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Power Transformers

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Power transformers are an essential part of the electricity network as they convert electrical energy from one voltage level to another. After having been generated in a power station, electrical energy needs to be transported to the areas where it is consumed. This transport is more efficient at higher voltage, which is why power generated at 10 to 30 kV is converted by transformers into typical voltages of 220 kV up to 400 kV, or even higher. There are power transformers in large transmission substations, usually at major transmission nodes close to large power plants, which add flexibility to transmission channels and connect to subtransmission level. Transformers or autotransformers installed there are here referred to as grid coupling transformers.

Since the majority of electrical installations operate at lower voltages, the high voltage needs to be converted back close to the point of use. The first step down is transformation to 33–150 kV. This is often the level at which power is supplied to major industrial customers. Distribution companies then transform power further, down to the consumer mains voltage.

In this way, electrical energy passes through an average of four transformation stages before being consumed. A large number of transformers of different classes and sizes are needed in the transmission and distribution network, with a wide range of operating voltages. Large transformers for high voltages are called system transformers. The last transformation step into the consumer mains voltage (in Europe 400/230 V) is done by the distribution transformer. Distribution transformers operated and owned by electricity distribution companies are responsible for supplying about 70% of low voltage electricity to final users and represent about 80% of distribution transformers' stock. Voltage levels are classified as:

- Extra high voltage: transmission grid (>150 kV) typically 220–400 kV (ultra high > 400 kV)
- High voltage >70 kV up to 150 kV: subtransmission (the interface between TSO and DSO)
- Medium voltage >1 kV up to 70 kV (typically up to 36 kV)
- Low voltage < 1 kV (e.g. 110 V, 240 V, 690 V).

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Power transformers provide very good opportunities for energy saving. There have been numerous attempts to assess the energy saving potential of transformers. As an example, in 2005 Leonardo ENERGY estimated that there was at least 200 TWh global energy saving potential from distribution transformers only.

According to the International Energy Agency (IEA, http://data.iea.org) energy statistics, the global generation of electricity in 2008 was 20 270 TWh, of which around 10%, i.e. 2000 TWh, was generated in generators, mostly renewables, that are interconnected at non-high voltage level (below 70 kV). Consumption was reported at 16 816 TWh, while losses were 1656 TWh. Making the balance, the remaining 1798 TWh was kept by the energy industry for its own use. At the same time, the world generating capacity was 4625 GW.

Looking into the breakdown of transmission and distribution (T&D) losses. Analysis performed in SEEDT project indicated the following T&D losses from transformers in Europe by the year 2000:

- distribution transformers 25%;
- HV/MV transformers 10%;
- transmission transformers 10%.

This share might have slightly reduced in the last ten years, but so far none of the following losses, not considered before, have been included in the estimate of the saving potential:

- generator transformers;
- transformers used by the energy industry for its own needs (supplying power station installation and auxiliaries);
- distributed energy (DER) transformers, integrating mainly renewables into electricity networks (including converter transformers for HVDC to AC connections).

Transformers installed in electricity networks worldwide are responsible for about 40% of the total T&D losses, which results in about 650 TWh. This estimate is based on energy statistics with the following provisions:

- Europe's 45% transformer losses contribution from the year 2000 has decreased because of some realization in saving potential already and is about 10% higher than the world's average due to the power factor.
- At the same time, European estimates do not include losses from transformers as stated above.

How much of these losses can be saved? Transformers are already quite efficient devices and great progress in the reduction of losses has been already achieved. The potential savings are, however, still high as there is still a reserve in design and technology, and because so many voltage transformation steps are in use in the electricity system. For example US and European studies during the preparation of transformer Minimum Energy Performance Standards (MEPS) have indicated that distribution transformers can be about 1% more efficient using today's best available technologies compared with the average units in operation and 0.5% compared with MEPS. As for power transformers, the gap is lower and

Table 3.1 Typical energy efficiencies of different transformer types

Transformer	S [kVA]	Current density [A/mm^2]	Energy efficiency
Miniature transformer	0.001	7.000	45.00%
Small transformer	0.100	3.000	80.00%
Industrial transformer	40.000	3.397	96.00%
Distribution transformer	200.000		98.50%
Bulk supply point transformer	40 000.000	3.000	99.50%
Generator transformer	600 000.000		99.75%

traditional technologies make it practical to increase efficiencies by 0.1% to 0.2% compared with current levels.

On average this can be a nearly 50% improvement for all the electricity network transformers, representing a savings potential of more than 300 TWh. In this chapter the focus will be mainly on distribution transformers.

The largest energy saving potential is, in effect, represented by distribution transformers. They still have the largest reserve for saving energy, have a very long lifetime and the proportion of the lifetime cost of losses to production costs is relatively high. Larger power transformers are already more efficient and the production (including design and tools) is different from the case of distribution transformers. These decrease, beyond a scaling factor of exponents of 3/4 for weight, cost and losses, the proportion of production cost to lifetime cost of losses and decrease the attractiveness of reaching much improvement in efficiency. However they are still relevant. Smaller transformers, as seen in Table 3.1, are much less efficient than distribution or power transformers, however their capacity and availability factors are so low as the life cycle costing for these transformers is very often beneficial for low first cost (production) units, as experienced in the preparatory study to the Energy related Products Directive, when analysing earthing transformers.

3.1 Losses in Transformers

Transformer losses can be classified 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 the 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 such as fans and pumps.

3.1.1 No-Load Losses

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

They are composed of the following:

- *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 20–50% of the total no-load losses.

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

3.1.2 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 the 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 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 the use of continuously transposed conductor (CTC), in which the strands are frequently transposed to average the flux differences and equalize the voltage.

A good example of how current density influences load losses is given in Table 3.2. The average commonly used value of 3 A/mm^2 will result in almost double the load resistive loss for only one-quarter (25%) higher current density, i.e. one-quarter less conductor material.

3.1.3 Auxiliary Losses

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

Table 3.2 Improvement in load losses by increasing the conductor cross-section

'Energetic payback' from using more copper (operating hours at full load)						
Specific loss in copper magnet wire					Time of operation	
at	1.00	A/mm^2	1.96	W/kg	1854	h
at	1.50	A/mm^2	4.41	W/kg	824	h
at	2.00	A/mm^2	7.84	W/kg	463	h
at	2.25	A/mm^2	9.92	W/kg	366	h
at	2.50	A/mm^2	12.25	W/kg	297	h
at	2.75	A/mm^2	14.82	W/kg	245	h
at	3.00	A/mm^2	17.64	W/kg	206	h
at	3.50	A/mm^2	24.01	W/kg	151	h
at	4.00	A/mm^2	31.35	W/kg	116	h
at	4.50	A/mm^2	39.68	W/kg	92	h
at	5.00	A/mm^2	48.99	W/kg	74	h
at	6.00	A/mm^2	70.55	W/kg	51	h
at	7.00	A/mm^2	96.02	W/kg	38	h
at	8.00	A/mm^2	125.42	W/kg	29	h

3.1.4 Extra Losses due to Harmonics, Unbalance and Reactive Power

This category of losses includes those extra losses that are caused by unbalanced harmonics and reactive power.

Power losses due to eddy currents depend on the square of frequency, so the presence of harmonic frequencies that are higher than the normal 50 Hz frequency causes extra losses in the core and windings. These additional losses deserve separate attention and are discussed below.

The reactive component of the load current generates a real loss even though it makes no contribution to useful load power. Losses are proportional to $1/(\cos \varphi)^2$ of the active power, but the power rating of the transformers always gives the apparent power. This reactive power is responsible for active power losses in supplying network coming from reactive power for transformer core magnetization and from reactive power stray losses. Low power factor loads should be avoided to reduce losses related to reactive power, also in transformers.

3.1.4.1 Harmonics

Before we start discussing harmonics considerations in transformers it should be stated that there is a non-univocal position if only current distortion and the harmonic effects on windings are worth practical consideration. Voltage harmonics as well as harmonics effects on no-load losses, according to some studies, may in some cases contribute significantly to extra losses in transformers.

Non-linear loads, such as power electronic devices, such as variable speed drives in motor systems, computers, UPS systems, TV sets and compact fluorescent lamps, cause harmonic currents on the network. Harmonic voltages are generated in the impedance of the network by the harmonic load currents. Harmonics increase both load and no-load losses due to increased skin effect, eddy current, stray and hysteresis losses.

3.1.4.2 Current Distortion

The most important of these losses is that due to eddy current losses in the winding, it can be very large and consequently most calculation models ignore the other harmonic-induced losses!

The precise impact of a harmonic current on load loss depends on the harmonic frequency and the way that the transformer is designed. In general, the eddy current loss increases by the square of the frequency and the square of the load current. So, if the load current contains 20% fifth harmonic, the eddy current loss due to the harmonic current component would be $5^{2*}0.2^2$ multiplied by the eddy current loss at the fundamental frequency, meaning that the eddy current loss would have doubled.

To avoid excessive heating in transformers supplying harmonic currents, two approaches are used:

1. Reducing the maximum apparent power transferred by the transformer, often called derating. To estimate the required derating of the transformer, the load's derating factor may be calculated. This method, used commonly in Europe, is to estimate by how much a standard transformer should be de-rated so that the total loss on harmonic load does not exceed the fundamental design loss. This derating parameter is known as 'factor K'.

   The transformer derating factor is calculated according to the formula:

$$K = \left[1 + \frac{e}{1+e}\left(\frac{I_h}{I}\right)^2 \sum_{n=2}^{n=N}\left(n^q\left(\frac{I_n}{I_1}\right)^2\right)\right]^{0.5}, \tag{3.1}$$

   where
   e = the eddy current loss at the fundamental frequency divided by the loss due to a DC current equal to the rms value of the sinusoidal current, both at reference temperature;
   n = the harmonic order;
   I = the rms value of the sinusoidal current including all harmonics given by:

$$I = \left(\sum_{n=1}^{n=N}(I_n)^2\right)^{0.5} = I_1\left[\sum_{n=1}^{n=N}\left(\frac{I_n}{I_1}\right)^2\right]^{0.5}, \tag{3.2}$$

   where
   I_n = the magnitude of the nth harmonic;
   I_1 = the magnitude of the fundamental current;
   q = exponential constant that is dependent on the type of winding and frequency. Typical values are 1.7 for transformers with round rectangular cross-section conductors in both windings and 1.5 for those with foil low voltage windings.

2. Developing special transformer designs rated for non-sinusoidal load currents. This process requires analysis and minimizing of the eddy loss in the windings, calculation of the hot spot temperature rise, individual insulation of laminations, and/or increasing the size of the core or windings. Each manufacturer will use any or all of these techniques according to labour rates, production volume and the capability of his plant and equipment. These products are sold as 'K rated' transformers. During the transformer selection process, the

designer should estimate the K factor of the load and select a transformer with the same or higher K factor, defined as:

$$K = \sum_{n=1}^{n=n_{\max}} I_n^2 n^2. \tag{3.3}$$

For example, when the current harmonic distortion factor THDI = 20%, additional losses in the transformer load circuit, caused by the presence of high harmonics in the load current, will increase by about 4% as related to the losses caused by the current fundamental harmonic.

As an example of specific transformer harmonics considerations the IEC 61378-1 deals with the specification, design and testing of power transformers and reactors that are intended for integration within semiconductor converter plants; it is not designed for industrial or public distribution of AC power in general. The scope of this standard is limited to applications of power converters, of any power rating, for local distribution, at moderate rated converter voltage, generally for industrial applications and typically with a highest voltage for equipment not exceeding 36 kV. The converter transformers covered by this standard may be of the oil-immersed or dry-type design. The oil-immersed transformers are required to comply with IEC 60076, and with IEC 60726 for dry-type transformers. Note also that EN 50464 Part 3 is dedicated on the Determination of the power rating of a transformer loaded with non-sinusoidal currents (K Factor).

3.1.4.3 Voltage Distortion

The common approach presented above assumes that although the magnetizing current does include harmonics, these are extremely small compared with the load current and their effect on the losses is minimal. As a result, in standards such as ANSI/IEEE C57.110 it is assumed that the presence of harmonics does not increase the core loss.

When not ignoring extra harmonic losses from voltage harmonics and also those generated in the transformer core, the full formula to calculate losses in transformers due to harmonics, is as follows:

$$P_{\mathrm{T}} = 3\sum_n I_n^2 \cdot R_n + P_{\mathrm{Fe}} \sum \left(\frac{V_n}{V_1}\right)^m \cdot \frac{1}{n^{2.6}}, \tag{3.4}$$

where

P_{T} = losses of transformer due harmonic distortion;
P_{Fe} = fundamental frequency iron losses;
R_n = equivalent copper loss resistance of transformer at the *n*th order;
V_1 = fundamental component voltage;
V_n = harmonic voltage of order *n;*
I_n = harmonic current of order *n;*
n = order of harmonic;
m = exponent empiric value (assumed to be the value 2).

The second component in the above equation represents losses in the transformer core caused by voltage distortion. This is a partly empiric formula that may still underestimate core harmonic losses caused by current distortion.

Metglas, the introducers of amorphous metal into transformer cores, formulated the following theory.

Current distortion in power networks leads to increased transformer core losses, since hysteresis and eddy current losses vary as f and f^m respectively, where f is the frequency and m varies from ∼1.5 to ∼2, depending on the core material. The situation is worse in transformers using conventional steels with relatively higher hysteresis and eddy current losses than amorphous metals. Therefore the difference in overall transformer loss in amorphous core and conventional silicon steel core transformers widens as higher harmonic contents increase in the power distribution line.

A breakdown of the losses in transformers with conventional and amorphous cores is presented in Table 3.3.

Losses also occur in the magnetic circuit and they increase in the presence of the voltage harmonics. They are eddy current losses, associated with the frequency of high harmonics and magnetic loss in the core, caused by the voltage high harmonics.

