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Energy performance of large power transformers (Um > 36 kV or Sr ≥ 40 MVA)

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National foreword

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Foreword

This document (EN 50629:2015) has been prepared by CLC/TC 14, "Power transformers".

The following dates are fixed:

- latest date by which this document has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2016-06-25
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For the relationship with requirements of Commission Regulation (EC) see informative Annex ZZ, which is an integral part of this document.

Introduction

This European Standard has been prepared at the request of the European Commission under the mandate EC 24/2011 and applies to large power transformers covered by the COMMISSION REGULATION (EU) N. 548/2014 of 21 May 2014.

For large power transformers (LPT) the strict definition of efficiency based on transmitted and absorbed active power alone is not useful for evaluating the energy performance because the losses are either fixed (no load loss), or depend on current (load loss) and therefore conventional efficiency would be zero if only reactive power is transmitted (reactive power transmission is very important for network operation). The conventional calculation of efficiency is therefore not helpful for comparing transformer designs which may be used over a range of operating conditions.

In general for LPT it is not possible to give optimal values for load and no load losses for a particular rated power because of the variety of applications which affect the energy performance.

In order to define an index that is specific to the transformer design, but applicable to a wide range of uses, rather than a figure that varies from second to second depending on system conditions, it is essential to characterize the energy performance of power transformers. For this reason a metric – Peak Efficiency Index (PEI) – has been developed which is based on real power losses and total power transmitted and is independent of load phase angle, load factor and rated power.

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

Setting a reasonable value of minimum Peak Efficiency Index will be effective in improving the overall efficiency of the installed transformer population by eliminating transformers with poor efficiency, with the exception of some transformers subject to specific limitations.

The use of a minimum value of Peak Efficiency Index sets a floor for transformer efficiency performance, but the use of proper loss capitalisation for purchasing transformers is essential to select a transformer with the optimal economically justified level of efficiency. Users not using loss capitalisation are strongly encouraged to investigate the benefits of doing so.

For large units above 100 MVA the economically achievable efficiency of a transformer may be limited by the technical parameters of the network (e.g. impedance), and specific transport and installation constraints. As the units concerned are usually purchased by large transmission system owners, who typically use high values of loss capitalization, those units above 100 MVA already tend to be state of the art as far as efficiency is concerned.

For transformers with unusual configurations and/or very severe size or weight limitations it may be unreasonable to meet the minimum efficiency requirement for either technical or economic reasons. In these cases it will be acceptable to demonstrate that the highest reasonable level of efficiency has been achieved (see Clause 6).

It is considered that the approach to energy performance set out in this document could also be applicable in principle to transformers outside the scope of this standard.

1 Scope

This European Standard applies to new three-phase and single-phase power transformers with a highest voltage for equipment exceeding 36 kV and a rated power equal or higher than 5 kVA, or a rated power equal to or higher than 40 MVA regardless of the highest voltage for equipment.

The scope of this European Standard is the following:

- Defining the appropriate energy efficiency criteria;
- Setting of benchmark minimum efficiency levels for new transformers based on an assessment of the energy efficiency of the European transformer population installed in the last 10 years;
- Proposing higher minimum efficiency levels for improving the energy efficiency of new transformers;
- Providing guidance for consideration of Total Cost of Ownership.

This European Standard provides also a form for efficiency data collection to inform future efficiency benchmark levels.

NOTE 1 This standard covers the transformers under the EU Regulation N. 548/2014 and gives additional specific guidance for single phase transformers, autotransformers, multi winding transformers and for transformers with OD and OF cooling systems, necessary for the correct application of energy efficiency requirements to these categories of transformers.

Transformers considered to be out of the scope of this document are the following:

- instrument transformers, specifically designed to supply measuring instruments, meters, relays and other similar apparatus,
- transformers with low-voltage windings specifically designed for use with rectifiers to provide a DC supply,
- transformers specifically designed to be directly connected to a furnace,
- transformers specifically designed for offshore applications and floating offshore applications,
- transformers specially designed for emergency installations,
- transformers and auto-transformers specifically designed for railway feeding systems,
- earthing or grounding transformers, this is, three-phase transformers intended to provide a neutral point for system grounding purposes,
- traction transformers mounted on rolling stock, this is, transformers connected to an AC or DC contact line, directly or through a converter, used in fixed installations of railway applications,
- starting transformers, specifically designed for starting three-phase induction motors so as to eliminate supply voltage dips,
- testing transformers, specifically designed to be used in a circuit to produce a specific voltage or current for the purpose of testing electrical equipment,
- welding transformers, specifically designed for use in arc welding equipment or resistance welding equipment,
- transformers specifically designed for explosion-proof and underground mining applications,
- transformers specifically designed for deep water (submerged) applications,
- medium Voltage (MV) to Medium Voltage (MV) interface transformers up to 5 MVA,
- large power transformers where it is demonstrated that for a particular application, technically feasible alternatives are not available to meet the minimum efficiency requirements set out by EU REGULATION N. 548/2014,
- large power transformers which are like for like replacements in the same physical location/installation for existing large power transformers, where this replacement cannot be achieved without entailing disproportionate costs associated to their transportation and/or installation.

For dry type large power transformers Minimum PEI values have been published in European Regulation and these values are included in Annex A.

NOTE 2 To retain consistency, the same list of exclusions in the EU Regulation N. 548/2014, has also been reproduced here. Within the above EU exclusion list, some had been excluded simply because no PEI data was available to CENELEC at the time on which to base appropriate PEI levels. Consequently, as such information becomes available in the future, it may be possible to derive suitable PEI Levels. Accordingly these particular categories are listed in Clause 6 as suitable for future consideration.

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.

EN 60076 (all parts), *Power transformers (IEC 60076, all parts)*

EN 60076-19, *Power transformers — Part 19: Rules for the determination of uncertainties in the measurement of the losses on power transformers and reactors (IEC/TS 60076-19)*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in EN 60076-1:2011 and the following apply.

3.1
Large Power Transformer
LPT
power transformer with a highest voltage for equipment exceeding 36 kV and a rated power equal or higher than 5 kVA, or a rated power equal to or higher than 40 MVA regardless of the highest voltage for equipment

3.2
load factor
k
ratio of actual input current over the rated current of transformer

Note 1 to entry: Normally $0 \le k \le 1$.

3.3
transmitted apparent power
kS_r
product of the load factor and the rated power

3.4
Efficiency Index
EI
ratio of the transmitted apparent power of a transformer minus electrical losses to the transmitted apparent power of the transformer

3.5
Peak Efficiency Index
PEI
highest value of efficiency index that can be achieved at the optimum value of load factor

3.6
load factor of Peak Efficiency Index
k_{PEI}
load factor at which Peak Efficiency Index occurs

3.7
declared value
regulatory value given in Table 1 which is to be used for market surveillance activities

Note 1 to entry: According to EN 60076-1, ‘declared value’ and ‘guaranteed value’ refer to two different concepts. ‘Guaranteed Values’ relate to the values cited in the commercial contract, whereas ‘declared values’ are those values which are cited to establish compliance with EU Regulation N. 548/2014.

4 Efficiency and Efficiency Index calculation

4.1 General

The energy performance of a transformer can be stated in a variety of ways, principally by giving:

a) The no-load and load losses at rated load or at a particular reference power;
b) The efficiency at a defined power factor and particular load factor, for example 50 % or 100 % of rated load;
c) The Peak Efficiency Index and the load at which it occurs.

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

For the scope of this standard the Peak Efficiency Index has been chosen to set benchmark efficiency figures because it does not impose a particular load factor (which may vary greatly depending on the application) and because it does not depend explicitly on the rated power of the transformer. Peak efficiency is an intrinsic parameter of the transformer that does not depend on whether the transformer has alternative ratings depending on cooling modes.

The Peak Efficiency Index includes the losses associated with the cooling system that is in service in the no-load condition. If additional cooling is required at the load factor where PEI occurs, then the additional cooling loss required for this cooling shall be computed in the calculation of PEI. Any further additional cooling and associated cooling loss necessary to achieve rated power is excluded.

NOTE 1 This applies to transformers equipped with heat-exchangers which need pumps and fans to provide heat dissipation (e.g. ODAF, ODWF, OFWF, OFAF, OFAN).

NOTE 2 If the loss capitalisation method is used in the transformer procurement process, then it may be expected that the Peak Efficiency Index 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 (See Annex D).

4.2 Efficiency Index general formula

The Efficiency Index at load factor k is calculated in accordance with Formula 1:

$$EI(\mathrm{k}) = \frac{\mathrm{kS_r} - (\mathrm{P_0} + \mathrm{P_{c0}}) - (\mathrm{k^2 P_k} + \mathrm{P_{ck}(k)})}{\mathrm{kS_r}} \quad \text{(pu)} \qquad (1)$$

Where

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

P_{c0} is the electrical power required by the cooling system for no load operation, derived from the type test measurements of the power taken by the fan and liquid pump motors;

P_k is the measured load loss at rated current and rated frequency on the rated tap corrected to reference temperature according to EN 60076-1;

$P_{ck}(k)$ is the additional electrical power required (in addition to P_{c0}) by the cooling system for operation at k times the rated load derived from the type test measurements of the power taken by the fan and liquid pump motors;

S_r is the rated power of the transformer or autotransformer on which P_k is based;

k is the load factor.

NOTE 1 This approach respects the philosophy of EN 60076 (all parts) which refers the rated power to the rated voltage and current of one of the transformer windings.

The derivation of P_{ck} at k_{PEI} involves establishing the total power consumption of the fans and the pumps (from type test measurements) and then ascribing a proportion of this total cooling loss to that required at PEI loading. The proportion used is the ratio of the average electrical loss of the fans and pumps used at k_{PEI} and average yearly ambient temperature (20 °C unless otherwise specified) to the total electrical loss of the pumps and fans installed.

If fans and pumps have variable speed drives, an additional type test measurement may be required to determine P_{ck} at k_{PEI}.

NOTE 2 No routine measurements of cooling power consumption are required.

For the PEI calculation, the following shall be considered.

a) The reference temperature for liquid immersed transformers with rated average winding temperature rise less than or equal to 65 K for OF or ON, or 70 K for OD is 75 °C;
b) For transformers with other rated average winding temperature rise, the reference temperature is equal to the rated average winding temperature rise + 20 °C, or rated winding temperature rise + yearly external cooling medium average temperature, whichever is higher.

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

For the scope of this document and for 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.

4.3 Peak Efficiency Index

Under the assumption that the cooling at no load is sufficient to operate at k_{PEI} (this assumption is used to simplify the calculation), the load factor which maximises the Efficiency Index is given by:

$$k_{PEI} = \sqrt{\frac{P_0 + P_{c0}}{P_k}} \text{ (pu)} \qquad (2)$$

For symbols meaning refer to 4.2, Formula 1.

