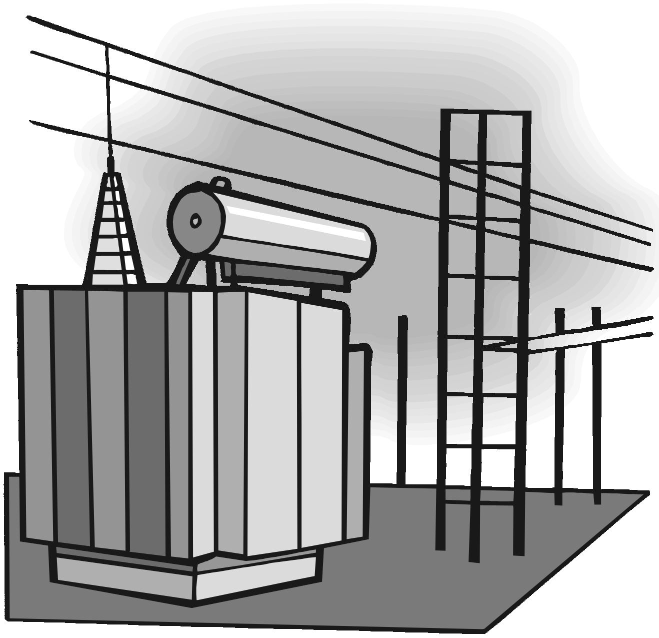

BEST PRACTICE MANUAL

TRANSFORMERS

CONTENTS

1 INTRODUCTION

1.1 Background

Distribution transformers are very efficient, with losses of less than 0.5% in large units. Smaller units have efficiencies of 97% or above. It is estimated that transformer losses in power distribution networks can exceed 3% of the total electrical power generated. In India, for an annual electricity consumption of about 500 billion kWh, this would come to around 15 billion kWh.

Reducing losses can increase transformer efficiency. There are two components that make up transformer losses. The first is "core" loss (also called no-load loss), which is the result of the magnetizing and de-magnetizing of the core during normal operation. Core loss occurs whenever the transformer is energized; core loss does not vary with load. The second component of loss is called coil or load loss, because the efficiency losses occur in the primary and secondary coils of the transformer. Coil loss is a function of the resistance of the winding materials and varies with the load on the transformer.

In selecting equipments, one often conveniently avoid the concept of life cycle costing. But the truth is that even the most efficient energy transfer equipment like a transformer, concept of life cycle cost is very much relevant. The total cost of owning and operating a transformer must be evaluated, since the unit will be in service for decades. The only proper method to evaluate alternatives is to request the manufacturer or bidder to supply the load and no-load losses, in watts. Then, simple calculations can reveal anticipated losses at planned loading levels. Frequently, a small increase in purchase price will secure a unit with lower operating costs.

The load profile of electronic equipment—from the computer in the office to the variable speed drive in the factory—drives both additional losses and unwanted distortion. Since transformer manufacturers test only under ideal (linear) conditions, a substantial gap exists between published loss data and actual losses incurred after installation. In fact, test results published in a 1996 IEEE Transaction paper documented an almost tripling of transformer losses when feeding 60kW of computer load rather than linear load. Slightly different practices are followed in USA and UK to account for harmonics while selecting transformers.

1.2 A guide to this guide

This Best Practice Manual for Electric Transformers summarise the approach for energy conservation measures pertaining to selection, application and operation of electric distribution transformers.

The details of design methodology and the varied approaches for materials, construction are not in the scope of this manual. However, some theoretical aspects are discussed where ever deemed fit.

Chapter-2 discusses principles of transformer action, description of losses and effect of non linear loads on transformer efficiency.

Chapter-3 discusses design aspects of transformers to improve efficiency

Chapter-4 discusses loss minimisation in application and operation

Chapter-5 discusses principles of economic evaluation of transformers

Chapter-6 discusses case studies from Indian and International scenario

2 FUNDAMENTALS

2.1 Principle of transformer action

A current flowing through a coil produces a magnetic field around the coil. The magnetic field strength H, required to produce a magnetic field of flux density B, is proportional to the current flowing in the coil. Figure 2.1 shown below explains the above principle

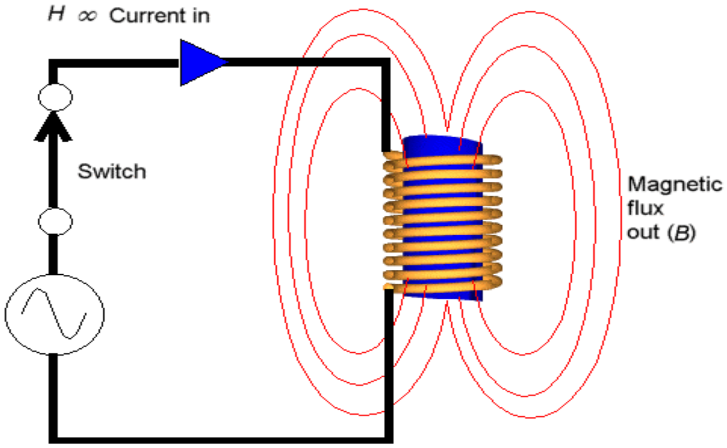

Figure 2.1: Relationship between current, magnetic field strength and flux

The above principle is used in all transformers.

A transformer is a static piece of apparatus used for transferring power from one circuit to another at a different voltage, but without change in frequency. It can raise or lower the voltage with a corresponding decrease or increase of current.

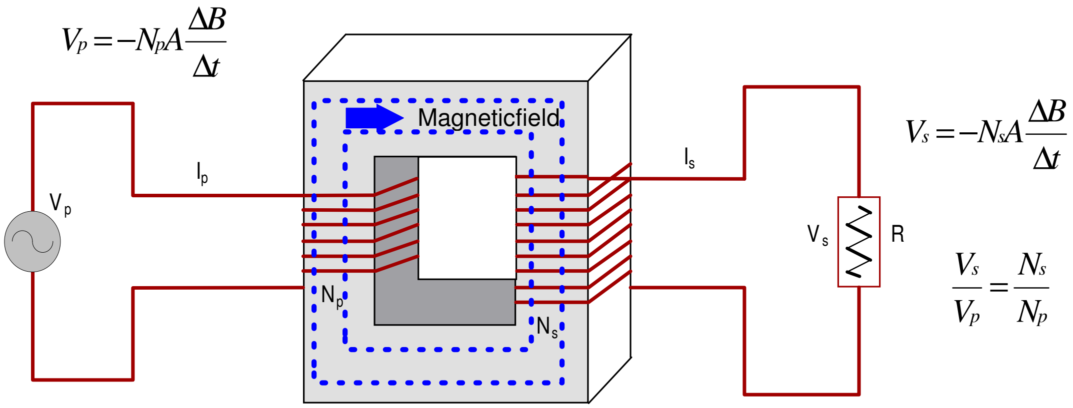

Fig 2.2: Transformer schematic

When a changing voltage is applied to the primary winding, the back emf generated by the primary is given by Faraday's law,

$$\text{EMF} = V_p = -N_p A \frac{\Delta B}{\Delta t} \text{ ----(1)}$$

A Current in the primary winding produces a magnetic field in the core. The magnetic field is almost totally confined in the iron core and couples around through the secondary coil. The induced voltage in the secondary winding is also given by Faraday's law

$$V_s = -N_s A \frac{\Delta B}{\Delta t} \quad \text{-----(2)}$$

The rate of change of flux is the same as that in primary winding. Dividing equation (2) by (1) gives

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

In Figure 2.1, the primary and secondary coils are shown on separate legs of the magnetic circuit so that we can easily understand how the transformer works. Actually, half of the primary and secondary coils are wound on each of the two legs, with sufficient insulation between the two coils and the core to properly insulate the windings from one another and the core. A transformer wound, such as in Figure 2.2, will operate at a greatly reduced effectiveness due to the magnetic leakage. Magnetic leakage is the part of the magnetic flux that passes through either one of the coils, but not through both. The larger the distance between the primary and secondary windings, the longer the magnetic circuit and the greater the leakage.

The voltage developed by transformer action is given by

$E = 4.44 \times f \times N \times B_{max} \times A_{core}$,

where E = rated coil voltage (volts),
f = operating frequency (hertz),
N = number of turns in the winding,
B_{max} = maximum flux density in the core (tesla), and
A_{core}, = cross-sectional area of the core material in Sq. metres.

In addition to the voltage equation, a power equation expressing the volt-ampere rating in terms of the other input parameters is also used in transformer design. Specifically, the form of the equation is

$kVA = 444 \times f \times N \times B_{max} \times A_{core} \times J \times A_{cond}$,

where, N, B_{max}, A_{core} and f are as defined above, J is the current density (A/ sq. mm), and A_{cond} is the coil cross-sectional area (mm^2) in the core window; of the conducting material for primary winding. J depends upon heat dissipation and cooling.

Sample calculation

A 50 Hz transformer with 1000 turns on primary and 100 turns on secondary, maximum flux density of 1.5 Tesla and core area of 0.01 m^2. J is taken as 2 Amps./Sq. mm and Acond as 30 mm^2 for this illustration. Voltage developed is given by

In primary winding,

$E_{primary} = 4.44 \times f \times Np \times B_{max} \times A_{core}$,
$= 4.44 \times 50 \times 1000 \times 1.5 \times 0.01$
$= 3330$ Volts

$E_{secondary}$ = 4.44 x f x Ns x B_{max} x A_{core},
= 4.44 X 50 X 1000 X 1.5 X 0.01
= 333 Volts

Volt-ampere capability is given by the following :

Power rating = 4.44 x f x Np x B_{max} x A_{core} x J x A_{cond}, X 0.001 KVA.
= 4.44 X 50 X 1000 X 1.5 X 0.01 X 2 X 30 X 0.001
= 200 kVA approximately.

Actual Rated KVA = Rated Voltage X Rated Current X 10^{-3} for single phase transformers.