First of all, the reason that they are ignored is the level of voltage distortion. It is usually at least one order of magnitude lower than the current distortion. However, voltage harmonics strengthen the effect of unbalanced zero sequence currents circulating in transformer delta windings and associated heat losses. Such losses also contribute to the 'additional' supplementary load losses. An experiment carried out with a small transformer can illustrate just how quickly this additional loss channel can attain a significant size. The series resistance of the delta-connected secondary winding is 0.1 Ω. A THD of only 3.2% in the primary voltage results in a circulating current of 2.3 A. The resulting $I^2 \times R$ loss is therefore about 0.5 W. Half a watt is about 1% of the total copper losses and doesn't actually sound that bad. If the voltage THD rises to 6.4%, which can occur in practice, the Joule heating loss would increase to 4% of the total copper losses or 4.6 A, which in this case would correspond to 28% of the rated current. The transformer load would therefore have to be reduced by 28% solely in order to prevent overheating of the secondary winding by the 150 Hz circulating current.

Now, let us take one more look at the voltage. There are a few particular situations in which the voltage can be so distorted that it has a detrimental effect on the performance of the transformer that it is driving. For example, it is an 'inherent characteristic' of small UPS

Table 3.3 Comparison of harmonics losses in amorphous and silicon steel transformers (THD = 25% at approx 56% transformer loading)

	Hysteresis loss [W]	Eddy current loss [W]	Load loss [W]	Total losses [W]
Non-distorted amorphous	99	33	966	1098
Distorted amorphous	99	74	1553	1726
Non-distorted CRGO	155	311	1084	1550
Distorted CRGO	155	698	1671	2524

systems (in other words, the alternatives are too expensive) that when power loss occurs, they generate a square wave, rather than a sinusoidal voltage. However, a non-stepped square wave will have a form factor that is 11% less than that of a sinusoidal waveform. The 11% is the factor linking the mean value and the RMS value. The quoted value is always the RMS value, or at least it should be. But the degree of magnetization depends on the mean value. The correct RMS value at the output side of a small UPS can cause significant overexcitation of the transformer to which it is connected. In addition, the harmonic distortion of a square wave is so high that very substantial no-load losses must be expected.

3.1.4.4 Mitigation of Extra Harmonic Losses

Despite transformers derating, which has already been described above, the effects of harmonics can largely be mitigated if transformers with different vector groups are installed across the system. Thanks to different phase shifts, such transformers would encourage harmonics with different phase angles to cancel each other. Also, zigzag transformers in which the delta-connected and the star-connected parts of the relevant winding have the same voltage, will minimize the effect of harmonics. Unfortunately such measures are rarely used as distribution network operators use the same vector grouping usually Dyn 5 or 11 to retain an option of transformers operating in parallel. Also the standardization and exchangeability of transformer stock are arguments against using different vector groups.

3.1.4.5 Unbalance

Transformers subject to negative sequence voltages transform them in the same way as positive-sequence voltages. The behaviour with respect to homopolar voltages depends on the primary and secondary connections and, more particularly, the presence of a neutral conductor. If, for instance, one side has a three-phase four-wire connection, neutral currents can flow. If at the other side the winding is delta-connected, the homopolar current is transformed into a circulating (and heat-causing) current in the delta. The associated homopolar magnetic flux passes through constructional parts of the transformer causing parasitic losses in parts such as the tank, sometimes requiring an additional derating. The indicative extra harmonic losses due to unbalance are presented in Table 3.4.

Table 3.4 Indicative unbalance losses in transformers

Ratio of neutral current to average phase currents	Transformers extra losses in %
0.5	6–8
1.0	15–20
1.5	35–50
2.0	70–90
3.0	150–200

3.2 Efficiency and Load Factor

The presented efficiencies are supposed to reflect the operating conditions (loading) of transformers. What matters a great deal is the load of a transformer. Transformers operate at their highest efficiency when the load and no-load losses are equal. This comes out from the following equations.

The ratio of the increments of losses to power should be a minimum:

$$\frac{\Delta P}{S} = \frac{\Delta P_O}{S} + \frac{\Delta P_k}{S} = \frac{\Delta P_O}{S} + \frac{\Delta P_k \left(\frac{S}{S_n}\right)^2}{S} = \frac{\Delta P_O}{S} + \frac{\Delta P_k}{S_n^2} S, \tag{3.5}$$

where

ΔP = increments of losses;
P_k = load;
Po = no load;
S = instantaneous power;
S_n = rated.

This minimum can be calculated from derivatives. The first derivative of the above relation is zero, while the second derivative is positive so the optimum power is given by the relation:

$$S_{opt} = S_n \sqrt{\frac{P_o}{P_k}} \tag{3.6}$$

In practice, the optimum efficiency of transformers where both losses are equal is between 25% and 50% of transformer load. Equation (3.6) shows how to find easily the loading at which a transformer reaches its highest efficiency. If, for example, the ratio of no-load losses by load losses is one by four, the square root of 0.25 is 0.5, which means optimum efficiency between 25% and 50% loading.

Examples of two transformers with different proportions of load (Cu) and no-load (Fe) losses are shown in Figure 3.1.

Table 3.5 compares losses and efficiency of different types of transformers 100% and 50% loaded.

Table 3.5 Losses and efficiency at 50% and 100% load

		Efficiency at		Loss at	
	Rated power	100% rated load	50% rated load	100% rated load	50% rated load
Transformer type	[MVA]	%	%	[kW]	[kW]
Generator transformer	1100	99.60	99.75	4400	1375
Interbus transformer	400	99.60	99.75	1600	500
Substation transformer	40	99.40	99.60	240	80
Distribution transformer	1	98.60	99.00	14	5

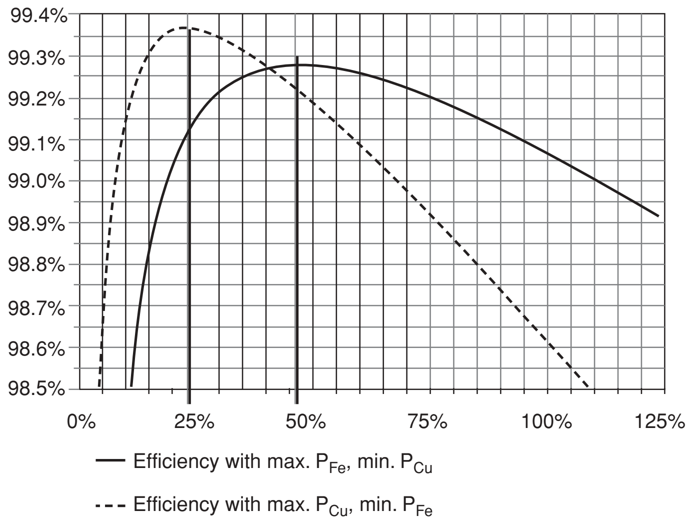

Figure 3.1 Transformer efficiency versus loading

3.3 Losses and Cooling System

Transformer losses in the form of heat have to be evacuated from the inside to the outside of the transformer. Air, gas or liquid can play the role of insulator and also of the cooling agent. However cooling can be natural or forced by fans or pumps. The cooling agent and the forced flow of the coolant are important aspects of transformer efficiency. Transformers follow some physical rules that relate certain parameters to their size. These relations can be expressed as:

$$\frac{Parameter_2}{Parameter_1} = \left(\frac{S_2}{S_1}\right)^x, \tag{3.7}$$

where the left-hand side of the equation represents selected parameters of transformers 2 and 1, while S_2 and S_1 are the apparent powers of transformers 2 and 1 and x is the exponent, which in theory is $x = {}^1\!/_4$ (one-quarter) for each of the transformer's dimensions width, length and height, hence ${}^3\!/_4$ for the volume. So the volume, approximately proportional to the mass of a transformer grows less than the power throughput or, expressed inversely, the power density increases with greater power ratings.

The surface of a transformer, which is responsible for heat dissipation, thereby increases even less. The exponent will be ${}^2\!/_3$ against any of the dimensions (width, length or height) and thus ${}^2\!/_3 \times {}^3\!/_4 = {}^1\!/_2$ against the power rating, while the relation for weight (including active materials proportion) and losses has an exponent value of ${}^3\!/_4$ (three-quarters).

It is clear now that larger transformers needed additional cooling. The first step is to introduce liquid cooling of the transformer windings. Further cooling can then be achieved by increasing the area of the transformer cooling surfaces. This type of cooling system is known as ONAN cooling (oil natural, air natural circulation). Forced cooling is used in transformers with ratings above about 40 MVA. In this type of cooling, known as ONAF cooling (oil natural, air forced circulation), liquid cooling is augmented by cool air blown in between the oil radiators by fans.

Above about 400 MVA, it becomes necessary to use pumps to help circulate the oil coolant. This form of cooling is abbreviated OFAF and stands for 'Oil Forced, Air Forced Circulation'. In transformers with power ratings greater than 800 MVA, simply circulating the oil is no longer sufficient and these transformers use ODAF cooling (oil directed, air forced cooling) in which a jet of cooling oil is directed into the oil channels of the transformer windings.

3.4 Energy Efficiency Standards and Regulations

Energy efficiency in transformers is supported by standards and energy policy instruments. Standards are international or country documents describing either test procedures including loss tests, tolerances and guiding on transformers application including lifetime costing, loading or derating for harmonics.

Policy instruments are used more to support principal targets, such as energy efficiency. They may include the following:

- a voluntary or mandatory minimum energy efficiency standard;
- labelling;
- incentives from obligations or certificate schemes;
- other financial or fiscal incentives;
- information and motivation;
- tool-kits for buyers;
- energy advice / audits;
- co-operative procurement;
- support for R&D and pilot or demonstration projects.

Although mandatory regulations guarantee the strongest enforcement it is important to mention that energy policy should always act as a mix of instruments. Regulations usually referred to MEPS (Minimum Energy Performance Standards) for transformers have evolved in many countries over the last decade. Except for China and European proposals of MEPS for 'non-distribution' power transformers, such regulations cover distribution transformers, both liquid-immersed and dry types of transformers.

The main international normative reference is IEC 60076, Power transformers – series. The IEEE equivalent standard for IEC 60076-1 (2000) is the IEEE C57.12.00 (2006). IEC 60076 gives detailed requirements for transformers for use under defined conditions of altitude, ambient temperature for both:

- oil-immersed transformers in IEC 60076-2, and
- dry-type transformers in IEC 60076-11.

The IEC 60076 series consists of the following parts relevant to energy efficiency:

- Part 1: 1993, General – definition of terms
- Part 2: 1993, Temperature rise
- Part 3: 1980, Insulation levels and dielectric tests
- Part 5: 1976, Ability to withstand short circuit

- Part 7: 2005, Loading guide for oil-immersed power transformers. This part provides recommendations for the specification and loading of power transformers complying with IEC 60076 from the point of view of operating temperatures and thermal ageing. It also provides recommendations for loading above the nameplate rating and guidance for the planner to choose rated quantities for new installations. The use of life time is based on the hot spot temperature in the winding. An increase of the hot spot temperature with 6K is a reduction of the life time by 50%.
- Part 8: 1997, Application guide.

The most important aspects are that the maximum allowable tolerance on the total losses (sum of the load and no-load losses) is +10% of the total losses (IEC 60076-1). This standard in clause IEC 60076-1/ 7.1 stipulates that the values of the losses or the efficiency class of the transformer is not mandatory information on the rating plate of the transformer.

It is worth mentioning the initiative of Technical Committee no. 14 of IEC, which has initiated a project of new IEC 60076-XX standard: Power transformers – Part XX: Energy efficiency for distribution transformers.

This standard is intended to guide purchasers of power transformers in choosing the most appropriate level of energy efficiency, and the most appropriate method of specifying that efficiency. It will also provide a guide on the loss measurement where not provided for in other standards, and tables of standard losses for certain types of transformers.

As justification it says ‘Energy efficiency is becoming more and more important as a worldwide issue for electricity transmission and distribution. A standard is needed to provide a method to calculate energy efficiency according to the way in which the transformer is to be used and the type of transformer, as the best balance between energy use and use of resources in the construction of the transformer will depend on these factors.’

The target of this standard will be:

- Calculation of energy efficiency according to the following parameters
- Type of load (inductive, reactive, resistive)
- Level of rated power
- To provide standard levels of load losses and no-load losses to suit particular efficiency requirements
- The ways in which loss measurement can be done
- The ways in which the uncertainties of measurement can be considered
- Tolerances on guarantees.

Now let us have a look into detailed MEPS in different countries.

There has been a substantial level of international activity concerning efficiency supporting instruments including MEPS for (distribution) transformers. Comparison of these international efficiency classes is not always obvious because of:

- differences in electricity distribution systems: grid voltages, grid frequencies (50 Hz versus 60Hz), etc.;
- differences in definitions for apparent power rating of the transformer (input power versus output power);

- differences in load levels at which the efficiency of the transformer is measured (50% load, 100% load, etc.);
- differences in normalized operating temperatures;
- different rated sizes of transformers.

In the process of preparing the MEPS the social, economic and technical feasibility aspects are taken into account. The common approach is to set the standards as close as possible to minimize the product life cycle. The environmental perspective is equally significant but although life cycle costing and life cycle assessment are different things, they lead to similar results for most transformers. The reason is that the use phase of a transformer, especially a distribution transformer, is usually responsible for even more than 95% of the life cycle environmental impact. The energy from transformer losses with associated emissions is the dominant component there. The potential for global warming and acidification, which are mostly energy related emissions have relative environmental impacts. All together there are seven environmental impacts, including GWP and acidification, as well as eutrophication, ozone depletion, etc. The impact of GWP and acidification are around 100 times larger than all the remaining impacts. The comparison of energy cost (including energy used in production and end of life phases) and life cycle for distribution transformers analysed in the European MEPS preparatory study is given in Figure 3.2.

The asterisks in Figure 3.2 designate amorphous core options that have not been considered as technology relevant for MEPS at the early stage. At this point it is worth delving deeper into the structure of life cycle costs.

