Power Transformers – Introduction to measurement of losses

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About the INTAS project

The aim of the INTAS project is to provide technical and cooperative support, as well as capacity building activities, to Market Surveillance Authorities (MSAs). The need for the INTAS project arises from the difficulty that MSAs and market actors face in establishing and verifying compliance with energy performance requirements for large industrial products subject to requirements of the Ecodesign Directive, specifically transformers and industrial fans. Therefore, the project aims to:

- Support European Member State MSAs deliver compliance for large products (specifically for transformers and large fans);

- Support industry to be sure of what their obligations are under the Ecodesign Directive and to deliver compliance in a manner that will be broadly accepted by MSAs;

- Foster a common European approach to the delivery and verification of compliance for these products.

List of project partners:

WIP Renewable Energies	Europe
European Environmental Citizens' Organisation for Standardisation	Europe
European Copper Institute	Europe
Engineering Consulting and Design	Europe
Waide Strategic Efficiency	Europe
Austrian Energy Agency	Austria
Federal Public Service Health, Foodchain, Safety and Environment	Belgium
SEVEn Energy Efficiency Center	Czech Republic
Danish Technological Institute	Denmark
Finnish Safety and Chemicals Agency	Finland
The Polish Foundation for Energy	Poland
Directorate General of Energy and Geology	Portugal
Romanian Regulatory Authority for Energy	Romania
Foundation for the Promotion of Industrial Innovation	Spain
Italian National Agency for New Technologies, Energy and Sustainable Economic Development	Italy
Food and Economic Safety Authority	Portugal
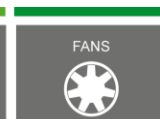
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1.   Power transformers – introduction

Transformers are static electrical devices that are used in electrical power systems to transfer electrical power among circuits through the use of electromagnetic induction.

The purpose of a transformer is to convert power from one system voltage to another. This voltage relationship, or voltage ratio, is determined by the ratio of the number of turns on the primary winding to the number of turns on the secondary winding.

A power transformer is a transformer for the purpose of transmitting electrical power.

The definitions of the different types of power transformers are not harmonised around the world and may be different.

INTAS considers three-phase and single-phase power transformers (including auto-transformers) with a minimum power rating of 1 kVA used electricity transmission and distribution networks or for industrial applications with the exception of small and special transformers such as:

- 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

- single-phase transformers with rated power less than 1 kVA and three-phase transformers less than 5 kVA

- transformers, which have no windings with rated voltage higher than 1 000 V

- traction transformers mounted on rolling stock

- starting transformers

- testing transformers

- welding transformers

- explosion-proof and mining transformers

- transformers for deep water (submerged) applications.

It is to be pointed out that for the INTAS scope all the transformer above have been considered large products even if the current EN definition of large power transformers is more stringent.
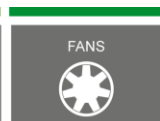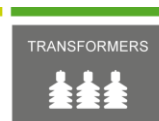
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A formal classification of power transformer has been introduced by CENELEC TC14 and EU Regulation N 348/14 (http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2014.152.01.0001.01.ENG):

- Small power transformer: a power transformer with a highest voltage for equipment not exceeding 1,1 kV.

- Medium power transformer: a power transformer with a highest voltage for equipment higher than 1,1 kV, but not exceeding 36 kV and a rated power equal to or higher than 5 kVA but lower than 40 MVA

- Large power transformer: a 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.
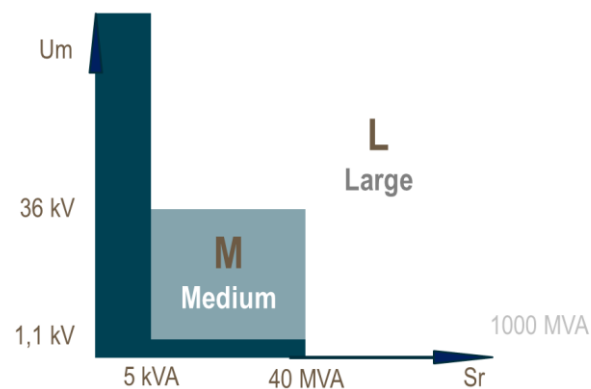

Figure 1 - Classification of power transformer according to EU Regulation N 348/14.