Rated KVA = V¯3 X Rated Line Voltage X Rated Line Current X 10^{-3} for three phase transformers.

2.2 Losses in Transformers

The losses in a transformer are as under.

1. Dielectric Loss
2. Hysteresis Losses in the Core
3. Eddy current losses in the Core
4. Resistive Losses in the winding conductors
5. Increased resistive losses due to Eddy Current Losses in conductors.
6. For oil immersed transformers, extra eddy current losses in the tank structure.

Basic description of the factors affecting these losses is explained below.

2.2.1 Dielectric Losses

This loss occurs due to electrostatic stress reversals in the insulation. It is roughly proportional to developed high voltage and the type and thickness of insulation. It varies with frequency. It is negligibly small and is roughly constant. (Generally ignored in medium voltage transformers while computing efficiency).

2.2.2 Hysterisis Loss

A sizeable contribution to no-load losses comes from hysteresis losses. Hysteresis losses originate from the molecular magnetic domains in the core laminations, resisting being magnetized and demagnetized by the alternating magnetic field.

Each time the magnetising force produced by the primary of a transformer changes because of the applied ac voltage, the domains realign themselves in the direction of the force. The energy to accomplish this realignment of the magnetic domains comes from the input power and is not transferred to the secondary winding. It is therefore a loss. Because various types of core materials have different magnetizing abilities, the selection of core material is an important factor in reducing core losses.

Hysteresis is a part of core loss. This depends upon the area of the magnetising B-H loop and frequency. Refer Fig 2.3 for a typical BH Loop.

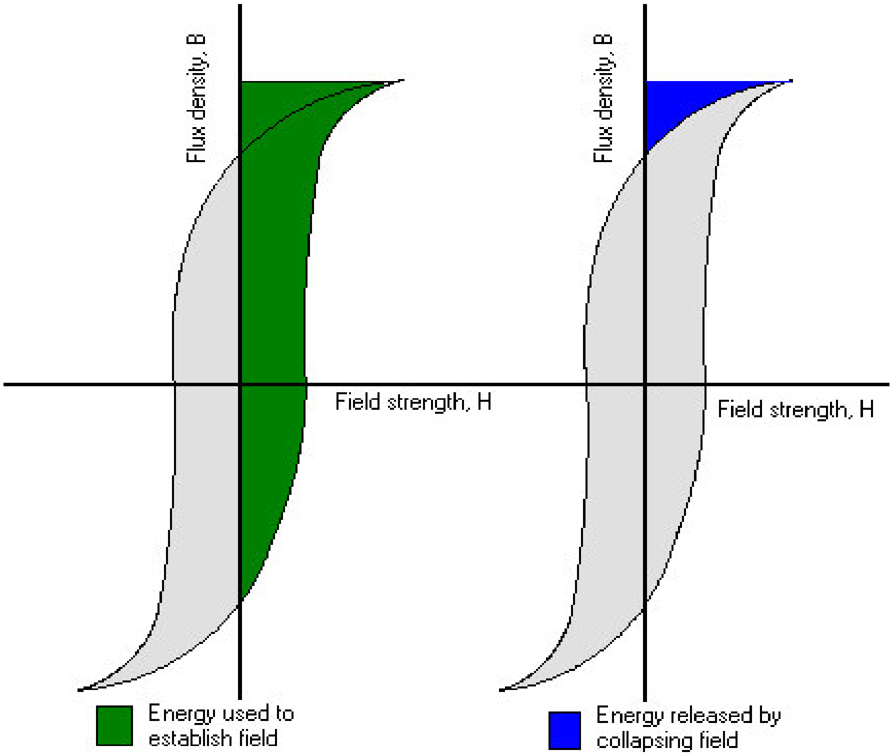

Fig 2.3: B-H Loop: Energy input and retrieval while increasing and decreasing current. Loss per half cycle equals half of the area of Hysteresis Loop.

The B-H loop area depends upon the type of core material and maximum flux density. It is thus dependent upon the maximum limits of flux excursions i.e. B_{max}, the type of material and frequency. Typically, this accounts for 50% of the constant core losses for CRGO (Cold Rolled Grain Oriented)sheet steel with normal design practice.

Hysterisis Losses, $W_h = K_h \times f \times B_m^{1.6}$ Watts/Kg.

Where K_h = The hysterisis constant
f = Frequency in Hertz
B_m = Maximum flux density in Tesla

2.2.3 Eddy Current Losses in The Core

The alternating flux induces an EMF in the bulk of the core proportional to flux density and frequency. The resulting circulating currents depends inversely upon the resistivity of the material and directly upon the thickness of the core. The losses per unit mass of core material, thus vary with square of the flux density, frequency and thickness of the core laminations.

By using a laminated core, (thin sheets of silicon steel instead of a solid core) the path of the eddy current is broken up without increasing the reluctance of the magnetic circuit. Refer fig 2.4 below for a comparison of solid iron core and a laminated iron core.

Fig. 2.4B shows a solid core, which is split up by laminations of thickness 'd_1' and depth d_2 as shown in C. This is shown pictorially in 2.4 A.

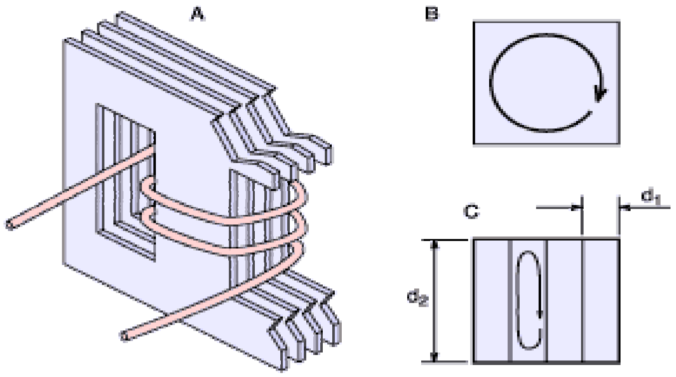

Fig 2.4: Core lamination to reduce eddy current losses

Eddy Losses, $W_e = K_e \times B_m^2 \times f^2 \times t^2$ Watts/Kg.

Where K_e = The eddy current constant
f = Frequency in Hertz.
B_m = Maximum flux density in Tesla
t = Thickness of lamination strips.

For reducing eddy losses, higher resistivity core material and thinner (Typical thickness of laminations is 0.35 mm) lamination of core are employed. This loss decreases very slightly with increase in temperature. This variation is very small and is neglected for all practical purposes. Eddy losses contribute to about 50% of the core losses.

2.2.4 Resistive losses in the windings

These represent the main component of the load dependent or the variable losses, designated as I^2R or copper losses. They vary as square of the r.m.s current in the windings and directly with d.c. resistance of winding. The resistance in turn varies with the resistivity, the conductor dimensions; and the temperature.

$$R = \frac{\rho \times l}{A}$$

Where R = Winding resistance, Ω
ρ = Resistivity in Ohms - mm^2/m.
l = Length of conductor in metres
A = Area of cross section of the conductor, mm^2

In addition, these losses vary with winding temperature and thus will vary with the extent of loading and method of cooling. The winding resistance at a temperature T_L is given by the following equation.

$$R_L = R_0 \times \left(\frac{T_L + 235}{T_0 + 235} \right)$$

The constant 235 is for Copper. For Aluminium, use 225 or 227 for Alloyed Aluminium.

Where R_0 = Winding resistance at temperature T_0, Ω
R_L = Winding resistance at temperature, T_L, Ω

The r.m.s value of current will depend upon the load level and also the harmonic distortion of the current.

2.2.5 **Eddy Current Losses in conductors:**

Conductors in transformer windings are subjected to alternating leakage fluxes created by winding currents. Leakage flux paths, which pass through the cross section of the conductor, induce voltages, which vary over the cross section. These varying linkages are due to self-linkage as also due to proximity of adjacent current carrying conductors. These induced voltages, create circulating currents within the conductor causing additional losses. These losses are varying as the square of the frequency.

For an isolated conductor in space, the varying self-linkage over the section, leads to clustering of the current near the conductor periphery. This is known as Skin Effect. The same effect, with the addition of flux from surrounding conductors, (Proximity effect) leads to extra losses in thick conductors for transformer windings. These losses are termed as Eddy Current Losses in conductors.

The Test Certificate mentions the load losses, which include these eddy losses in conductors at supply frequency (50 Hertz) as also the eddy losses in tank structure in general at the same frequency in the case of oil cooled transformers. For dry type transformers, tank losses are absent.

The contribution of eddy losses including tank losses, over the basic copper losses for an equivalent D.C. current, can be estimated from the difference in measured load losses and expected copper losses at the test current at the test temperature. For normal designs it ranges from 5% to 15%. Detailed subdivision is available only from design data. It can be taken as 10% of load losses in the absence of specific design data. These extra losses vary with square of frequency and square of per unit harmonic current.

The eddy losses in the tank structure are equivalent to the dissipation in a loaded secondary with leakage reactance. The variation is not as the square of frequency, and it is customary to take a value of 0.8 for the exponent.

The Eddy losses in a thick conductor can be reduced by decreasing the radial thickness by sectionalising the conductors (multi-stranded) and increasing the axial dimension. The sectionalised conductor has to be transposed to make it occupy all possible positions to equalise the e.m.fs to the extent possible.

A simplified expression for eddy current losses in conductors is given below.

