explicitly on the rated power of the transformer. The PEI is an intrinsic parameter that does not depend on whether the transformer has alternative ratings depending on cooling modes.

NOTE 2 If the loss capitalisation method is used in the transformer procurement process, then it can be expected that the PEI will occur at approximately the loading where the ratio between load and no-load losses is equal to the ratio between the capitalisation rates for load and no-load loss, except where this has been modified by the relative cost of reducing load and no-load losses.

It can be advantageous to switch on the cooling at a lower temperature than is required by the maximum temperature rise requirement to increase the life span of the transformer insulation and reduce total losses, because of the effect of winding temperature on losses.

4.3 Method A

4.3.1 Efficiency index general formula

The efficiency index according to method A is calculated according to the following formula expressed per unit:

$$\mathrm{EI_A} = \frac{kS_\mathrm{r} - (P_0 + P_\mathrm{c0}) - (k^2 P_\mathrm{k} + P_\mathrm{ck}(k))}{kS_\mathrm{r}} \quad \text{(p.u.)} \tag{4}$$

where

P_0 is the no-load loss measured at rated voltage in W, rated frequency and on rated tap;

P_c0 is the electrical power in W required by the cooling system for no-load operation derived from the type test measurement of the power taken by the fan and pump motors;

P_k is the measured load loss in W at rated current and rated frequency on the rated tap corrected to reference temperature according to the requirement below;

$P_\mathrm{ck}(k)$ is the additional electrical power in W required (in addition to P_c0) by the cooling system for operation at load factor k, derived from the type test measurement of the power taken by the fan and pump motors;

S_r is the rated power in VA of the transformer or autotransformer as defined in IEC 60076-1 on which P_k is based;

k is the load factor.

This approach respects the philosophy of the IEC 60076 series, which refers the rated power to the rated voltage and current of one of the transformer windings.

For the calculation, the following shall be considered:

a) for liquid-immersed transformers with a rated average winding temperature rise less than or equal to 65 K for OF or ON, or 70 K for OD, the reference temperature is 75 °C;

b) for transformers with other rated average winding temperature rises, the reference temperature is equal to the rated average winding temperature rise +20 °C, or rated winding temperature rise + the yearly external cooling medium average temperature, whichever is higher.

If a purchaser needs to compare a transformer with different insulation systems and different average winding temperature rises, the reference temperature should be according to b) above.

The reference temperature at the rated power chosen for the losses shall be in accordance with IEC 60076-1.

4.3.2 Peak efficiency index

The peak efficiency index (PEI) is obtained when no-load loss equals load loss and is given by substituting k in Equation (4) with k_PEI as in the expression below:

$$k_\mathrm{PEI} = \sqrt{\frac{P_0 + P_\mathrm{c0} + P_{\mathrm{ck}_\mathrm{PEI}}}{P_\mathrm{k}}} \quad \text{(p.u.)} \tag{5}$$

$P_{\mathrm{ck}_\mathrm{PEI}}$ is the additional electrical power required (in addition to P_c0) by the cooling system for operation at k_PEI.

The formula for calculating the PEI is therefore given by Equation (6):

$$\mathrm{PEI} = 1 - \frac{2(P_0+P_{c0}+P_{ck_{PEI}})}{S_r\sqrt{\frac{P_0+P_{ck_{PEI}}+P_{c0}}{P_k}}} \quad \text{(p.u.)} \qquad (6)$$

The losses shall be measured in accordance with the methods specified in the IEC 60076 series.

NOTE The value of Equation (6) depends on the ratio $S_r / \sqrt{P_K}$ which does not vary significantly if S_r is changed (for example by changing the cooling mode) provided that P_K is measured at S_r.

4.4 Method B

4.4.1 Efficiency index general formula ($\mathrm{EI_B}$)

This formula is only applicable to transformers with natural cooling AN, ONAN, KNAN, GNAN and LNAN. For forced cooled transformers, method A shall apply.

The general way to calculate the efficiency index is given by Equation (7). This is different from the usual definition of rated power as per IEC 60076-1 as shown by this method. This method is named method B.

$$\mathrm{EI_B} = \frac{kS_u}{kS_u + P_0 + k^2 T_f P_k} \quad \text{(p.u.)} \qquad (7)$$

where

P_0 is the no-load loss measured in W at rated voltage, rated frequency and on rated tap;

P_k is the measured load loss in W at the rated current and the rated frequency on the rated tap corrected to the reference temperature of 85 °C;

S_u is the rated power in VA of the transformer or autotransformer as defined in IEEE C57.12.80 on which P_k is based. S_u is used for distinction from S_r;

k is the load factor;

T_f is the temperature correction factor used to correct the losses from the standard reference temperature to the reference temperature used for calculation of the EI at a load factor lower than 1.

This method should be applied when an efficiency value is not specified by the purchaser or in local regulation.

4.4.2 Efficiency index at 50 % loading ($\mathrm{EI_{B50}}$)

In some countries, regulations are based on an efficiency index calculated according to method B (Equation (7)) at a load factor k of 50 %.

The efficiency index when the load factor k = 50 % is calculated with Equation (8):

$$\mathrm{EI_{B50}} = \frac{0{,}5\, S_u}{0{,}5\, S_u + P_0 + 0{,}25 \times T_f \times P_k} \quad \text{(p.u.)} \qquad (8)$$

where

T_f shall be taken as unity.

The exact correction factor T_f depends at least on the type of winding conductor (copper or aluminum) and the reference temperature at full load and ratio of eddy to I^2R losses.

In some countries, for transformers with an assumed average winding temperature (yearly average ambient plus reduced temperature rise due to under-loading conditions) at 50 % load factor, of 55 °C for liquid immersed transformers, and 75 °C for dry type transformers, T_f is approximated to an arbitrary value of 0,91.

Other values of T_f are based on the temperature correction of losses given in IEC 60076-1 and IEC 60076-2.

If T_f is not equal to 1, the value of T_f shall be given when $\mathrm{EI_{B50}}$ is stated.

S_u is the rated power of the transformer or autotransformer as defined in IEEE 57.12.80.

NOTE There is no provision for cooling losses in the formula, and different ratings for different cooling modes are not accounted for.

5 Specification of energy performance

The energy performance of a transformer may be specified in one of the following ways:

a) minimum PEI (method A, see 4.3) with load and no load loss capitalisation values;

b) maximum load losses and maximum no load losses;

c) minimum efficiency index at a load factor of 50 % $\mathrm{EI_{B50}}$ (method B, see 4.4).

To minimize the total cost of ownership (TCO) of the transformer, a loss capitalisation method should be used with all methods in addition to the minimum requirement. See Annex A.

Additional requirements may be added, for example, by specifying the level of total losses or the level of individual losses or the efficiency at another load factor and/or power factor.

NOTE Specifying a k_PEI with PEI will achieve the same goal as far as compliance with this standard is concerned, nevertheless this may not produce the optimum economical design.