With reference to the type of installation, a pole mounted transformer is a power transformer with a rated power of up to 315 kVA suitable for outdoor service and designed to be mounted on the support structures of overhead power lines.

Liquid-filled transformers, most often used by electric utilities, have several performance advantages over dry-type transformers. Liquid-filled transformers tend to be more energy performant, have greater overload capability and have a longer service life. This longer service life is due to a greater ability to reduce coil hot-spot temperatures and to have higher dielectric withstand ratings. Liquid-filled transformers are also physically a smaller than dry-type for a given rating, which can be important in areas with restricted space. However, liquid-filled transformers are often filled with mineral oil which has a higher flammability potential than dry-types and local environmental laws may require containment troughs or other facilities to guard against insulating fluid leaks.

Dry-type transformers tend to be used most often by commercial and industrial customers. Generally, the installation location can be a critical consideration here – higher-capacity transformers used outdoors are almost always liquid-filled, while lower-capacity transformers used indoors are often dry-type. Dry-type transformers typically are housed in enclosures, with the windings insulated through varnish, vacuum pressure impregnated (VPI) varnish, epoxy resin or cast resin.

2. Losses

Power transformer losses can be divided into two main components: no-load losses and load losses. These types of losses are common to all types of transformers, regardless of transformer application or power rating. There are, however, two other types of losses; extra losses created by non ideal quality of power and losses which may apply particularly to larger transformers – cooling or auxiliary losses, caused by the use of cooling equipment like fans and pumps.

2.1 No-Load losses

These losses occur in the transformer core whenever the transformer is energised (even when the secondary circuit is open). They are also called iron losses or core losses and are constant.

They are composed of:

- Hysteresis losses, caused by the frictional movement of magnetic domains in the core laminations being magnetized and demagnetized by alternation of the magnetic field. These losses depend on the type of material used to build a core. Silicon steel has much lower hysteresis than normal steel but amorphous metal has much better performance than silicon steel. Hysteresis losses can be reduced by material processing such as cold rolling, laser treatment or grain orientation. Hysteresis losses are usually responsible for more than a half of total no-load losses (~50% to ~80%). This ratio was smaller in the past (due to the higher contribution of eddy current losses).

- Eddy current losses, caused by varying magnetic fields inducing eddy currents in the laminations and thus generating heat. These losses can be reduced by building the core from thin laminated sheets insulated from each other by a thin varnish layer to reduce eddy currents. Eddy current losses usually account for 20% to 50% of total no-load losses

There are also less significant stray and dielectric losses which occur in the transformer core, accounting usually for no more than 1% of total no-load losses.

2.2 Load losses

These losses are commonly called copper losses or short circuit losses. Load losses vary according to the transformer loading. They are composed of:

- Ohmic heat loss, sometimes referred to as copper loss, since this resistive component of load loss dominates. This loss occurs in transformer windings and is caused by the resistance of the conductor. The magnitude of these losses increases with the square of the load current and is proportional to the resistance of the winding. It can be reduced by increasing the cross sectional area of conductor or by reducing the winding length. Using copper as the conductor maintains the balance between weight, size, cost and resistance; adding an additional amount to increase conductor diameter, consistent with other design constraints, reduces losses.