The formula to be used for Peak Efficiency Index calculation is therefore Formula 3, which is obtained from Formula (1) by replacing k with k_{PEI} as defined in Formula (2) and by assuming $P_{ck}(k_{PEI})=0$:

$$PEI = 1 - \frac{2(P_0 + P_{c0})}{S_r \sqrt{\frac{P_0 + P_{c0}}{P_k}}} \text{ (pu)} \qquad (3)$$

For symbols meaning refer to 4.2, Formula 1.

NOTE 1 Demonstration of the mathematical derivation is given in B.1.

NOTE 2 An example is given in B.2.2.

As mentioned in 4.1, if additional cooling is required at the load factors where PEI occurs, then the assumption $P_{ck}(k_{PEI}) = 0$ does not hold, then the term $P_{ck}(k_{PEI})$ shall be added to P_{c0} in the formula for PEI for the transformers in the scope of this standard.

$$\text{PEI} = 1 - \frac{2[\text{P}_0+\text{P}_{\text{c0}}+\text{P}_{\text{ck}}(k_{PEI})]}{\text{S}_\text{r}\sqrt{\frac{[\text{P}_0+\text{P}_{\text{c0}}+\text{P}_{\text{ck}}(k_{PEI})]}{\text{P}_\text{k}}}} \text{ (pu)} \quad (4)$$

NOTE 3 An example is given in B.2.3.

NOTE 4 The value of Formula 3 depends on the ratio $S_r/\sqrt{P_k}$ which does not vary significantly if S_r is changed (for example by changing cooling mode) provided P_k is measured at S_r.

5 Minimum Peak Efficiency Index values

5.1 Standardised values of Minimum PEI

The Minimum Peak Efficiency Index values for liquid immersed transformers are given in Table 1 and those for dry type LPT are given in Annex A.

The T1 values are based on the results of the survey described in Annex D set at approximately the level of the lower quartile (25 %). This is considered to be an achievable level of efficiency which is likely to be economically justified.

The T2 values are set at approximately the median level (50 %) of the surveyed transformer efficiencies and represent an ambitious target which needs to be applied with due consideration of economic efficiency. The intention is that these levels represent an ambition that needs to be validated.

These figures take into consideration the need to remove distortions introduced into the data collected by specific designs, the uneven spread of data over the size range, and the necessity for coordination with the efficiency standard for transformers with rated voltages lower than 36 kV and rated powers below 40 MVA (the resulted graph of PEI values versus the rated power values is reported in B.3).

Table 1 — Values of minimum Peak Efficiency Index for liquid immersed transformers

S_r (MVA)	PEI – T1 (%)	PEI – T2 (%)
≤ 4	99,465	99,532
5	99,483	99,548
6,3	99,510	99,571
8	99,535	99,593
10	99,560	99,615
12,5	99,588	99,640
16	99,615	99,663
20	99,639	99,684
25	99,657	99,700
31,5	99,671	99,712
40	99,684	99,724
50	99,696	99,734
63	99,709	99,745
80	99,723	99,758
≥ 100	99,737	99,770
NOTE For clarity the PEI values in the table are expressed in percent.		

For rated powers different from the ones reported in Table 1, the corresponding PEI value can be obtained by linear interpolation from the two adjacent values.

The PEI requirements apply to transformers and auto-transformers.

For auto-transformers the reference power for PEI values is the rated power.

For transformer with rated power lower than 4 MVA it might not be possible (technically and economically justified) to reach the PEI value given for 4 MVA.

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

The PEI requirements in Table 1 apply to autotransformers and separate winding transformers having three windings as follows. Assuming that ratings are x/y/z, then:

- if x and y are equal and z is lower than or equal to one third of x or y, the PEI shall be the one corresponding to x or y rating and the losses of winding z shall not be considered for PEI calculation (e.g. 600/600/65 MVA)
- if x is equal to the sum of y and z, the PEI shall be the one corresponding to x rating and the three winding losses shall be considered for PEI calculation (e.g. 100/60/40 MVA)
- In all other cases, the PEI shall be the one corresponding to maximum of the three ratings. Load loss shall be measured for each winding pairs and the load combination to be used for PEI calculation is:

$$x \,/\, \mathrm{y}\frac{\mathrm{x}}{\mathrm{y}+\mathrm{z}} \,/\, \mathrm{z}\frac{\mathrm{x}}{\mathrm{y}+\mathrm{z}}$$

NOTE 1 In general, transformers of similar design criteria, but with more than two windings, have higher total losses and lower PEI values. This formula also allows for the verification of PEI requirements in transformers other than two winding transformers, such as three winding transformers and autotransformers. For the computation of the load loss for each winding, the criteria given in IEC 60076-8 can be taken as reference.

NOTE 2 E.g. for a 60/60/30 MVA, it is essential that the PEI limit be that of 60 MVA and the load combination for load loss calculation be:

$$60 \,/\, 60\frac{60}{60+30} \,/\, 30\frac{60}{60+30} \quad \Rightarrow \quad 60 \,/\, 40 \,/\, 20$$

The approach used for three winding transformers can be applied in principle to transformers with more than three windings.

For transformers with re-connectable windings PEI calculation shall be made based on loss measurements taken at the highest rated voltage(s).

Specific power transformers with factors such as size and weight limitations, transportation restrictions, unusual combinations of windings and voltages (see also D.4) may not meet PEI value of Table 1.

NOTE 3 Where these transformers do not meet the minimum PEI in Table 1, then it is important to show by using a proper method, as for example the capitalisation method given in Clause 7, that the transformer has the highest economically justified efficiency within the limitations of the intended application.

5.2 Optimization of transformer losses according to application

The minimum PEI value prescribed, which shall be met in all cases, can be obtained with different combinations of no load and load losses. This is equivalent to different load factors at which PEI occurs. The ratio of the load and no load losses needs to be tailored to the application in order to obtain the best actual efficiency in service. In order to achieve this, the following methods are available:

- Providing capitalisation values for no load and load losses that reflect the anticipated loading (this is the recommended method);
- Prescribing maximum values for no load and load losses;
- Specifying minimum efficiency index at a specific load factor.

NOTE 1 The associated PEI may occur at a different load factor.

NOTE 2 Typical values of the ratio between load and no load loss can range between 3 for heavily loaded transformers (such as GSU) up to 6-7 and sometimes more than 10 for lightly loaded units (i.e. transmission and distribution transformers).

5.3 Rating plate data

In addition to EN 60076-1 requirements, the following values shall be shown on the rating plate:

- PEI based on measurements;
- $k_{PEI,}$ at which PEI occurs in pu;
- P_0, the no load loss measured at rated voltage and rated frequency, on the rated tap;
- P_{c0}, the electrical power required by the cooling system for no load operation derived from the type test measurements of the power taken by the fan and liquid pump motors;
- P_k, the measured loss at rated current and rated frequency on the rated tap corrected to reference temperature according to EN 60076-1;
- Nature of the conductor (for instance copper, aluminium, copper/aluminium);
- Mass of the conductor;
- Nature of the core material (for instance silicone steel, amorphous steel);
- Mass of the active part, if different from the untanking mass.

5.4 Transformer asset data

In Annex C a pro-forma for further data collection is given. The scope of the pro-forma is to collect data for improving the present standard and to determine any issues that may arise in the general application of T2 values. A completed copy of the pro-forma shall be supplied to the purchaser of the transformer preferably in electronic format.

NOTE Such data collection is required for an effective review by the European Commission of the efficiency of the installed base of large power transformers and to provide efficiency benchmarks. The practical method to collect data in Annex C is currently under definition.

5.5 Tolerances, measurement uncertainties and market surveillance

5.5.1 Factory acceptance

No tolerances are applicable to the minimum PEI value.

The PEI calculated from the contractually guaranteed and the measured values of load and no-load losses shall be equal to or higher than the PEI value specified in this standard.

The test report of the transformers shall report the PEI value and the corresponding $k_{PEI.}$

The tolerances for the measured values to the guaranteed values of load and no-load losses are subject to agreement between manufacturer and purchaser within the limits prescribed by EN 60076-1.

The losses shall be measured in compliance with the methodologies stated in the EN 60076 series of standards in order to achieve an acceptable level of uncertainty.

5.5.2 Verification procedure for market surveillance

During the market surveillance, with reference to ANNEX III of the EU Regulation N. 548/2014, market surveillance authority will measure no load and load loss. PEI value shall then be calculated by the market surveillance authority by this formula:

$$PEI = 1 - \frac{2(P_{A0}+P_{Ac0})}{1{,}05 \cdot S_r \sqrt{\frac{P_{A0}+P_{Ac0}}{P_{Ak}}}} \text{ (pu)} \qquad (5)$$

Where

P_{A0} is the no load loss measured at rated voltage and rated frequency, on the rated tap by the market surveillance authority;

P_{Ac0} is the electrical power required by the cooling system for no load operation as determined by the market surveillance authority from the type test measurements of the power taken by the fan and liquid pump motors;

P_{Ak} is the measured load loss at rated current and rated frequency on the rated tap corrected to reference temperature according to EN 60076-1 by the market surveillance authority;

S_r is the rated power of the transformer or autotransformer on which P_k is based;

NOTE The factor 1,05 represents the verification tolerance on loss components which is allowed to market authority during surveillance checks according to ANNEX III of EU Regulation N.548/2014.

The test results of the loss measurements are expressed as a numerical quantity which is not an exact number but suffers from uncertainty. How wide this margin of uncertainty is depends on the quality of the test installation, particularly its measuring system, on the skill of the staff and on measurement difficulties presented by the test object. The submitted test result shall contain the most correct estimate that is possible, based on the measurements that have been carried out. This value shall be accepted as it stands. The uncertainty margin shall not be involved in the judgement of compliance for guarantees with no positive tolerance or tolerance ranges for performance data of the test object. However, a condition for acceptance of the whole test is that the measurements themselves have to fulfil certain requirements of quality (see EN ISO 9001).

The measurement uncertainty applicable to the market surveillance authority shall be:

- The expanded uncertainty, as defined in EN 60076-19 and referring to a coverage factor k = 2 (i.e. to a confidence level of about 95 % assuming a normal distribution).
- The measurement uncertainty defined in this way, expressed as a relative value shall not exceed 5 %.

This procedure is detailed in Annex F.

6 Transformers categories currently excluded

The following categories of transformers are considered to be relevant for energy performance evaluation criteria, but since no data was available, a decision on minimum peak efficiency levels was not taken. In the future, after appropriate data has been collected, they will be considered.

- transformers with low-voltage windings specifically designed for use with rectifiers to provide a DC supply (converter transformers),
- transformers specifically designed to be directly connected to a furnace,
- transformers specifically designed for offshore applications and floating offshore applications,
- transformers specially designed for emergency installations,
- transformers and auto-transformers specifically designed for railway feeding systems,
- gas insulated transformers.

7 Capitalisation of losses

Capitalisation of losses is considered to be the most economically correct method to optimize transformer design in accordance with the customer needs. The method is described in Annex E.

It is recognized that to get the benefits of standardization of transformer design, the capitalisation of losses is normally considered over the fleet of transformers rather than for individual units.