6 Energy performance levels

6.1 General

This document provides two levels of recommended minimum PEIs, two levels of recommended losses and two levels of recommended efficiency indexes at a load factor of 50 %:

- level 1 is for basic energy performance;
- level 2 is for high energy performance.

The level chosen should be economically validated for the intended application.

For transformers having a rated power not included in these tables, the value of efficiency shall be linearly interpolated between the figures given for the nearest higher and lower rated powers:

a) 6.2.1 and 6.3.1 can be applied to all sizes and types of transformers in the scope;

b) 6.2.3 and 6.3.2 are included for the rationalization of transformer cores and coils for transformers generally produced in mass production;

c) 6.2.3 and 6.3.3 are applicable to particular sizes and types of transformers and are included because they reflect practices in some countries.

NOTE 1 In addition, Annex A provides a general method to compare energy performances and Annex C provides Japanese practices.

NOTE 2 Tables 5, 11 and 12 are derived from US Federal regulation. 10 CRF 431.196.

6.2 Liquid immersed transformers

6.2.1 Minimum PEI method A

6.2.1.1 PEI values for single-phase transformers with $U_m \leq 12$ kV and $S_r \leq 100$ kVA

For single-phase two winding transformers with

- $U_m \leq 12$ kV,
- $S_r \leq 100$ kVA,
- a second winding maximum voltage ≤ 1,1 kV,
- a de-energised tapping range ≤ ± 5 %,

Table 1 applies.

Table 1 – PEI values for single-phase transformers with $U_m \leq 12$ kV and $S_r \leq 100$ kVA

Rated power kVA	**PEI level 1** %	**PEI level 2** %
15	98,38	98,48
25	98,50	98,65
33	98,61	98,80
50	98,73	98,89
100	98,90	99,08

6.2.1.2 PEI values for transformers with $U_m \leq 36$ kV and $S_r \leq 3\,150$ kVA

For two winding transformers, single or three phase with vector group Dyn or Yzn

- with $U_m \leq 36$ kV,
- $S_r \leq 3\,150$ kVA,
- with a second winding maximum voltage ≤ 1,1 kV,
- with a de-energised tapping range ≤ ± 5 %,
- not within the applicability of 6.2.1.1, Table 2 applies.

Conditions for the application of the PEI are given in Clause 5.

Three-phase or single-phase transformers shall be evaluated against the rated power of the individual transformer.

Table 2 – PEI values for transformers with U_m ≤ 36 kV and S_r ≤ 3 150 kVA

	U_m ≤ 24 kV		24 kV < U_m ≤ 36 kV	
Rated power kVA	**PEI level 1** %	**PEI level 2** %	**PEI level 1** %	**PEI level 2** %
≤25	97,992	98,445	97,742	98,251
50	98,741	99,014	98,584	98,891
100	98,993	99,194	98,867	99,093
160	99,122	99,281	99,012	99,191
250	99,210	99,363	99,112	99,283
315	99,248	99,395	99,154	99,320
400	99,297	99,439	99,209	99,369
500	99,330	99,465	99,247	99,398
630	99,373	99,500	99,295	99,437
800	99,416	99,532	99,343	99,473
1 000	99,431	99,541	99,360	99,484
1 250	99,483	99,544	99,418	99,487
1 600	99,488	99,550	99,424	99,494
2 000	99,495	99,558	99,432	99,502
2 500	99,504	99,568	99,442	99,514
3 150	99,506	99,572	99,445	99,518
NOTE Although the values in this table have been developed from 50 Hz transformer data, they are also applicable to 60 Hz transformers.				

National practices may require the use of the highest voltages for equipment up to (but not including) 52 kV (such as U_m = 38,5 kV or U_m = 40,5 kV), when the rated voltage is less than 36 kV. This is considered to be an unusual case and, for these transformers, the requirements for power transformers with U_m = 36 kV in the Table 2 apply.

6.2.1.3 PEI values for transformers with U_m > 36 kV or S_r > 3 150 kVA

For transformers not covered by Table 1 or Table 2, Table 3 applies.

Conditions for the application of PEI are given in Clause 5.

Three-phase or single-phase transformers shall be evaluated against the rated power of the individual transformer.

Table 3 – PEI values for transformers with U_m > 36 kV or S_r >3 150 kVA

Rated power kVA	**PEI level 1** %	**PEI level 2** %
> 3 150 and ≤ 4 000	99,465	99,532
5 000	99,483	99,548
6 300	99,510	99,571
8 000	99,535	99,593
10 000	99,560	99,615
12 500	99,588	99,640
16 000	99,615	99,663
20 000	99,639	99,684
25 000	99,657	99,700
31 500	99,671	99,712
40 000	99,684	99,724
50 000	99,696	99,734
63 000	99,709	99,745
80 000	99,723	99,758
≥ 100 000	99,737	99,770
NOTE Although the values in this table have been developed from 50 Hz transformer data, they are also applicable to 60 Hz transformers.		

6.2.2 Maximum load losses and maximum no load losses for transformers with rated frequency equal to 50 Hz

For two-winding transformers

- with a rated frequency of 50 Hz,
- with U_m ≤ 24 kV,
- S_r ≤ 3 150 kVA,
- with a second winding maximum voltage ≤ 1,1 kV,
- with a de-energised tapping range ≤ ± 5 %,

Table 4 applies.

Table 4 – Maximum load losses and maximum no load losses for transformers with rated frequency equal to 50 Hz

	Level 1		Level 2	
Rated power kVA	**Maximum load losses** (in W)	**Maximum no-load losses** (in W)	**Maximum load losses** (in W)	**Maximum no-load losses** (in W)
≤ 25	900	70	600	63
50	1 100	90	750	81
100	1 750	145	1 250	130
160	2 350	210	1 750	189
250	3 250	300	2 350	270
315	3 900	360	2 800	324
400	4 600	430	3 250	387
500	5 500	510	3 900	459
630	6 500	600	4 600	540
800	8 400	650	6 000	585
1 000	10 500	770	7 600	693
1 250	11 000	950	9 500	855
1 600	14 000	1 200	12 000	1 080
2 000	18 000	1 450	15 000	1 305
2 500	22 000	1 750	18 500	1 575
3 150	27 500	2 200	23 000	1 980
NOTE In some countries, higher losses are allowed in regulations for transformers outside the scope of this table, for example with a wider tapping range, dual LV windings or higher voltage.				

If economically justified, compliant with local regulation and agreed between the manufacturer and the purchaser, for transformers outside the scope of this table, the loss values in this table can be increased by not more than 20 %.

6.2.3 Efficiency index method B

6.2.3.1 60 Hz transformers

For two-winding transformers:

- with S_r ≤ 2 500 kVA three-phase or ≤ 833 kVA single-phase,
- with a rated frequency of 60 Hz,

Table 5 applies.