- Conductor eddy current losses. Eddy currents, due to magnetic fields caused by alternating current, also occur in the windings. Reducing the cross-section of the conductor reduces eddy currents, so stranded conductors with the individual strands insulated against each other are

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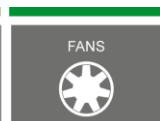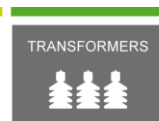
used to achieve the required low resistance while controlling eddy current loss. Effectively, this means that the 'winding' is made up of a number of parallel windings. Since each of these windings would experience a slightly different flux, the voltage developed by each would be slightly different and connecting the ends would result in circulating currents which would contribute to loss. This is avoided by transposing the conductors to average the flux differences and equalise the voltage.

2.3 Auxiliary losses

These losses are caused by using energy to run cooling fans or pumps which help to cool larger transformers.

2.4 Extra losses due to harmonics and unbalance

Distorted or unbalanced voltages or currents result in extra losses.

Power losses due to eddy currents depend on the square of frequency so the presence of harmonic frequencies which are higher than rated frequency causes extra losses in the core and windings.

Transformers subject to negative sequence voltages transform them in the same way as positive-sequence voltages. The behavior with respect to homopolar voltages depends on the primary and secondary connections and, more particularly, the presence of a neutral conductor.

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3. Measurement of losses

3.1 Load loss

The measurement of load loss on a large transformer requires considerable care and good measuring equipment because of the low power factor and the often large test currents.

The load loss for a pair of windings is measured at rated frequency with voltage applied to the terminals of one winding, with the terminals of the other winding short-circuited, and with possible other windings open-circuited.

The supplied current should be equal to the relevant rated current. The measurements shall be performed quickly so that temperature rises do not cause significant errors.

The measured value of load loss shall be multiplied with the square of the ratio of rated current to test current.

The resulting figure shall then be corrected to reference temperature. The ohmic losses are usually and conventionally taken as varying directly with the temperature and all other losses inversely with the temperature.

On a three-winding transformer, measurements are performed on the three different two winding combinations. The results are re-calculated, allocating losses to individual windings. Total losses for specified loading cases involving all these windings are determined accordingly.

Any errors and external circuit losses should be minimized. Correction for measuring transformer errors and for resistance of the test connections should be applied unless they are obviously negligible.
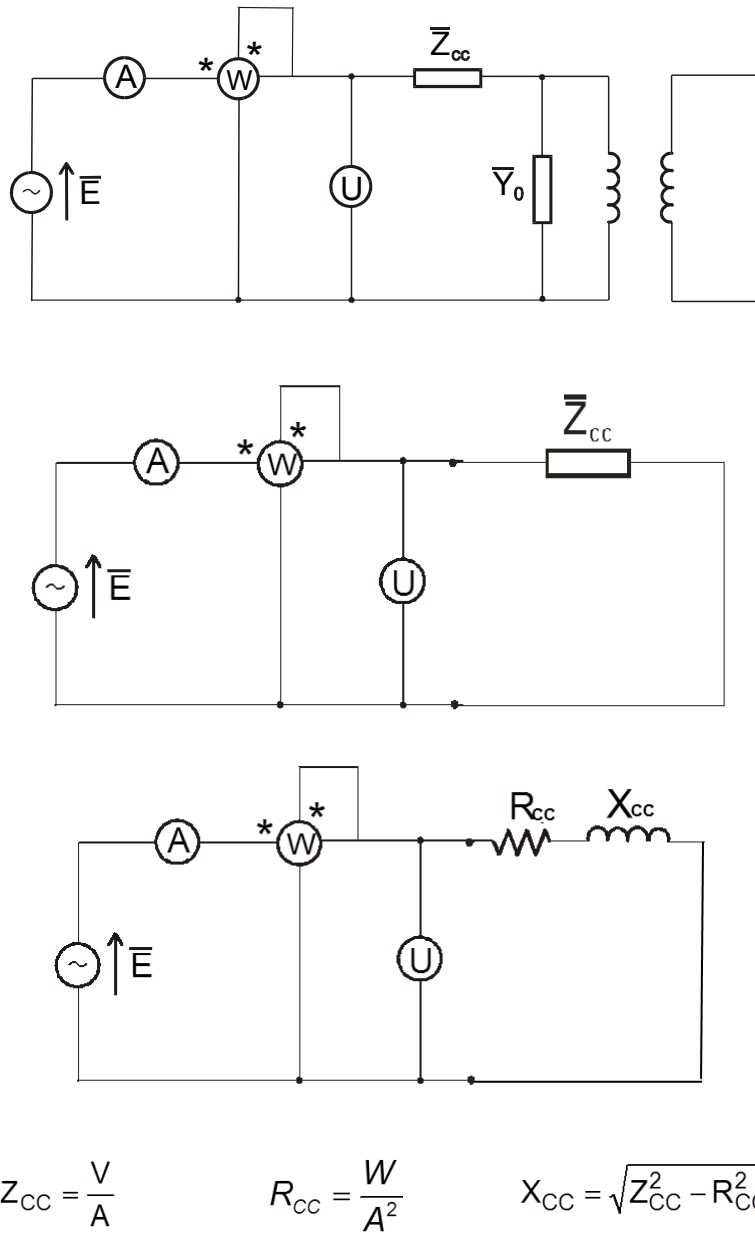
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$$Z_{CC} = \frac{V}{A} \qquad R_{CC} = \frac{W}{A^2} \qquad X_{CC} = \sqrt{Z_{CC}^2 - R_{CC}^2}$$

