SIST

SLOVENSKI STANDARD
SIST EN 50629:2015

01-september-2015

Energijski izkoristek velikih transformatorjev (Um > 36 kV ali Sr ≥ 40 MVA)

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

Energiekennwerte von Großleistungstransformatoren (Um > 36 kV oder Sr ≥ 40 MVA)

Performance énergétique des transformateurs de grande puissance (Um > 36 kV ou Sr ≥ 40 MVA)

Ta slovenski standard je istoveten z: EN 50629:2015

ICS:

27.015	Energijska učinkovitost. Ohranjanje energije na splošno	Energy efficiency. Energy conservation in general
29.180	Transformatorji. Dušilke	Transformers. Reactors

SIST EN 50629:2015 **en**

EUROPEAN STANDARD

NORME EUROPÉENNE

EUROPÄISCHE NORM

EN 50629

June 2015

ICS 29.180

English Version

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Performance énergétique des transformateurs de grande puissance (Um > 36 kV ou Sr ≥ 40 MVA)

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

CEN-CENELEC Management Centre: Avenue Marnix 17, B-1000 Brussels

Ref. No. EN 50629:2015 E

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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
- latest date by which the national standards conflicting with this document have to be withdrawn	(dow)	2018-06-25

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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:

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

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.

$$\text{PEI} = 1 - \frac{2[P_0 + P_{c0} + P_{ck}(k_{PEI})]}{S_r \sqrt{\frac{[P_0 + P_{c0} + P_{ck}(k_{PEI})]}{P_k}}} \text{ (pu)} \qquad (4)$$

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:

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

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.