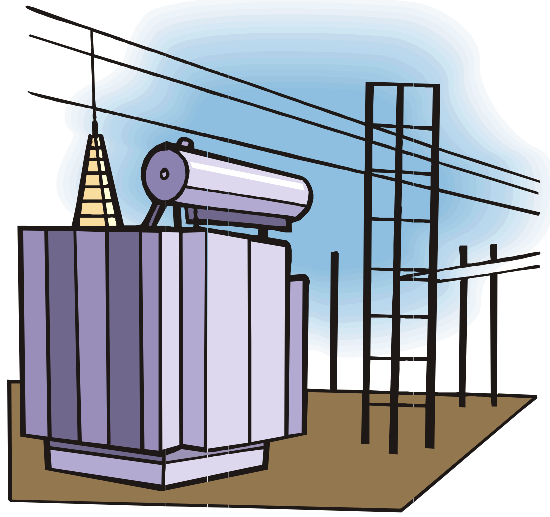
BEST PRACTICE MANUAL



TRANSFORMERS

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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 avoids 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

Annexures are given to familiarize the users with the installation and maintenance of transformers

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

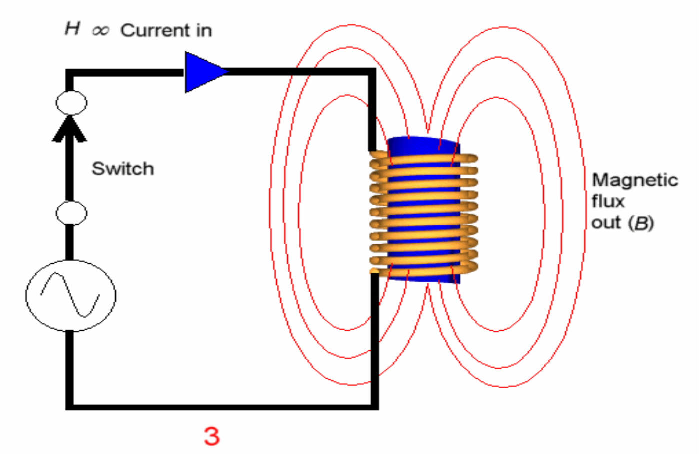

Figure 2-1: Relationship between current, magnetic field strength and flux

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.

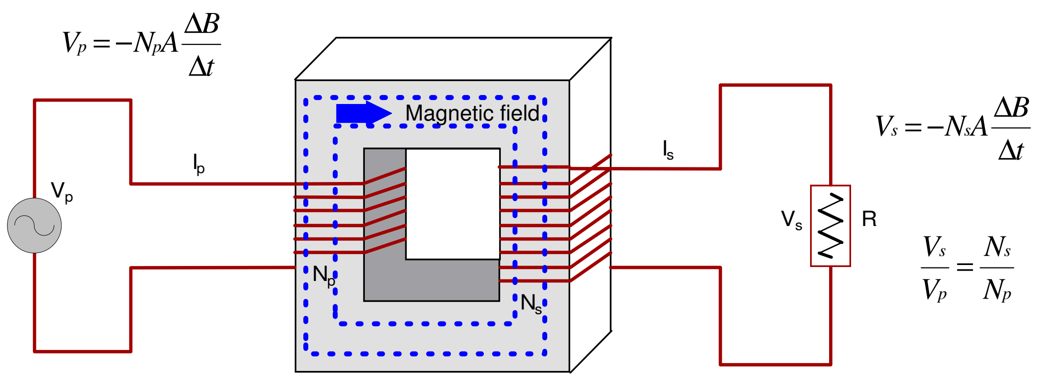

Figure 2-2: Transformer schematic

When a changing voltage is applied to the primary winding, the back e.m.fs generated by the primary is given by Faraday's law,

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

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 2.2, 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 following figure shows actual construction of a single phase transformer.

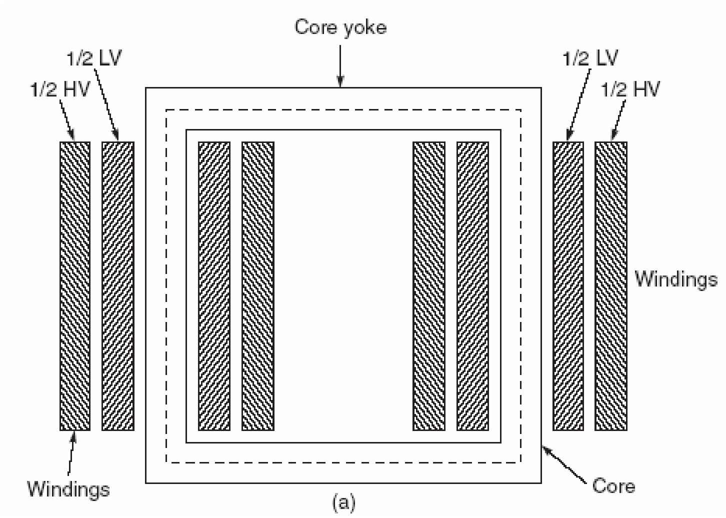

Figure 2-3: Transformer construction

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

$$VA = 4.44 \times f \times N \times B_{max} \times A_{core} \times J \times A_{cond}$$

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.