Figure 2 – Short circuit test single phase equivalent circuits.

3.2 Measurement of no-load losses

The no-load losses shall be measured on one of the windings at rated frequency and at a voltage corresponding to rated voltage. The remaining winding or windings shall be left open-circuited.
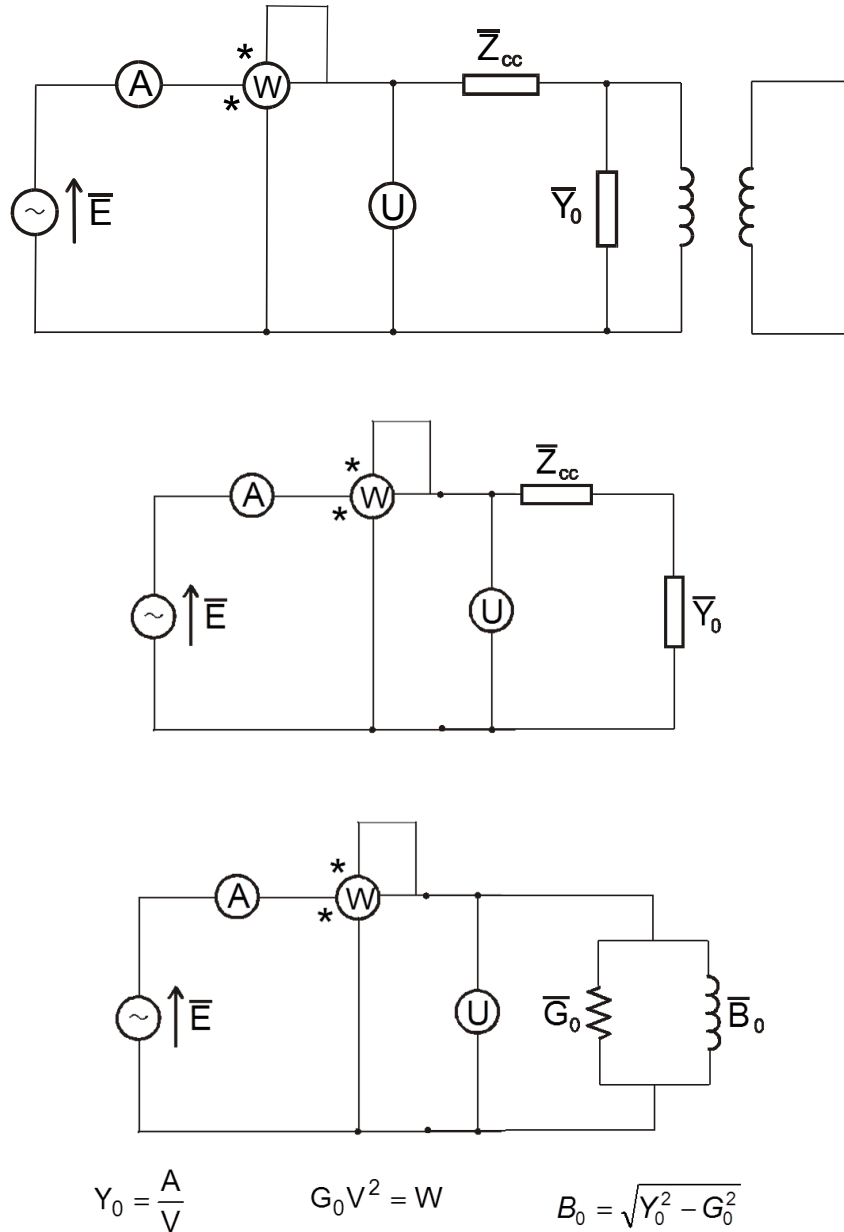