For transformers not covered by Table 5 and when an efficiency value is not specified by the purchaser or in local regulation, the values in Table 2 or Table 3 shall be applied preferably using a method A efficiency calculation. For these transformers, calculation using method B with values from Table 2 or Table 3 is possible. In this case, for forced cooling transformers, the cooling losses shall be taken into account.

For applications where the load factor is not close to 50 %, the load factor or capitalization values shall be provided by the purchaser.

This table is based on rated frequency 60 Hz transformers using a winding temperature of 55 °C.

Table 5 – EI_{B50} value for liquid-immersed 60 Hz transformers

Single phase			Three phase		
Rated power kVA	EI_{B50} % Level 1	EI_{B50} % Level 2	Rated power kVA	EI_{B50} % Level 1	EI_{B50} % Level 2
≤ 10	98,62	98,70	≤15	98,36	98,65
15	98,76	98,82	30	98,62	98,83
25	98,91	98,95	45	98,76	98,92
37,5	99,01	99,05	75	98,91	99,03
50	99,08	99,11	112,5	99,01	99,11
75	99,17	99,19	150	99,08	99,16
100	99,23	99,25	225	99,17	99,23
167	99,25	99,33	300	99,23	99,27
250	99,32	99,39	500	99,25	99,35
333	99,36	99,43	750	99,32	99,40
500	99,42	99,49	1 000	99,36	99,43
667	99,46	99,52	1 500	99,42	99,48
833	99,49	99,55	2 000	99,46	99,51
			2 500	99,49	99,53

NOTE Level 1 values are in compliance with the United States of America Department of Energy (DOE) ruling 2010 and level 2 values are in compliance with the amended ruling 2016.

6.2.3.2 50 Hz transformers

For two-winding transformers

- with $S_r \leq 3\,150$ kVA,
- with a rated frequency of 50 Hz,

Table 6 applies.

For transformers not covered by Table 6 and when an efficiency value is not specified by the purchaser or in local regulation, the values in Table 2 or Table 3 shall be applied preferably using a method A efficiency calculation. For these transformers, calculation using method B with values from Table 2 or Table 3 is possible. In this case, for forced cooling transformers, the cooling losses shall be taken into account.

For applications where the load factor is not close to 50 %, the load factor or capitalization values shall be provided by the purchaser.

This table is based on 50 Hz transformers using T_f equal to 0,91, calculated from the maximum loss values given in Table 4.

Table 6 – EI_{B50} value for liquid-immersed 50 Hz transformers

Rated power kVA	**EI_{B50}** **level 1** %	**EI_{B50}** **level 2** %
≤ 25	97,849	98,429
50	98,657	99,004
100	98,925	99,178
160	99,078	99,271
250	99,175	99,360
315	99,214	99,394
400	99,267	99,440
500	99,300	99,464
630	99,344	99,499
800	99,364	99,515
1 000	99,372	99,518
1 250	99,451	99,520
1 600	99,455	99,526
2 000	99,459	99,530
2 500	99,463	99,539
3 150	99,466	99,544

6.3 Dry type transformers

6.3.1 Minimum PEI value method A

6.3.1.1 PEI values with U_m ≤ 36 kV and S_r ≤ 3 150 kVA

For two-winding transformers

- with U_m ≤ 36 kV,
- S_r ≤ 3 150 kVA,
- with a second winding maximum voltage ≤ 1,1 kV,

with a de-energised tapping range ≤ ± 5 %,

Table 7 applies.

Conditions for the application of PEI are given in Clause 5.

Table 7 – PEI values for dry type transformers with U_m ≤ 36 kV and S_r ≤ 3 150 kVA

	U_m ≤ 24 kV		24 kV ≤ U_m ≤ 36 kV	
Rated power kVA	**PEI** level 1 %	**PEI** level 2 %	**PEI** level 1 %	**PEI** level 2 %
≤ 50	97,668	97,922	97,377	97,662
100	98,485	98,653	98,296	98,485
160	98,654	98,791	98,486	98,640
250	98,875	98,991	98,735	98,865
400	98,984	99,129	98,858	99,020
630	99,082	99,158	98,968	99,053
800	99,194	99,235	99,093	99,140
1 000	99,253	99,291	99,160	99,203
1 250	99,288	99,325	99,199	99,240
1 600	99,332	99,366	99,248	99,287
2 000	99,355	99,388	99,275	99,312
2 500	99,386	99,418	99,309	99,345
3 150	99,419	99,449	99,347	99,381
NOTE Although the values in this table have been developed from 50 Hz transformer data, they are also applicable to 60 Hz transformers.				

National practices may require the use of the highest voltages for equipment up to (but not including) 52 kV, when the rated voltage is less than 36 kV (such as U_m = 38,5 kV or U_m = 40,5 kV). This is considered to be an unusual case, where the requirements are those for the power transformer with U_m = 36 kV.

6.3.1.2 PEI values for transformers with U_m ≤ 36 kV and S_r > 3 150 kVA

For transformers not within the conditions of Table 7, Table 8 applies.

Conditions for the application of the PEI are given in Clause 5.

Table 8 – PEI values for transformers with U_m ≤ 36 kV and S_r > 3 150 kVA

Rated power kVA	**PEI** level 1 %	**PEI** level 2 %
> 3 150 and ≤ 4 000	99,348	99,382
5 000	99,354	99,387
6 300	99,356	99,389
8 000	99,357	99,390
≥ 10 000	99,357	99,390

6.3.1.3 PEI value for transformers with U_m > 36 kV

Table 9 – PEI values for transformers with U_m > 36 kV

Rated power MVA	**PEI** level 1 %	**PEI** level 2 %
≤ 4	99,158	99,225
5	99,200	99,265
6,3	99,242	99,303
8	99,298	99,356
10	99,330	99,385
12,5	99,370	99,422
16	99,416	99,464
20	99,468	99,513
25	99,521	99,564
31,5	99,551	99,592
40	99,567	99,607
50	99,585	99,623
≥ 63	99,590	99,626

Minimum PEI values for MVA ratings that fall in between the ratings given in Table 9 shall be calculated by linear interpolation.

6.3.2 Maximum load loss and maximum no load loss for transformers with rated frequency equal to 50 Hz

For two-winding transformers

- with U_m ≤ 24 kV,
- S_r ≤ 3 150 kVA,
- with a second winding maximum voltage ≤ 1,1 kV,
- with a de-energised tapping range ≦ ± 5 %,

Table 10 applies.