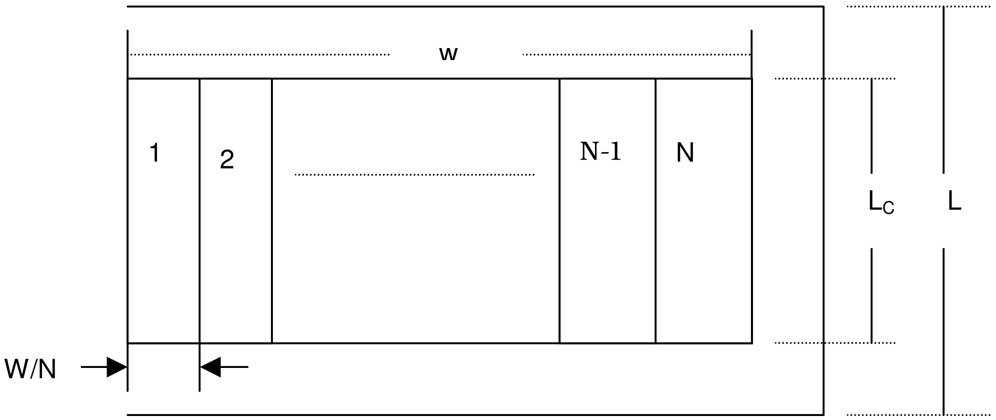

Fig 2.5 : Sectionalised transformer winding - Schematic

The total radial thickness of conductor of W cm is subdivided into N parts of W/N thickness each. Ke is the ratio of the total losses including eddy loss, to the loss due to D.C. current.

Ke = $1+(\alpha W/N)^4 \times \frac{N^2}{9}$

Where α = $\sqrt{\frac{(\pi \times 4\pi \times 10^{-7} \times f) \times Lc}{\rho \times L}}$ where 4π X 10 $^{-7}$ is permeability of space.

Where Lc = Axial length of coil.
L = Window Height
W = Radial total conductor width in metres
W'= Width per subdivision W/N in centimetres.
ρ = Resistivity, in Ohm-metres

For Copper at 60C, $\alpha \approx 100 \times \sqrt{\frac{Lc}{L}}$. ρ= 2 X 10 $^{-8}$ Ohm-metres

If W' is in cm, W = W'/100

Hence αW/N $\approx w' \times \sqrt{\frac{Lc}{L}}$, α^4 is thus proportional to f^2 .

As the number of subdivisions increase, W' becomes smaller and Ke comes nearer to 1; but always above 1. For a given geometry, eddy losses increase as square of frequency.

It is important to transpose each layer so that each layer is connected in series with a path in each one of the possible N positions before being paralleled. Thus circulating current is forced to flow in a relatively very thin conductor.

2.2.6 Extra Eddy Losses in Structural Parts

Some leakage flux, invariably goes in air paths away from the transformer. Strength of this stray flux diminishes and varies inversely with distance. If it links with any conducting material, it will produce eddy losses in that material. For oil immersed transformers, some stray flux links with some parts of the tank and causes extra eddy current losses in the structure. These losses are absent in dry type transformers.

Similarly, extra flux due to outgoing L.T. conductors carrying large currents cause extra eddy current losses in the structural portion surrounding the leads.

Both these losses vary with frequency $^{0.8}$, as stated earlier.

The above discussion on transformer losses is given only to gain familiarity with the fundamental principles. The most important losses are core loss and copper loss. The other losses are described mainly to give a complete picture on losses.

3 TRANSFORMER OPERATION

3.1 Variation of losses during operation

The losses vary during the operation of a transformer due to loading, voltage changes, harmonics and operating temperature.

3.1.1 Variation of losses with loading level

$$\%\ \text{Efficiency} = \frac{\text{Output} \times 100}{\text{Output} + \text{Losses}}$$

$$= \frac{\text{P} \times \text{kVA rating} \times \text{p.f.} \times 1000 \times 100}{\text{P} \times \text{kVA rating} \times \text{p.f.} \times 1000 + \text{N.L} + \text{L.L.} \times \text{P}^2 \times \text{T}}$$

Where,

P = Per unit loading
N.L. = No load losses in Watts
L.L. = Load losses in Watts at full load, at 75 C
T = Temperature correction factor
p.f. = Load power factor

The basic D.C. resistance copper losses are assumed to be 90% of the load losses. Eddy current losses (in conductors) are assumed to be 10% of the load losses. Basic I^2R losses increase with temperature, while eddy losses decreases with increase in temperature. Thus, 90% of the load losses vary directly with rise in temperature and 10% of the load losses vary inversely with temperature. Calculations are usually done for an assumed temperature rise, and the rise in temperature is dependant on the total losses to be dissipated.

Operating temperature = Ambient temperature + Temperature rise

To estimate the variation in resistance with temperature, which in turn depends on the loading of the transformer, the following relationship is used.

$$\frac{R_{T-op}}{R_{T-ref}} = \frac{F + T_{amb} + T_{rise}}{F + T_{ref}}$$

Where F= 234.5 for Copper,
= 225 for Aluminium
= 227 for alloyed Aluminium
R_{T-op} = Resistance at operating temperature
T_{ref} = Standard reference temperature, 75 C

$$\text{Temperature correction factor, T} = \frac{\text{Load losses at operating temperature}}{\text{Load losses at reference temperature}}$$

$$= 0.9 \times \left(\frac{R_{T-op}}{R_{T-ref}}\right) + 0.1 \times \left(\frac{R_{T-ref}}{R_{T-op}}\right)$$

If a more realistic subdivision of load losses is known from design data, the above expression can be modified accordingly.

If operating temperature is 100 C, $\frac{R_{T-op}}{R_{T-ref}} = \frac{234.5 + 100}{234.5 + 75}$ = 1.0808

Hence T = 0.9 x 1.0808 +0.1/1.0808 = 1.06523

3.1.2 Variation in Constant losses

The iron loss measured by no load test is constant for a given applied voltage. These losses vary as the square of the voltage.

Variation in iron losses due to system voltage harmonics: The system input voltage may contain voltage harmonics due to aggregate system pollution in the grid. The current harmonics of the local harmonic load adds to this by causing additional harmonic voltage drop depending upon magnitude of a particular harmonic and the system short circuit impedance at the point of supply, and the transformer impedance for that specific harmonic frequency. The combined total harmonics affect the flux waveform and give added iron losses. The increase in constant loss is quite small, due to this voltage distortion.

3.1.3 Variation in Load Losses

About 90% of the load losses as measured by short circuit test are due to I^2R losses in the windings. They vary with the square of the current and also with winding temperature.

$$\text{Load Losses} = (\text{Per Unit Loading})^2 \times \text{Load Losses at Full Load} \times \left(\frac{F + T_{op}}{F + T_{ref}}\right)$$

F = Temperature coefficient = 234.5 for Copper and 227 for Aluminium.

T_{ref} = 75 °C usually, or as prescribed in the test certificate

Variation in load losses due to load power factor: Any reduction in current for the same kW load by improvement in p.f. reduces load losses.

Variation in losses due to current harmonics: The system current harmonics increase the r.m.s current and thus increase the basic I^2R losses. In addition, the major increase comes from the variation in eddy current losses in the windings (Usually 5 to 10% of the total load losses), which vary with the square of the frequency.

3.2 Loss Minimisation in Application & Operation

Transformers have a long life and do not generally suffer from technical obsolescence. The application details are not clearly known during selection and the load and the type of load also changes with time. Hence transformer rating is likely to be over-specified. However, this is generally not a disadvantage from the view point of energy consumption. The usual best efficiency point is near 50% load.

3.2.1 Selection of Rating and Number of Transformers

In general, selection of only one transformer of large rating gives maximum efficiency and simpler installation. For large plants with long in plant distances, two or more transformers of equal rating may be selected. Moreover for critical continuous operation plants, power may be had from two independent feeders at similar or different voltage levels. In all such cases, each transformer may be sufficient to run the plant. Thus normal operation may be at 50% load. Such a situation can lead to lower than 25% load at times. For non-continuous operation of plants with holidays or seasonal industries, switching off one transformer to save part load losses is generally considered.

Planning for growth of loads and addition of non linear loads is becoming increasingly important. The factors to be considered are:

- Expected growth of load over around five to ten years
- Margin for minimum 15 to 20% growth
- 10 to 15% margin for non-linear loads
- Availability of standard rating

Generally, 30 to 50% excess capacity, reduces load losses, but the extra first cost is rarely justified by energy saving alone. On the contrary, a close realistic estimate permits extra first cost on a smaller transformer designed on the basis of Least Total Ownership Cost (TOC) basis. Economic evaluation of transformers is discussed in chapter 5.

For nonlinear loads, transformers with minimum eddy losses in total load loss is preferred. Transformer losses may be specified at a standard reference temperature of 75 C. They have to be corrected to expected site operating temperature. Basic I^2R losses increase with temperature, while eddy losses decrease with increase in temperature.

For nonlinear loads, the derating factor may be worked out taking a K-factor of 20. Details of K factor evaluation is given in section 3.4 of this chapter. This will need derating of 12% for 10% nonlinear load to about 27% for 40% nonlinear load.

The load factor affects the load losses materially and an estimate of annual r.m.s. load current value is useful.

Transformers with relatively low no load losses(Amorphous Core Type) will maintain good efficiency at very low loads and will help in cases where high growth is expected, but risk of slow growth is to be minimised.

3.2.2 Energy Saving by Under-utilisation of transformers

Table 3.1 summarises the variation in losses and efficiency for a 100 kVA transformer and also shows the difference in losses by using a 1600 kVA transformer for the same. The 1000 kVA transformer has a no load loss of 1700 watts and load loss of 10500 Watts at 100% load. The corresponding figures for 1600 kVA transformer are 2600 Watts and 17000 Watts respectively. Loading is by linear loads. Temperatures assumed equal.