Figure 3 – No load test single phase equivalent circuits.

$$Y_0 = \frac{A}{V} \qquad G_0 V^2 = W \qquad B_0 = \sqrt{Y_0^2 - G_0^2}$$

The transformer shall be approximately at factory ambient temperature. Usually the no load losses are not corrected for any effect of temperature.

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3.3 Measurement of auxiliary losses

Measurement of cooling equipment consumption refers to specific product standards and basically consists in electrical energy or power measurement in given conditions.

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4.   Energy performance metrics

There are different metrics in use for assessing the energy-performance of a power transformer. All of them fundamentally refer to two main categories: maximum losses and minimum efficiency.

Each approach offers certain strengths, but also has some weaknesses. Hereunder the different approaches are shortly discussed in light of the experience built up with the new European Regulation.

Table 1 - Categorization of main metrics used for assessing energy-performance of power transformers.

Maximum losses	Minimum Efficiency
Load and no-load at full load	Efficiency at a defined loading point
Total losses at a specified loading point	Peak efficiency index

4.1 Maximum losses

The benefits of setting the maximum no load and load losses separately in the attempt to either regulate or standardize transformer energy performances can be summarized as follows:

- One of the most important goals of standardization is unification. Unification allows to open a horizontal market, with very important implications for future developments of scale economies, interchangeability, etc...

- No load and load losses are never greater than a certain value regardless of the applied load, which is generally difficult to predict on rms, on a daily, seasonal or life cycle basis across the stock of identically rated transformers. This means that a minimum level of performance is assured whatever the level of loading applied to the transformer.

- Maximum losses are not dependent from the application but only from the product while efficiency is an index depending on the application and this introduces additional uncertainty.

- In the most situations, the expected load profile is known with a quite high uncertainty. The knowledge of the load profile to be used for optimization ex ante is typically not enough to reach the theoretical optimum promised by efficiency approaches.

- Flexibility related to efficiency approaches is a pro but leaves more space than a loss list to distorted behavior of the market and frauds etc.

- Setting a mandatory maximum level of load and no load losses does not mean that it's not possible to standardize or simply to choose other values optimizing each specific application.
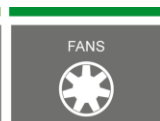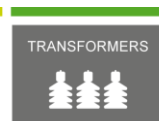
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- All these considerations are valid for medium power transformers, which are typically produced in large series and do not allow single special optimization neither by the user nor by the manufacturer.

- For such reasons the European Regulation of energy performances of medium power transformers was based on maximum no load and load losses.