Table 10 – Maximum load loss and maximum no load loss for transformers with rated frequency equal to 50 Hz

	Level 1		**Level 2**	
Rated power kVA	**Maximum load losses** (in W)	**Maximum no-load losses** (in W)	**Maximum load losses** (in W)	**Maximum no-load losses** (in W)
≤ 50	1 700	200	1 500	180
100	2 050	280	1 800	252
160	2 900	400	2 600	360
250	3 800	520	3 400	468
400	5 500	750	4 500	675
630	7 600	1 100	7 100	990
800	8 000	1 300	8 000	1 170
1 000	9 000	1 550	9 000	1 395
1 250	11 000	1 800	11 000	1 620
1 600	13 000	2 200	13 000	1 980
2 000	16 000	2 600	16 000	2 340
2 500	19 000	3 100	19 000	2 790
3 150	22 000	3 800	22 000	3 420

NOTE In some countries, higher losses are allowed in regulations for transformers outside the scope of this table, for example with a wider tapping range, dual LV windings or higher voltage.

If economically justified, compliant with local regulation and agreed between the manufacturer and the purchaser, for transformers outside the scope of this table, the loss values in this table can be increased by not more than 20 %.

6.3.3 Efficiency index method B at 50 % load factor

6.3.3.1 60 Hz transformers

6.3.3.1.1 Single-phase transformers

For two-winding transformers

- with $S_r \leq 833$ kVA,
- with a rated frequency of 60 Hz,

Table 11 applies.

This table is based on transformers with a rated frequency of 60 Hz, based on a winding temperature of 75 °C.

For applications where the load factor is not close to 50 %, the load factor or capitalization values shall be provided by the purchaser.

Table 11 – EI_{B50} values for single-phase dry type 60 Hz transformers

	Level 1 %			**Level 2** %		
Insulation level withstand voltage	**< 60 kV**	**≥60 kV** **≤ 95 kV**	**> 95 kV**	**< 60 kV**	**≥ 60 kV** **≤ 95 kV**	**> 95 kV**
Rated power kVA	EI_{B50}	EI_{B50}	EI_{B50}	EI_{B50}	EI_{B50}	EI_{B50}
≤ 15	98,10	97,86		98,10	97,86	
25	98,33	98,12		98,33	98,12	
37,5	98,49	98,30		98,49	98,30	
50	98,60	98,42		98,60	98,42	
75	98,73	98,57	98,53	98,73	98,57	98,53
100	98,82	98,67	98,63	98,82	98,67	98,63
167	98,96	98,83	98,80	98,96	98,83	98,80
250	99,07	98,95	98,91	99,07	98,95	98,91
333	99,14	99,03	98,99	99,14	99,03	98,99
500	99,22	99,12	99,09	99,22	99,12	99,09
667	99,27	99,18	99,15	99,27	99,18	99,15
833	99,31	99,23	99,20	99,31	99,23	99,20

NOTE Level 1 values are in compliance with the United States of America Department of Energy (DOE) ruling 2010 and level 2 values are in compliance with the amended ruling 2016.

6.3.3.1.2 Three-phase transformers

For two-winding transformers

- with $S_r \leq 2\,500$ kVA,
- with a rated frequency of 60 Hz,

Table 12 applies.

For transformers not covered by Table 12 and when an efficiency value is not specified by the purchaser or in local regulation, the values in Table 7, Table 8 or Table 9 shall be applied, preferably using a method A efficiency calculation. For these transformers, calculation using method B with values from Table 7, Table 8 or Table 9 is possible.

This table is based on transformers with a rated frequency of 60 Hz based on a winding temperature of 75 °C. For applications where the load factor is not close to 50 %, the load factor or capitalization values shall be provided by the purchaser.

Table 12 – EI_{B50} values for three-phase dry type 60 Hz transformers

	Level 1 %			**Level 2** %		
Insulation level withstand voltage	**< 60 kV**	**≥ 60 kV** **≤ 95 kV**	**> 95 kV**	**< 60 kV**	**≥ 60 kV** **≤ 95 kV**	**> 95 kV**
Rated power kVA	**EI_{B50}**	**EI_{B50}**	**EI_{B50}**	**EI_{B50}**	**EI_{B50}**	**EI_{B50}**
≤15	97,50	97,18		97,50	97,18	
30	97,90	97,63		97,90	97,63	
45	98,10	97,86		98,10	97,86	
75	98,33	98,12		98,33	98,13	
112,5	98,49	98,30		98,52	98,36	
150	98,60	98,42		98,65	98,51	
225	98,73	98,57	98,53	98,82	98,69	98,57
300	98,82	98,67	98,63	98,93	98,81	98,69
500	98,96	98,83	98,80	99,09	98,99	98,89
750	99,07	98,95	98,91	99,21	99,12	99,02
1 000	99,14	99,03	98,99	99,28	99,20	99,11
1 500	99,22	99,12	99,09	99,37	99,30	99,21
2 000	99,27	99,18	99,15	99,43	99,36	99,28
2 500	99,31	99,23	99,20	99,47	99,41	99,33

NOTE Level 1 values are in compliance with the United States of America Department of Energy (DOE) ruling 2010 and level 2 values are in compliance with the amended ruling 2016.

6.3.3.2 50 Hz transformers

For two-winding transformers

- with $S_r \leq 3\,150$ kVA,
- with a rated frequency of 50 Hz,

Table 13 applies.

For applications where the load factor is not close to 50 %, the load factor or capitalization values shall be provided by the purchaser.

This table is based on 50 Hz transformers using T_f equal to 0,91, calculated from the maximum loss values given in Table 10.

Table 13 – EI_{B50} values for dry type 50 Hz transformers

Rated power kVA	EI_{B50} Level 1	EI_{B50} Level 2
≤ 50	97,707	97,958
100	98,529	98,694
160	98,693	98,825
250	98,905	99,017
400	99,009	99,158
630	99,110	99,180
800	99,226	99,258
1 000	99,286	99,316
1 250	99,316	99,345
1 600	99,359	99,387
2 000	99,380	99,406
2 500	99,410	99,434
3 150	99,444	99,468

7 Tolerance

7.1 General

The maximum losses and minimum efficiencies in tables are not intended to include tolerances.

7.2 Losses

- The measured values of load and no-load losses shall not be greater than the appropriate value given in the tables.
- If the agreed value of any guaranteed loss is lower than the appropriate value given in the table, then the tolerances as set out in IEC 60076-1 may be used for the purpose of acceptance or rejection provided that the appropriate value given in the tables is not exceeded.
- The treatment of any losses in excess of guarantees which do not lead to rejection shall be subject to the contract or to the agreement between the manufacturer and the purchaser.

7.3 PEI

- No tolerances are applicable to the minimum PEI value given in the tables as it is a minimum value.
- The PEI calculated from the declared and the measured values of load and no-load losses shall not be lower than the PEI value as set out in the tables.
- In addition the tolerance prescribed in IEC 60076-1 applies unless otherwise specified on the individual guaranteed losses.