These have three main components: transformer price, cost of load and cost of no-load losses. Here we focus more on transformer price and its relation to losses. Figure 3.3 compares product price with the capitalized cost of losses for distribution transformers. Ideally the increased price of the transformer is fully compensated for by the decreased cost of losses.

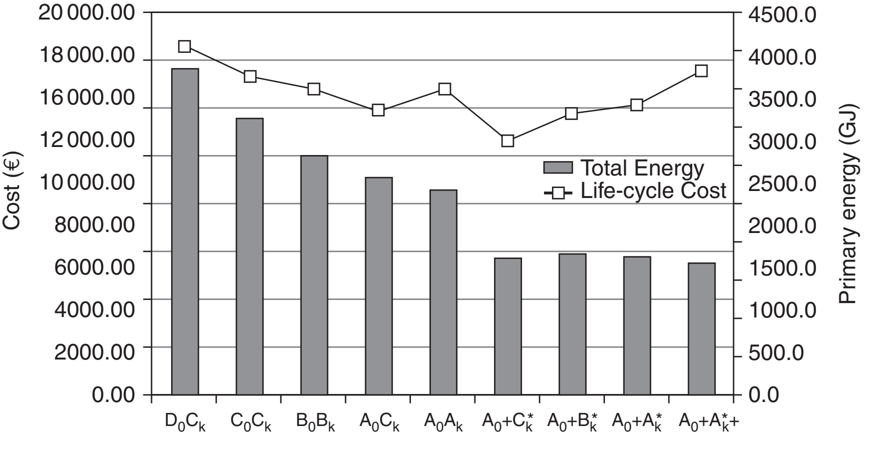

Figure 3.2 Environmental performance, life cycle costs versus primary energy for 400 kVA oil transformer

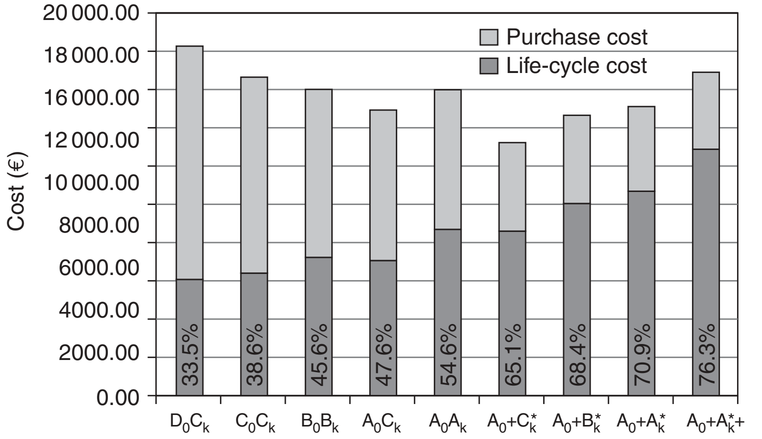

Figure 3.3 Environmental performance, price versus capitalized cost of losses for 400 kVA oil transformer

In this case the lowest life cycle cost (LLC) is at A_0C_k loss level, and this is the proposed MEPS for transformers up to 630 kVA. However, as the difference in LLC between A_0A_k and A_0C_k decreases with increase of transformer size due to higher loading and lower relative production cost, the A_0A_k loss mix is proposed for larger transformers (>630 kVA) as MEPS. At the same time, even on the given example, A_0A_k compared with A_0C_k losses provides incentive in the form of more than 100 GJ of primary energy and this value is expected to increase more than proportionally with transformer rating (the conversion factor 1 kWhe = 10.5 MJ given in the European methodology for preparatory studies was used to convert the electricity consumption).

The precise analysis of all variants that shows differences in transformer cost is presented in Table 3.6.

It is obvious that reduction of losses and associated costs comes at some expense. The US Department of Energy estimated that an increase in the energy efficiency of one percentage point increases the transformer price by 73% (DOE, 2001). The recent EuP study shows that a 400 kVA oil transformer – the size that has been selected as the most representative for the average sold distribution transformers – experiences a rate of loss reduction similar to the price increase but loss reductions at a higher efficiency level, as expected, come at a higher price increment. See the last row in Table 3.6.

MEPS are organized in the form of either maximum loss tables or efficiency tables calculated at certain loading levels; 100%, or more often 50%, which represents loading closer to real operating conditions and closer to optimum efficiency as well. The Japanese top runner scheme uses formulae to calculate efficiency for different transformers from their kVA value at 40% load. India applied an interesting idea of specifying maximum losses for two transformer loading levels 50% and 100%. This is to secure that transformers have the required proportion of no- load to load losses.

In addition to losses, European standards specify noise levels together with no-load losses as the noise in transformers is mostly related to core magnetization.

Table 3.6 Environmental performance, comparison of different options, production, losses

		D0Ck	C0Ck		B0Bk		A0Ck		A0Ak		A0 + Ck*	
			Relative	Absolute	Relative	Absolute	Relative	Absolute	Relative	Absolute	Relative	Absolute
Core	Core steel (kg)	468.7	1.12	524.94	1.22	571.81	1.35	632.75	1.45	679.62	1.59	747
Windings	Aluminium wire (kg)	21.44	1.06	22.73	1.44	30.87	1.37	29.37	2.07	44.38	1.59	82
	Copper wire (kg)	144.72	1.06	153.4	1.44	208.4	1.37	198.27	2.07	299.57	1.59	206
	Copper sheet (kg)	48.24	1.06	51.13	1.44	69.47	1.37	66.09	2.07	99.86	1.59	76.88
Other	Tank (kg)	266.7	1.1	293.68	1.29	343.78	1.36	361.71	1.64	438.61	1.63	434.79
	Paper (kg)	16	1.1	17.61	1.29	20.62	1.36	21.7	1.64	26.31	1.63	26.08
	Ceramic (kg)	6.02	1.1	6.63	1.29	7.76	1.36	8.16	1.64	9.9	1.63	9.81
	Oil (kg)	265.5	1.1	292.36	1.29	342.24	1.36	360.09	1.64	436.64	1.63	432.84
	Cardboard (kg)	3.65	1.1	4.02	1.29	4.71	1.36	4.96	1.64	6.01	1.63	5.96
	Plastics (kg)	2.05	1.1	2.25	1.29	2.64	1.36	2.78	1.64	3.37	1.63	3.34
	Wood (kg)	4.38	1.1	4.83	1.29	5.65	1.36	5.95	1.64	7.21	1.63	7.15
	Powder coating/Paint (kg)	5.79	1.1	6.37	1.29	7.46	1.36	7.85	1.64	9.52	1.63	9.43
	Total (kg)	1253		1380		1615		1699		2060		2041
	Volume of final product (m^3)	2.11	1.1	2.32	1.29	2.72	1.36	2.86	1.64	3.47	1.63	3.44
	P_0 (W)	750		610		520		430		430		196
	P_k (W)	4600		4600		3850		4600		3250		4554
	Efficiency at 50% load %	99.05	1.073	99.12	1.221	99.26	1.168	99.21	1.347	99.38	1.294	99.33
	Electricity losses (kWh/year)	7858		6632		5633		5055		4677		2992
	Product price (€/unit)	6122	1.05	6428	1.19	7285	1.16	7101	1.42	8693	1.41	8632
Ratio: price increase versus total loss reduction at 50% load				98%		97%		97%		105%		109%

An overview of existing transformer efficiency schemes is given below.

3.4.1 MEPS

Main international MEPS are listed in Table 3.7.

Table 3.7 International MEPS

Country	Title
Australia	AS 2374.1.2-2003 : Power transformers – Minimum Energy Performance Standard (MEPS) requirements for distribution transformers (10-2004)
Canada	Mandatory MEPS for Transformers (01-01-2005)
EU member countries	Energy Performance Standard for Distribution and Power Transformers under preparatory work in frame of Energy related Products Directive
India	MEPS for Distribution Transformers of ratings 16, 25, 63, 100, 125, 200 kVA capacity (2010)
Israel	MEPS for Distribution Transformers – Israel
New Zealand	AS 2374.1.2 – Power Transformers Part 1.2: Minimum Energy Performance Standard (MEPS) requirements for distribution transformers (01-10-2004)
People's Republic of China	GB 20052-2006 – Minimum Allowable Values of Energy Efficiency and the Evaluating Values of Energy Conservation for Three-Phase Distribution Transformers (2006)
The United States	MEPS for Distribution Transformers (2010)

3.4.2 Mandatory Labelling

Main international efficiency labelling programmes are listed in Table 3.8.

Table 3.8 International efficiency labelling

India	Star Rating Plan – Distribution Transformer (2010)
Israel	Energy Label for Distribution Transformers – Israel
Japan	Label Display Program for Retailers – 'Top runner program' – Transformers
People's Republic of China	China Energy Label – Power Transformer (2010)

3.4.3 Voluntary Programmes

Main international voluntary schemes are listed in Table 3.9.

Table 3.9 International voluntary schemes

Chinese Taipei	Greenmark – Transformers (1992)
People's Republic of China	CQC Mark Certification – Power Transformer (2010)
Republic of Korea	Certification of high energy efficiency appliance program for Transformers (–)
The United States	ENERGY STAR – Transformers (1995)

The comparison of selected international MEPS, taking into account the lack of full equivalency as explained earlier in this section, is presented in Table 3.10.

Table 3.10 Comparison of international MEPS

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Rating kVA	USA oil	USA dry	USA BAT oil	USA BAT dry MV	Australia oil	Australia dry	Australia oil High eff.	China S11	EU oil proposed	EU dry proposed	India	EU25 fleet	EU25 market
15 or 16	98.36%	97.00%	99.31%	98.75%								97.12%	97.80%
25					98.28%	97.17%	98.50%				98.36%	97.58%	98.24%
30	98.62%	97.50%	99.42%	98.95%								97.56%	98.36%
45	98.76%	97.70%	99.47%	99.05%								97.84%	98.44%
50								98.67%	98.54%			98.15%	98.44%
63 or 75	98.91%	98.00%	99.54%	99.17%	98.62%	97.78%	98.82%				98.82%	98.27%	98.66%
100					98.76%	98.07%	99.00%	98.86%	98.84%	98.58%	98.98%	98.52%	98.76%
112.5	99.01%	98.20%	99.58%	99.25%									
150	99.08%	98.30%	99.61%	99.30%									
160								98.96%	99.00%	98.75%	99.05%	98.67%	98.86%
200					98.94%	98.46%	99.11%				99.12%		
225	99.17%	98.50%	99.65%	99.37%									
250								99.08%	99.11%	98.92%	99.15%	98.88%	99.01%
300 or 315	99.23%	98.60%	99.67%	99.41%	99.04%	98.67%	99.19%		99.15%				
400								99.17%	99.21%	99.09%	99.18%	99.00%	99.15%
500	99.25%	98.70%	99.71%	99.48%	99.13%	98.84%	99.26%		99.25%		99.26%		
630								99.24%	99.29%	99.12%		99.13%	99.28%
750	99.32%	98.80%	99.66%	99.42%	99.21%	98.96%	99.32%		99.46%			99.22%	99.31%
1000	99.36%	98.90%	99.68%	99.46%	99.27%	99.03%	99.37%	99.25%	99.47%	99.29%		99.16%	99.29%
1500	99.42%		99.71%	99.51%	99.35%	99.12%	99.44%						
1600								99.34%	99.48%	99.37%		99.33%	99.39%
2000	99.46%		99.73%	99.54%	99.39%	99.16%	99.49%			99.39%			
2500			99.74%	99.57%	99.40%	99.19%	99.50%		99.49%	99.42%		99.35%	99.37%

Comments on Table 3.10

All presented efficiencies apply to three-phase transformers.

Losses in the table cannot be compared directly. They are given as in the original documents and are compared with schemes where they appear as the maximum allowable losses further recalculated to efficiency levels. One particular difference exists when comparing efficiencies in 50 Hz and 60 Hz systems. Transformers for 60 Hz tend to have higher no-load and lower load losses, if all the other parameters are kept the same. The resulting differences are about 10% at 50% load if the optimum efficiency of a transformer is close to 40%. In fact in its first attempt Australia ‘recalculated’ the American 60 Hz NEMA TP1 efficiency standard to Australia’s 50 Hz frequency and also linearly interpolated the efficiencies at the size ratings that in Australia are different from USA. In practice a sort of check would be to deduct 0.2% from the USA standard for efficiency levels below 99% and deduct 0.1% for levels above 99% to get rough equivalency of standards. If we do so, we will observe that the USA rule is by far the most demanding scheme worldwide. In Europe levels are also quite demanding, particularly for sizes above 630 kVA, having in mind that they are dedicated to transformers with magnetic steel cores. Currently amorphous transformers are not at all a mainstream product in Europe and there is the uncertainty on the availability in the short term of amorphous material and transformer production in the EU, therefore the proposed levels are ambitious but possible to achieve with non-amorphous technology.

As comment to this, more than 95% of amorphous transformers are sold in Asia and the USA, primarily in India, China and Japan with emerging demand from the USA. Not long ago, in 2006, Spanish Endesa, a company that made some purchases of amorphous transformers reported that about 22 000 tons of amorphous steel is used. Hitachi Metals/Metglas in 2009 indicated that the production capacity of amorphous iron was 50 000 tons in 2008 and this was expected to rise up to 100 000 ton by 2010 (however not necessarily all this production will have to be dedicated to the transformer market). If we take 400 kVA as the average rating of transformers installed, at 600 kg core material, about 37 000 amorphous transformers are produced each year (based on 2006 figures). This is about 1.2% of the total annual sales worldwide.

Columns 4 and 5 specify DOE efficiency levels of the best available technology (BAT), which are possible to achieve if the cost is no issue. They were added to the final rule to demonstrate the gap between BAT and MEPS. Column 8 is Australian MEPS, not for ordinary but for ‘high efficiency power transformers’. Finally, columns 13 and 14 are given to compare standards with current practice in Europe (source – SEEDT). Column 13 gives equivalent efficiency for the average transformers operating in Europe, while column 14 specifies average efficiencies of transformers sold in Europe in the year 2005.