- An alternative to having separate requirements for maximum no-load and load losses is to combine the total losses into one value. Similar to the minimum efficiency set, there will be an implicit least cost point of manufacturer at a given loading point, which may or may not be optimal for a given market. If this loading point does not match the load where the least cost transformer is being installed, the least cost transformer's optimal performance point would not coincide with the installation loading, resulting in lost energy savings.

4.2 Minimum efficiency

Efficiency is a more neutral technological metric, which allows flexibility in designing and manufacturing of transformers. In fact, it allows transformer design engineers to trade-off no-load and load losses while trying to produce an optimized transformer for a specific customer and application. At the same time, it shall be noticed that if a transformer is purchased simply on a least cost basis, its optimal loading point may not coincide with the average loading at all installation sites, resulting in lost energy savings.

Thus, the transformer procurement practice needs to keep all these aspects in mind and minimize the cost of losses over the array of projected load profiles. This is feasible for large power transformers (few very important units specified by expert professionals one by one), but it is practically unfeasible for medium power transformers produced in thousands of units for the general market.

Efficiency is expressed as follows:

$$\text{Efficiency} = \frac{S_{input} - \text{Losses}}{S_{input}} = \frac{S_{output}}{S_{output} + \text{Losses}}$$

The defined power can be either input power (EN) or output power (IEEE) resulting in two methods for calculation of efficiency and historically both methods have been used.

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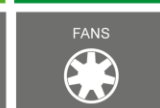
The peak efficiency index is a unit-less metric, which was developed as a regulatory option for the European ecodesign process.

The Peak Efficiency Index is obtained when no-load loss equals load loss and is given by substituting k in equation with kPEI as in the expression below:

$$k_{PEI} = \sqrt{\frac{P_0 + P_{c0} + P_{ckPEI}}{P_k}} \quad (pu)$$

Where:

- P0 is the no-load loss measured at rated voltage, rated frequency and on rated tap

- Pc0 is the electrical power required by the cooling system for no-load operation derived from the type test measurement of the power taken by the fan and pump motors.

- Pk is the measured load loss at rated current and rated frequency on the rated tap corrected to reference temperature according to IEC 60076-1.

- Pck(k) is the additional electrical power required (in addition of Pc0) by the cooling system for operation at load factor k, derived from the type test measurement of the power taken by the fan and pumps motors

- Sr is the rated power of the transformer or autotransformer as defined in IEC60076-1 on which Pk is based

- k is the load factor

- P_{ckPEI} is the additional electrical power required (in addition of Pc0) by the cooling system for operation at kPEI.

The formula for calculating Peak Efficiency Index (PEI) is therefore given by equation:

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

The value of equation depends on the ratio Sr /√PK which does not vary significantly if Sr is changed (for example by changing cooling mode) provided that PK is measured at Sr.

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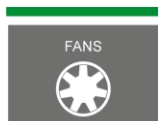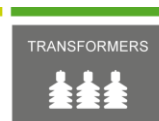
The peak efficiency index (PEI) is defined and set to:

- take into account also energy performances of units required to transform reactive power only

- have an index not depending from the application but related to the product only

Such index includes both no-load and load losses, but the equation is written in such a way that it does not require a specified loading point. Instead, the index finds the point where the no-load loss equals the load loss, and calculates the value. This approach has an advantage over others, because it does not require prescribing or implying a loading point.

At the same time, considering that in a competitive market environment all manufacturers are trying to minimize their costs, prescribing only minimum values for the PEI can be somehow risky. In fact, there may be a mismatch between the no load and load loss ratio which minimizes the transformer cost and the one which optimizes the energy performance during service (provided that in both cases the minimum PEI value is fulfilled). For this reason, it is important that transformer users prescribe suitable capitalization figures or specify minimum efficiency values at certain load factors in order to obtain the highest energy savings. The importance of this issue is higher for smaller units, while larger power transformers tend to be already today state of the art for what concerns efficiency.

More information
about the INTAS project activities
and all of its results
are published on:

www.INTAS-testing.eu

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