Annex A
(informative)

Capitalisation of losses

A.1 General theory, concept of capitalisation

Capitalisation of losses is an effective means of minimising the total cost of transformers, taking into account the initial cost of the transformer and the lifetime cost of the electricity supplying the losses. Capitalisation of losses will increase the initial cost of the transformer over the value that is required to meet the basic specification, but the additional investment is justified by the capitalisation calculation and the consequential reduction of losses.

In essence, the process of capitalisation involves the calculation of the value today of the savings from reduced losses over the lifetime of the transformer. This means that the energy savings need to be calculated along with their yearly value. In turn, this means that the cost of the electricity saved needs to be predicted over a 30 to 50 year period for the analysis. The production of energy consumed in losses and the cost of electricity, considered for each year of the analysis period and discounted at an appropriate interest rate to represent their value today, gives the total value of losses to be evaluated against the cost of reducing the losses.

This calculation of the net present value of electricity in the future is inevitably a prediction, and thus involves a significant degree of uncertainty. The calculation of the appropriate capitalisation factors involves judgement and a sophisticated financial approach and should be carried out by experts with specialist knowledge of the issues. The capitalisation factor may be subject to significant regional variations due to differences in electricity production and distribution, and the cost of capital.

The tender for the transformer is then assessed on the basis of the initial cost plus the capitalised value of load and no-load losses so that the transformer with the lowest overall lifecycle costs (TCO = total cost of ownership) can be selected.

The capitalisation of losses is considered as the best method of optimizing the economic efficiency of the transformers.

Depending on the forecast economic conditions, the use of the capitalisation formula can result in transformer efficiencies better than those given in the tables. In these circumstances, using a higher efficiency transformer is appropriate.

If using the capitalisation formula would result in transformer efficiencies lower than those in the table, then the value in the table shall be used as a minimum because this represents a minimum standard reflecting established practices justified by long-term sustainable environmental considerations.

The initial cost of the transformers is not the only cost, and it should be associated with the cost of the installation under circumstances where sizes and weight are limited by infrastructure or transport considerations. These restrictions need to be included in the transformer specification, and the transformer optimised within these limitations.

All parameters and equations provided here represent basic explanations of the most important parameters, such as energy price and discount rates. A deeper investigation for each parameter by the user is recommended.

A.2 Impact of capitalisation values

Increasing the capitalisation values will result in a decrease in losses and an increase in initial cost, size and weight up to the point at which the cost of further decreasing the losses equals the capitalisation values, or to the point where the extra size and weight exceeds the limits in the specification.

It is important that relevant external factors such as carbon prices are included in the costs saved – these may already be included in the cost of electricity through the ETS[1] scheme or may need to be added in separately.

The capitalisation values represent the avoided costs associated with the marginal cost of energy due to no-load and load losses saved.

A.3 Capitalisation formula

A.3.1 General

To be fully relevant, capitalisation should be based on the forecast cost of energy for each year of the transformer's life, and on the actual losses during this period, and relate these future cash flows to today's money using the appropriate discount rate.

The losses used for capitalisation evaluation should include the cooling losses, with the no-load losses for the part always on, and with the load losses for the variable part.

The total cost of ownership is then defined by:

$$\mathrm{TCO} = IC \times A \times (P_0 + P_{\mathrm{c0}}) + B \times (P_{\mathrm{k}} + P_{\mathrm{cs}} - P_{\mathrm{c0}}) \qquad \text{(A.1)}$$

where

IC is the initial cost of the transformer; this cost may include installation costs such as foundation and erection costs (requires a more sophisticated evaluation);

P_0 is the no-load loss (kW) measured at the rated voltage and rated frequency, on the rated tap;

P_{c0} is the cooling power (kW) needed for no-load operation;

P_{k} is the load loss (kW) due to the load, measured at the rated current and rated frequency on the rated tap at a reference temperature;

P_{cs} is the total cooling power (kW) needed for operation at the rated power (including three-winding operation if any);

A is the factor representing the cost of capitalisation of no-load losses in cost per kW;

B is the factor representing the cost of capitalisation of the losses due to load in cost per kW.

In the event that different transformer technologies are used, additional differences related to installation costs should be considered.

---

[1] ETS: Emissions Trading System. The overall carbon content of electricity in Europe is controlled at an EU level through the ETS. This means that pan-European measures are used for controlling CO_2, as any national measures which are applied to reduce CO_2 simply provide scope for other countries to increase their CO_2 emissions to take advantage of the extra headroom then made available. Inclusion of CO_2 costs in the price of electricity is one measure to encourage CO_2 reductions without having dysfunctional effects.

A.3.2 Calculation of factor A

A is the cost of capitalisation of no-load losses in cost per kW.

The no-load losses and their associated cooling losses are present as soon as the transformer is energized. Therefore, the capitalisation cost is the valorization cost of energy multiplied by the operating time over the full life expectancy of the transformer as shown in Equation (A.2):

$$A=\sum_{j=1}^{n}\frac{O_{0j}\times C_j}{(1+i_j)^j} \tag{A.2}$$

where

O_{0j} is the operating time of the transformer at year j in h;

C_j is the valorisation of the energy at year j in cost per Wh if losses are expressed in W;

i_j is the real discount rate at year j in per unit;

n is the life expectancy of the transformer in years.

NOTE 1 Discount rates can be expressed in either real (excluding inflation) or nominal (including inflation) terms, with both leading to identical answers providing the associated cash flows are also expressed in similar terms. However, the use of real discount rates simplifies the calculations as it assumes that all costs rise identically at the rate of inflation. If a particular cost rises in excess or below inflation, for example the marginal cost of electricity, then this excess above inflation can be more easily dealt with through a modification of the discount rate used. Accordingly, all discount rates used in this analysis are real.

For simplification, if the discount rate is considered constant and the cost of energy (in real terms) equal to that at the mid-life of the transformer, then assuming that the transformer is always energized, at year n Equation (A.2) can be simplified to the form shown in Equation (A.3):

$$A=8760\times C_{n/2}\times\frac{\frac{1}{1+i}\left(1-\left(\frac{1}{1+i}\right)^n\right)}{1-\frac{1}{1+i}}=8760\times C_{n/2}\times\frac{1-\left(\frac{1}{1+i}\right)^n}{i} \tag{A.3}$$

where

$C_{n/2}$ is the evaluation of the energy at mid-life of the transformer in cost per kWh if losses are expressed in kW;

i is the discount rate fixed over the whole life of transformer (n years);

n is the useful economic life of the transformer in years, which in the past has been close to the transformer's physical life expectancy (30 to 50 years).

NOTE 2 Use of $C_{n/2}$ is an approximation and overvalues the losses somewhat, but is acceptable in the context of other uncertainties.

A.3.3 Calculation of factor B

B is the capitalisation cost of the losses due to load. It is highly dependent on the load profile.

The load of a transformer can usually be split between the fixed load which is constant and present all year round, and the variable load which depends on ambient conditions and may be present only part of the time. Figure A.1 illustrates this load split.