A better illustration of how demanding MEPS are with the recalculation of 60 Hz frequency to 50 Hz is presented in Figure 3.4.

One extreme (the most ambitious) is USA efficiency level here referred to as BAT, in the original expressed as ‘if costs were no issue’. The other extreme would be far out of scale as the South African standard SANS 780, 2004 specifies losses that at 50% loading are equivalent to an efficiency of 96.45%! It is a good example of how energy costs, which have been known to be low in South Africa, can discourage more ambitious efficiency levels.

The details of standards are presented in Section 9 of this chapter.

3.5 Life Cycle Costing

The annual energy losses of a transformer can be estimated from the following formula:

$$W_{\text{loss}} = (P_0 + P_K * L^2) * 8760h, \tag{3.8}$$

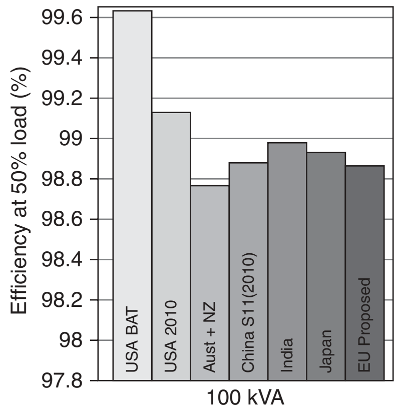

Figure 3.4 Graphical comparison of selected MEPS normalized at 50 Hz 100 kVA

where

W_{loss} is the annual energy loss in kWh;

P_0 is the no-load loss in kW – this factor is available from the transformer specifications or can be measured;

P_K is the short-circuit loss (or load loss) in kW – this factor is available from the transformer specifications or can be measured;

L is the average per-unit load on the transformer (This is absolutely precise for constant load but becomes less precise, the more the load varies);

8760 is the number of hours in a year.

To calculate the cost of these losses, they need to be converted to the moment of purchase by assigning capital values, in order to put them into the same perspective as the purchase price. This is called the Total Capitalized Cost of the losses, TCC_{loss}. This can be calculated using the following equation:

$$TCC_{loss} = W_{loss} \times \frac{(1+i)^n - 1}{i \cdot (1+i)^n} \times C \times 8760, \qquad (3.9)$$

where

C = estimated average cost per kWh in each year;

i = estimated interest rate;

n = expected life time of the transformer.

3.5.1 Life Cycle Cost of Transformers

To perform the economical analysis of the transformer, it is necessary to calculate its life cycle cost, sometimes called the Total Cost of Ownership, over the life span of the transformer or, in other words, the capitalized cost of the transformer. All these terms mean the same – in one equation, costs of purchasing, operating and maintaining the transformer need to be compared, taking into account the time value of money.

The concept of the ‘time value of money’ is that a sum of money received today has a higher value – because it is available to be exploited – than a similar sum of money received at some future date.

In practice, some simplification can be made. While each transformer will have its own purchase price and loss factors, other costs, such as installation, maintenance and decommissioning will be similar for similar technologies and can be eliminated from the calculation. Only when different technologies are compared, e.g. air-cooled dry-type transformers with oil cooled transformers will these elements need to be taken into account.

Taking only purchase price and the cost of losses into account the Total Cost of Ownership can be calculated by the base formula:

$$TCO = PP + A * P_0 + B * P_k, \tag{3.10}$$

where

PP = purchase price of transformer;
A = assigned cost of no-load losses per watt;
P_0 = rated no-load loss;
B = assigned cost of load losses per watt;
P_k = rated load loss.

P_0 and P_k are transformer rated losses. The A and B values depend on the expected loading of the transformer, and energy prices.

The choice of the factors A and B is difficult, since they depend on the expected loading of the transformer, which is often unknown, and energy prices, which are volatile, as well as the interest rate and the anticipated economic lifetime. If the load grows over time, the growth rate must be known or estimated and the applicable energy price over the lifetime must be forecast. Typically, the value of A ranges from less than 1 to 8€/W and B is between 0.2 and 5€/W.

Below we propose a relatively simple method for determining the A and B factor for distribution transformers.

The A and B factors are calculated as follows.

No-load loss capitalization

$$A = \frac{(1+i)^n - 1}{i(1+i)^n} \times C_{\text{kwh}} \times 8760 \tag{3.11}$$

Load loss capitalization

$$B = \frac{(1+i)^n - 1}{i(1+i)^n} \times C_{\text{kwh}} \times 8760 \times \left(\frac{I_l}{I_r}\right)^2 \tag{3.12}$$

where

i = interest rate [%/year];
n = lifetime [years];
C_{kWh} = kWh price [€/kWh];
8760 = number of hours in a year [h/year];
I_l = loading current [A];
I_r = rated current [A].

These formulae assume that energy prices and the loading are constant over the transformer life. We will comment on this later.

Usually, the loss evaluation figures *A* and *B* form part of the request for a quotation and are submitted to the transformer manufacturers, who can then start the process of designing a transformer to give the required performance. The result of this open process should be to use the cheapest transformer, i.e. the one with the lowest total cost of ownership, optimized for a given application. The drawback of this process is, as mentioned, the difficulty in predicting the future load profile and electricity costs and tariffs with any confidence. On the other hand, these optimization efforts depend on the prices of materials, particularly active materials, i.e. conductor and core material. Dynamic optimization makes sense when there is the different price volatility for different materials such as aluminium and copper or high and low loss magnetic steel.

For large transformers, above a few MVA, the cost of losses are so high that transformers are custom-built, tailored to the loss evaluation figures specified in the request for a quotation for a specific project.

For distribution transformers, often bought in large batches, the process is undertaken once every few years. This yields an optimum transformer design, which is then retained for several years – less so nowadays because of the volatility of metal prices – until energy prices and load profiles have changed dramatically.

To make the capitalization more attractive, so that the use of TCO is easier, we propose the use of a graph, shown in Figure 3.5, which allows factor *A* to be determined.

Factor *A* expresses the relation between the cost of no-load losses and the following:

- electricity price;
- discount rate or company interest rate or average cost of capital;
- capitalization period or expected lifetime of the transformer.

This example illustrates that for an electricity price of 100€/MWh, an interest rate of 5% and a 10-year capitalization period, the cost of no-load loss will be 6.75 €/watt.

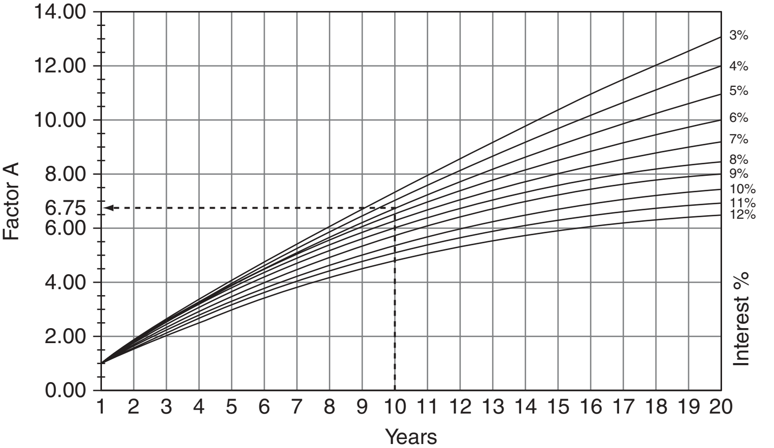

Figure 3.5 Simplified chart for calculation of factor *A* at electricity cost 100 €/MWh

Factor A is directly proportional to the electricity price, so it can simply be scaled to account for electricity price changes as long as the interest rate and capitalization period remain unchanged.

It is important to note that, for small interest rates, a doubling of the capitalization period will result in almost doubling the cost of losses. On the other hand, applying too high a capital rate by making, for example, too high a provision for risk, will produce a low value of loss.

Factor B, as explained previously, is simply the product of factor A and the square of the loading factor ($B = A\ (Loading)^2$). The loading factor used here is the expected average load over the lifespan of the transformer, possibly taking harmonics into account.

For larger power transformers the formula for total cost of ownership is more complex. First of all additional component should be added to the base formula, reflecting capitalized losses of auxiliary losses for fans or pumps calculated analogically as load losses. The next element treated in more detail here is peak responsibility, which is intended to compensate for the transformer peak load losses that do not occur at the system peak losses. This means that only a fraction of the peak transformer losses will contribute to the system peak demand. This relation is the ratio of two transformer loads:

- β_{syst}, transformer load at time of system peak; and
- β_{s}, transformer peak load.

Finally, the base equation for cost of energy is now composed of an additional element C_{inv}, which reflects system investment to the cost of generation and transmission facilities related to 1 kWh of energy transmitted through a transformer, which is necessary to supply the additional demand resulting from the transformer losses at the system peak. Since a transformer located directly at a generating station does not require an investment in transmission facilities, this value used to evaluate the losses in the generating station transformer should be less than in a transformer located at a certain location downwards transmission network.

A method for determining this value involves adding the construction cost of a recently completed or soon to be completed generating station to the cost of the transmission facilities required to connect the transformer to the plant. If power is purchased rather than self-generated, this value can be determined by dividing the demand charge by the fixed charge rate. There can be different methods to estimate such a cost, sometimes referred to as avoided cost of generation and transmission capacity. The selected method should yield the most realistic results.

In conclusion, the simplified equation that includes peak load responsibility and T&D capacity will have the following notation:

$$C = C_{\text{kWh}} + C_{\text{inv}} \times \left(\frac{\beta_{\text{syst}}}{\beta \text{s}}\right)^2. \tag{3.13}$$

The cost of the losses also depends on voltage level and less strongly on rated power, location or transformer type. Some examples or indicative values of the cost of losses in transformers are as follows.

For distribution transformers they are between 3 and 10 USD/W, sometimes even higher if very high electricity prices together with low interest rates and long lifetimes apply.

For power transformers, due to the scale, no-load losses are related to kW instead of watts and are usually between 2000 to 7000 USD/kW and average around 5000 USD/kW. There is also differentiation in accordance with generation: mostly variable fuel cost and operating costs of the transmission system.

As for load losses, the specified values are a certain fraction of no-load losses that are strictly dependent on assumed loading. In the case of distribution transformers this fraction is usually at a level of 15-20% of the cost of no-load loss (equivalent to roughly 40% loading) while for transmission transformers they are higher, usually between 30% to 50% of the cost of no-load losses (between 55% and 70% loading).

3.5.2 Detailed Considerations

Transformer loading plays a very special role in life cycle costing. Load losses vary with the square of the load.

Ideally, to calculate the load losses it would be necessary to integrate the squares of all momentary ratios of actual load to the rated load. This is practically impossible, so a methodology to analyse load losses based on the summation of energy consumed in transformers has been developed.

The formula to calculate load losses is presented below:

$$\sum P_{\mathrm{k}} = \beta_{\mathrm{S}}^2 \times \tau \times P_{\mathrm{k}}, \tag{3.14}$$

where

$\sum P_{\mathrm{k}}$ is sum of load losses in given period of time, usually one year;
β_{s} is the peak load of a transformer in given period of time;
τ is time duration of peak loss;
P_{k} is rated load loss of a transformer.

It should be noted that $(I_{\mathrm{l}}/I_{\mathrm{r}})^2$ value from the B factor calculation formula can be expressed as ${\beta_{\mathrm{s}}}^2 \times \tau$. The relationship between the time duration of the peak losses τ and the time duration of peak load T_{s} is shown in Figure 3.6.

T_{s} represents the fraction of yearly time in which energy is transformed at peak load conditions equivalent to the actual energy transformed. τ_{s} represents the fraction of yearly time of peak loss (which occurs at peak load) equivalent to actual load losses.

Different empirical models have been developed to define the relationship:

$$\tau_{\mathrm{s}} = f(T_{\mathrm{s}})$$

and some examples are:

$$\frac{\tau_{\mathrm{s}}}{8760} = \left(\frac{T_{\mathrm{s}}}{8760}\right)^x \tag{3.15}$$

with 'x' varying around a value of 1.7 to 1.8 or

$$\tau_{\mathrm{s}} = A \cdot \left(\frac{T_{\mathrm{s}}}{8760}\right) + B \cdot \left(\frac{T_{\mathrm{s}}}{8760}\right)^2 \tag{3.16}$$

with A being between 0.15 to 0.5 and the B value between 0.5 and 0.85, with additional feature of $A + B = 1$ (but there are exclusions from the last condition). The physical interpretation of all these formulae is hard and is not always proven.

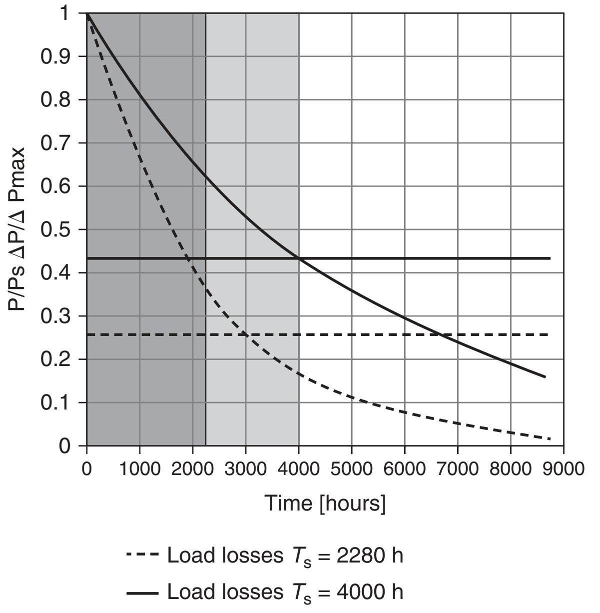

Figure 3.6 Explanation of the relationship between time of peak losses τ and time of peak load in situations when for half a year the load is 200% of the average load and for the remaining half a year is zero

In SEEDT they have compared and analysed these formulae from the accuracy point of view. The 'x' value that gives the best results is 1.73 or an A value of 0.3 and a B value of 0.7.