Table 3.1: Comparison of transformer losses

	1000 kVA, No load losses = 1700 W				**1600 kVA. No load losses = 2600 W**		**Difference in losses, W**
Per unit load	**Load losses, W**	**Total losses, W**	**Output, kW**	**Efficiency, %**	**Load losses, W**	**Total losses, W**	
0.1	105	1805	100	98.23	60	2660	861
0.2	420	2120	200	98.95	265	2865	745
0.3	945	2645	300	99.13	597	3197	552
0.4	1680	3380	400	99.16	1062	3662	282
0.5	2625	4325	500	99.14	1660	4267	-58
0.6	3780	5480	600	99.09	2390	4990	-490
0.7	5145	6845	700	99.03	3258	5853	-992
0.8	6720	8420	800	98.96	4250	6850	-1570
0.9	8505	10205	900	98.88	5379	7979	-2226
1.0	10500	12200	1000	98.78	6640	9240	-2960

The efficiency of 1000 kVA transformer is maximum at about 40% load.Using a 1600 kVA transformer causes underloading for 1000 kW load. The last column shows the extra power loss due to oversized transformer. As expected, at light loads, there is extra loss due to dominance of no load losses. Beyond 50% load, there is saving which is 2.96 kW at 1000 kW load.

The saving by using a 1600 kVA transformer in place of a 1000 kVA transformer at 1000 kW load for 8760 hours/annum is 25960 kWh/year. @Rs 5.0 /kWh ,this is worth Rs 1.29 lakhs. The extra first cost would be around Rs 15.0 lakhs. Hence deliberate oversizing is not economically viable.

3.2.3 Reduction of losses due to improvement of power factor

Transformer load losses vary as square of current. Industrial power factor vary from 0.6 to 0.8. Thus the loads tend to draw 60% to 25% excess current due to poor power factor. For the same kW load, current drawn is proportional to KW/pf. If p.f. is improved to unity at load end or transformer secondary, the saving in load losses is as under.

Saving in load losses

$$= \text{(Per unit loading as per kW)}^{2} \text{ X Load losses at full load X } \left(\left[\frac{1}{\text{pf}} \right]^{2} - 1 \right)$$

Thus , if p.f is 0.8 and it is improved to unity, the saving will be 56.25% over existing level of load losses. This is a relatively simple opportunity to make the most of the existing transformer and it should not be missed. It should also be kept in mind that correction of p.f downstream saves on cable losses, which may be almost twice in value compared to transformer losses.

3.2.4 Segregation of nonlinear loads

In new installations, non-linear loads should be segregated from linear loads. Apart from ease of separation and monitoring of harmonics, it can be supplied from a transformer which is specially designed for handling harmonics. The propagation of harmonics can be controlled much more easily and problems can be confined to known network. Perhaps a smaller than usual transformer will help in coordinating short circuit protection for network as well as active devices. The only disadvantage apart from additional cost is the increased interdependence of sensitive loads.

3.3 Effect of operating temperature

The losses have to be dissipated through the surface area. When the transformer volume increases, the ratio of surface area to volume reduces. Thus, larger transformers are difficult to cool. Oil cooling uses a liquid insulating medium for heat transfer. In cold countries the ambient temperature is lower, giving a lower operating temperature. In tropical countries, ambient temperature is higher giving a higher operating temperature.

Oil cooled transformers operate at lower temperatures compared to dry type transformers. Every 1C rise in operating temperature gives about 0.4% rise in load losses. A reference temperature of 75 C is selected for expressing the losses referred to a standard temperature. The operating temperature limit is decided by the type of insulation used and the difficulties of cooling. This gives an additional factor for comparing losses during design. Higher temperature permits reduction in material content and first cost. Operating temperature beyond the limits prescribed for the insulation, reduces life expectancy materially.

Oil cooled transformers operate at lower temperatures compared to dry type transformers.

3.4 Assessing the effects of Harmonics

Load loss performance of a design or an installed transformer with known data can be done if the levels of harmonic current are known or estimated.

IEC 61378-1 'Transformers for Industrial Applications' gives a general expression for estimating load losses for loads with harmonics. This standard is specifically meant for transformers and reactors which are an integral part of converters. It is not meant for power distribution transformers. The method is applicable for estimation in power distribution transformers. It can be used for oil cooled transformers or dry type transformers.

The alternative approaches for power distribution transformers using K-Factor and Factor-K are given later.

As per IEC 61378-1 the total load losses with current harmonics are given as under

$$P_T = P_{DC1} \times \left(\frac{I_L}{I_1}\right)^2 + P_{WE1} \times \left[\sum_1^n \left(\frac{I_h}{I_1}\right)^2 \times h^2\right] + (P_{CE1} + P_{SE1}) \times \left[\sum_1^n \left(\frac{I_h}{I_1}\right)^2 \times h^{0.8}\right]$$

Where P_T = Total load losses and 'h' is the order of the harmonic.

$$I_L^2 = \sum_{n=1}^{2} I_n^2$$

P_{DC1}= Basic copper losses for fundamental frequency

P_{WE1}= Winding eddy losses for fundamental

P_{CE1} = Eddy losses in structural parts due to current leads for fundamental

P_{SE1} = Eddy losses in structural parts for fundamental

I_n = Current for harmonic order n

I_1 = Fundamental current

P_{CE1} and P_{SE1} are not applicable to dry type transformers

3.4.1 U.S. Practice – K- Factor

The K-Factor rating assigned to a transformer and marked on the transformer case in accordance with the listing of Underwriters Laboratories, is an index of the transformer' s ability to supply harmonic content in its load current while remaining within its operating temperature limits.

The K-Factor is the ratio of eddy current losses when supplying non-linear loads as compared to losses while supplying linear loads. In U.S., dry type of transformers are used in majority of applications.

$$k = \sum_{n=1}^{2} I_n^2 . n^2$$

I_n= Per unit harmonic current , and n = Order of harmonic.

For specification in general, the U.S. practice is to estimate the K – Factor which gives ready reference ratio K for eddy losses while supplying non-linear loads as compared to linear loads.

K = 1 for Resistance heating motors, distribution transformers etc.

K = 4 for welders Induction heaters, Fluorescent lights
K = 13 For Telecommunication equipment.
K = 20 For main frame computers, variable speed drives and desktop computers.

The eddy losses in conductors, are assumed to vary as $\left(I_n/I\right)^2 \times n^2$ where I is the total r.m.s. current and is assumed to be 100 % i.e. rated value.

$I = \sqrt{\left(I_1^2 + I_2^2 + \ldots + I_n^2\right)}$ where I_1 is taken as 1. Now, since I is defined, loss variation is taken as $\left(I_n/I\right)^2 \times n^2$ including fundamental.

K is ratio of Eddy losses at 100 % current with harmonics and Eddy losses at 100 % current with fundamental.

$$K = \sum_{n=1}^{n} \left(I_n/I\right)^2 \times n^2 \Big/ \left(I_1/I_1\right)^2 \times 1^2$$

$$K = \sum_{n=1}^{n} \left(I_n/I\right)^2 \times n^2$$

The K-Factor is used directly to specify transformers for a given duty. The total losses, if needed can be estimated at any X % loading as under if the contribution of eddy losses in load losses at fundamental frequency test is known from design; or assumed typically as 10 %. Copper losses are then assumed to be the balance 90 %.

Total load losses at 100 % load = (0.9 + 0.1 x K)

If K = 11, eddy losses at 100% load with this harmonic pattern are 11 times the eddy losses at fundamental.

Total load losses at 100% load = 0.9 + 1.1 = 2
Total load losses at X % load = X^2 x 2.

If total load losses are assumed to be 100% or 1 for same temperature rise, then X^2 = 1/K = 1/2. X = $1/K^{0.5}$ or 70.7 %. Thus the transformer can work at 70% of its rated load current specified for linear loads.

A sample K- factor calculation is given for a given set of harmonic measurements, based on the above relationships.

Table 3-2: Estimation for K factor

Harmonic No.	RMS Current	I_n/I_1	$(I_n/I_1)^2$	(I_n/I)	$(I_n/I)^2$	$(I_n/I)^2xn^2$
1	1	1	1	0.6761	0.4571	0.4571
3	0.82	0.82	0.6724	0.5544	0.3073	2.7663
5	0.58	0.58	0.3364	0.3921	0.1538	3.8444
7	0.38	0.38	0.1444	0.2569	0.0660	3.2344
9	0.18	0.18	0.0324	0.1217	0.0148	1.2000
11	0.045	0.045	0.0020	0.0304	0.0009	0.1120
Total r.m.s	1.479					
Sum			2.1876			11.6138

$I_{r.m.s.} = \sqrt{2.1876} = 1.479 = I$. K-Factor is given by last column.
K factor = 11.618

A K13 rated transformer is recommended for this load.

3.4.2 European Practice- 'Factor K'

The European practice as defined in BS 7821 Part 4 and HD 538.3.S1 defines a derating factor for a given transformer by a 'Factor-K'.

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

e = Eddy current loss at fundamental frequency divided by loss due to a D.C. current equal to the r.m.s. value of the sinusoidal current.
I_n = magnitude of nth harmonic current.
q = Exponential constant dependent on type of winding and frequency
= 1.7 for round / rectangular section
= 1.5 for foil type low voltage winding.
I = R.M.S. value of the current including all harmonics

$$= \left(\sum_{n=1}^{n=N} I_n^{\ 2}\right)^{0.5}$$

The objective is to estimate the total load losses at 100% current, when that current contains harmonics. The base current is thus I the r.m.s. current which is 100%. This is equal to the rated current at which the load losses are measured at fundamental frequency. The basic copper losses vary as the square of the r.m.s. current and hence are equal to the measured losses at fundamental frequency.
Total load losses at fundamental are taken as unity i.e. 1.
$1 = I^2R$ + Eddy Losses, Eddy Losses = $e \times I^2R$ losses.
$1 = I^2R(1 + e)$
Eddy Losses as a fraction of total load losses = $e \times I^2R / I^2R(1 + e) = e / 1 + e$
Eddy Losses at I (100%) = $(e / 1 + e) \times \Sigma_{n=1} (I_n / I)^2 \times n^q$
Since harmonics are expressed as fractions of fundamental,

$$\text{Eddy Losses} = \left(\frac{e}{1+e}\right) \times \left(\frac{I_1}{I}\right)^2 \times \sum_{n=1}^{n} \frac{\left(I_1^2 \times 1^q + I_3^2 \times 3^q + \ldots + I_n^2 \times n^q\right)}{I_1^2}$$

$$= \left(\frac{e}{1+e}\right) \times \left(\frac{I_1}{I}\right)^2 \times \left(1 + \sum_{n=n+2}^{n} \frac{\left(I_1^2 \times 1^q + I_3^2 \times 3^q + \ldots + I_n^2 \times n^q\right)}{I_1^2}\right)$$

$I = I_1^2 + I_H^2$ where I_H^2 equals the sum of squares for harmonics, but excluding fundamental.