If the efficiency of a transformer purchased using a loss capitalisation formula exceeds the benchmark peak efficiency proposed for that transformer, it should be used, as the benchmark simply sets a lower floor for transformer efficiency – it does not attempt to set an optimal value.

Annex A
(normative)

Minimum PEI for dry type large power transformers

The following data are reproduced from Table I.8 of the COMMISSION REGULATION (EU) No 548/2014 of 21 May 2014, although not based on data collected by CENELEC.

Table A.1 — Minimum Peak Efficiency Index requirements for dry-type large power transformers

Rated Power (MVA)	Tier 1 (01.07.2015)	Tier 2 (01.07.2021)
	Minimum Peak Efficiency Index (%)	
≤ 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 A.1 shall be calculated by linear interpolation.

Annex B
(informative)

Peak Efficiency Index formula, graphs and calculations

B.1 Calculation of k_{PEI}

This part of Annex B shows the mathematical derivation of the load factor which maximizes the Efficiency Index.

Efficiency Index general formula is:

$$EI = \frac{kS_r - (P_0 + P_{c0}) - (k^2 P_k + P_{ck}(k))}{kS_r}$$

Under the assumption that the cooling at no load is sufficient to operate at k_{PEI} , the P_{ck} term in the general formula is neglected.

Hence, the function EI(k) is at its maximum when its derivative is null, then:

$$EI'(k) = \left[\frac{k.S_r - (P_0+P_{c0}) - k^2.P_k}{k.S_r}\right]'$$

So $$EI'(k) = \frac{\left[k.S_r - (P_0+P_{c0}) - k^2.P_k\right]'.k.S_r - \left[k.S_r - (P_0+P_{c0}) - k^2.P_k\right].\left[k.S_r\right]'}{[k.S_r]^2}$$

i.e. $$EI'(k) = \frac{\left[S_r - 2k.P_k\right].k.S_r - \left[k.S_r - (P_0+P_{c0}) - k^2.P_k\right].\left[S_r\right]}{k^2.S_r^2}$$

i.e. $$EI'(k) = \frac{k.S_r^2 - 2k^2.P_k.S_r - k.S_r^2 + (P_0+P_{c0}).S_r + k^2.P_k.S_r}{k^2.S_r^2}$$

i.e. $$EI'(k) = \frac{-k^2.P_k.S_r + (P_0+P_{c0}).S_r}{k^2.S_r^2}$$

i.e. $$EI(k) = \frac{-k^2.P_k + (P_0+P_{c0})}{k^2.S_r}$$

i.e. $$EI'(k) = \frac{(P_0+P_{c0})}{k^2.S_r} - \frac{P_k}{S_r}$$

it comes that η'(k) = 0 when: $$\frac{P_k}{S_r} = \frac{(P_0+P_{c0})}{k^2.S_r}$$

i.e. $$k^2 = \frac{(P_0+P_{c0})}{S_r}\frac{S_r}{P_k}$$

So the Peak Efficiency is a maximum when $k = k_{PEI} = \sqrt{\frac{(P_0+P_{c0})}{P_k}}$

And then

$$PEI = EI(k_{PEI}) = 1 - \frac{2(P_0+P_{c0})}{S_r\sqrt{\frac{P_0+P_{c0}}{P_k}}}$$

B.2 Graph of Efficiency Index and load factor with loss contributions

B.2.1 General

This paragraph shows in a graphical way what is the influence of P_0, P_{c0}, P_k and P_{ck} on the efficiency index EI(k) by means of two numerical examples. Such examples demonstrate also the rationale behind the prescription given in this standard about including either P_{c0} or [P_{c0} + $P_{ck}(k_{PEI})$] in the formula for PEI calculation.

B.2.2 Example of a typical ONAN or ONAN/ONAF transformer

Table B.1

Transformer data		
S_r	40000	kVA
P_0	20	kW
P_k	160	kW
Cooling consumption		
P_{c0}	0	kW
P_{ck} (step1 k > 0,75)	7	kW

According to 4.3, Formula (2) gives k_{PEI} = 0,354 and Formula (3) gives PEI = 99,717 %.

The graph in Figure B.1 shows the influence of loss parameters and as in this case there is no influence of the cooling system in the PEI determination.

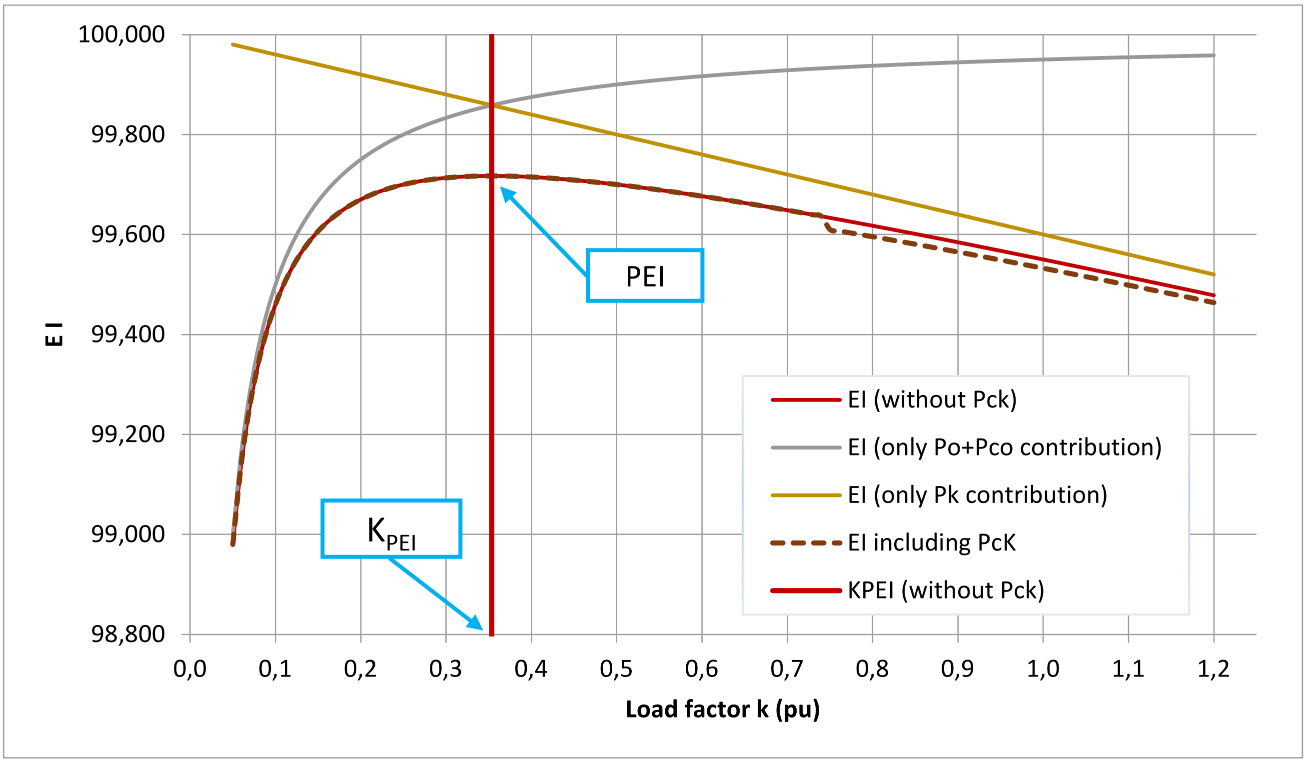


Figure B.1 — Graph illustrating relationship between efficiency index and load factor

B.2.3 Example of a typical ONAN or ONAN/ONAF transformer

Table B.2

Transformer data		
S_r	40000	kVA
P_0	28	kW
P_k	115	kW
Cooling consumption		
P_{c0}	3	kW
P_{ck} (step1 k>0,4)	7	kW
P_{ck} (step 1+2 k>0,75)	14	kW

According to Formula (2) in 4.3, k_{PEI} = 0,519. Since at 0.519 load factor the first stage of cooling is operating, for the calculation of PEI Formula (4) in 4.3 shall be used, giving: PEI = 99,701 %.

The graph in Figure B.2 shows as for the given data, not only P_{c0} has to be added to P_0, but also P_{ck} has to be taken into account in the PEI calculation for the part that is switched on before k_{PEI}. It shall be noticed that in the calculation of k_{PEI} the term P_{ck} is not considered anyway.

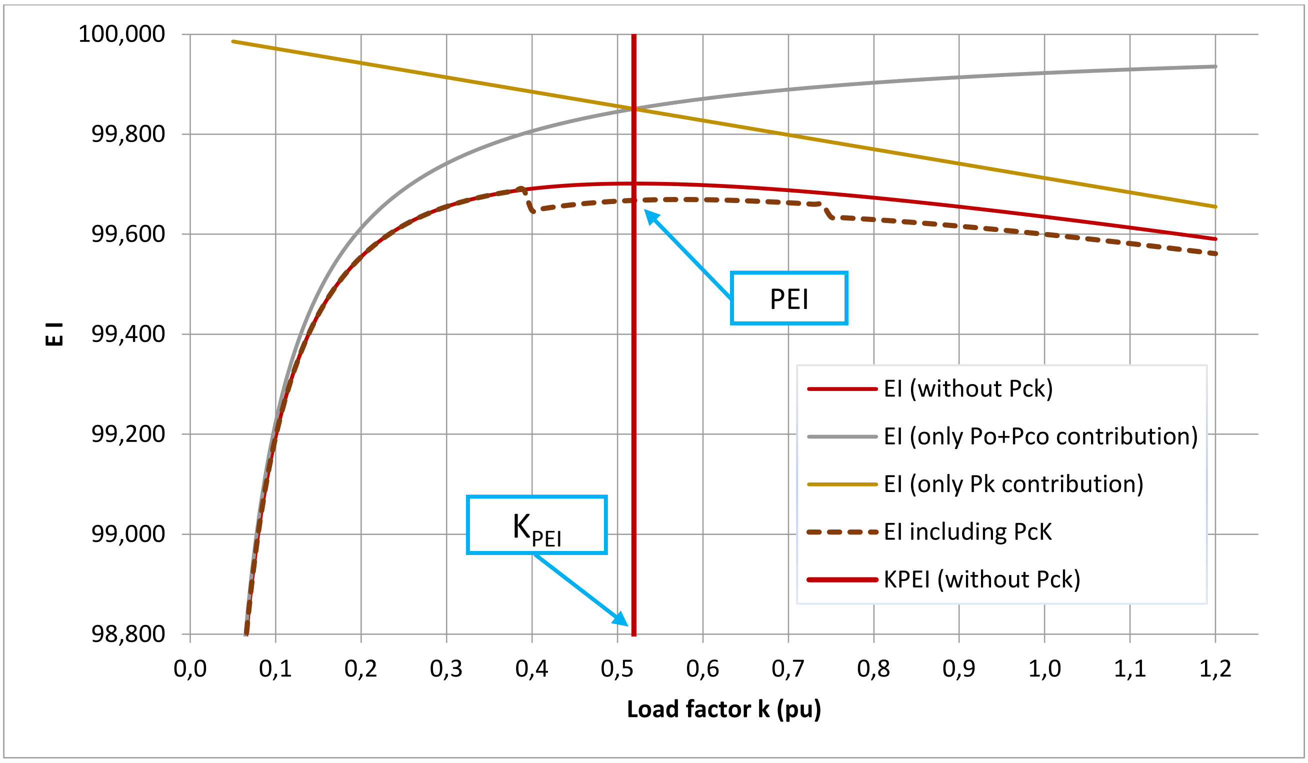


Figure B.2 — Graph illustrating relationship between efficiency index and load factor

B.3 Graphs of prescribed PEI values and rated power

This part of the annex shows the trend of the Peak Efficiency values prescribed in this standard and the rated power value of transformers.