The average loading of distribution transformers in electricity distribution companies in the EU-27 is 18.9% and peak load is 0.53 (53%). The time of peak load is 0.36 and the time of peak loss is 0.2. Transformers in electricity distribution companies have such low loadings for many reasons, such as the anticipated high variability of load and the need to reserve capacity to provide resilience against failure of other units and sections of the network. Another reason could also be the limiting of loading on transformers that are in a poor technical condition (e.g. moist insulation and risk of its further degradation leading to failure). A further reason might be that distribution transformers are protected against short circuit, but not against overload or excessive temperature and large margins are used. These are the average figures and the situation may be quite different in different countries.

Industrial transformers are loaded higher than transformers owned by distribution companies. The average load is 37.7%, peak load above 0.7, while the times of peak load and peak loss are about 0.3 and 0.15, which means that the load (with peaks and lows) is fairly intermittent.

It is quite apparent that the τ value is around 50 to 60% of the T value. Theoretically τ is 50% of T in situations where the T curve in Figure 3.6 is a straight line between the peak load and zero (load is continuously and uniformly distributed between peak load and zero). On the other hand, when the T curve is a straight horizontal line (equal load all the year), the values T and τ will be equal.

It is necessary to understand the influence of loading conditions to calculate the *B* factor. In practical situations additional effort should also be made to anticipate loading changes over time.

The relative weighting given to load losses and no-load losses in the design of a transformer that is so much loading dependant, determines whether the transformer has more conductor material in the coil windings and less core material or vice versa. The design choices made will also affect the transformer's operational behaviour, particularly its losses. For instance, optimum efficiency can be achieved at a load factor of 24% or at 47% depending on the design (see Figure 3.1). When compared at constant current density, a transformer with more conductor material will exhibit greater load losses, or 'copper losses', as they are also known. Strictly speaking, a more accurate trivial name for these losses would be 'aluminium losses', as the losses in an aluminium conductor are 35% greater than those in a copper conductor of identical cross-section. But the term 'copper losses' is unlikely to change, as it reflects the fact that copper is, historically, the standard conductor material used in transformers.

If the magnetic flux density, frequency and iron quality are held constant, the no-load losses in a transformer (also known as 'core losses' or 'iron losses') depend only on the amount of iron used in the core. Similarly, if the current density is held constant, then, roughly speaking, the copper losses will depend only on the amount of copper used. On the other hand, iron losses can be reduced by increasing the number of turns on the core and thus reducing the magnetic flux density (induction). In contrast, copper losses can be reduced by operating at a higher flux density and using fewer windings on the core – but this can only be realized within strict limits, as high-quality magnetic materials have quite sharp magnetic saturation points and most conventionally designed transformers operate close to this limit. The primary means of reducing copper losses is to lower the current density, while maintaining the number of turns and the core cross-section and modifying the core in such a way that the winding window is larger and thicker wire can then be used for the windings.

A transformer that spends most of life operating under no load or minimal load conditions should therefore be designed to minimize the no-load losses, i.e. less iron and more copper. It would however be wrong to conclude from this that any transformer designed for permanent full-load operation (something that only really occurs in generator transformers in power stations and in certain industrial applications) should contain as little copper as possible. In this case, the preferred approach is to maximize the cross-section of the iron core in order to minimize the number of turns. The cross-section of the conducting wires should also be as large as possible in transformers running under continuous full load.

So far we have not included the effects coming from extra losses due to harmonics, unbalance and reactive power in life cycle costing. For harmonics and unbalance there is no easy approach and some guidance is provided in Section 3.1. In general, as an average, extra losses from harmonics are at the level of a few percent of nominal losses, however in some industrial applications and office buildings when electrical power is supplying distorting loads these losses can even double nominal losses. As for reactive power influence, this is even harder to make accurate calculation. There are some indications that the equivalent active power losses in supplying network from reactive power flowing in a transformer may be at the level of 0.15 kW/kvar.

So far we have also not considered the increase in power and energy flow in a transformer due to the connection of new customers and new loads. This may sometimes be very important as such yearly increments may lead to very high additional losses and the transformer running further and further away from the optimum (loading) point. In cases when load increase is expected to be significant, the sum of all the annual losses calculated on the basis of expected annual transformer loading should be analysed.

The last but not least of the elements to consider are energy costs. They may also increase with time as new capacities are expected to be more costly due to more expensive technologies and decreased capacity factors, as in the case of renewables or some other peak generators. There are even ideas of differentiating between the cost of energy for no-load and load losses. In the case of load losses, the higher cost of generation and increased cost of energy dispatch combined with the quadratic relation of Joule losses to load may result in the cost of energy load loss being doubled or even higher than the nominal cost of energy.

3.6 Design, Material and Manufacturing

Thanks to improved data processing with mathematical tools and models it is now possible to design a transformer using the finite-element method with the provision of electrical and mechanical strengths, heat transfer and dynamic properties, including short-circuit conditions. As a practical outcome two- or three-dimensional field plots are drawn, helping to design different transformer elements and also keep losses at desired levels with the best balance between costs and efficiency. In practice it is to minimize the influence of an out of proportion increase of one of the cost components, either the conductor, insulant, or core material for the purpose of loss optimization at the design stage.

Material and material processing technology developments have the largest influence on losses. Without evolution in material technologies the progress in transformer efficiency improvement would be impossible on so large a scale. In this section only these improvements that have effects on loss reduction are described.

Fabrication technics may incorporate some improvements; better stacking, precision in manufacturing, insulating and shielding against stray magnetic flux add smaller but still significant loss reductions.

3.6.1 Core

The materials used in both the core and the coils contribute significantly to the cost of a power transformer, whose manufacture is in any case a highly labour-intensive process.

The main milestones in core material developments have been:

- The development of cold-rolled grain-oriented (CGO) electrical steels
- The introduction of thin coatings with good mechanical properties
- The improved chemistry of the steels, e.g., Hi-B steels
- Further improvement in the orientation of the grains
- The introduction of laser-scribed and plasma-irradiated steels
- The continued reduction in the thickness of the laminations to reduce the eddy loss component of the core loss
- The introduction of amorphous ribbon (with no crystalline structure) –manufactured using rapid cooling technology – for use with distribution and small power transformers.

Chronologically these improvements are illustrated in Table 3.11.

Table 3.11 Historical development of core sheet steels

Year	Material	Thickness	Loss (50 Hz)	at flux density
1895	Iron wire		6.00 W/kg	1.0 T
1910	Warm rolled FeSi sheet	0.35 mm	2.00 W/kg	1.5 T
1950	Cold-rolled, grain-oriented	0.35 mm	1.00 W/kg	1.5 T
1960	Cold-rolled, grain-oriented	0.30 mm	0.90 W/kg	1.5 T
1965	Cold-rolled, grain-oriented	0.27 mm	0.84 W/kg	1.5 T
1970	Cold-rolled HiB sheet	0.30 mm	0.80 W/kg	1.5 T
1975–	Amorphous iron	0.03 mm	0.2 W/kg	1.3 T
–2005	Amorphous iron improved HB1	0.02 mm	0.15 W/kg	1.3 T + 10%
1980	Cold-rolled, grain-oriented	0.23 mm	0.75 W/kg	1.5 T
1980	Cold-rolled HiB sheet	0.23 mm	0.70 W/kg	1.5 T
1983	Laser treated HiB sheet	0.23 mm	0.60 W/kg	1.5 T
1985	Cold-rolled, grain oriented	0.18 mm	0.67 W/kg	1.5 T
1987	Plasma treated HiB sheet	0.23 mm	0.60 W/kg	1.5 T
1991	Chemically etched HiB sheet	0.23 mm	0.60 W/kg	1.5 T

3.6.1.1 Cold-Rolled Grain Oriented and HiB Magnetic Steel

Selecting the right sheet steel for the laminations, accurate stacking with frequent staggering (every two sheets), and minimization of the residual air gap are all key parameters in reducing open-circuit currents and no-load losses. Today, practically all core laminations are made from cold-rolled, grain-oriented steel sheet (the thinner the laminations, the lower the eddy currents) despite the significantly higher cost of this type of steel.

Applying gradually improved better grades of non-grain-oriented steel, technology of cut, decreasing laminations thickness led to reduction of these losses by approximately a factor of two over the last 30 years. When comparing these losses with the levels of the middle of the last century the factor would be more than three.

A good illustration of this progress is the SEEDT model presented in Figure 3.7. The chart presents transformers' relative age populations together with their relative shares of no-load and load losses in Europe. To help to read this picture properly one conclusion will be that, for example, replacing 10% of the oldest (and presumably based on the model, least efficient) part of the population will turn into phasing out no-load losses contributing in 21.5% to whole no-load losses. The relevant figure for load losses will be 15.2%. Similarly, taking the oldest 20% of the population out of service will save almost 35% of the total no-load losses and about 30% of total load losses.

It would not be fair if we did not mention the progress in efficiency improvement in large and very large power transformers. Although amorphous metal has not entered this part of the transformer fleet yet (and will hardly do so without major developments in amorphous cores), other improvements have resulted in about 60% no-load reductions and close to 50% load loss reductions over the last 50 years. At the same time, acoustic noise has been reduced from more than 80 dB(A) to less than 50 dB(A).

One of the key aspects in core construction is ensuring the absence of eddy current loops. It is for this reason that even in small transformers with ratings of above about 1 kVA (depending on the manufacturer), the clamping bolts are electrically insulated on one side, although these

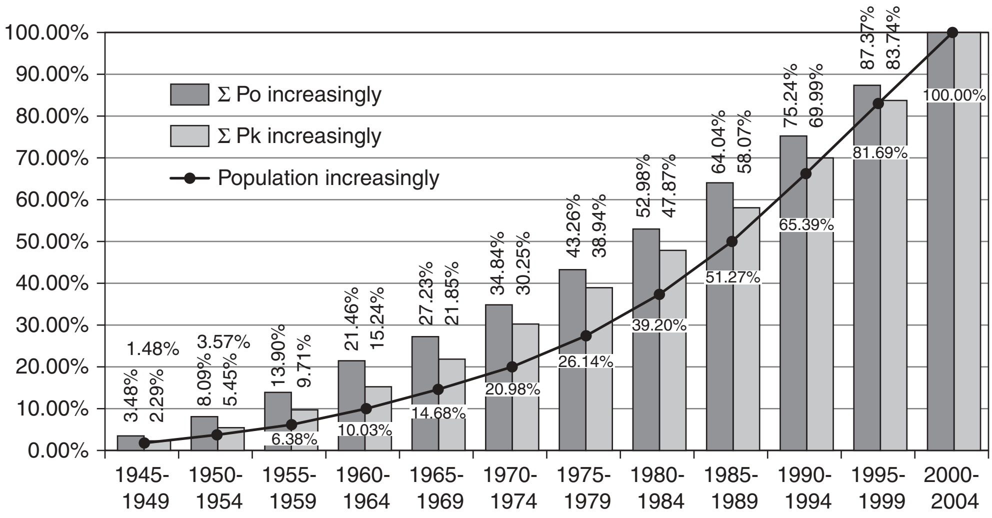

Figure 3.7 Age distribution of transformer population versus losses

benefits would also be apparent in transformers with power ratings below 100 VA. Given the advantages that insulated fastening bolts can yield in relatively small transformers, the benefits gained in much larger distribution and high-power transformers should be obvious.

In larger transformers in yoke frames made of steel pofiles rather than wood the holes have to be large enough so that an insulating bushing can be pushed over the shaft of the bolt to ensure that the bolt does not come into contact with the burred edges of the yoke plates and touches only one side of the yoke frame. If multiple contact points occur, it essentially short circuits the relevant section of the yoke. In addition, cutting bolt holes effectively reduces the cross-sectional area of the core, and eddy currents are also induced in the bolt, which, for obvious reasons, cannot be manufactured from laminated sheet. Sometimes clamping bolts made of stainless steel are chosen, because, perhaps surprisingly, stainless steel is not in fact ferromagnetic although it consists predominantly of iron and nickel – both ferromagnetic elements. The magnitude of the magnetic field in these stainless steel bolts is therefore lower, thus reducing eddy current losses. In addition, stainless steel is much better at suppressing eddy currents because its electrical conductivity is only about one-seventh that of conventional steels.

A better means of clamping the yoke laminations, though more costly than employing stainless steel bolts, is to use a clamping frame that wraps around the yoke (Figure 3.8). However, it is essential to ensure that the clamping ring does not form a closed electrical circuit that would short-circuit the yoke.

Figure 3.8 also shows transformer tap changers in a high-voltage winding, which allow for any variation in the input voltage (typically two steps of +2.5% above the nominal voltage, and two steps of −2.5% below). These are located in the central section of the winding and not at its upper or lower ends. This ensures that the effective axial height of that portion of the high-voltage coil that carries current is essentially constant as is the relative height of the HV and LV coils. Without the tight clamping, a number of windings at the upper or

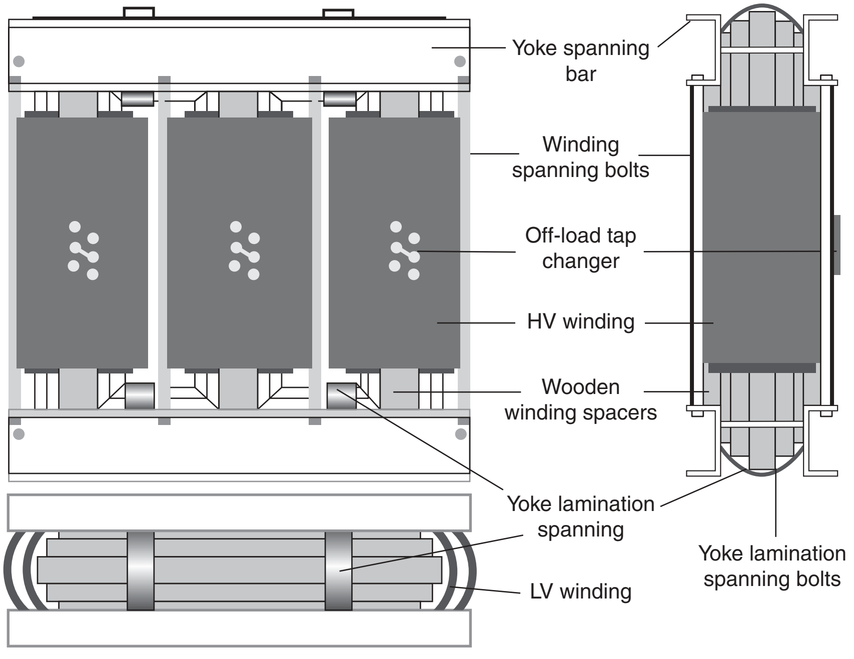

Figure 3.8 The structure of a transformer's core-and-coil assembly ('active part'). The design shown here is the more 'elegant' solution with unperforated yokes

lower end of the coil would be lost if a short circuit caused a significant force in the axial direction between the coils. In transformers that have been in service for a long time, the coils may no longer be as rigidly clamped as they were at the time of manufacture and the insulating materials may be showing signs of age. A short circuit in such a transformer or a breakdown of the insulation material as a result of a lightning strike often causes the device to fail completely. At installations where short circuits or lightning strikes occur only every few decades, a transformer can remain operational for as long as 60 years before finally having to be replaced for economic reasons.