Total losses =

$$I^2R + \left(\frac{e}{1+e}\right) \times \left(I_1^2 + I_H^2\right) \big/ I^2 - \left(\frac{e}{1+e}\right) \times \left(\frac{I_H^2}{I^2}\right) + \left(\frac{e}{1+e}\right) \times \left(\frac{I_1}{I}\right)^2 \times \sum_{n=n+2}^{n} \left(\frac{I_n}{I_1}\right)^2 \times n^q$$

If the term for I_H^2 is neglected, there is an error on safe side with a total deviation of only 2% to 4% depending upon I_H, since e/ 1+ e itself is about 9% to 10% of total losses at fundamental. The addition to eddy losses may be 10 to 15 times due to harmonics. The first two terms equal the total losses at fundamental and thus equals 1.The Factor K is taken as the square root of total losses. The expression thus simplifies to the form stated earlier. The summation term is for n > 1 and thus covers harmonics only.
At X% load, Load Losses = $X^2 K^2$ and since new load losses should be equal to 1,
X= 1/K .

Typical calculation (taking q as 1.7 and assuming that eddy current loss at fundamental as 10% of resistive loss i.e. e= 0.1) is given below.

Table 3-1: estimation of Factor K

Harmonic No.	RMS Current	I_n/I_1	$(I_n/I_1)^2$	n^q	$n^q (I_n/I)^2$
1	1	1	1	1	1
3	0.82	0.82	0.6724	6.473	4.3525
5	0.58	0.58	0.3364	15.426	5.1893
7	0.38	0.38	0.1444	27.332	3.9467
9	0.18	0.18	0.0324	41.900	1.3576
11	0.045	0.045	0.0020	58.934	0.1193
Sum			2.1876		Ó= 15.9653

$I_{r.m.s.}$ =√ 2.1876 = 1.457.
K^2 = 1 + (0.1/ 1.1) x (1/1.457) ^{2} x (15.9653 –1) = 1.641
K = 1.28

Transformer derating factor **=** **1**/K = 1/1.28 x 100 = 78.06%

4 REDUCTION OF LOSSES AT DESIGN STAGE

4.1 Introduction

The design approaches for reduction of losses are well known and proven. They consists of

1. Using more material
2. Better material
3. New Material
4. Improved distribution of materials
5. Improvement in cooling medium and methods

Each design tries to achieve desired specifications with minimum cost of materials or minimum weight or volume or minimum overall cost of ownership. Worldwide, more and more consumers are now purchasing transformers based on the total ownership costs, than just the first cost.

4.2 Minimising Iron Losses

The evolution of materials used in transformer core is summarised below.

YEAR (approx.)	CORE MATERIAL	THICKNESS (mm)	Loss (W/kg at 50Hz)
1910	Warm rolled FeSi	0.35	2 (1.5T)
1950	Cold rolled CRGO	0.35	1 (1.5T)
1960	Cold rolled CRGO	0.3	0.9 (1.5T)
1965	Cold rolled CRGO	0.27	0.84 (1.5T)
1975	Amorphous metal	0.03	0.2 (1.3T)
1980	Cold rolled CRGO	0.23	0.75 (1.5T)
1985	Cold rolled CRGO	0.18	0.67 (1.5T)

There are two important core materials are used in transformer manufacturing. Amorphous metal and CRGO. It can be seen that losses in amorphous metal core is less than 25% of that in CRGO. This material gives high permeability and is available in very thin formations (like ribbons) resulting in much less core losses than CRGO.

The trade off between the both types is interesting. The use of higher flux densities in CRGO (upto 1.5 T) results in higher core losses; however, less amount of copper winding is required, as the volume of core is less. This reduces the copper losses.

In amorphous core, the flux density is less and thinner laminations also helps in reducing core losses. However, there is relatively a larger volume to be dealt with, resulting in longer turns of winding, i.e higher resistance resulting in more copper losses. Thus iron losses depend upon the material and flux density selected, but affect also the copper losses.

It becomes clear that a figure for total losses can be compared while evaluating operating cost of the transformers. The total operating cost due to losses and total investment cost forms the basis of Total Ownership Cost of a transformer.

4.3 Minimising Copper losses

The major portion of copper losses are I^2R losses. Using a thicker section of the conductor i.e. selecting a lower current density can reduce the basic I2R losses. However, an arbitrary increase in thickness can increase eddy current losses. In general, decreasing radial thickness by sectionalisation leads to reduction in eddy current losses. A properly configured foil winding is useful in this context. The designer has to take care of the proper buildup of turns with transposition and also take care of the mechanical strength to sustain short circuit in addition to needed insulation and surge voltage distribution.

All the same, designers can always try to get minimum basic I^2R and minimum eddy current losses for a given design and specified harmonic loading.

5 ECONOMIC ANALYSIS

5.1 Introduction

For any investment decision, the cost of capital has to be weighed against the cost/benefits accrued. Benefits may be in cash or kind, tangible or intangible and immediate or deferred. The benefits will have to be converted into their equivalent money value and deferred benefits have to be converted into their present worth in money value for a proper evaluation. Similarly , future expenses have to be accounted for.

The cost of capital is reckoned as the rate of interest, where as the purchasing power of the currency measured against commodities determines the relative value of money in a given economic domain. Thus interest rates increases value of capital where as inflation degrades the value of capital.

The deferred monetary gains/expenses are expressed in terms of their present worth(PW). If Rs 90.91 is invested at an annual interest of 10% , it will yield 90.91x (1+10/100) = Rs 100/- at the end of one year. Hence the present worth of Rs 100 after one year is Rs 90.91/- , if the annual rate of interest is 10% .

$$PW = \frac{1-\left[\frac{1+a}{1+i}\right]^{n}}{i-a}$$ where PW is present worth.

a = per unit inflation index, annual

i = per unit interest rate

n = number of years

Purchase of a transformer involves first cost and subsequent payment of energy charges during a given period. The effective first cost or the total ownership cost can be had by adding the present worth of future energy charges. The **TOC** $_{EFC}$ i.e. . Total Ownership Cost:- Effective First Cost adds an appropriate amount to account for energy expenses and shows a better measure of comparing an equipment with higher first cost, but having a higher efficiency and thus lower running charges.

The concept of evaluation can be applied to transformers with the assumptions that the annual losses and the load level remain steady at an equivalent annual value, the tariff is constant and the rates of inflation and interest are constant. These assumptions have obvious limitations, but the **TOC** $_{EFC}$ concept is widely used method for evaluation. The period of 'n' years may be 10 to 15 years. The longer the period, greater the uncertainty. Generally, 'n' will be roughly equal to the economic life of the equipment governed by the technical obsolescence, physical life and perceptions of return of capital of the agency making the investment decision.

5.2 Total Ownership cost of transformers

TOC $_{EFC}$ = **Price** + **Cost of Core loss** + **Cost of Load loss**

Cost of core loss $_{EFC}$ = A X Core loss in Watts

Cost of Load loss $_{EFC}$ **=** B X Load loss in Watts

Where A = Equivalent first cost of No load losses, Rs/Watt

$$= \frac{PW \times EL \times HPY}{1000}$$

PW = Present worth, explained in previous section 5.1

EL = Cost of electricity, Rs/ Kwh, to the owner of the transformer

HPY = Hours of operation per year

B = Equivalent first cost of load losses

$= A \times p^2 \times T$

P = Per Unit load on transformer

T = Temperature correction factor, details of calculation given in section 3.1.1.

5.3 Decisions for changeover to new equipment

In this case there is an added cost of the existing working equipment. The value left in a working equipment can be evaluated either by its technical worth, taking its left over life into consideration or by the economic evaluation by its depreciated value as per convenience. For transformers, the prediction of life is very difficult due to varying operating parameters. Moreover, for any equipment, there is a salvage value, which can be taken as equivalent immediate returns.

Thus $\mathbf{TOC_{EFC}}$ = (Present depreciated effective cost of old equipment – Salvage value) + A X Core loss + B X Load loss

6 CASE STUDIES

6.1 Introduction

Five case studies are presented from European data as presented in the publication 'Energy Saving in Industrial Distribution Transformers' From KEMA, Netherlands. One case study from Indian industry is given.

The case studies from KEMA, assume full details of No Load Loss and Load Loss as well as portion of Eddy Losses in Load Loss as being available from transformer manufacturer or from relevant standard. No tests are conducted at site.

The harmonic content of the load is given for each typical application. The applicability of Low Loss designs in each rating is analysed and payback period is found out. The case studies also give the energy saving gains in terms of reduction in carbon dioxide (Co2) emission. The likely penalty/gain per Ton of Co2 in monetary terms are taken as 0.3 kg/kWh to 0.6 kg/kWh with a cost ranging from Euro 10 to Euro 33/ ton. This gives a monetary factor of 0.003 Euro/ kWh to 0.02 Euro/kWh. The energy price is taken as 0.04 Euro/kWh. Thus Co2 cost can be 15 % to 50 % of Energy cost. This factor however is not applicable for payback and it is thus not considered for payback in the tables presented.

The payback is considered for extra price to be paid for the low loss transformer and it is around 2 to 3 years. The Load Loss figures given in the tables give the Load Losses considering the harmonics in the load. In the first case study, the factor for enhanced eddy losses in the first load loss is shown for illustration only for illustrating rough order of values. All studies are presented in the year 2002.