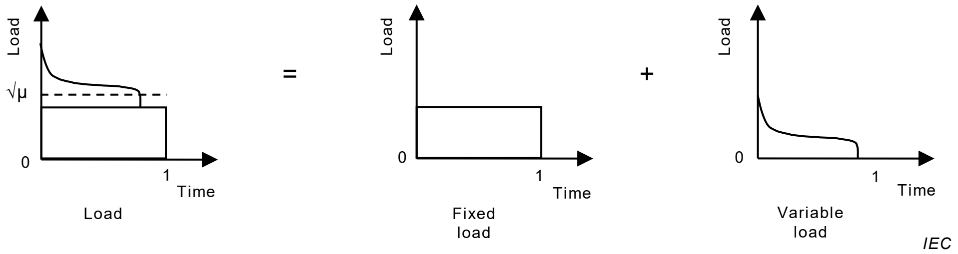

Figure A.1 – Load profile

For the sake of calculation, it is useful to define the average load loss factor (μ) as the square of the RMS value of the instantaneous load factors by:

$$\mu = \frac{1}{T}\int_0^T (k(t))^2 dt \tag{A.4}$$

where

T is equivalent to one year; if $k(t)$ is defined per h T is 8 760 h; if $k(t)$ is defined per minutes T is 525 600 min;

$k(t)$ is the load factor as a function of time.

The load losses capitalisation cost comes as the sum of the load factors multiplied by the cost of energy and corrected by the increase of load and the increase of transformer installed base. In Equation (A.5), the losses are split into two parts, with each one weighted by its time base utilization:

$$B = \sum_{j=1}^{n} \frac{\mu \times c_j \times (O_{aj} \times T_{aj} + O_{fj} \times T_{fj})}{(1+i_j)^j} \left(\frac{1+C_{\mu j}}{1+C_{aj}}\right)^{2j} \tag{A.5}$$

where

μ is the average load loss factor as defined in Equation (A.4);

C_j is the total cost of the energy at year j in cost per Wh if losses are expressed in W;

i_j is the discount rate at year j in per unit;

O_{aj} is the operating time of the transformer at variable load during year j in h;

O_{fj} is the operating time of the transformer at fixed load during year j in h, usually 8 760 h if the transformer is operated all year round;

T_{aj} is the share of variable load in the total load loss factor at year j;

T_{fj} is the share of fixed load in the total load loss factor at year j;

$T_{aj} + T_{fj} = 1$

n is the life expectancy of the transformer in years;

$C_{\mu j}$ is the rate of load loss factor increase at year j;

C_{aj} is the rate of installed power increase at year j.

Usually $C_{\mu j}$ and C_{aj} are taken equal as zero, which corresponds to a situation where the investment is assessed on the basis that the average loading of the transformer is invariant. If this is not the case, special care shall be taken to avoid overloading the transformer during a certain year, as if $C_{\mu j}$ is greater than C_{aj}, the final factor is greater than one.

If the transformer is energized all year round and if the cost of energy is considered constant and equal to the energy evaluation at the mid-life of the transformer, and if usage of the transformer is assumed as invariant during its whole life, and if the discount rate is considered constant, then the formula can be simplified as shown in Equation (A.6):

$$B=\mu\times C_{n/2}\times(O_\mathrm{a}\times T_\mathrm{a}+8760\times T_\mathrm{f})\times\frac{\dfrac{(1+C_\mu)^2}{(1+i)\times(1+C_\mathrm{a})^2}\times\left[1-\left(\dfrac{(1+C_\mu)^2}{(1+i)\times(1+C_\mathrm{a})^2}\right)^n\right]}{1-\dfrac{(1+C_\mu)^2}{(1+i)\times(1+C_\mathrm{a})^2}} \tag{A.6}$$

where

μ is the average load loss factor as defined above;

$C_{n/2}$ is the valorisation of the energy at the mid-life of the transformer in cost per Wh if losses are expressed in W;

i is the discount rate in per unit;

O_a is the operating time of the transformer at variable load in h;

O_f is the operating time of the transformer at fixed load in h, usually 8 760 h if the transformer is operated all year round;

T_a is the share of variable load in the total load loss factor;

T_f is the share of fixed load in the total load loss factor;

$T_\mathrm{a} + T_\mathrm{f} = 1$

n is the life expectancy of the transformer in years;

C_μ is the rate of load loss factor increase;

C_a is the rate of installed power increase.

As a further simplification, if the load factors and load profile are assumed to remain constant in the future, then the formula may be simplified as shown in Equation (A.7):

$$B=\mu\times C_{n/2}\times(O_\mathrm{a}\times T_\mathrm{a}+8760\times T_\mathrm{f})\times\frac{1-\left(\dfrac{1}{1+i}\right)^n}{i} \tag{A.7}$$

For the meaning of the symbols, refer to Equation (A.5).

A.3.4 Use of *A* and *B* for tender evaluation

In a transformer enquiry, the user should give the values of *A* and *B* in terms of monetary value per kW (for example, €/kW). This allows the manufacturer to offer the most economical transformer taking into account the TCO implied by the capitalisation values.

During the tender evaluation process, the purchaser will evaluate each bid according to the TCO calculated using Equation (A.1) incorporating the guarantee load and no-load losses provided by the manufacturers.

The transformer manufacturer will therefore optimize the TCO in such way that the value of a reduction of losses is greater than the associated cost increase of the transformer.

The most economical transformer will be the one offering the lowest total cost of ownership as calculated with Equation (A.1). The economical evaluation of the bids should be based on this TCO.

A.3.5 Determination of factors A and B

Utility companies will already probably have a corporate value for factor A based on strategic policies, energy mix, governmental and political decisions, incentives for environmental concerns and prospective scenarios, discount rates, and investment time horizons. Factor B is normally derived from factor A by means of standardised loading profiles.

Industrial or private customers not subject to such considerations can determine values A and B in a simple manner with the formulae defined in this paragraph using the inputs defined as follows.

$$A = 8760 \times C_{n/2} \times \frac{1-(\frac{1}{1+i})^n}{i} \tag{A.8}$$

$$B = 8760 \times C_{n/2} \times \frac{1-(\frac{1}{1+i})^n}{i} \tag{A.9}$$

where

n is the useful economic life of the transformer in years;

$C_{n/2}$ is the forecast cost of electricity at mid useful economical life of the transformer in terms of monetary value per kWh;

i is the discount rate set by the company as appropriate for the investment proposed in p.u. By default, the weighted average costs of capital should be used unless an alternative specific rate has been calculated for the investment.

NOTE The sensitivity of the capitalization value to n decreases as n increases. The higher the cost of the energy, the greater the savings from a lower loss level will be, thus justifying a higher initial cost of the transformer. The lower the discount rate, the higher the present value of the losses will be. A low discount rate justifies high spending on reducing losses.