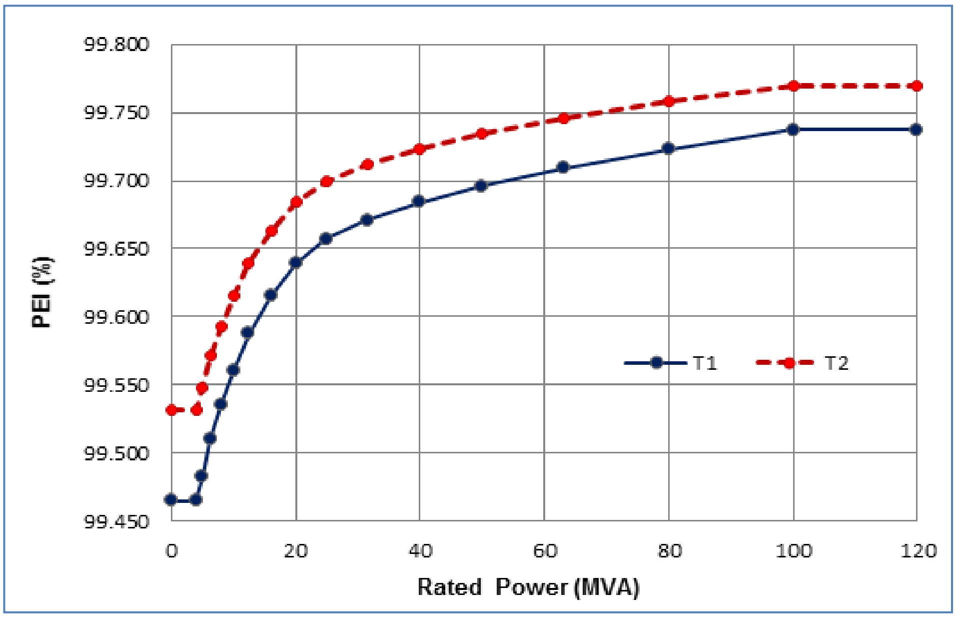


Figure B.3 — Graph of minimum Peak Efficiency Index

B.4 Independence of PEI to rated power

This part of the annex show that PEI value determined for a given transformer is independent of rated power assigned to such transformer.

PEI is:

$$PEI = 1 - \frac{2(P_0+P_{c0})}{S_r\sqrt{\frac{P_0+P_{c0}}{P_k}}} = 1 - \frac{2}{S_r}\sqrt{(P_0+P_{c0})P_k}$$

For a given transformer, load losses at the rated power are proportional to the square of the rated power:

$$P_{k2} = P_{k1}\left(\frac{S_{r2}}{S_{r1}}\right)^2$$

Replacing this into the PEI formula demonstrates independence of PEI to rated power.

Therefore:

$$PEI_2 = 1 - \frac{2}{S_{r2}}\sqrt{(P_0+P_{C0})P_{k2}}$$

Which becomes

$$PEI_2 = 1 - \frac{2}{S_{r2}}\sqrt{(P_0+P_{C0})P_{k1}\left(\frac{S_{r2}}{S_{r1}}\right)^2}$$

i.e.

$$PEI_2 = 1 - \frac{2}{S_{R2}}\left(\frac{S_{r2}}{S_{r1}}\right)\sqrt{(P_0+P_{C0})P_{k1}}$$

$$PEI_2 = 1 - \frac{2}{S_{r1}}\sqrt{(P_0+P_{C0})P_{k1}}$$

Then PEI is independent of the rated power

$PEI_2 = PEI_1$

B.5 Calculation of losses from PEI, k_{PEI} and S_r

This section gives some formulas which are obtained from the formulas given in 4.2 and 4.3 in order to help the user of this standard to get confidence with PEI methods prescribed in this standard.

NOTE It is important to remember if $P_{c0} \neq 0$ to use k_{PEI} calculated including P_{c0}.

No load loss:

$$(P_0 + P_{c0}) = \frac{(1 - PEI) \cdot S_r \cdot k_{PEI}}{2}$$

Load Loss:

$$P_k = \frac{(1 - PEI) \cdot S_r}{2 \cdot k_{PEI}}$$

Losses ratio:

$$\frac{\mathrm{P_k}}{\mathrm{P_0} + \mathrm{P_{c0}}} = \frac{1}{\mathrm{k_{PEI}^2}}$$

Other useful formulas to calculate P_k or P_0 having the PEI value, are:

$$(P_0 + P_{c0}) = \frac{[S_r \cdot (1 - PEI)]^2}{4 \cdot P_k}$$

$$P_k = \frac{[S_r \cdot (1 - PEI)]^2}{4 \cdot (P_0 + P_{c0})}$$

Annex C
(informative)

Form for data requested

C.1 Example of form for data requested

In the form below an example of the data to be required for energy performance investigation is reported. The purpose is to collect statistical data of all type of transformers.

Table C.1

Description	Measuring unit	Indications	Column to be filled
Category	--	*Generator Step-Up, transmission, network primary, distribution, furnace, rectifier, industrial applications, track side, HVDC, Other to be specified*	
Type of transformer		*Separate winding Transformer, Auto-Transformer*	
Number of units	(number)	*Of the same design*	
Frequency	(Hz)	*Value*	
Phase number	-	*1 or 3*	
Rated power	(MVA)	*Maximum rating power*	
Rated power of tertiary	(MVA)		
Cooling system	-	*ONAN, OFAF, ODAF, OFWF, OFAF, ONAN-ONAF, AN, AF, (dry type) or other combinations*	
Power absorbed by that portion of cooling system permanently on (P_{c0} - usually first stage)	(kW)		
Power absorbed by the cooling system at rated load (P_{ck} - usually full cooling power)	(kW)		
Rated voltage HV winding	(kV)		
Rated voltage MV winding	(kV)		
Connection symbol	**-**	Ref. EN 60076-1:2011, Clause 7	
Total range of tapping	(%)		
Type of tap changer	-	*OLTC, DETC, None*	
Voltage regulation winding	-	*HV, MV1, MV2*	

Description	Measuring unit	Indications	Column to be filled
Short-circuit impedance on rated tap	(%)		
PEI	(%)		
Load factor at which PEI occurs	(pu)	k_{PEI}	
No-load loss at rated voltage	(kW)		
Load Loss on the main tapping at rated power	(kW)		
Loss criteria	-	*Stated level of Maximum losses or Capitalization*	
No load loss capitalization	(€/W)		
Load loss capitalization	(€/W)		
Ref. temperature for load loss	(°C)		
Core Material		*Silicon steel, amorphous, others*	
Core mass	(kg)		
Sound Power Level	dB(A)	*At no load, rated voltage and rated frequency w/o cooling equipment*	
Conductor material		*Copper, aluminium, aluminium alloy, others*	
Conductor mass	(kg)	*if more than one use the format …/…*	
User company	-	*Name*	
User country	-	*Name*	
Manufacturer		*Name*	
Year of manufacturing		*Number*	
Reasons for exception from minimum PEI	-	*Size and weight limitations, Transport restrictions, Unusual combinations of windings and voltages, other*	
NOTE Track side: stationary rail way transformers.			

C.2 Indications for filling the table

In filling the table the data concerning cooling system, load loss and short-circuit impedance shall be referred to the maximum rated power of the transformer.

For three-phase bank consisting in three single-phase transformers, the data shall refer to a single-phase unit.

Annex D
(informative)

Benchmark of Peak Efficiency Index

D.1 General

To prepare this document for a number of transformers the loss data have been collected by users via CENELEC National Committees.

Whilst it is acknowledged that the optimal level of transformer efficiency is that at which the extra costs of the transformer are balanced by the savings in energy and other costs on a lifecycle basis, such an analysis is quite complicated because the optimum efficiency level will vary with local costs and electricity prices as well as transformer usage. In contrast, setting a minimum floor for efficiency should be more feasible as no attempt is being made to optimize. Instead optimization is achieved through the use of capitalisation rates which justify the exact efficiency above the minimum floor which is required.

Data from a wide range of oil immersed transformers has been submitted to the survey so that although the values can be considered to relate predominantly to the most common types (which are three phase two winding transformers without specific transport or installation limits), but the extremes represent transformers with particular technical or loss capitalisation requirements.

For this report peak efficiency index has been studied and evaluated on a large number of transformers and the result of the data analysis is that peak efficiency can be expressed approximately using the natural logarithm of the rated power as shown in the formula below.

$$PEI = a \cdot \ln(S_r) + b \qquad (D.1)$$

This annex displays the computed Peak Efficiency Index of the transformer installed in Europe since 2002.

D.2 Benchmark figures

The following tables characterise the data that has been collected in the survey.

The data collected were provided by a selection of European countries, and consist of a mixture of transformers acquired through tenders using capitalized losses and others using stated losses levels given in the Tender. The cooling system consumption has not always been provided on a consistent basis. Similarly different voltage levels, impedance etc are mixed in the proposed benchmark data.

Accordingly there are limitations in the data on which the analysis has been performed, and this has meant that the selection of the Peak Efficiency levels has not been to choose the optimal level, but rather to choose a reasonable minimum as an efficiency floor. Capitalisation can then be used to choose the optimal level above this floor.

The data has been analysed in two different ways:

- by number of installed units, this better represents the practical implementation of different designs used on the networks, since some particularly high or low efficiency designs are only for niche applications, have low installed numbers and the replication of these designs generally would not be economic;
- by transformer design, in this case each design is given equal weight, irrespective of the number of installed units, so that this represents the span of technically feasible designs.