6.2 Case Study 1

The case study considers a large company in the Iron and Steel sector. The average loading is 400 MW out of which about 60 MW is through H.T. utilization by H.T. Motors. The remaining 340 MW is through distribution transformers. Load is constant during 24 hours a day, 7 days a week. Transformer ratings vary from 800 kVA to 4800 kVA. There are about 400 Transformers. About 200 Nos. are of 1250 kVA, and about 100 Nos. of 1600 kVA while the remaining 100 Numbers are of different ratings. Most of the transformers are replaced between 1982 to 1990. Almost all the transformers are of Dry Type due to problems faced in the earlier oil cooled transformers.

The company follows the total ownership cost (TOC) concept and has used A and B figures of EUR 2.27/W for no load losses and EUR 1.63/W for load losses.

The comparative figures are given for 1250 kVA transformers.

Table 5.1 input data 1250 kV transformer

Transformer load	65% (constant load, 24/24h) with 6 pulse harmonics												
Economic lifetime	10 years												
Interest rate	7%												
Energy price	EUR 40/MWh												
Harmonic spectrum	1	3	5	7	9	11	13	15	17	19	21	23	25
%	100	0	29	11	0	6	5	0	3	3	0	2	2
A (no-load loss evaluation)	EUR 2,46 /W												
B (load loss evaluation)	EUR 1,04 /W												

6.2.1 Illustrative calculations:

Inflation is not considered and hence the present worth expression is simplified using **a** = zero.

Present worth = $$\frac{1-\left[\frac{1+a}{1+i}\right]^n}{i-a} = \frac{1-{}^{1}\!/\!_{(1+i)^n}}{i} = \frac{(1+i)^n-1}{i(1+i)^n}$$

Interest Rate 7 % i.e. 0.07 per unit. Period is 10 years

$$P_w = \frac{(1+0.07)^{10}-1}{0.07(1.07)^{10}} = 7.0236$$

EL = 0.04 EUR/kWh

$$\mathrm{A} = \frac{\mathrm{Pw}\times\mathrm{EL}\times 8760}{1000} = \mathrm{EUR}2.46\,/\,\mathrm{Watt}$$

B = A x P^2 x T,

P = 65 % , i.e. 0.65,
T = 1

B = 2.46 x 0.65 x 0.65
= 1.039
= EUR 1.04/watt

6.2.2 Factor for Harmonics

Factor for eddy losses $= \sum_{h=1}^{h=n} \left({}^{I_h}\!/\!_{I_1}\right)^2 \times h^2$

If harmonics are absent, this factor is one, The tested load losses have eddy losses at fundamental. If data from design is available for percentage of eddy loss at fundamental, it should be used in the calculation. In the absence of specific data, copper losses due to I^2R can be taken as 90 % and 10% of the specified Load Losses can be attributed to eddy losses at fundamental frequency.

Thus Load Losses at fundamental frequency = Load Losses x (p.u. loading)^2 x (0.9 + (0.1) x 1)

The Extra addition is over and above eddy losses due to fundamental frequency and hence extra harmonic factor

$$K_h = \sum_{h=1}^{h=n} \left({}^{Ih}\!/\!_{I1}\right)^2 \times h^2 - 1 \quad \text{Or} \quad K_h = \sum_{h=3}^{h=n} \left({}^{Ih}\!/\!_{I1}\right)^2 \times h^2$$

For the given six pulse harmonics, the fifth has 29% value of the fundamental.

Hence $K_5 = (0.29)^2 \times 5 \times 5$ = 2.1025

$$K_h = (0.29)^2 \times 25 + (0.11)^2 \times 49 + (0.06)^2 \times 121 + (0.05)^2 \times 169 + (0.03)^2 \times 287$$
$$+ (0.03)^2 \times 361 + (0.02)^2 \times 529 + (0.02)^2 \times 625$$

$$= 2.1025 + 0.5929 + 0.4356 + 0.4225 + 0.2601 + 0.3249 + 0.2116 + 0.25$$
$$= 4.6001$$

Total eddy loss factor = 4.6001 + 1 = 5.6

6.2.3 Percentage of Eddy Losses in Load Losses:

The next step is to evaluate full load losses with harmonic loading for the given transformer and also for the relatively low loss transformer of similar rating being considered for replacement. This requires data on percentage of Eddy Losses in conductors in the total Load Losses for the existing transformer and the nearest low loss substitute. For 1250 kVA rating, the existing and new low loss design have following data for the subdivision of eddy losses, the figures are inferred from the final load loss figures given in the KEMA publication.

	Existing 1250 kVA	Low Loss 1250 kVA
No Load	2400 W	2200 W
Rated Load Loss	9500 W	8200 W
Assumed % Copper Losses	90.69%	90.69%
Assumed % Eddy Losses	9.31 %	9.31%

6.2.4 Full load losses for Harmonic Loading:

Existing Transformer:

Full load load losses on Harmonic Load = Rated load load losses on linear loads x (p.u. Copper + K (p.u. Eddy loss))

= $9500 \times (0.9069 + 5.6 \times 0.093)$

= 9500×1.42826

= 13568.47 Or 13568 Watts

For Suggested Low Losses transformer

Full load load losses = 8200 x 1.42826
= 11711.73 or 11712 watts.

It can be noted that inferred distribution is very close to assumed distribution of 90% and 10% . This is not always true as can be seen from tables given in the annexure.

For 1600 kVA transformer, the distribution works out to 88.68% copper losses and 11.32% for eddy losses. For similar harmonic load factor of 5.6 the multiplier comes to 1.5207. Thus rated full load loss (Linear) of 10000 w yields a figure of 10000 x 1.5207 = 15207 w. The low loss substitute has full load loss (linear) = 9500 x 1.5207
= 14447 w

The actual figure stated is 14218 w. Thus a slightly different distribution is considered for the low loss substitute. The method thus illustrates the steps to calculate full load loss (harmonic loads) if the distribution is known. If design data is not available, 90% and 10% subdivision can give a reasonable value.

Incidentally it shows that due to harmonic loads the full load losses have gone up by 42% in 1250 kVA, and 52% in 1600 kVA transformer.

The needed derating would be $\sqrt{\left(1/_{1.42}\right)} = 0.839$ and $\sqrt{\left(1/_{1.52}\right)} = 0.811$

For 1250 kVA and 1600 kVA respectively for harmonic loading. The actual loading is only 65% and hence all alternatives considered are safe from the view point of temperature rise.

6.2.5 Relative economics for low loss transformers (All Dry type) for 1250 kVA and 1600 kVA transformers.

The data worked out for 1250 kVA and 1600 kVA are given in Table 5.2and Table 5.3.

Table 5.2 1250 kVA transformer

	Unit	**Dry transformer**	**Dry transformer, low losses**	**Difference**
Transformer rating	kVA	1250	1250	
Rated no-load loss	W	2400	2200	-200
Rated load loss	W	13568	11712	-1856
Total annual losses	**kWh/a**	**71241**	**62618**	**-8623**
CO_2 emission @ 0,4 kg/kWh	**ton/a**	**28,5**	**25,0**	**-3,5**
Purchase price	EUR	12250	13000	750
Present value no-load loss	EUR	5907	5414	-493
Present value load loss	EUR	14108	12178	-1930
Capitalised costs	**EUR**	**32265**	**30592**	**-1673**
Pay back (years)				**2,2**
Internal rate of return				**45%**

Table 5.4 1600 kVA transformer

	Unit	**Dry transformer**	**Dry transformer, low losses**	**Difference**
Transformer rating	kVA	1600	1600	
Rated no-load loss	W	2800	2670	-130
Rated load loss	W	15207	14218	-989
Total annual losses	**kWh/a**	**80809**	**76012**	**-4797**
CO_2 emission @ 0,4 kg/kWh	**ton/a**	32,3	30,4	**-1,9**
Purchase price	EUR	14451	14990	539
Present value no-load loss	EUR	6891	6571	-320
Present value load loss	EUR	15812	14784	-1028
Capitalised costs	**EUR**	37154	36345	**-809**
Pay Back (years)				**2,8**
Internal rate of return				**34%**

Comments:

The figures for 1250 kVA, existing transformer are illustrated first.
Rated No Load Loss = 2400 w = 2.4 kW
Rated load loss = 13568 W = 13.568 kW (full load)
Annual losses for 65% loading for 8760 hours

= 2.4 x 8760 + 13.568 x 0.65 x 0.65 x 8760 kWh
= 21024 + 50216.5
= 71240.5 = 71241 kWh/annum.

Carbon Dioxide emission at 0.4 kg/kWh = 71241 x 0.4
= 28496 kg
= 28.5 Tons/annum

Purchase Price is given as EUR 12250 (About Rs.673750)
Present value of noload losses 2.46 x 2400 = 5904
Taken as EUR 5907
Present value of Load Loss = 13568 x 1.04 = EUR 14110
Taken as EUR 14108
Total Capitalised Cost = EUR 32265

A similar figure for low loss transformer is EUR 30592

This figure favours the low loss type with an initial purchase price of EUR 13000 which is EUR 750 of added investment.

Payback for extra investment of EUR 750:
The low loss transformer consumes 62618 kWh/annim, saving thereby 8623 kWh/annum.

Thus the annual saving = EUR 0.04 x 8623
= EUR 345

Simple payback = $\frac{750}{345} = 2.17$ or 2.2 years. (For about 6.12 % Extra Investment)

Internal Rate of Return = $\frac{100}{2.2} = 45$% about.

A similar calculation for 1600 kVA shows a saving of 4797 kWh and a payback of 2.8 years for an added investment of EUR 539 (about 3.73 % extra cost). IRR 34 %.

6.2.6 Summary:

1. Due to somewhat higher load loss figures used for TOC during initial purchase, higher investments have been preferred. Hence it is not very attractive to replace existing transformers by scrapping.
2. If a transformer is to be replaced for any reason, the low loss substitutes show an attractive payback of 2.2 to 2.8 years.