2.2. 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 A_{cond} as 30 mm^2 for this illustration. Voltage developed is given by

In primary winding,

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

In secondary winding

$E_{secondary}$ = 4.44 x f x Ns x B_{max} x A_{core},
= 4.44 X 50 X 100 X 1.5 X 0.01
= 333 Volts

Volt-ampere capability is given by the following relationship:

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.

2.3. Winding connection designations

The winding connections in a transformer are designated as follows.

High Voltage Always capital letters
Delta - D
Star - S
Interconnected star - Z
Neutral brought out - N

Low voltage Always small letters
Delta - d
Star - s
interconnected star - z
Neutral brought out - n

Phase displacement: Phase rotation is always anti-clockwise. (International adopted convention). Use the hour indicator as the indicating phase displacement angle. Because there are 12 hours on a clock, and a circle consists out of 360°, each hour represents 30°.

Thus 1 = 30°, 2 = 60°, 3 = 90°, 6 = 180° and 12 = 0° or 360°.

The minute hand is set on 12 o'clock and replaces the line to neutral voltage (sometimes imaginary) of the HV winding. This position is always the reference point. Because rotation is anti-clockwise, 1 = 30° lagging (LV lags HV with 30°) and 11 = 330° lagging or 30° leading (LV leads HV with 30°)

To summarise:

Dd0: Delta connected HV winding, delta connected LV winding, no phase shift between HV and LV.
Dyn11: Delta connected HV winding, star connected LV winding with neutral brought out, LV is leading HV with 30°

YNd5: Star connected HV winding with neutral brought out, delta connected LV winding, LV lags HV with 150°

2.4 Parallel operation of transformers

The parallel operation of transformers is common in any industry. This mode of operation is frequently required. When operating two or more transformers in parallel, their satisfactory performance requires that they have:

1. The same voltage-ratio
2. The same per-unit (or percentage) impedance
3. The same polarity
4. The same phase-sequence and zero relative phase-displacement

Out of these conditions 3 and 4 are absolutely essential and condition 1 must be satisfied to a close degree. There is more latitude with condition 2, but the more nearly it is true, the better will be the load-division between the several transformers.

Voltage Ratio: An equal voltage-ratio is necessary to avoid no-load circulating current, other wise it will lead to unnecessary losses. The impedance of transformers is small, so that a small percentage voltage difference may be sufficient to circulate a considerable current and cause additional I^2R loss. When the secondaries are loaded, the circulating current will tend to produce unequal loading conditions and it may be impossible to take the combined full-load output from the parallel-connected group without one of the transformers becoming excessive hot.

Impedance: The impedances of two transformers may differ in magnitude and in quality (i.e. ratio of resistance to reactance) and it is necessary to distinguish between per-unit and numerical impedance. Consider two transformers of ratings in the ratio 2:1. To carry double the current, the former must have half the impedance of the latter for the same regulation. The regulation must, however, be the same for parallel operation, this condition being enforced by the parallel connection. Hence the currents carried by two transformers are proportional to their ratings, if their numerical or ohmic impedances are inversely proportional to those ratings, and their per-unit impedances are identical.

A difference in quality of the per-unit impedance results in a divergence of phase angle of the two currents, so that one transformer will be working with a higher, and the other with a lower, power factor than that of the combined output.

Polarity: This can be either right or wrong. If wrong it results in a dead short circuit.

Phase-Sequence: This condition is associated only with polyphase transformers. Two transformers giving secondary voltages with a phase-displacement cannot be used for transformers intended for parallel-operation. The phase sequence or the order, in which the phases reach their maximum positive voltages, must be identical for two paralleling transformers; otherwise during the cycle each pair of phases will be short-circuited.

The two power transformers shall be paralleled only for a short duration, because they may be risking a higher fault level during this short period. The system impedance reduces when the two or more transformers are paralleled and hence increases the fault level of the system.

2.5. 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 given below.

2.5.1. 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).

2.5.2. Hysteresis 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 them 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 2.4 for a typical BH Loop.