Table D.1 — Benchmark figures by number of units (PEI)

S_r (MVA)	10	16	20	25	31,5	40	50	63	80	100	>100
Units	162	58	272	300	108	531	120	98	29	189	626
10 %	0,9968	0,9944	0,9963	0,9965	0,9967	0,9967	0,9974	0,9969	0,9977	0,9963	0,9972
25 %	0,9968	0,9959	0,9964	0,9965	0,9970	0,9967	0,9974	0,9969	0,9977	0,9967	0,9978
50 %	0,9968	0,9959	0,9964	0,9965	0,9977	0,9973	0,9977	0,9969	0,9983	0,9967	0,9983
75 %	0,9968	0,9959	0,9968	0,9969	0,9977	0,9975	0,9977	0,9977	0,9986	0,9973	0,9988
85 %	0,9968	0,9959	0,9968	0,9970	0,9977	0,9976	0,9977	0,9977	0,9986	0,9974	0,9988

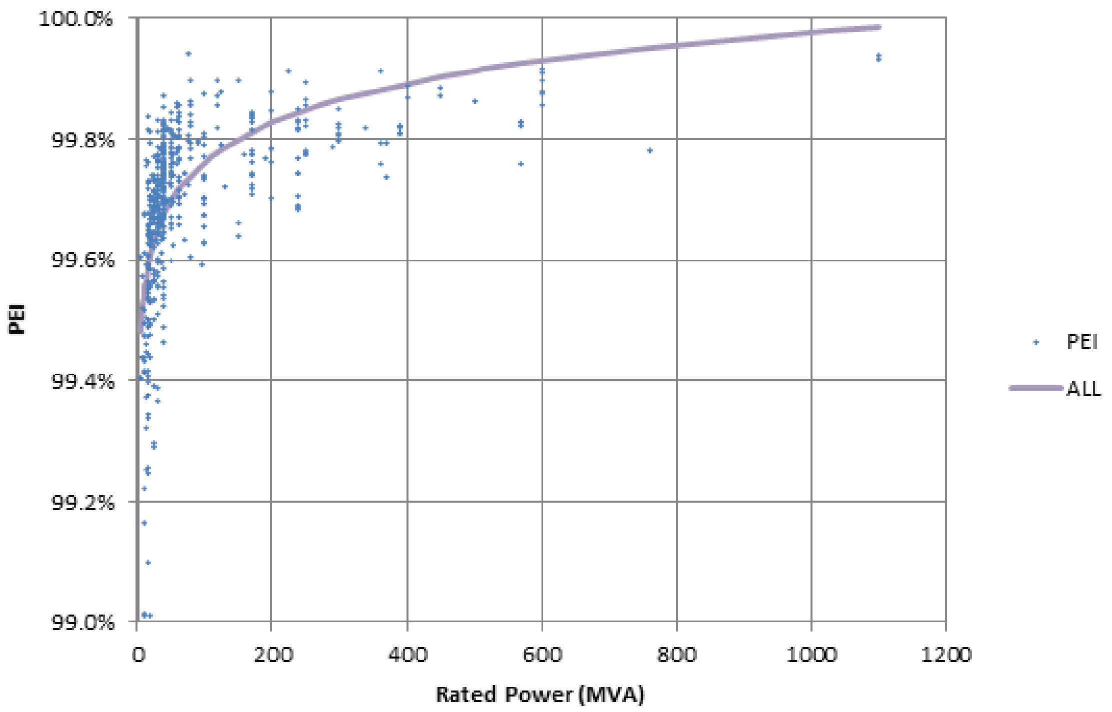
NOTE 25 % of the population have an efficiency lower than the lower quartile, 50 % of the population have an efficiency lower than the median and 25 % of the population have an efficiency higher than the upper quartile.

Table D.2 — Benchmark figures by design (PEI)

S_r (MVA)	10	16	20	25	31,5	40	50	63	80	100	>100
Designs	14	18	32	31	47	103	31	20	10	20	96
10 %	0,9882	0,9923	0,9948	0,9951	0,9959	0,9965	0,9966	0,9967	0,9962	0,9963	0,9972
25 %	0,9913	0,9937	0,9955	0,9957	0,9967	0,9968	0,9972	0,9970	0,9978	0,9967	0,9977
50 %	0,9948	0,9955	0,9964	0,9967	0,9971	0,9974	0,9976	0,9977	0,9983	0,9970	0,9982
75 %	0,9954	0,9962	0,9969	0,9970	0,9977	0,9977	0,9979	0,9981	0,9986	0,9976	0,9985
85 %	0,9966	0,9966	0,9971	0,9972	0,9977	0,9979	0,9981	0,9984	0,9988	0,9980	0,9988

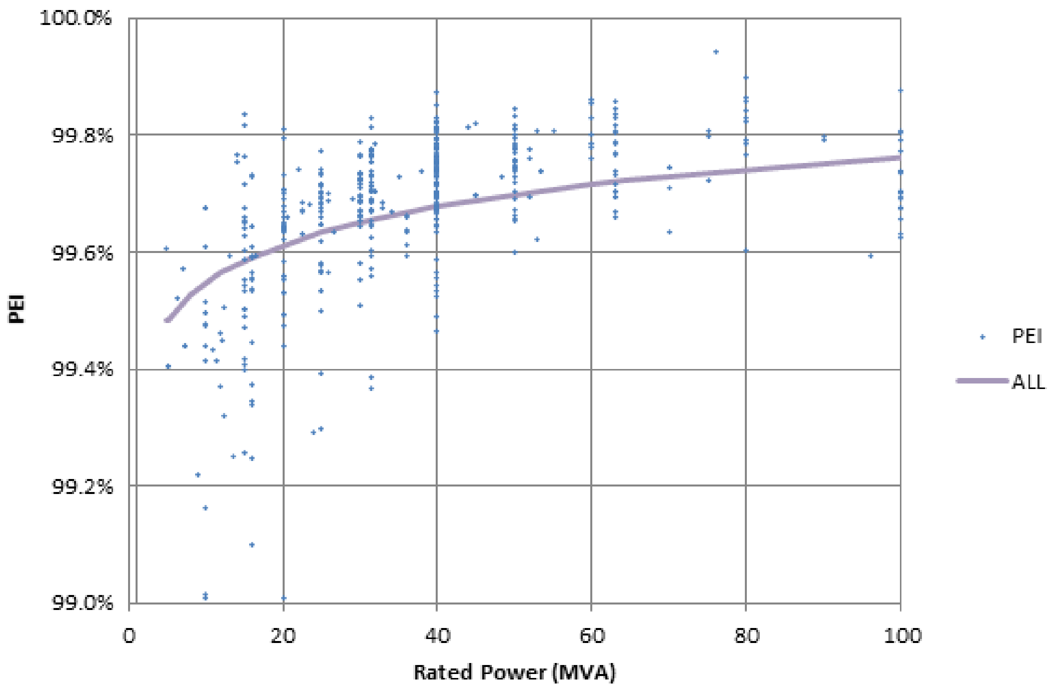
NOTE 25 % of the population have an efficiency lower than the lower quartile, 50 % of the population have an efficiency lower than the median and 25 % of the population have an efficiency higher than the upper quartile.

The main transformer characteristics in term of PEI from data collected are reported in the graphs below.



The subfigure represents the trend per number of units of the data collected up to 1000 MVA.

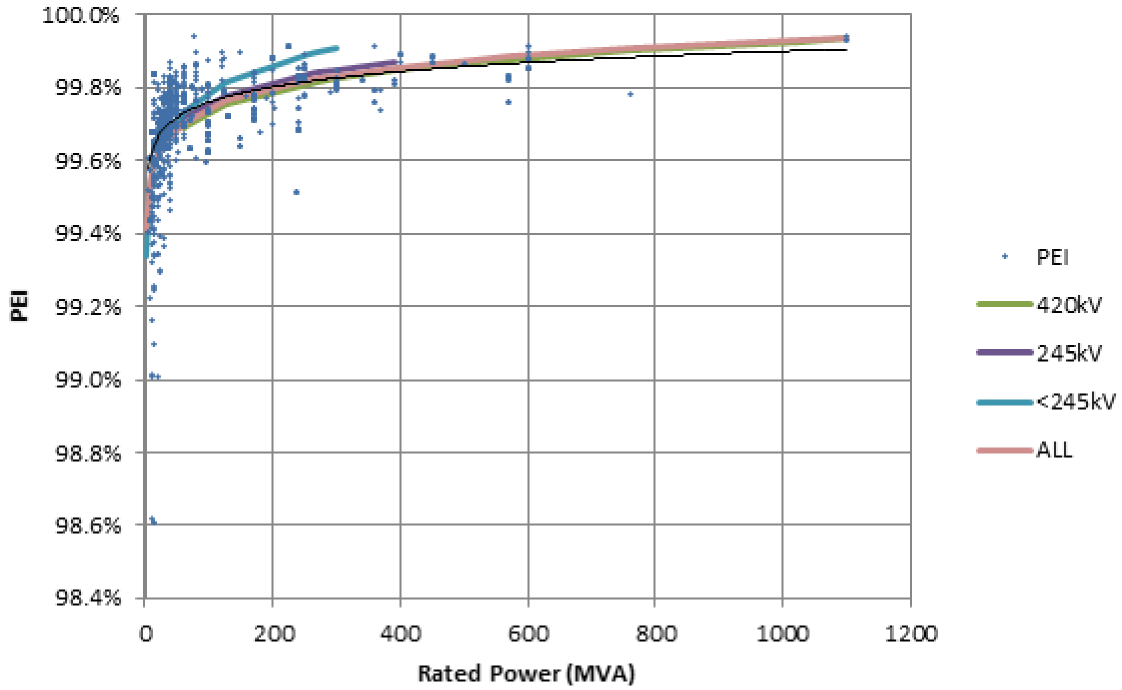
a)



The subfigure represents the trend per number of units of the data collected up to 100 MVA.