The total saving potential for replacing ALL 400 transformers is given below in Table _______.

Table 5.5 (Page34)

The total saving potential of 2939 Mwh/year is equivalent to EUR 117564/year and is 0.084% of the total consumption of 3.5 x 10^6 Mwh/year.

6.3 Case Study-2: Non ferrous metal sector

In a large company in the non ferrous metal sector, the total loading is about 190 MW. But almost 180 MW are consumed through dedicated high voltage transformers for electrolysis. The scope for distribution transformers is limited is only to 10 MW. Out of it, the load variation is about 45% during 10 hours, 35% during 14 hours.

Total number of transformers is 25, wherein a good number is at 1000 kVA. Excepting 3 new dry type installed in 1999, most of the transformers are old(1965 to 1970). The loss pattern is

No load = 1900 Watts

Load loss = 10250 Watts

Calculations for1000 kVA old transformer with the loading pattern and 5 years of life wit 7% interest rate gives the A factor = EUR 1.44/watt

And B factor = EUR 0.24/Watt. Harmonics are not considered.

Since the loading is low, giving a very low B factor, direct replacement is not economically viable. Table 5.5 summarises the data for dry transformers and oil cooled transformers for future replacement.

Table 5.5 outcome 1000 kVA transformer

	Unit	**Dry HD 538 transformer**	**Oil C-C' ransformer**	**Difference**
Transformer rating	kVA	1000	1000	
Rated no-load loss	W	2000	1100	-900
Rated load loss	W	8600	9500	900
Total annual losses	**kWh/a**	**30336**	**23793**	**-6543**
CO_2 emission @ 0,4 kg/kWh	**ton/a**	12,1	9,5	**-2,6**
Purchase price	EUR	10074	8007	-2067
Present value no-load loss	EUR	2873	1580	-1293
Present value load loss	EUR	2102	2322	220
Capitalised costs	**EUR**	15049	11909	**-3140**
Pay back (years)				**N/A**
Internal rate of return				**N/A**

In this case, the oil transformer has a lower first cost and also lower losses. Hence it is the most favoured choice and the rate of return is not applicable; since the low loss transformer also happens to have a lower first cost.

Table 5.6 summarise the overall potential for the saving. This is equal to EUR 6560 and 0.0099% of the total electricity charges because only a small fraction of the total load is qualifying for calculation of savings.

Table 5.6 Annual savings potential

Transformer size	**Total number**	**Energy saving (MWh)**	**CO_2 emission saving (tonnes)**
1000 kVA	12	78,5	31,2
Other	13	85,1	33,8
Total	**25**	**164**	**65**

6.4 Case Study-3: Paper & Pulp Company

A paper mill started fuctioning since 1978 and was expanded in 1986, the peak electrical loading is about 110 MW, out of which 72 MW are used at high voltage for HT motors. The remaining is distributed with 52 transformers with ratings of 1000 kVA and 3150 kVA. The dominant number(28) are 3150 kVA transformers with LV of 690 Volts. Average loading is 65% . The highlight of the case study is that in 1986, the company took special care to select transformers with low losses for long term gains. These transformers are better compared to the low loss transformers available today.

The case is presented for 3150 kVA transformer for which the input data is given in table 5.7.

Table 5.7 : Input data of 3150 kVA transformer

Transformer size	3150 kVA oil-type
Transformer load	65% during 24/24 hours with 6 pulse harmonics
Economic lifetime	20 years
Interest rate	7%
Energy price	EUR 40/MWh
Harmonic spectrum	6 pulse according to IEC 146-1-1
A (no-load loss evaluation)	EUR 3,71 /W
B (load loss evaluation)	EUR 1,57 /W

The comparison of the 1986 low loss transformer is made with the original supply of 1978 based on the likely prices as prevalent in 2002.

The results are shown in table 5.8. It is seen that even though 1986 transformer is about 30% more expensive, it still gives large savings with an internal rate of return of 33 % and a payback period for extra investment of 3 years.

Table 5.8: Outcome of 3150 kVA transformer

	Unit	**Oil 1978 transformer**	**Oil 1986 Transformer**	**Difference**
Transformer rating	kVA	3150	3150	
Rated no-load loss	W	2870	3150	-280
Rated load loss	W	24500	16800	-7700
Total annual losses	**kWh/a**	**181908**	**135092**	**-46816**
CO_2 emission @ 0,4 kg/kWh	**ton/a**	72,8	54,0	**-18,8**
Purchase price	EUR	19329	24987	5658
Present value no-load loss	EUR	10654	11693	1039
Present value load loss	EUR	66432	45553	-20879
Capitalised costs	**EUR**	**96415**	**82233**	**-14182**
Pay back (years)				**3,0**
Internal rate of return				**33%**

It is estimated that the company is already saving 46816 kWh/year due to these transformers.

6.5 Case Study-4 Chemical Industry

In the KEMA studies, it is observed that; despite variations in the processes, common trends are observed regarding electrical installations. High reliability requirements lead to redundancy in transformer installations and a low average loading of about 40%. Based on the general observations, a fictitious but representative case study is prepared.

Average loading is 110 MW, out of which 40 MW are for electrolysis or H.V. motors and thus out of the purview. Loading is continuous round the clock and loads are non-linear. A typical rating is 1250 KVA (60 out of 71 transformers). The remaining transformers are 630, 1000 and 1600 KVA.

The study compares 1250 KVA HD538 transformer and 1250 KVA low loss transformer. Life time is considered 5 years and harmonics are not considered. Interest rate is taken as 7%. Energy price EUR 50/MWH. A= EUR 1.8/W and B= EUR 0.29/W (40% loading).

Highlights: For the chosen parameters, the differences are marginal. The extra cost of Low Loss type is EUR 750 over EUR 12250, and payback is 4.2 years with a rate of return of 6%. This is a case where the chosen parameters of lifetime, harmonics etc. can significantly affect the decision. If the Low Loss type is chosen, the potential savings can be 214.4 MWH/yr. Which can also mean savings in CO_2 emission of 85.8 Ton.

6.6 Case Study 5 Case of A Large Data Hotel Start Up

This is a high growth rate business with computers as a major load. The startup load connection is typically 100 MW in the growth expectation of 200% to 300% rise per year for a few years. The economic life time is considered as only one year and interest 7%. Figures assumed are 25% initial 24 Hrs. loading which reaches 70% at the end of one year. Energy at EUR 60/MWH, high harmonic loading, A= EUR 0.52/W initial and also the same value for no load losses. B= EUR 0.03/W initial and 0.24/W at the end of the year.

Highlights: The study shows that due to selection of one year as economic life, the preference is clearly in favour of lowest first cost. It is revealed that compared to 1600 KVA Dry type normal and 1600 KVA low loss Dry type, the cheapest would be an oilcooled CC' type transformer. The capitalised costs with harmonics are EUR 16714, and 17132 (low loss) respectively initially. At the end of one year the figures are EUR 22311 and 22366. Thus the low loss transformer is still not attractive. There is a net saving of 8222 KWH/year after one year which equals about EUR 411. The extra price of EUR 539 can not be recovered in the economic life prescribed. The oilcooled transformer is a winner in the short run, with a capitalised cost for initial period as EUR 12951 including harmonics.

Even for this transformer, higher operating temperature due to harmonics suggests a drastic decrease in operating life from 30 years to 6 years. Even then the selected short economic life span makes this choice viable, provided the hot spot temperature is acceptable. By the same consideration a smaller rating 1000 KVA transformer gives a capital saving of 25% even though it has an energy penalty.

It is important to note that the payback period is not affected by the choice of economic life span, but the relatively longer payback loses its significance due to short time investment perception. In such a case, enforcing minimum loss norms only can help. Alternatively the investment in the transformer can be made by the utility with a long term perception to make energy saving possible. The utility can shift the transformer later to a suitable load as needed.

6.7 Summary of European Case Studies:

There is an interesting summary of the sensitivity of the payback period to input parameters. Table 5.9 gives a summary of effect of Low, Medium and High values of parameters on the payback period. Loading and electricity price are two most important factors. Loading should be carefully evaluated for a proper choice.

Table 5.9 Parameter sensitivity on the payback period

Parameter		**Parameter variation**			**Payback time (years)**		
	Unit	**L**	**M**	**H**	**L**	**M**	**H**
Harmonic spectrum		None	12 pulse	6 pulse	3,3	3,1	2,7
Electricity price	EUR/MWh	40	60	80	4,5	3,1	2,4
CO2 emissions	kg/kWh	0,3	0,4	0,6	3,2	3,1	3,0
CO2 costs	EUR/tonne	0	10	33	3,3	3,1	2,7
Loading profile	%	20	40	60	5,2	3,1	1,9
Economic lifetime	years	1	5	10	3,1	3,1	3,1
Interest	%	5	7	9	3,1	3,1	3,1
Purchase price	%	80	100	120	2,5	3,1	3,7

6.8 Case Study: Tea Industry (India)

Energy Audit for Tea Factories making C.T.C. Tea, managed by H/S C.W.S (India) Ltd., District Coimbatore. Audit was conducted in may 1990 for Mayura and Parlai Tea factories. Power is received at 22 kV and 11 kV by separate lines. This is stepped down by two 500 kVA Transformer o 22 kV/433 V an 11 kV/433 V which fee segregated loads.

The typical loss figures for 500 kVA transformers are 1660 W for no load and 6900 W as load losses for 100% load.

Recommendation : Parallel both transformers for a total 500 kVA load on secondary side and in lean season and holidays when the load is 5% to below 25% , cut off one transformer on H.V. and H.V. sides.

Brief Analysis :

For total load of 500 kVA, There are three options.

a) Only one transformer takes full 500 KVA LOAD.