Determining load and operating time can be simplified as, for most of the industry, the base load is predominant and therefore T_a can be considered as negligible. The formula can then be simplified as shown in Equation (A.10), where μ can be well approximated:

$$\mu = (\frac{S}{S_r})^2 \tag{A.10}$$

where

S_r is the rated power of the transformer;

S is the average forecast load.

In the calculation of A (see Equation (A.8)), if the transformer is not energised continuously, the yearly 8 760 h can be adjusted to reflect the actual use of the transformer. For example, a two-shift industry would typically have a ratio of 2/3, resulting in 5 840 h.

In the calculation of B (see Equation (A.9)), if the transformer is not loaded continuously, the yearly 8 760 hours can be adjusted to reflect the actual use of the transformer. For example, a two-shift industry would typically have a ratio of 2/3, resulting in 5 840 h.

Annex B

(informative)

Efficiency based on a survey of world practices

B.1 General

The following table presents the set equations developed from an analysis of existing world standards and regulations in 2013 for distribution transformers with a primary voltage of 36 kV and below, liquid-filled or dry-type, single- or three-phase, from 5 kVA to 1 000 kVA on single-phase and from 15 kVA to 3 150 kVA on three-phase.

Tier 1 is the least efficient level and Tier 5 is the most efficient.

B.2 50 Hz efficiency

The equations in Table B.1 yield the per cent efficiency at 50 % of rated load for 50 Hz operation using method A described in 4.3 (i.e., based on power input).

Table B.1 – Efficiency equations for transformers with a primary voltage of 36 kV and below, from 5 kVA to 1 000 kVA single-phase and 15 kVA to 3 150 kVA three-phase, 50 Hz and 50 % load method A

Type	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Liquid-filled three-phase	$= 1 - \frac{0{,}037\,0}{S^{0{,}22}}$	$= 1 - \frac{0{,}031\,1}{S^{0{,}22}}$	$= 1 - \frac{0{,}027\,0}{S^{0{,}22}}$	$= 1 - \frac{0{,}022\,6}{S^{0{,}22}}$	$= 1 - \frac{0{,}019\,3}{S^{0{,}22}}$
Liquid-filled single-phase	$= 1 - \frac{0{,}035\,5}{S^{0{,}22}}$	$= 1 - \frac{0{,}029\,5}{S^{0{,}22}}$	$= 1 - \frac{0{,}025\,4}{S^{0{,}22}}$	$= 1 - \frac{0{,}021\,0}{S^{0{,}22}}$	$= 1 - \frac{0{,}016\,9}{S^{0{,}22}}$
Dry-type three-phase	$= 1 - \frac{0{,}062\,8}{S^{0{,}26}}$	$= 1 - \frac{0{,}051\,4}{S^{0{,}26}}$	$= 1 - \frac{0{,}042\,5}{S^{0{,}26}}$	$= 1 - \frac{0{,}035\,5}{S^{0{,}26}}$	$= 1 - \frac{0{,}029\,2}{S^{0{,}26}}$
Dry-type single-phase	$= 1 - \frac{0{,}062\,0}{S^{0{,}30}}$	$= 1 - \frac{0{,}049\,0}{S^{0{,}30}}$	$= 1 - \frac{0{,}041\,2}{S^{0{,}30}}$	$= 1 - \frac{0{,}035\,1}{S^{0{,}30}}$	$= 1 - \frac{0{,}031\,0}{S^{0{,}30}}$

B.3 60 Hz efficiency

The equations in Table B.2 yield the per cent efficiency at 50 % of the rated load for 60 Hz operation using Method B described in 4.4 (i.e., based on power output).

The equations in Table B.2 are the values in Table B.1 adjusted to convert to 60 Hz operation and using method B.

Table B.2 – Efficiency equations for transformers with a primary voltage of 36 kV and below, from 5 kVA to 1 000 kVA single-phase and 15 kVA to 3 150 kVA three-phase, 60 Hz and 50 % load method B

Type	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Liquid-filled three-phase	$= 1 - \frac{0{,}035\,84}{S^{0{,}227}}$	$= 1 - \frac{0{,}030\,19}{S^{0{,}227}}$	$= 1 - \frac{0{,}026\,27}{S^{0{,}227}}$	$= 1 - \frac{0{,}022\,03}{S^{0{,}227}}$	$= 1 - \frac{0{,}018\,51}{S^{0{,}227}}$
Liquid-filled single-phase	$= 1 - \frac{0{,}034\,6}{S^{0{,}227}}$	$= 1 - \frac{0{,}028\,99}{S^{0{,}227}}$	$= 1 - \frac{0{,}024\,76}{S^{0{,}227}}$	$= 1 - \frac{0{,}020\,31}{S^{0{,}227}}$	$= 1 - \frac{0{,}016\,49}{S^{0{,}227}}$
Dry-type three-phase	$= 1 - \frac{0{,}063\,52}{S^{0{,}26}}$	$= 1 - \frac{0{,}052\,7}{S^{0{,}26}}$	$= 1 - \frac{0{,}043\,83}{S^{0{,}26}}$	$= 1 - \frac{0{,}036\,82}{S^{0{,}26}}$	$= 1 - \frac{0{,}030\,45}{S^{0{,}26}}$
Dry-type single-phase	$= 1 - \frac{0{,}040\,44}{S^{0{,}30}}$	$= 1 - \frac{0{,}031\,32}{S^{0{,}30}}$	$= 1 - \frac{0{,}025\,85}{S^{0{,}30}}$	$= 1 - \frac{0{,}021\,69}{S^{0{,}30}}$	$= 1 - \frac{0{,}018\,96}{S^{0{,}30}}$

Annex C
(informative)

Japanese practices

C.1 General

Annex C refers to Japanese practices.

C.2 Scope

The requirements apply to two-winding transformers having both 50 Hz and 60 Hz, single-phase, from 5 kVA to 500 kVA, and three-phase from 10 kVA to 2 000 kVA excluding the following transformers:

- gas-filled transformers;
- H class insulation transformers;
- Scott-connected transformers and Leblanc and three- to single-phase;
- pole-mounted transformers;
- water-cooled type.

C.3 Maximum losses calculation methods

The method for measuring and calculating losses is shown in Equation (C.1).

$$E_\mathrm{a} = W_\mathrm{i} + (m/100)^2 \times W_\mathrm{c} \tag{C.1}$$

where

E_a total loss in W;

W_i no-load loss in W;

m load factor in %; the load factor is 40 % for 500 kVA or below and 50 % for 500 kVA and above;

W_c load loss in W.

NOTE Further information can be found in Japanese standards JIS C 4304 – 2013 (6 kV liquid-filled distribution transformers) and JIS C 4306 – 2013 (6 kV encapsulated-winding distribution transformers).

C.4 Maximum losses

The requirement specifies a weighted average of maximum losses that should be achieved across a production of the transformers in a year running from 1 April to 31 March. The maximum losses equations are specified in Table C.1.