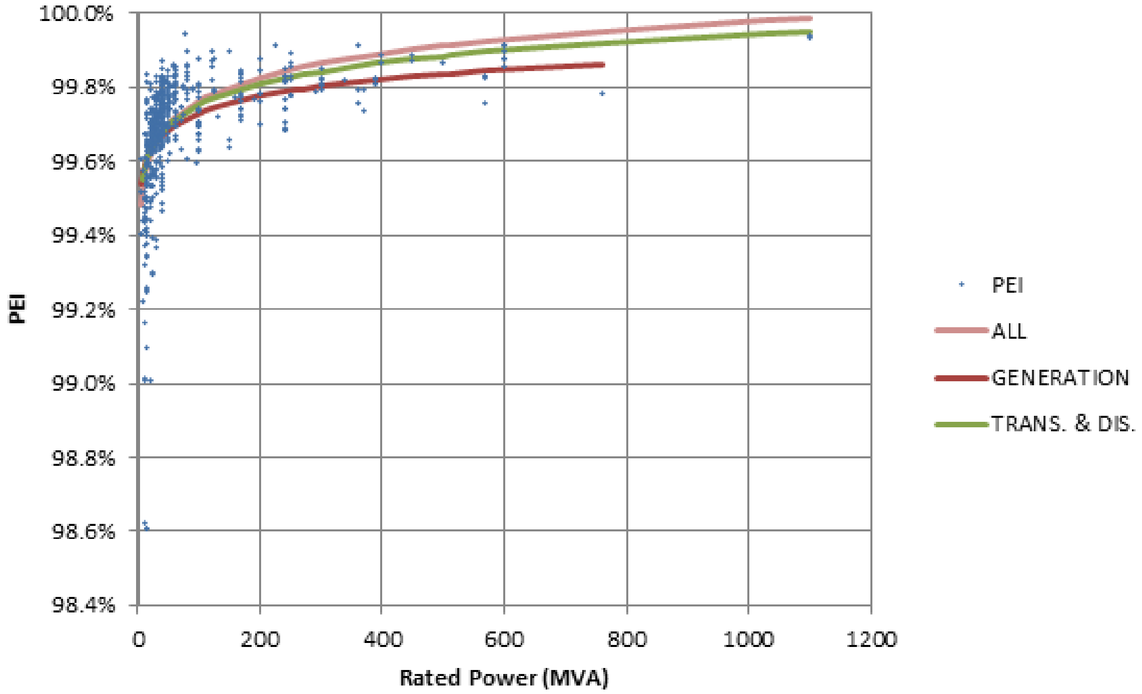
b)

Figure D.1 — PEI distribution



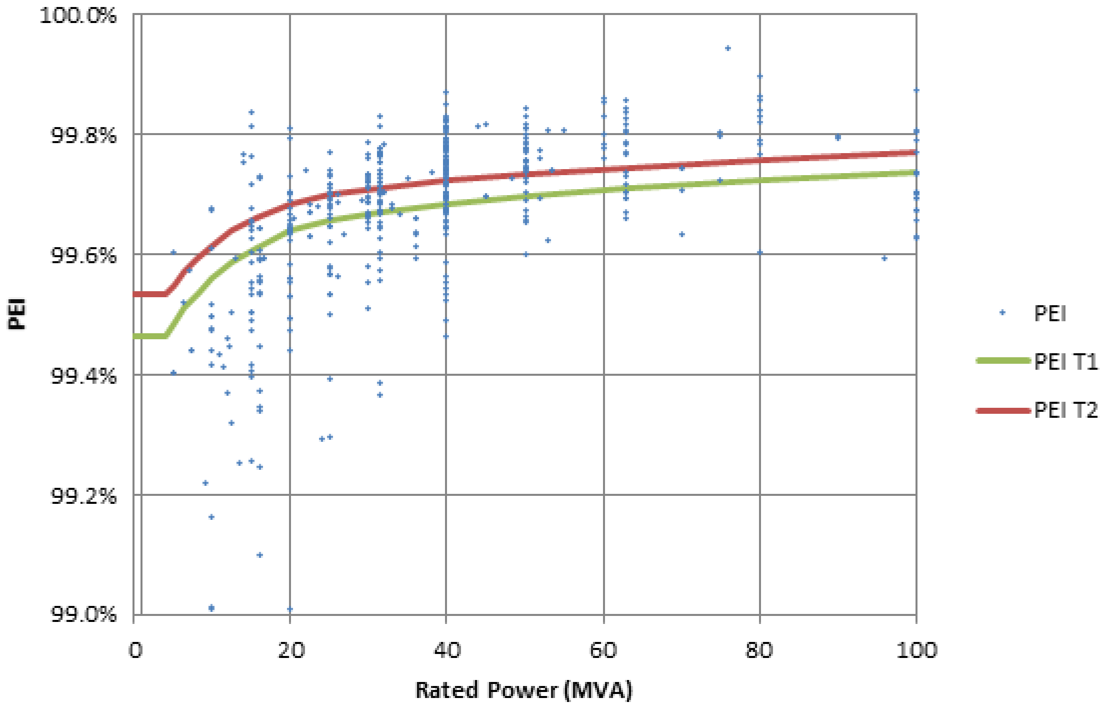
The graph represents the trend per number of units of the data collected up to 1000 MVA for different voltage levels.

Figure D.2 — PEI distribution per voltage class



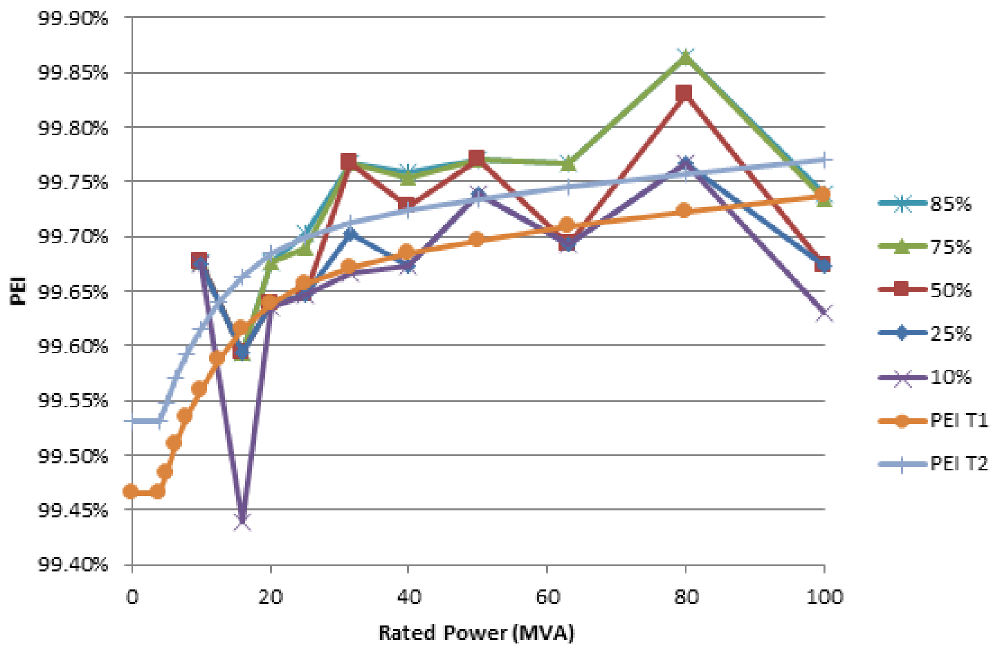
The graph represents a comparison of the trend of the data collected per design up to 1000 MVA for different transmission & distribution and generation transformers.

Figure D.3 — PEI distribution per usage



The graph represents the trend of the data collected up to 100 MVA against the values of minimum PEI.

Figure D.4 — PEI statistical distribution comparison with T1 and T2



The graph represents the trend of the data collected up to 100 MVA against the values of minimum PEI.

NOTE The 10 MVA can be considered outlier because most units have the same design.

Figure D.5 — Benchmark effective percentile values comparison with T1 and T2

D.3 Variations from the benchmark

D.3.1 General

There are a range of factors which may influence the efficiency of a transformer and therefore affect the value of efficiency in relation to the benchmark. The following is not a comprehensive list of factors, but it does represent some of the main reasons for variations in efficiency from the benchmark, and therefore where variation from the benchmark that can be explained by capitalisation of losses.

D.3.2 Autotransformers

Usually autotransformers have a higher peak efficiency than separate winding transformers of same rated power. In some cases, requirement for a third winding is provided.

If the tertiary winding has a rated power not exceeding 1/3 of the rated power of the autotransformer or it is provided only for compensation, its contribution to the total loss formation can be disregarded.

For other functional characteristic an allowance is required.

D.3.3 Voltage and insulation level

In principle a higher insulation level at a given rated voltage is expected to reduce transformer efficiency because of the insulation requirements.

In practice the effect is not evidenced in the data. As the rated voltage generally increases with the power no correction is proposed, but allowance could be required for transformers with low rated power and high voltage.

D.3.4 More than two windings

The efficiency of a transformer with more than two windings depends on the type of application and on the rated power of each winding.

This is true even for low rated power third winding, as usually the short circuit withstand requirement will impose a minimum design power of about ⅓ of the rated power. The data include approximately 40 % of transformers with a tertiary so the benchmark figures include the effect of the tertiary winding.

Transformers with many windings may require an allowance, particularly where several different voltages are required.

D.3.5 Short-circuit impedance

The short-circuit impedance of a transformer may have to be specified at a high value in order to reduce short circuit currents to a safe level for circuit breaker operation or because parallel operation is required. High impedance will reduce efficiency because of the increase in the magnetic leakage flux and the larger gap required between windings.

The data and the benchmark consider the majority of transformers with impedances between 10 % and 20 % so no allowance is proposed in this range but an allowance may be required for higher impedances.

D.3.6 Tapping range

The tapping range is determined by the requirement to overcome the voltage drop caused by the transformer impedance and the range of supply voltage variation.

In principle the inclusion of a tap winding particularly with a large tapping range (greater than ± 10 %) will reduce efficiency. In practice, since the efficiency is measured on the nominal tap rather than a maximum or minimum tap, the effect is not evident in the data.

There are many confounding factors such as the detailed design and position of the tap winding (coarse/fine or reversing, constant or variable flux).

D.3.7 Losses on taps different that rated tap

For simplicity the load loss used for the PEI are related to rated tap but it has to be evidenced that significant increases in load loss are usually observed on the extreme taps and some consideration should be given to evaluating these losses depending on how long operation is expected on these taps.

A general formula to take into account the load loss in extreme tap positions and different modalities of voltage regulation is the following:

$$P_{k_w}=\alpha P_{k_r}+\beta P_{k+}\ +\gamma P_{k-}$$

$$\text{with: } \alpha+\beta+\gamma=1$$

where

- P_{kr} is the load loss measured at rated current and rated frequency on the rated tap at a reference temperature;
- P_{k+} is the load loss measured at rated tapping current and rated frequency on the maximum positive tap (+) at a reference temperature;
- P_{k-} is the load loss measured at rated tapping current and rated frequency on the minimum negative tap (-) at a reference temperature;
- α is the weighting factor attributer to the rated tap, it represents the portion of time spent on or near the rated tap;
- β is the weighting factor attributer to the maximum positive tap (1), it represents the portion of time spent on or near the maximum positive tap (1);
- γ is the weighting factor attributer to minimum negative tap (n), it represents the portion of time spent on or near the minimum negative tap (n).

NOTE α, β, γ are dependent on the proposed transformer usage.

If the rated tap position has more than one possible winding configuration, ignoring run through positions, than the average losses of the different configurations can be taken.

For instance a network transformer which will be used equally both ways above and below rated tap would have weighting factors of: $\alpha = 0{,}5$ and $\beta = \gamma = 0{,}25$.

As another example, transformers used in a converter station or in a position where the extreme taps have been defined for emergency reasons such as network restoration after an outage, would have weighting factors of: $\alpha = 0{,}75$ and $\beta = \gamma = 0{,}125$.

Such an item is important and has to be taken into account by both user and manufacturer in the specification and in the calculation of loss capitalisation values.

D.3.8 Separate phases

If the three-phase bank consists of three separate single-phase units, the no-load losses may be expected to be higher and the efficiency consequently lower. To compensate for this the transformer efficiency should be assessed on the rating of each individual single phase transformer. This does not fully allow for the expected reduction in efficiency, but the inherent loss in efficiency by the choice of single phases should be mitigated by a more efficient design. Generally the reason for choosing single-phase designs over a three-phase design may be some transport mass restriction. Railway supply transformers normally have to be single phase.