3.6.1.2 Amorphous Steel

America's Allied-Signal admits spending more than 25 years and a great deal of R&D effort to achieve the commercial production of Metglas® amorphous alloys. The joint Hitachi/Metglas group is the world's largest promoter of amorphous technology in distribution transformers.

No-load losses can be reduced by lowering the magnetic flux density and by using special core steels. The thinner the sheet steel is, the smaller the extent of eddy current formation. Eddy currents are completely absent in core materials that do not conduct electricity (so-called ferrites), but these are reserved for radio-frequency applications as their magnetizability is too low for transformers operating at grid frequencies. Amorphous steel is a new type of core material that offers a compromise between sufficiently high magnetizability and significantly reduced core losses. While the resulting core material has a saturation magnetization of approximately 1.5 T compared with the 1.75 T exhibited by modern cold-rolled grain-oriented steels, the no-load losses in a transformer with an amorphous steel core are around 60% lower. As the saturation flux density of the core material is lower, these transformers tend to be larger and heavier and correspondingly more expensive. The transformer with an amorphous steel core is also about 6 dB louder.

Amorphous steel is made by atomizing the liquid metal and spraying it on to a rotating roller where it is quenched extremely quickly, so rapidly in fact that it cannot crystallize and remains in a disordered amorphous state, hence the name. The structure is similar to glass and therefore amorphous metals are often called metallic glass (Metglass, the licenced manufacturer). The structure is also similar to undercooled liquid. Domain walls can move freely through the random atomic structure.

The risk exists that this 'free' structure will crystallize with time and temperature. Thus crystallization limits the life time of amorphous alloys:

- 550 years when temperature is 175°C;
- 25 years when temperature is 200°C;
- 2 hours when temperature is 350°C.

So, significant overheating of amorphous core shortens its life as amorphous alloy.

The application of amorphous steel tapes is limited to distribution transformers. In the past it was commonly believed that amorphous wound cores are most suitable for smaller, single-phase units. Brittleness, mechanical sensitivity, cutting and stacking problems due to thickness in the range of only 20 to 30 μm and the necessity of annealing in the magnetic field after manufacturing seem to be prohibitive for the application in larger power transformers. Most of the advantage of the excellent loss values at low induction was compensated for by the higher stacking factor and the lower saturation point where losses increase rapidly. The recent years show that disadvantages are gradually removed, amorphous tapes may be wider and larger than 1 MVA units can be normally produced.

Amorphous metal performance offers a huge opportunity for no-load losses reduction compared with conventional transformer steel. The empiric formula to calculate magnetic losses is:

$$Magnetic\ loss = Af + B\,d^l\,f^m\,B^n/\rho,$$

where A and B are constants.

The explanation and comparison of amorphous metal and silicon steel are given in Table 3.12.

Table 3.12 Comparison of magnetic properties of amorphous metal and silicon steel

Property/Exponent	Amorphous metal	Silicon steel
ρ (resistivity)	~1.30 [μΩ m]	~50 [μΩ cm]
d (thickness)	~20 [μm]	200 [μm]
l	1–2	2
m	~1.5	~2
n	~2	~2

Metglas, as stated above, has improved amorphous material over the recent years, particularly the amorphous metals' deficiency of reduced saturation induction has been partly compensated. The new material reaches saturation at induction closer to these (even slightly above 1.4 T), characterizing traditional magnetic steel. This makes cores more compact and the transformers smaller and lighter than older amorphous designs. The makers also tried to remove other drawbacks such as brittleness and the associated difficulties during core making.

3.6.2 Windings

While the transformer core serves the magnetic circuit, the windings form the electrical circuit of a transformer. The resistive losses are directly dependent on the resistance of both primary and secondary windings. The losses will be lower if the length and the cross-section of the windings decreases. The length of the windings and the number of turns depends on the core geometry and properties of the core material. The cross-section and losses are very closely related (see Table 3.2).

According to an old rule of thumb within the transformer industry, the production cost optimum lies somewhere around a ratio of steel to copper usage of 2:1. However, it is a fairly flat optimum and, of course, varies with the ratio of steel to copper price. Independently of this, it should be taken into consideration that the operating properties of the transformer also vary when the share of metals are varied, especially with respect to losses: holding the current densities in the windings and the magnetic flux density in the core constant, the loss per kilogramme of copper or steel, respectively, will be more or less constant. So a transformer designed according to this philosophy, but with more iron and less copper, tends to have higher iron losses, and one with more copper and less iron will have higher copper losses. But this does not mean that skimping on copper and steel pays off! Rather, enhancing the core cross-section while keeping the number of turns constant will reduce core losses, and enhancing the copper cross-section, while keeping the core cross-section constant will reduce copper losses. In short: the bulkier transformer will always be more efficient, and metal prices will always be an obstacle against its implementation.

Continuously transposed conductors (Figure 3.9) are a particular development in the design of power transformers windings. Conductor design has been improved by the introduction

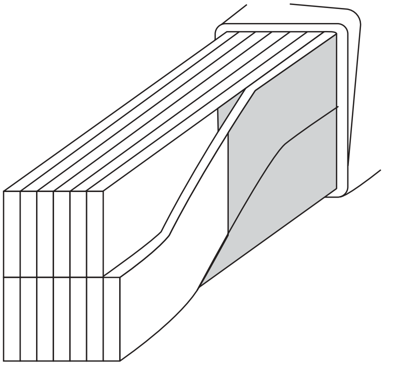

Figure 3.9 Continuously transposed conductors

of continuously transposed conductors (a single conductor subdivided into several flat sub-conductors that are regularly transposed and insulated against each other), reducing the skin effect and eddy current losses and allowing better packing density of the winding.

3.6.2.1 Superconducting (High Temperature, HTS)

In a superconducting transformer the windings, made of a high temperature superconducting material (HTS), are cooled with liquid nitrogen at about 77K, so that the resistance is almost negligible. Load losses, even after adding losses from nitrogen processing, can be still reduced by 50%. The cooling power however has to be supplied continuously at its maximum required level, thus increasing the no-load losses, despite the fact, that in practice, the transformer hardly ever runs at full load, and when it does, then only for a short time. When all these factors are taken into account, overall loss reductions turn out to be minimal.

The use of HTS transformers on a larger scale may be economically justified as cooling systems improve and the cost of liquid nitrogen, which is greatly related to cost of electrical energy production, When electricity cost falls, the benefit of loss reduction also falls. Another important factor is progress in the processing of long lengths of HTS conductors.

These transformers excluding cooling plant have lower weight and volume and are more resistant to overload but cost about 150% to 200% of the price of conventional transformers.

HTS transformers are suitable in applications where the load losses make up a high proportion of the total losses, so are not ideal in distribution transformers. The one place where superconducting transformers could be used effectively would be in railway vehicles. Once these transformers go into industrial production they will save not only weight (and therefore extra energy), but also space. The weight and space limitations in railway vehicles mean that the transformers currently in use in railway vehicles are working at their design limits and are thus significantly less efficient than comparable grid transformers. A locomotive transformer has a power rating of ≈5 MVA and weighs ≈10 t. Its efficiency is ≈95%. A stationary transformer of this power range would weigh some 50 t and reach ≈99% efficiency. During the service life of the locomotive this would yield ≈1 GWh of electricity savings due to the 4% loss reduction while an additional demand of ≈1 GWh would be needed for transporting the additional 40 t of active material (copper and magnetic steel). Obviously this would not really pay off. In such applications, transformers are much more ‘squeezed’ (by forced cooling) to cut the weight.

The most important advantages and disadvantages of superconducting transformers are listed in Table 3.13.

Table 3.13 Advantages and disadvantages of HTS

Pros	Cons
• Oil free, (liquid nitrogen 77K) • Lower weight (10–30%) excluding cooling plant • Slightly smaller volume • 25% overloading without accelerated ageing • Immediate short-circuit current limitation ability	• 150–200% of the price of traditional transformer • Additional maintenance cost (cryogenic system) • Installation site (extra requirements)

3.6.3 Other Developments

3.6.3.1 Gas-Insulated Transformers

Efficiency can also be improved by increasing the rate of heat dissipation from a transformer as load losses are highly temperature dependant. The example here can be gas-insulated transformer. A few power transformers use sulphur hexafluoride (SF_6) gas and they are sometimes referred to as gas-insulated transformers. Their application has strong implications on environmental issue because SF_6 has a strong impact on global warming (1 unit SF_6 = 23 600 units CO_2).

Because of the limited performance of SF_6 as an insulation and heat dissipation agent such transformers with natural or forced gas cooling have to be very efficient because the current densities need to be low by design.

This special type of transformer was (re-)developed in 1987. Gas-cooled transformers had in fact already been the subject of quite long research. When gas cooling is involved, physicists tend to think immediately of hydrogen as it has a very high heat capacity. However, heat capacity is generally expressed relative to mass, and the density (i.e. the mass per-unit volume) of hydrogen is almost one tenth that of air. If, on the other hand, the key parameter is the speed of circulation in a cooling circuit, then heat capacity per volume is more relevant, as the resistance to flow is proportional to the square of the volume flow in any given system. The gaseous material therefore selected was sulphur hexafluoride (SF6), a well-known substance that was already being used as an insulating material in switchgear and that has a density five times that of air and has a considerably better dielectric strength. Engineers carrying out electrical breakdown tests on a specially designed open-top test vessel were able to enjoy the rather unusual observation of air-filled balloons apparently floating mid-air within the test vessel. The balloons were of course resting on a bed of higher density SF6 that had been slowly and carefully filled into the container. By the way, breathing in this completely non-toxic and chemically inert gas (its inertness is directly linked to its high dielectric strength) results in the opposite of the well-known helium 'squeak'. The engineers who carried out these experiments on themselves all lived to tell the tale, proving just how harmless the gas sulphur hexafluoride is. Similar tests using hydrogen should, however, be avoided at all costs – especially by smokers! Although the heat capacity of a kilogramme of SF6 is only half that of a kilogramme of air, its heat capacity per litre is 2.5 times greater. That means that if SF6 is used as the coolant, it only needs to circulate at 40% of the speed used in air-cooled devices in order to produce the same cooling effect. As a result, the fan power can be reduced to about 32% of that needed in an equivalent forced-air cooling system. Two prototype transformers, each with a power rating of 2 MVA, a corrugated tank and internal forced cooling (i.e. cooling class GFAN – gas-forced, air natural) were built and operated in an explosion hazard area within a chemical manufacturing plant owned by the gas manufacturing company, which, it goes without saying, had an understandable interest in these trials.

3.7 Case Study – Evaluation TOC of an Industrial Transformer

Large electrical utilities are usually able to dedicate enough resources to work on economical analysis of their power distribution transformers and also have enough statistical historical data to fill databases for evaluating factors A and B. Users, on the contrary, usually do not have enough reliable data to perform the same analysis.

Table 3.14 The standard industrial consumers chosen for the calculations

Code	Annual consumption [kWh]	Average demand [kW]	Annual utilization [hours]
Ic	160.000	100	1.600
Id	1.250.000	500	2.500
Ie	2.000.000	500	4.000
If	10.000.000	2.500	4.000
Ig	24.000.000	4.000	6.000
Ih	50.000.000	10.000	5.000
Ii	70.000.000	10.000	7.000

So the scope of this case study is the evaluation of not just a single case, but a series of industrial users with different characteristics and consumptions to provide statistical results in which a user can eventually identify itself.

The study focuses on the evaluation of the present worth of the losses and on the TOC of MV/LV oil-immersed distribution transformers for an industrial customer.

Seven standard industrial consumers have been selected from the nine classified in the EUROSTAT [1] database. Only those supplied in MV have been considered; these consumers are characterized in terms of annual consumption of electrical energy, average demand and annual utilization (see Table 3.14).

The rated power and the number of transformers owned by each standard consumer has been assumed accordingly to Table 3.15.

3.7.1 Method

The *reference TOC* of the transformer(s) has been calculated for each standard consumer assuming that the transformer(s) belongs to the EN 50464-1 EoDk list. The *comparable TOC* of the transformer(s) has been calculated by considering the following features:

- oversizing the transformer in order to achieve maximum efficiency by coping with market availability;
- B_k-D_0 transformer(s);

Table 3.15 Rated power and number of transformers owned by each standard consumer

Standard consumer	Average demand [kW]	Power factor @ average demand	Number of transformers	Rated power [kVA]
Ic	100	0.90	1	160
Id	500	0.90	1	630
Ie	500	0.90	1	630
If	2500	0.90	3	1000
Ig	4000	0.90	2	2500
Ih	10 000	0.90	5	2500
Ii	10 000	0.90	5	2500

- the combination of the above solutions;
- B_k-C_0 transformer(s);
- A_k-B_0 transformer(s).