Table C.1 – Maximum losses

Type	Number of phases	Rated frequency	Rated power kVA	Target standard value calculation formula of standard energy consumption efficiency	Category
Oil-filled transformer	One phase	50 Hz	≤ 500	$E = 11{,}2 \times (S_r)^{0{,}732}$	I
		60 Hz	≤ 500	$E = 11{,}1 \times (S_r)^{0{,}725}$	II
	Three phases	50 Hz	≤ 500	$E = 16{,}6 \times (S_r)^{0{,}696}$	III-1
		50 Hz	> 500	$E = 11{,}1 \times (S_r)^{0{,}809}$	III-2
		60 Hz	≤ 500	$E = 17{,}3 \times (S_r)^{0{,}678}$	IV-1
		60 Hz	> 500	$E = 11{,}7 \times (S_r)^{0{,}790}$	IV-2
Cast resin transformer	One phase	50 Hz	≤ 500	$E = 16{,}9 \times (S_r)^{0{,}674}$	V
		60 Hz	≤ 500	$E = 15{,}2 \times (S_r)^{0{,}691}$	VI
	Three phases	50 Hz	≤ 500	$E = 23{,}9 \times (S_r)^{0{,}659}$	VII-1
		50 Hz	> 500	$E = 22{,}7 \times (S_r)^{0{,}718}$	VII-2
		60 Hz	≤ 500	$E = 22{,}3 \times (S_r)^{0{,}674}$	VIII-1
		60 Hz	> 500	$E = 19{,}4 \times (S_r)^{0{,}737}$	VIII-2
Key E: Standard energy consumption efficiency of transformer (unit: W) S_r: Rated power of transformer (unit: kVA)					

In case of semi-standard products, the target standard value calculation formula of the standard energy consumption efficiency of each category is multiplied by the following value:

- oil-filled transformers: 1,10;
- cast resin transformers: 1,05.

Bibliography

IEC 60076-11, *Power transformers – Part 11: Dry-type transformers*

IEC 60076-16, *Power transformers – Part 16: Transformers for wind turbine applications*

IEC 60076-19, *Power transformers – Part 19: Rules for the determination of uncertainties in the measurement of losses on power transformers and reactors*

IEC 60146 (all parts), *Semiconductor converters*

IEC 61378 (all parts), *Converter transformers*

IEC 61378-1, *Converter transformers – Part 1: Transformers for industrial applications*

IEC 61869-1, *Instrument transformers – Part 1: General requirements*

EN 50329, *Railway applications – Fixed installations – Traction transformers*

IEEE C57.12.80, *IEEE Standard Terminology for Power and Distribution Transformers*

JIS C 4304 – 2013, *6 kV liquid-filled distribution transformers*

JIS C 4306 – 2013*, 6 kV encapsulated-winding distribution transformers*

10 CRF 431.196 US Federal regulation

This page deliberately left blank

NO COPYING WITHOUT BSI PERMISSION EXCEPT AS PERMITTED BY COPYRIGHT LAW

British Standards Institution (BSI)

BSI is the national body responsible for preparing British Standards and other standards-related publications, information and services.

BSI is incorporated by Royal Charter. British Standards and other standardization products are published by BSI Standards Limited.

About us

We bring together business, industry, government, consumers, innovators and others to shape their combined experience and expertise into standards -based solutions.

The knowledge embodied in our standards has been carefully assembled in a dependable format and refined through our open consultation process. Organizations of all sizes and across all sectors choose standards to help them achieve their goals.

Information on standards

We can provide you with the knowledge that your organization needs to succeed. Find out more about British Standards by visiting our website at bsigroup.com/standards or contacting our Customer Services team or Knowledge Centre.

Buying standards

You can buy and download PDF versions of BSI publications, including British and adopted European and international standards, through our website at bsigroup.com/shop, where hard copies can also be purchased.

If you need international and foreign standards from other Standards Development Organizations, hard copies can be ordered from our Customer Services team.

Copyright in BSI publications

All the content in BSI publications, including British Standards, is the property of and copyrighted by BSI or some person or entity that owns copyright in the information used (such as the international standardization bodies) and has formally licensed such information to BSI for commercial publication and use.

Save for the provisions below, you may not transfer, share or disseminate any portion of the standard to any other person. You may not adapt, distribute, commercially exploit, or publicly display the standard or any portion thereof in any manner whatsoever without BSI's prior written consent.

Storing and using standards

Standards purchased in soft copy format:

- A British Standard purchased in soft copy format is licensed to a sole named user for personal or internal company use only.
- The standard may be stored on more than 1 device provided that it is accessible by the sole named user only and that only 1 copy is accessed at any one time.
- A single paper copy may be printed for personal or internal company use only.

Standards purchased in hard copy format:

- A British Standard purchased in hard copy format is for personal or internal company use only.
- It may not be further reproduced – in any format – to create an additional copy. This includes scanning of the document.

If you need more than 1 copy of the document, or if you wish to share the document on an internal network, you can save money by choosing a subscription product (see 'Subscriptions').

Reproducing extracts

For permission to reproduce content from BSI publications contact the BSI Copyright & Licensing team.

Subscriptions

Our range of subscription services are designed to make using standards easier for you. For further information on our subscription products go to bsigroup.com/subscriptions.

With **British Standards Online (BSOL)** you'll have instant access to over 55,000 British and adopted European and international standards from your desktop. It's available 24/7 and is refreshed daily so you'll always be up to date.

You can keep in touch with standards developments and receive substantial discounts on the purchase price of standards, both in single copy and subscription format, by becoming a **BSI Subscribing Member**.

PLUS is an updating service exclusive to BSI Subscribing Members. You will automatically receive the latest hard copy of your standards when they're revised or replaced.

To find out more about becoming a BSI Subscribing Member and the benefits of membership, please visit bsigroup.com/shop.

With a **Multi-User Network Licence (MUNL)** you are able to host standards publications on your intranet. Licences can cover as few or as many users as you wish. With updates supplied as soon as they're available, you can be sure your documentation is current. For further information, email subscriptions@bsigroup.com.

Revisions

Our British Standards and other publications are updated by amendment or revision.

We continually improve the quality of our products and services to benefit your business. If you find an inaccuracy or ambiguity within a British Standard or other BSI publication please inform the Knowledge Centre.

Useful Contacts

Customer Services
Tel: +44 345 086 9001
Email (orders): orders@bsigroup.com
Email (enquiries): cservices@bsigroup.com

Subscriptions
Tel: +44 345 086 9001
Email: subscriptions@bsigroup.com

Knowledge Centre
Tel: +44 20 8996 7004
Email: knowledgecentre@bsigroup.com

Copyright & Licensing
Tel: +44 20 8996 7070
Email: copyright@bsigroup.com

BSI Group Headquarters

389 Chiswick High Road London W4 4AL UK