D.4 Exceptions from benchmark

D.4.1 General

The following type of transformers need to be considered as exceptions from comparison with the benchmark.

D.4.2 Transformers with unusual combinations of windings and voltages

Where the transformer has a requirement for an unusual or complicated combination of windings that makes the design difficult, it is possible that high efficiency cannot be achieved.

D.4.3 Installation restrictions

Where the transformer has to be installed in an existing situation such as in a building, underground substation or on a plinth that would be unreasonably expensive to change, then efficiency can be compromised to achieve a practical design so the benchmark is not relevant. In general it is appropriate to take into account the cost of installation in the overall economic evaluation.

D.4.4 Offshore installation

Offshore installation has particular implications for the increase in cost of installation if the mass is increased by efficiency requirements. Such situations require a completely separate evaluation.

D.4.5 Transportation restrictions

Transport size and mass restrictions can be either insurmountable, for example bridge heights, tunnel dimensions and railway gauges, or unreasonably expensive to overcome. If these considerations apply then comparison with the benchmark efficiency is not relevant.

D.4.6 Transformers for temporary installation

Transformers that are intended for temporary installation, for example to recover the network following a failure whilst a permanent repair or replacement is made, do not need to be considered because they will make only a small contribution to overall losses and cost and transport considerations will dominate.

D.4.7 Converter transformers

The efficiency of transformers that are incorporated in HVDC convertor stations is usually considered as part of the complete scheme and so does not require separate consideration.

D.4.8 Dry-type and gas insulated transformers

Dry-type and gas insulated transformers with Um > 36 kV are generally only used for projects where specific features are required and their use would be subject to an economic evaluation taking into account a range of parameters other than just efficiency.

D.4.9 Other exemptions

Where it can be shown that the cost of meeting a benchmark efficiency is excessive in relation to the savings from an improvement in efficiency according to a full and properly conducted evaluation, then the most economic solution can be adopted. It is not expected that this will apply to normal transformers just because of the application of inappropriate economic values.

Annex E
(informative)

Capitalisation of losses

E.1 General Theory, Concept of Capitalisation

Capitalisation is not used to minimise transformer losses, it is used to minimise the investment required to obtain the greatest energy savings for the least cost. This in turn results in the selection of transformers whose losses are economically optimal, but not minimal.

In essence the process of capitalisation involves the calculation of the value today of the savings from losses over the lifetime of the transformer. This means that the kWh savings shall be calculated, as their yearly value shall be. In turn means that the cost of the electricity saved shall be predicted over the 30-50 year lifetime of the analysis, and the product of kWh and electricity cost then discounted at an appropriate interest rate to a Present Value today.

This calculation has great uncertainty involved and 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 Tender for the Transformer is then assessed on the basis of Initial cost plus the capitalized 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 by members of the Working Group as the best method of optimizing transformer design in accordance with the customer needs.

Nevertheless the definition of the costs to be included in the capitalisation of losses needs to be consistent in order to truly optimize benefits to society and to take externalities into account. This is especially true for Utilities which are regulated, and where the Regulator's goal is to optimize user investments in the wider context of society.

This is a short description of the capitalisation concept of Losses to get an optimal TCO where the Initial Cost and Capitalized Losses shall be the best choice for the transformer's lifetime.

All parameters and formulae here are given a rough explanation but the most important parameters as energy price and discount rates shall be given a very deep investigation for each Tender by the User. This cannot be done in such a paper.

E.2 Impact of capitalisation values

Any increase in the capitalisation values will result in a decrease in losses, up to the point at which the cost of decreasing the losses further equals the capitalisation values, or where the extra size and weight associated exceed the limits in the Specification.

It is important that relevant externalities 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.

[1] ETS Emissions Trading System. The overall carbon content of electricity in Europe is controlled at an EU level through the Emissions Trading System. This means that pan-European measures shall be 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.

The capitalisation values represent the avoided costs associated with the marginal kW of Iron and Copper losses saved, so that if for branding or other reasons companies wished to reduce transformer losses further in a cost effective and transparent manner, two quotes should be sought, one for Transformer design using capitalized loses and the second for a similar design but with (say) 10 % less losses.

In this way the actual cost of the extra 10 % reduction in losses is known and can be seen as to whether it provides fair value.

The variation of losses with capitalisation values is shown in the example below (however this is only an example but illustrates the typical impact).

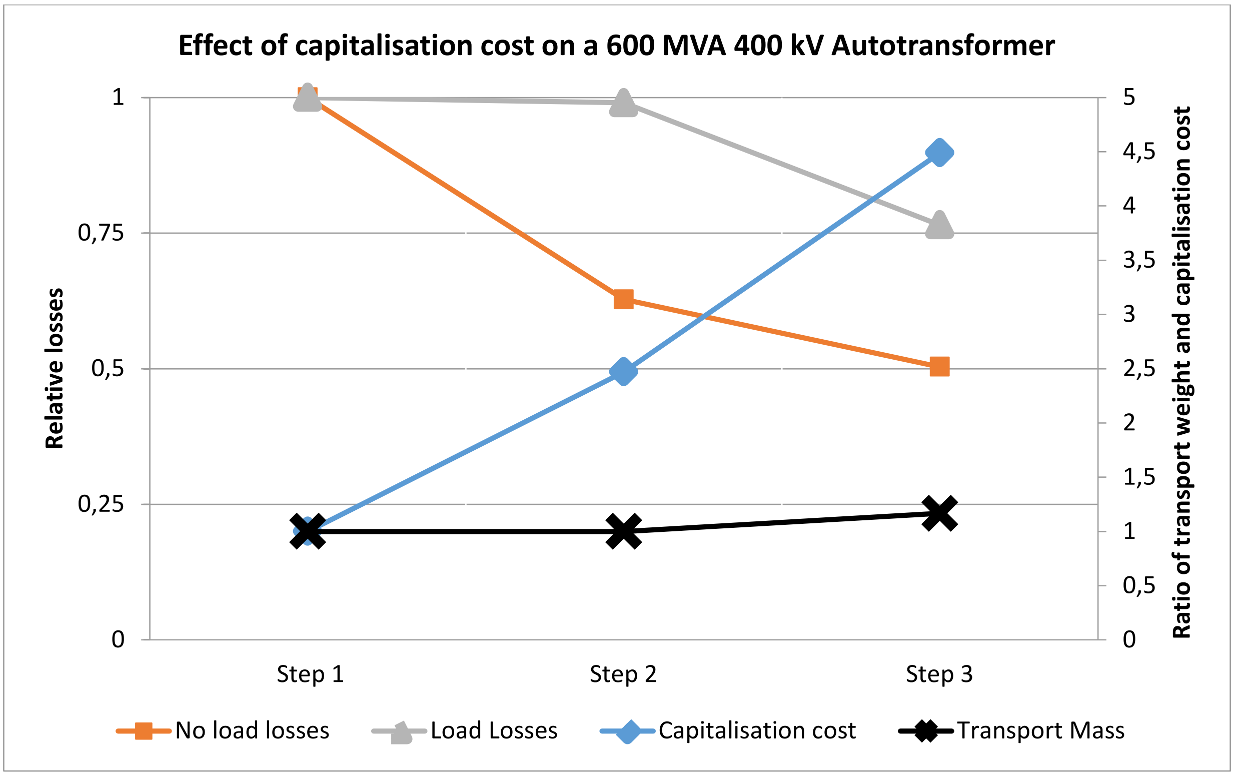


Figure E.1 — Example of the effect of capitalisation cost on transformer losses

In this example the capitalisation costs have been increased by a factor 4,5 and as a consequence the no load losses have halved and the load losses reduced by a third.

It shall be noticed that a very important limiting factor is the maximum transport weight. As in Step 2 in Figure E.1, even with an increase of cost of capitalisation of a factor 2,5 the load losses did not decrease because of transport weight limitations.

E.3 Capitalisation formula

E.3.1 General

To be fully relevant capitalisation should be based on the forecast cost of energy each year of the transformer life and, on the actual losses at this period, and relate these future cash flows to today using the appropriate discount rate. Unfortunately the parameters required are not easily available and are often too uncertain in value to determine the capitalisation values accurately.

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 Ownership Cost being then defined by:

$$TCO = IC + A\cdot(P_0 + P_{c0}) + B\cdot(P_k + P_{cs} - P_{c0}) \quad (E.1)$$

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 rated voltage and rated frequency, on the rated tap summed;
- P_{c0} is the cooling power (kW) needed for No Load operation;
- P_k is the Load Loss (kW) due to load, measured at rated current and rated frequency on the rated tap at a reference temperature;
- P_{cs} is the Total Cooling Power needed for operation at rated power (including three winding operation if any).

E.3.2 Calculation of factor A

A is the cost of capitalisation of no load losses in €/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 valorisation cost of energy multiplied by the operating time over the full life expectancy of the transformer as shown:

$$A = \sum_{j=1}^{n} \frac{O_{0\,j} * C_j}{(1+i_j)^j} \quad (E.2)$$

where

- O_{0j} is the operating time of the transformer at year j in hours;
- C_j is the valorisation of the energy at year j in €/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 e.g. marginal cost of electricity, then this excess above inflation can be more easily dealt with through a modification of the cash flow 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 mid-transformer life, then assuming that the transformer is always energized then at year **n** Formula (E.2) can be simplified to the form shown below:

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

where

- $C_{n/2}$ is the valorisation of the energy at mid life of the transformer in €/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 transformers physical life expectancy (30-50 years).