The case of the EN 50464-1 **EoDk** transformer has been assumed as the reference case for the comparison of the different solutions. The methodology consists of analysing the following outcomes:

- the TOCs of the different solutions;
- the balance between purchase cost increase and present worth of losses savings;
- the difference in the present worth of losses and TOC of the different solutions with respect to the baseline.

The TOC has been calculated on the basis of the formula given in EN 50464-1. The costs per rated watt of no-load losses (*A* factor) and the costs per rated watt of load losses (*B* factor) have been determined using the following formulae:

$$A = (12C_\mathrm{d} + 8760C_\mathrm{e})F_\mathrm{c} \quad (€/\mathrm{kW\ year}), \tag{3.17}$$

$$B = (C_\mathrm{e}h)\left(\frac{S_\mathrm{L}}{S_\mathrm{r}}\right)^2 F_\mathrm{c} \quad (€/\mathrm{kW\ year}), \tag{3.18}$$

$$F_\mathrm{c} = \frac{(1+i)^n - 1}{i(1+i)^n}, \tag{3.19}$$

where
C_d is the demand rate (€/kW);
C_e is the cost of energy (€/kWh);
h is the working hours (hours);
S_L is the average apparent power of the load (kVA);
S_r is the transformer rated power (kVA);
F_c is the capitalization factor.

Energy prices are taken from EUROSTAT, the VAT-excluded energy price has been considered in the calculations (Figure 3.10). The demand rate has been determined on the basis of the Italian tariff structure for MV unbounded customers.

In the basic scenario, a 10-year lifetime has been assumed for a typical industrial transformer; calculations have been performed also for 15 and 20 years. Energy prices and load profile have been considered flat over the transformer lifetime.

3.7.2 Results

The major outcomes with the new ranks can be summarized as follows.

- the B_k-D_0 transformer(s) shows the lowest TOC;
- oversizing the transformer in order to reach the maximum efficiency level is not a feasible approach with respect to TOC;

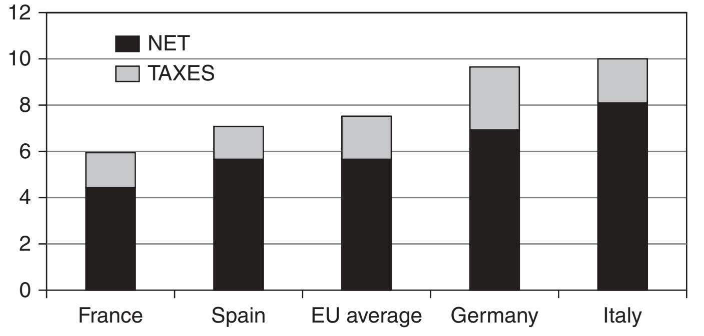

Figure 3.10 EE prices (24 GWh/y – c€/kWh – 0.1 Y/kWh)

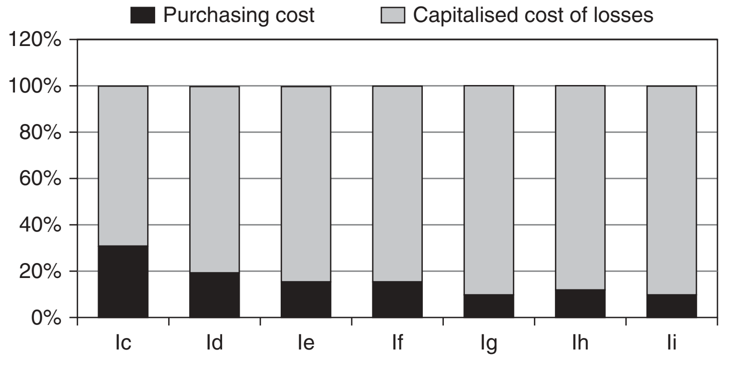

Figure 3.11 EoDk transformer composition of TOC

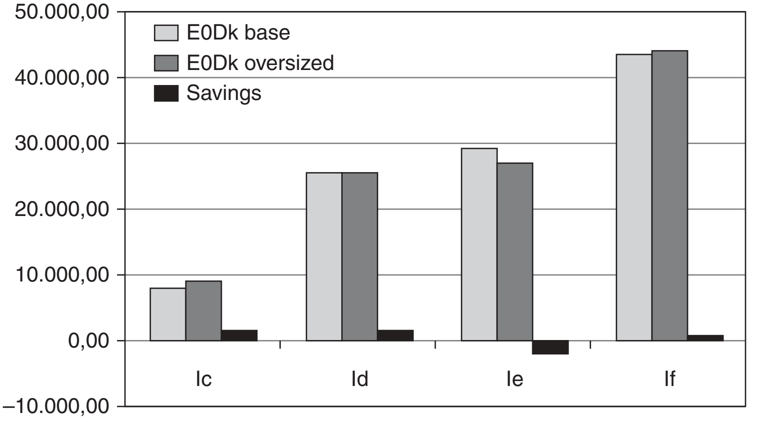

Figure 3.12 Oversized EoDk transformer TOC values (€)

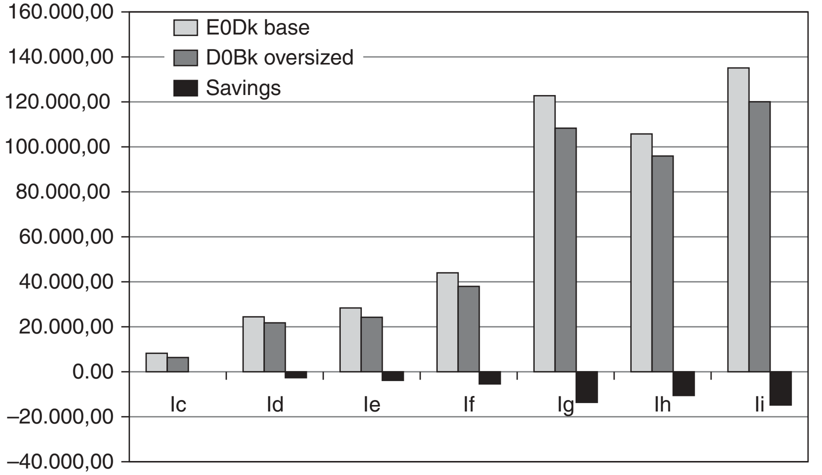

Figure 3.13 D0BK transformer TOC values (€)

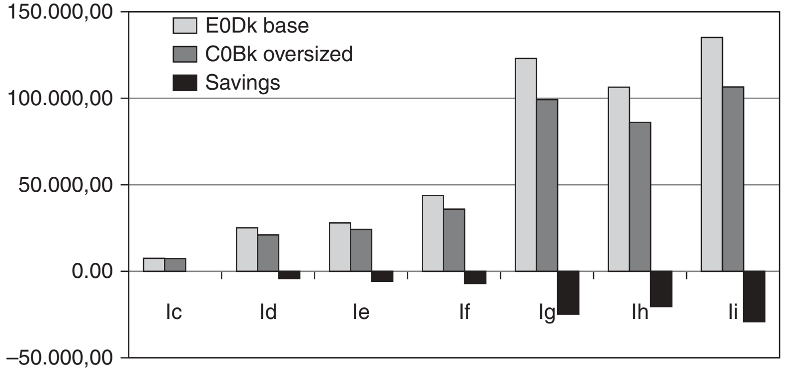

Figure 3.14 C0BK transformer TOC values (€)

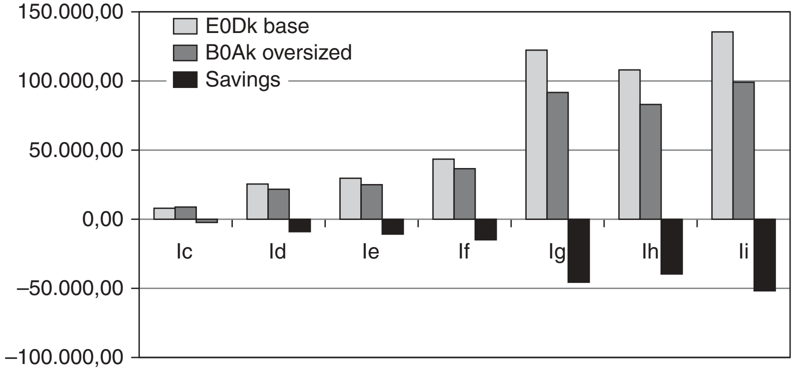

Figure 3.15 B0AK transformer TOC values (€)

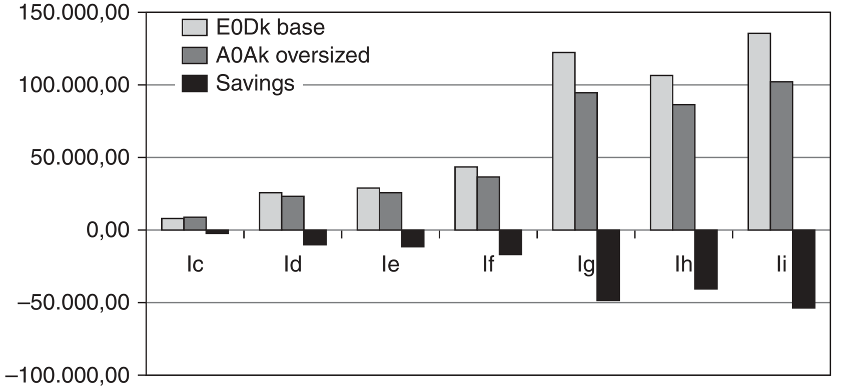

Figure 3.16 A0AK transformer TOC values (€)

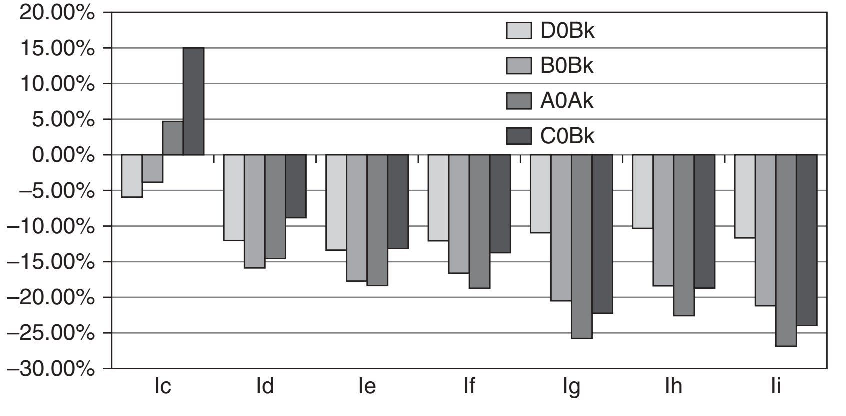

Figure 3.17 TOC saving comparison

- the combination of the two approaches seems to give no synergetic effect, on the contrary the solution B_k-D_0 seems to be more attractive;
- the solution B_k-D_0 shows the lowest payback time;
- the new A_k-B_0 list shows a comparable value of TOC savings but longer payback time, due to higher investment costs.

Figure 3.11 shows TOC composition, Figures 3.12 to 3.17 compare TOC for different industrial users and different transformer classes.

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Further Readings

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3.A Annex

3.A.1 Selected MEPS

3.A.1.1 Australia

The Minimum Energy Performance Standards (MEPS) for distribution transformers are set out as power efficiency levels at 50% of rated load according to AS 2374.1.2 when tested in accordance with AS 2374.1 or AS 2735, as applicable (Tables 3.16 and 3.17).

Australia also has a standard that is applied for the 'High Energy Efficiency Transformers', which have an efficiency of about 20% higher than the 'standard MEPS'.

Table 3.16 Minimum power efficiency levels for oil-immersed transformers

Type	kVA	Power efficiency @ 50% load
Single phase (and SWER)	10	98.30
	16	98.52
	25	98.70
	50	98.90
Three phase	25	98.28
	63	98.62
	100	98.76
	200	98.94
	315	99.04
	500	99.13
	750	99.21
	1000	99.27
	1500	99.35
	2000	99.39
	2500	99.40

Table 3.17 Minimum power efficiency levels for dry-type transformers

Type	kVA	Power efficiency @ 50% load	
		$U_m = 12$ kV	$U_m = 24$ kV
Single phase (and SWER)	10	97.29	97.01
	16	97.60	97.27
	25	97.89	97.53
	50	98.31	97.91
Three phase	25	97.17	97.17
	63	97.78	97.78
	100	98.07	98.07
	200	98.46	98.42
	315	98.67	98.59
	500	98.84	98.74
	750	98.96	98.85
	1000	99.03	98.92
	1500	99.12	99.01
	2000	99.16	99.06
	2500	99.19	99.09

3.A.1.2 USA

The Department of Energy Minimum Efficiency Levels for Regulation of Liquid-immersed Distribution Transformers.

The USA, like Australia, have also more demanding max-tech levels for liquid-insulated (Table 3.18) transformers and dry-type transformers (Tables 3.19 and 3.20). The max-tech level represents the transformer designs that would exist if cost were no object and all design efforts were focused solely on having the highest possible efficiency level. In other words,

Table 3.18 Liguid immersed distribution transformers

Single phase		Three phase	
kVA	Efficiency (%)	kVA	Efficiency (%)
10	98.62	15	98.36
15	98.76	30	98.62
25	98.91	45	98.76
37.5	99.01	75	98.91
50	99.08	112.5	99.01
75	99.17	150	99.08
100	99.23	225	99.17
167	99.25	300	99.23
250	99.32	500	99.25
333	99.36	750	99.32
500	99.42	1000	99.36
667	99.46	1500	99.42
833	99.49	2000	99.46

Table 3.19 Medium-voltage dry-type distribution transformers at 60 Hz

	Single-phase efficiency				Three-phase efficiency		
kVA	20–45 kV BIL	46–95 kV BIL	≥96 kV BIL	kVA	20–45 kV BIL	46–95 kV BIL	≥96 kV BIL
15	98.10	97.86		15	97.50	97.18	
25	98.33	98.12		30	97.90	97.63	
37.5	98.49	98.30		45	98.0	97.86	
50	98.60	98.42		75	98.33	98.12	
75	98.73	98.57	98.53	112.5	98.49	98.30	
100	98.8	98.67	98.63	150	98.60	8.42	
167	98.96	98.83	98.80	225	9873	98.57	98.53
250	99.07	98.95	98.91	300	98.82	98.67	98.63
333	99.14	99.03	98.99	500	98.96	98.83	98.80
500	99.22	99.12	99.09	750	99.07	98.95	98.91
667	99.27	99.18	99.15	1000	99.14	99.03	98.99
833	99.31	99.23	99.20	1500	99.22	99.12	99.09
–				2000	99.27	99.18	99.15

Note: BIL means basic impulse insulation level. All efficiency values are at 50% of nameplate rated load, determined according to the DOE Test-Procedure. 10 CFR Part 431, Subpart K, Appendix A.