Losses = 1.66 (No Load) + $(500/500)^2$ x 6.9 kW (load losses)

b) One transformer takes segregated 300 kVA while second akes 200 kVA segregated load.

$$\text{Loss} = 1.66 + (300/500)^2 \text{x} 6.9 + 1.66 + (200/500)^2 \text{ x } 6.9 \text{ kW}$$

c) Both are paralleled to take 250 kVA each.

$$\text{Loss} = 2\,(1.66 + (250/500)^2 \text{ x } 6.9)\text{kW} = 6.77 \text{ kW}.$$

Thus on major load, the losses are minimum by paralleling both transformers.

Operation at higher loads during leave season :

a) Two paralleled transformers

Losses = 2 (1. 66 + $(0.25/2)^2$ x 6.9} kW = 3.54 kW at 25% load
Losses = 2 { (1.66) + $(0.05/2)^2$ x 6.9} kW = 3.33 kW at 5% load

b) Only one transformer is energized

Losses = 1.66 x $(0.25)^2$ x 6.9 = 2.09 kW at 25% load
Losses = 1.66 x $(0.05)^2$ x 6.9 = 1.68 kw at 5% load

Thus losses are minimum at low loads using only one transformer.

The tariff was kVA of M.D. x Rs. 60 + Rs. 0.89 x kWh + Rs. 150 meter rent.

The total annual consumption for the factory was 1856479 kWh per year and the electricity bill was Rs. 2038694 giving Rs. 1.0094/kWh as average cost.

The saving by paralleling and switching off one transformer were conservatively estimated at a minimum of 10000 kWh/year with no investment giving a little over Rs. 10000/year as a saving. Power factor improvement was already made but some scope for further improvement was suggested. This would reduce M.D. and save on M.D. charges and also give savings on transformer and cable losses.

APPENDIX-I: DATA REGARDING AVAILABLE DESIGNS

A.1 Data Source : This data is based on the data given in the reference viz 'Energy Saving in Industrial Distribution Transformers' May 2002 by W.T.J. Hulsthorst and J.F. Groeman of KEMA – Netherlands.

The data is intended give a basic feel about the loss levels and distribution for distribution transformers and their relative costs/prices; as per current European Practice.

The prices are for comparision only but a general conversion factor of 1 Euro = Rs. 55 is considered whenever applicable.

The energy price is stated to be roughly in the range of 40 Euro/Mwh i.e. 0.04 Euro/kWh.

Table A1.
Data For Transformers Used In The Utilities

Rating	KVA	100				400						1600					
HV	KV	20				10						20					
LV	V	400				400						690					
Loss-Level	HD428	A-A'	C-C'	A AMDT	C AMDT	A-A'	A-A'	C-C'	C-C'	A AMDT	C AMDT	A-A'	A-A'	C-C'	C-C'	A AMDT	C AMDT
No-Load Losses	W	320	210	60	80	930	930	810	810	150	180	2.600	2.600	1.700	1.700	380	420
Load Losses	W	1.750	1.475	1.750	1.475	4.600	4.600	3.850	3.850	4600	3.850	14.000	14.000	17.000	17000	17.000	14.000
Total Mass	Kg	520	650	740	770	1.190	1.200	1300	1400	1590	1750	3.300	3.240	3.370	9680	4.310	4550
Core Mass	Kg	150	220	220	225	435	440	450	540	570	600	1.100	1.210	1.200	1.460	1400	1.550
Flux Density	T	183	1.45	1.35	1.35	1.83	1.84	1.85	1.6	1.35	1.35	1.84	1.84	1.7	1.6	1.35	1.35
Conduct or Material	Cu/Al	Cu	Cu	Cu	Cu	Cu	Al	Cu	Al	Cu	Cu	Cu	Al	Cu	Al	Cu	Cu
Winding Mass	Kg	85	115	130	155	203	145	350	220	360	450	505	295	725	465	1.120	1.225
Current Density	A/mm2	2.9	2.3	2.35	2	2.9	1.55	2.1	1.1	2.3	1.85	3.65	2	2.75	1.4	2.45	2.1
Height	Mm	1300	1300	1300	1300	1330	1.420	1350	1550	1400	1400	1.890	1.820	1860	2000	1870	1900
Length	Mm	890	830	1050	1100	1320	1.100	1010	1130	1340	1240	1.820	2000	1710	1850	17770	1770
Width	Mm	600	560	620	620	800	840	800	780	770	800	1.180	1280	1100	1020	1320	1200
Efficiency (*)	%	97.94	98.32	98.19	98.46	98.62	98.82	98.89	98.89	98.81	99.00	98.78	98.78	99.02	99.02	98.91	99.10
Sound Power	Db (A)	57	36	59	59	61	68	56	58	68	68	68	72	63	63	76	76
Unit Cost	Euro	2539	2800	3458	3667	4385	4236	4881	4705	6373	6797	9692	9261	10307	10119	15050	15531
Unit Cost	%	90.7	100	121.6	127.5	93.2	91.1	103.7	100	135.5	144.5	95.8	91.4	101.9	100	143.7	153.5

Data for Oil immersed transformers, 100 KVA to 1600 KVA used in the utilities. AMDT refers to Amorphous Core Dry Type.

Table A-2: Data for calculated losses for Industry Transformers of 1000 to 4000 KVA.

Typical Industry Transformer Parameters																	
rating	**kVA**	**1000**				**1600**				**2500**				**4000**			
HV	**kV**	**10**				**10**				**10**				**10**			
LV	**V**	**420**				**420**				**420**				**420**			
Uk	**%**	**6**				**6**				**8**				**8**			
LOSS-LEVEL		Oil CC'	Oil DD'	Dry base	Dry Low	Oil CC'	Oil DD'	Dry base	Dry Low	Oil CC'	Oil DD'	Dry base	Dry Low	Oil CC'	Oil DD'	Dry base	Dry Low
NO-LOAD LOSSES	W	1100	935	2000	1735	1700	1445	2800	2670	2500	2125	4300	4130	3800	3230	7000	5540
LOAD LOSSES 75 ºC	W	9500	8075	8600	7270	14000	11900	10000	9350	22000	18700	18000	14930	34000	28900	27000	26630
TOTAL MASS	kg	2715	3157	2530	2800	3900	4210	3840	3900	4925	6065	5350	5410	8885	10108	7660	7710
HEIGHT	mm	1890	1800	1560	1620	2090	2090	1830	1820	1925	1915	2040	2130	2485	2415	2470	2410
LENGTE	mm	1500	1540	1710	1690	1875	1795	1920	1840	2360	2370	2160	1980	2545	2545	2310	2360
WIDTH	mm	950	1800	940	940	1155	2090	940	940	1235	2370	1230	1230	1375	2545	1230	1230
T HS (F)	K	65	65	100	100	65	65	100	100	65	65	100	100	65	65	100	100
T LS (H)	K	65	65	100	100	65	65	100	100	65	65	100	100	65	65	100	100
SOUND POWER	dB(A)	56	51	68	61	68	57	70	67	69	59	74	73	72	60	80	77
EFFICIENCY (*)	%	98,94	99,10	98,94	99,10	99,02	99,17	99,20	99,25	99,02	99,17	99,11	99,24	99,06	99,20	99,15	99,20
UNIT COST	Euro	8007	10353	10074	11108	10865	12832	14451	14990	13670	17887	17951	19073	24987	29402	25527	27494
UNIT COST	%	**100**	129	126	139	**100**	118	133	138	**100**	131	131	140	**100**	118	102	110

(*) at full load and cos phi = 1

Table A-3: Data for calculated estimation from design data for percentage of extra eddy losses in windings and structural parts. For Oil immessed and Dry Type Transformers (KEMA Table 4.6 Page 29-30).

	1000 kVA		**1600 kVA**		**2500 kVA**		**4000 kVA**	
	In winding P_{WE}	Other P_{SE} + P_{CE}	In winding P_{WE}	Other P_{SE} + P_{CE}	In winding P_{WE}	Other P_{SE} + P_{CE}	In winding P_{WE}	Other P_{SE} + P_{CE}
Oil CC' HD 428	6%	5%	9%	13 %	11%	14 %	13%	28 %
Oil DD' HD 428	6%	5%	9%	13 %	11%	14 %	13%	28 %
Dry type HD538	6%	–	9%	–	11%	–	13%	–
Dry type low losses	6%	–	9%	–	11%	–	13%	–

Table A-4: Distribution Transformers Loss Standards

	Load Losses				No-Load Losses			
Rated Power	Oil-Filled (HD428) Up to 24 kV[2]			Dry Type (HD538)	Oil-Filled (HD428) Up to 24 kV[2]			Dry Type (HD538)
	List A	List B	List C	12 kV Primary	List A'	List B'	List C'	12 kV Primary
KVA	W	W	W	W	W	W	W	W
50	1100	1350	875	N/A	190	145	125	N/A
100	1750	2150	1475	2000	320	260	210	440
160	2350	3100	2000	2700	460	375	300	610
250	3250	4200	2750	3500	650	530	425	820
400	4600	6000	3850	4900	930	750	610	1150
630 /4%	6500	8400	5400	7300	1300	1030	860	1500
630 /5%	6750	8700	5600	7600	1200	940	800	1370
1000	10500	13000	9500	10000	1700	1400	1100	2000
1600	17000	20000	14000	14000	2600	2200	1700	2800
2500	26500	32000	22000	21000	3800	3200	2500	4300
4000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

1 The short-circuit impedance of the transformers is 4% or 6%, in most cases. This technical parameter is of importance to a utility for designing and dimensioning the low-voltage network fed by the transformer. Transformers with the same rated power but with different short-circuit impedance have a different construction and therefore slightly different losses. For HD428 / HD538 compliant distribution transformers, the preferred values for the short-circuit impedance are 4% for transformers up to and including 630kVA, and 6% for transformers of 630kVA and above.

REFERENCES

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3. *Harmonics related documents* from Underwriters Laboratory, USA

4. *The Scope of Energy Saving in European Union Through Use of Energy Efficient Distribution Transformers* – European Copper Institute, Belgium