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

E.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 fix load which is constant and present all year round and affine load which depends on ambient conditions and may be present only part time. The figures below illustrate this load split

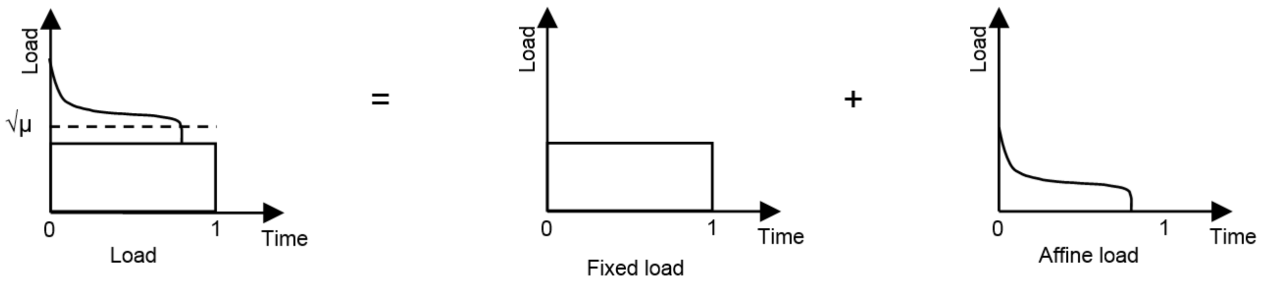


Figure E.2 — Load profile illustration

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

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

where

- T is equivalent to one year if k(t) is defined per hours T is 8760 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 loads factors multiplied by the cost of energy and corrected by the increase of load and the increase of transformer installed base. In the following Formula (E.5) below the losses are split into two parts, with each one weighted by its time base utilization:

$$B = \sum_{j=1}^{n} \frac{\mu.C_j.(O_{aj}.\tau_{aj}+O_{fj}.\tau_{fj})}{(1+i_j)^j}\left(\frac{1+C_{\mu j}}{1+C_{aj}}\right)^{2j} \tag{E.5}$$

where

- μ is the average load loss factor as defined above;
- C_j is the valorisation of the energy at year j in €/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 affine load during year j in hours;
- O_{fj} is the operating time of the transformer at fixed load during year j in hours usually 8760 h if the transformer is operated all year round;
- T_{aj} is the share of affine 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 to zero which corresponds to a situation where the investment is assessed on the basis that the average loading of transformer as invariant. If this is not the case special care shall be taken to avoid overloading of transformer from 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 around and if the cost of energy is considered constant and equal to the energy valorisation at mid life of the transformer, and if usage of transformer is assumed as invariant during its all life, and if discount rate is considered constant then the formula can be simplified as in the formula below:

$$B = \mu . C_{n/2} . (O_a . \tau_a + 8760 . \tau_f) . \frac{\frac{(1+C_\mu)^2}{(1+i).(1+C_a)^2} . \left[1 - \left(\frac{(1+C_\mu)^2}{(1+i).(1+C_a)^2}\right)^n\right]}{1 - \frac{(1+C_\mu)^2}{(1+i).(1+C_a)^2}} \qquad \text{(E.6)}$$

where

- μ is the average load loss factor as defined above;
- $C_{n/2}$ is the valorisation of the energy at mid life of the transformer in €/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 affine load in hours;
- O_f is the operating time of the transformer at fixed load in hours usually 8760 h if the transformer is operated all year round;
- T_a is the share of affine load in the total load loss factor;
- T_f is the share of fixed load in the total load loss factor;

  $T_a + T_f = 1$;
- 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 simplifies as shown in the formula below.

$$B = \mu . C_{n/2} . (O_a . \tau_a + 8760 . \tau_f) . \frac{1-\left(\frac{1}{1+i}\right)^n}{i} \qquad (E.7)$$

For symbols meaning refer to Formula (E.5).

The B factor (€/kW of Load Loss) represents the value today of the total Load Losses saved over the lifetime of the transformer. Unlike No Load ('Iron') Losses, the Load Losses ('Copper Losses') are highly dependent on how heavily the transformer is loaded and over how long a period, with the Load Losses increasing dramatically with Transformer loading (proportional to the square of the load). So a transformer with 400 identical customers will not have twice the load losses of a transformer with 200 customers, but will actually have four times the losses.

Following the same logic as for No Load Losses, a purchaser would be willing to spend anything up to B €/kW on extra costs in improving the transformer, because as long as this extra investment is less than B, there is a positive gain to be made. However there are declining returns with increasing investment so that at some stage the benefits from the extra investment cost more than the losses saved, at which stage no further investment is economic. At this point the value of the Load Losses saved is balanced by the extra transformer investment cost per kW, and this value is B €/kW

In practical terms this means that for transformers with heavy loads (e.g. Industrial /commercial loads, urban areas), copper losses will be predominant and will give a strong return on investment; whereas on transformers with low loads (rural transformers) a very poor return on copper losses would be made, and Iron losses are predominant.

E.3.4 Use of A and B for tender evaluation

In a transformer tender the user should give the values of A & B which will be applied during the evaluation stage to assess the Total Cost of Ownership (TCO).

The TCO is defined by Formula E.1 and represents not only the initial purchasing cost but also the cost of the losses. 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 by Formula E.1.

E.3.5 Determination of factors A and B

The definition of the components of the above formulae is complex and requires very specialized skill.

Utility policies, energy mix, government political decisions, incentive for environmental concerns and prospective scenarios, discount rates and investment time horizon, as well as budget constraints can greatly affect the value used for determining the A and B factors. The variety of parameters and the fact that some of the values are necessarily subjective, or subject to considerable uncertainty can explain the diversity of capitalisation costs actually used by utilities.

For industrial or private customers not subject to such considerations, determining values for the formulae components should be simpler, as many of the assumptions needed for the definition of the capitalisation costs will have already been made during the establishment of the project business plan.

Therefore the inputs are defined as follows:

- n is the useful economic life of the transformer. The sensitivity of the capitalisation value to n decreases as n increases;
- $C_{n/2}$ should be derived from forecasted commodity prices. The higher the cost of the energy, the greater the savings from a lower loss level will, thus justifying a higher initial cost of the transformer;
- i is the discount rate set by the company as appropriate for the investment proposed. By default the weighted average costs of capital should be used unless an alternative specific rate has been calculated for the investment. The lower the discount rate, the higher will be the present value of the losses. 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 below:

$$B = \mu . C_{n/2} .\ 8760 . \frac{1-\left(\frac{1}{1+i}\right)^n}{i} \qquad \text{(E.8)}$$

where μ can be well approximated by the following formula:

$$\mu = \left(\frac{S}{S_r}\right)^2 \qquad \text{(E.9)}$$

where

S_r is the rated power of the transformer;

S is the average forecast load.

If the process is not continuous, 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.

Attention shall be paid to getting a good value for the average forecast load (S). This is because the loss utilization factor is predominant in determining the balance between load and no load losses. Achieving a correct balance between load and no load losses is critical to achieving a good efficiency in service. Specifying a low load factor will lead to a transformer having relatively higher load loss and lower no load loss which would be inefficient if used at high loads. Conversely specifying a high load factor will lead to a transformer having relatively higher no load losses and lower load losses which would be inefficient if used at low loads.

Then the capitalisation factors are calculated as follow:

- No load losses capitalisation cost A is determined according to Formula E.2, or Formula E.3.
- Load losses capitalisation cost B is determined according to Formula E.5, Formula E.6, Formula E.7, or in simpler manner by Formula E.8.

Annex F
(informative)

Background on verification tolerances during market surveillance

In ANNEX III of COMMISSION REGULATION (EU) No 548/2014 it is stated that during market surveillance checks, verification tolerances of 5 % apply to the declared values of load loss, no load loss and electrical power required by the cooling system for no load operation (individually). In addition, it is also specified that such verification tolerances relate to measurements performed by market surveillance authorities only. Consequently, they cannot be used by manufacturers during factory acceptance tests.

In this annex it is explained how verification tolerances on losses have been taken into account in order to determine the procedure described in 5.5.2 that market surveillance authorities shall use when verifying PEI.

Because of its definition, the same value of PEI can be obtained through different combination of no load, load and cooling equipment loss. This fact is graphically shown in Figure F.1, where the solid line named curve 1 represents combinations of no load and load loss fulfilling the PEI prescribed for the transformer under verification (to avoid complicating the graph, cooling loss at no load operation is considered to be zero).

The dotted line named curve 2 is obtained from curve 1, translating it by an amount of + 5 % on both axes in order to visualize the effect of verification tolerance on no load and load loss. Three areas can be identified:

- Area 1, which includes all points not above curve 1, representing combination of losses which fulfill the PEI
- Area 3, which includes all points above curve 2, representing combination of losses which do not fulfill the PEI
- Area 2, which contains all points above curve 1 but not above curve 2, representing combination of losses which are within the verification tolerances allowed to be used by market surveillance authorities

Provided that combination of guaranteed and measured losses by the manufacturer shall be within Area 1, during a market surveillance check, authorities may measure any point included in Area 1 and Area 2 for the verification to be passed, whereas measurement points in Area 3 would result in a verification failed.

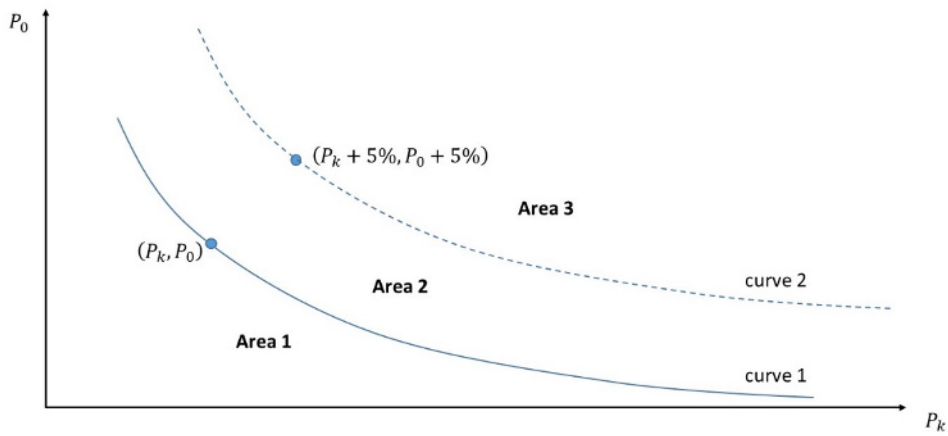


Figure F.1 — combination of loss values

Annex ZZ
(informative)

Relationship between this European Standard and the requirements of Commission Regulation (EC) No 548/2014 of 21 May 2014 on implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to small, medium and large power transformers

This European Standard has been prepared under a mandate given to CENELEC by the European Commission and the European Free Trade Association to provide a means of conforming to requirements of *Commission Regulation (EC) No 548/2014 of 21 May 2014 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for small, medium and large power transformers.*

Once this standard is cited in the Official Journal of the European Union under that Commission Regulation, compliance with the clauses of this standard given in Table ZZ.1 confers, within the limits of the scope of this standard, a presumption of conformity with the corresponding requirements of that and associated EFTA regulations.

Table ZZ.1 — Correspondence between this European Standard and Commission Regulation (EU) N.548/2014

Requirements of Commission Regulation (EC) No 548/2014	Clauses and sub-clauses of this EN
Annex I **Minimum energy efficiency requirements for large power transformers.** **Table I.7** Minimum Peak Efficiency Index requirements for liquid immersed large power transformers.	**Sub-clause 5.1** Table 1 presents the values of minimum Peak Efficiency Index. Column “PEI – T1” refers to requirements applicable from 1 July 2015 (Tier 1), whereas column “PEI – T2” refers to requirements applicable from 1 July 2021 (Tier 2).
Annex I **Minimum energy efficiency requirements for large power transformers.** **Table I.8** Minimum Peak Efficiency Index requirements for dry-type large power transformers.	Annex A Annex A contains Table A.1, taken from the Commission Regulation (EC) No 548/2014.
Annex I **Product information requirements.** **Technical documentation**	**Sub-clause 5.3 and 5.4**
ANNEX III	**Definition 3.7 and sub-clause 5.5.2**

WARNING — Other requirements and other EU Directives may be applicable to the product(s) falling within the scope of this standard.

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