Table 3.20 Low-voltage dry-type distribution transformers at 60 Hz

Single phase		Three phase	
kVA	Efficiency (%)	kVA	Efficiency (%)
10	97.7	15	97.0
15	98.0	30	97.5
25	98.2	45	97.7
37.5	98.3	75	98.0
50	98.5	112.5	98.2
75	98.6	150	98.3
100	98.7	225	98.5
167	98.8	300	98.6
250	98.9	500	98.7
333	97.7	750	98.8
		1000	98.9

the Max Tech. levels represent the upper limit of efficiency values considered by the US Department of Energy in the final rule it published in October 2007. These values represent roughly between 20 to 30% higher efficiency that MEPS.

3.A.1.3 Europe

3.A.1.3.1 European EN 50464-1 Standard – Liquid Filled

Standardized European level of losses for liquid immersed transformers with different rated voltages and short circuit impedances are listed in the tables from Tables 3.21 to 3.23.

Table 3.21 Europe, liquid filled, voltage below 24 kV, load losses

Power rating Sn kVA		Rel. short-circuit volt u_k			Oil-immersed transformer, in watts			
		List D_K	List C_K		List B_K		List A_K	
		≤24 kV	≤24 kV	≤36 kV	≤24 kV	≤36 kV	≤24 kV	≤36 kV
		P_K	P_K	P_K	P_K	P_K	P_K	P_K
50	4%	1350	1100	1450	875	1250	750	1050
100	4%	2150	1750	2350	1475	1950	1250	1650
160	4%	3100	2350	3350	2000	2550	1700	2150
250	4%	4200	3250	4250	2750	3500	2350	3000
315	4%	5000	3900		3250		2800	
400	4%	6000	4600	6200	3850	4900	3250	4150
500	4%	7200	5500		4600		3900	
630	4%	8400	6500	8800	5400	6500	4600	5500
630	6%	8700	6750		5600		4800	
800	6%	10 500	8400	10 500	7000	8400	6000	7000
1000	6%	13 000	10 500	13 000	9000	10 500	7600	8900
1250	6%	16 000	13 500	16 000	11 000	13 500	9500	11 500
1600	6%	20 000	17 000	19 200	14 000	17 000	12 000	14 500
2000	6%	26 000	21 000	24 000	18 000	21 000	15 000	18 000
2500	6%	32 000	26 500	29 400	22 000	26 500	18 500	22 500

Table 3.22 Europe, liquid filled, voltage below 24 kV, no-load losses

Power rating Sn kVA	No-load losses oil-immersed transformer									
	List E_0		List D_0		List C_0		List B_0		List A_0	
	≤24 kV		≤24 kV		≤24 kV		≤24 kV		≤24 kV	
	P_0 W	Noise dB (A)	P_0 W	Noise dB (A)	P_0 W	Noise dB (A)	P_0 W	Noise dB (A)	P_0 W	Noise dB (A)
50	190	55	145	50	125	47	110	42	90	39
100	320	59	260	54	210	49	180	44	145	41
160	460	62	375	57	300	52	260	47	210	44
250	650	65	530	60	425	55	360	50	300	47
315	770	67	630	61	520	57	440	52	360	49
400	930	68	750	63	610	58	520	53	430	50
500	1100	69	880	64	720	59	610	54	510	51
630	1300	70	1030	65	860	60	730	55	600	52
630	1200	70	940	65	800	60	680	55	560	52
800	1400	71	1150	66	930	61	800	56	650	53
1000	1700	73	1400	68	1100	63	940	58	770	55
1250	2100	74	1750	69	1350	64	1150	59	950	56
1600	2600	76	2200	71	1700	66	1450	61	1200	58
2000	3100	78	2700	73	2100	68	1800	63	1450	60
2500	3500	81	3200	76	2500	71	2150	66	1750	63

Table 3.23 Europe, liquid filled, voltage below 36 kV, no-load losses

	No-load losses oil-immersed transformer					
	List C_{036}		List B_{036}		List A_{036}	
	≤36 kV		≤36 kV		≤36 kV	
Power rating Sn kVA	P_0 W	Noise dB(A)	P_0 W	Noise dB(A)	P_0 W	Noise dB(A)
50	230	52	190	52	160	50
100	380	56	320	56	270	54
160	520	59	460	59	390	57
250	780	62	650	62	550	60
400	1120	65	930	65	790	63
630	1450	67	1300	67	1100	65
800	1700	68	1450	68	1300	66
1000	2000	68	1700	68	1450	67
1250	2400	70	2100	70	1750	68
1600	2800	71	2600	71	2200	69
2000	3400	73	3150	73	2700	71
2500	4100	76	3800	76	3200	73

3.A.1.3.2 European EN 50541-1, Dry Type

Standardized European level of losses for dry-type transformers with different rated voltages and short circuit impedances are listed in the tables from Tables 3.24 to 3.28.

Table 3.24 Europe, dry-type rated voltage ≤12 kV short circuit voltage 4%

	Pk	Pk	Po	Lwa	Po	Lwa	Po	Lwa
Sr	Ak	Bk	Ao		Bo		Co	
kVA	W	W	W	dB (A)	W	dB (A)	W	dB (A)
100	1800	2000	260	51	330	51	440	59
160	2500	2700	350	54	450	54	610	62
250	3200	3500	500	57	610	57	820	65
400	4500	4900	7000	60	880	60	1150	68
630	6700	7300	1000	62	1150	62	1500	70

3.A.1.3.3 Proposed European MEPS

The proposed European MEPS are the following ones:

- Oil-immersed transformers: units ≤630 kVA: A_oC_k, units >630 kVA: A_0A_k.
- Additionally in tier 1, optionally low loss core material (≤0.95 W/kg at 1.7 T at 50 Hz) is proposed as minimum requirement if it is not possible to meet generic MEPS.
- Dry-type transformers: A_0A_k.

Table 3.25 Europe, dry-type rated voltage $\leq$12 kV short circuit voltage 6%

	Pk	Pk	Po	Lwa	Po	Lwa	Po	Lwa
Sr	Ak	Bk	Ao		Bo		Co	
kVA	W	W	W	dB (A)	W	dB (A)	W	dB (A)
100	1800	2000	260	51	330	51	440	59
160	2600	2700	350	54	450	54	610	62
250	3400	3500	500	57	610	57	820	65
400	4500	4900	700	60	880	60	1150	68
630	7100	7300	1000	62	1150	62	1500	70
800	8000	9000	1100	64	1300	65	1800	71
1000	9000	10 000	1300	65	1500	67	2100	73
1250	11 000	12 000	1500	67	1800	69	2500	75
1600	13 000	14 500	1800	68	2200	71	2800	76
2000	15 500	18 000	2200	70	2600	73	3600	78
2500	18 500	21 000	2600	71	3200	75	4300	81
3150	22 000	26 000	3150	74	3800	77	5300	83

Table 3.26 Europe, dry-type rated voltage 17.5 and 24 kV short circuit voltage 4%

	Pk	Pk	Po	Lwa	Po	Lwa	Po	Lwa	Po	Lwa
Sr	Ak	Bk	Ao		Bo		Co		Do	
kVA	W	W	W	dB (A)	W	dB (A)	W	dB (A)	W	dB (A)
100	1350	1750	330	51	360	51	400	59	600	59
160	1800	2500	450	54	490	54	580	62	870	62
250	2700	3450	640	57	660	57	800	65	1100	65
400	3800	4900	850	60	970	60	1100	68	1450	68
630	5300	6900	1250	62	1270	62	1600	70	2000	70

Table 3.27 Europe, dry-type, rated voltage 17.5 kV and 24 kV short circuit voltage 6%

	Pk	Pk	Po	Lwa	Po	Lwa	Po	Lwa
Sr	Ak	Bk	Ao		Bo		Co	
kVA	W	W	W	dB (A)	W	dB (A)	W	dB (A)
100	1800	2050	280	51	340	51	460	59
160	2600	2900	400	54	480	54	650	62
250	3400	3800	520	57	650	57	880	65
400	4500	5500	750	60	940	60	1200	68
630	7100	7600	1100	62	1250	62	1650	70
800	8000	9400	1300	64	1500	64	2000	72
1000	9000	11 000	1550	65	1800	65	2300	73
1250	11 000	13 000	1800	67	2100	67	2800	75
1600	13 000	16 000	2200	68	2400	68	3100	76
2000	16 000	18 000	2600	70	3000	70	4000	78
2500	19 000	23 000	3100	71	3600	71	5000	81
3150	22 000	28 000	3800	74	4300	74	6000	83

Table 3.28 Europe, dry-type, rated voltage 36 kV short circuit voltage 6%

	Pk	Pk	Pk	Po	Lwa	Po	Lwa	Po	Lwa
Sr	Ak	Bk	Ck	Ao		Bo		Co	
kVA	W	W	W	W	dB (A)	W	dB (A)	W	dB (A)
160	2500	2700	2900	850	57	900	62	960	66
250	3500	3800	4000	1000	59	1100	64	1280	67
400	5000	5400	5700	1200	61	1300	65	1650	69
630	7000	7500	8000	1400	63	1600	68	2200	71
800	8400	9000	9600	1650	64	1900	69	2700	72
1000	10 000	11 000	11 500	1900	65	2250	70	3100	73
1250	12 000	13 000	14 000	2200	67	2600	72	3600	75
1600	14 000	16 000	17 000	2550	68	3000	73	4200	76
2000	17 000	18 500	21 000	3000	72	3500	74	5000	78
2500	20 000	22 500	25 000	3500	73	4200	78	5800	81
3150	25 000	27 500	30 000	4100	76	5000	81	6700	83

3.A.1.4 Formulae for Losses Evaluation – American and European

Selected formulae used in analysis of transformer losses are listed in Table 3.29.

Table 3.29 Selected formulae used in analysis of transformer losses

	American			European		
	Item	Definition	Name	Symbol	Definition	Name
1	Annual peak (kW)	Peak power (kW)	Peak	P	The maximum yearly power	Peak power
2	Power Factor	Load (kVA) / Power (kW)	PF	$\cos\varphi$		
3	Annual PU peak	Ratio peak load to nominal power of transformer $Annual\ PU\ peak = {peak}\Big/{S_B \cdot PF}$	Annual PU peak	B_{av}	$\beta_s = \dfrac{P}{\cos\varphi \cdot S_n}$	Relative peak load
4	Annual PU avg. load	$Annual\ PU\ avg.\ load = \dfrac{Annual\ energy}{8760 \cdot S_B \cdot PF}$	Annual PU avg. load	B_{av}	$\beta av = \dfrac{E}{8760 \cdot S_n \cdot \cos\varphi}$	Relative average load

(*continued overleaf*)

Table 3.29 (*Continued*)

	American			European		
	Item	Definition	Name	Symbol	Definition	Name
5	Annual Loss Factor	Ratio of losses at average load to losses at peak load $L_sF = \left(\frac{S_{RMS}}{Peak}\right)^2$	L_sF	No equivalent		
6	Load Factor	Ratio of average load to peak load	LF	T_w	$T_w = T_s / 8760$	Relative time of peak load $T_s = E/P_s$ E – energy kWh
7		$L_sF = LF^{1.732}$ or $L_SF = 0.85 \cdot LF^2 + 015 \cdot LF$		No equivalent but: $\tau_w = T_w^{1.7}$		
8	Annual average per unit (PU) load of all transformer	$PU\ load = \frac{sales(MWh)}{8760 \cdot installed\ MVA \cdot PF}$	$PU\ load = S$	$\beta * av$	$\beta * av = \frac{\sum E[kWh\}}{8760 \cdot N \cdot S_n \cdot \cos\varphi}$ S_n – rated power of transformers N – number of transformers	Average relative load

(*continued overleaf*)

Table 3.29 (*Continued*)

	American			European		
	Item	Definition	Name	Symbol	Definition	Name
9	PU load	$PU\ load = S = \frac{E}{8760 \cdot S_B \cdot PF}$	S	β_{av}	$\beta av = \frac{E}{8760 \times S_n \times \cos\varphi}$	Average relative transformer load
10	Annual PU load factor	$PU\ load\ factor = \frac{E}{peak \cdot 8760 \cdot PF}$	$PU\ load/PF$	$\frac{T_w}{\cos\varphi}$	$\frac{T_w}{\cos\varphi} = \frac{E}{8760P_s \times \cos\varphi} = \frac{T_s}{8760 \times \cos\varphi}$	Relative duration of peak load
11	Annual PU rms load	$(S_{RMS})^2 = L_sF \cdot (peak)^2]$ $\cdot 8760 \cdot \Delta P_z \cdot (S_{RMS})^2 = annual\ loss\ energy$ $S_{RMS} \approx 1,1 \cdot S$	S_{RMS} PU	Yearly energy losses: $8760 \cdot \Delta P_z \cdot \beta_s \cdot \tau_w$ and thus: $(S_{RMS})^2 = (\beta_s)^2 \cdot \tau_w$		Equivalent average yearly load that generates average yearly losses