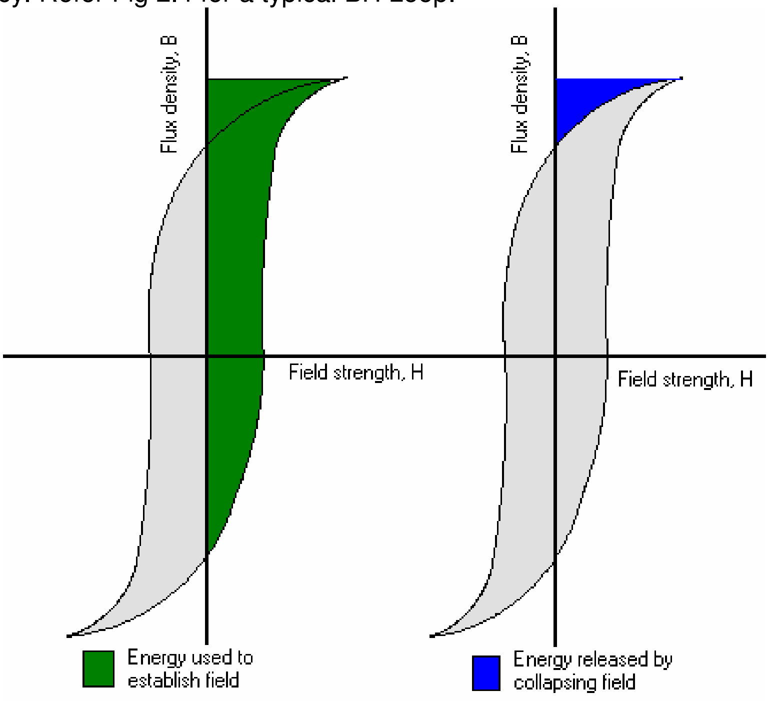

Figure 2-4: B-H Loop

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.

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

Where Kh = the hysteresis constant
f = Frequency in Hertz
B_m = Maximum flux density in Tesla

2.5.3. 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 current 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 2.5 below for a comparison of solid iron core and a laminated iron core.

Fig. 2.5B shows a solid core, which is split up by laminations of thickness '$_{d1}$' and depth d_2 as shown in C. This is shown pictorially in 2.5 A.

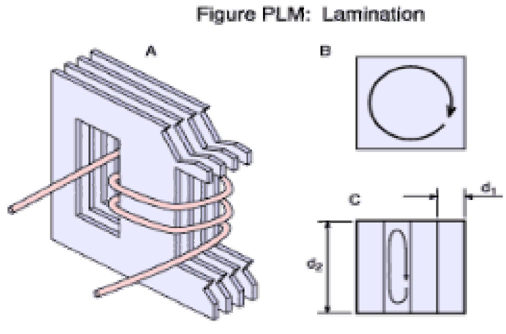

Figure 2-5 Core lamination to reduce eddy current losses

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

Where Ke = 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.

2.5.4. 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.

2.5.5. 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.

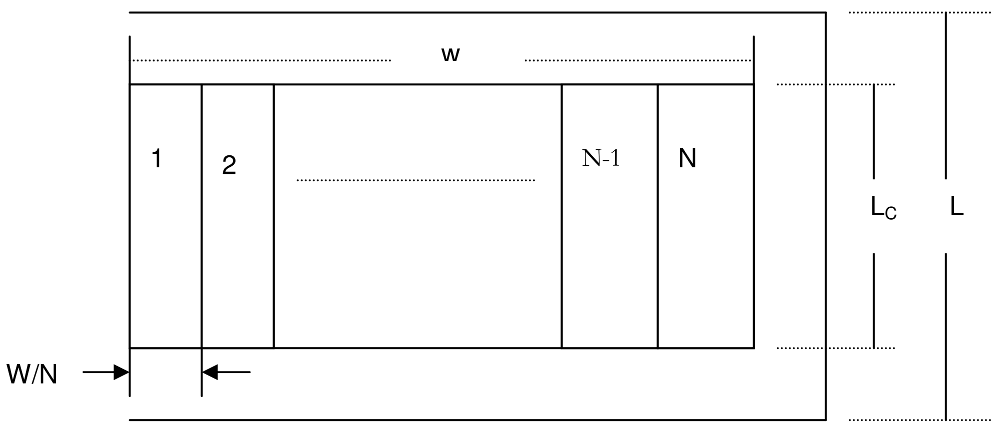

Figure 2-6: Sectionalised transformer winding - Schematic

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 $\alpha = \sqrt{\frac{(\pi \times 4\pi \times 10^{-7} \times f) \times Lc}{\rho \times L}}$ where $4\pi \times 10^{-7}$ 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 centimeters.
ρ = Resistivity, in Ohm-metres

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

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

Hence $\alpha W/N \approx w' \times \sqrt{\frac{Lc}{L}}$, 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.

2.3.6 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 OPERATIONS

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

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

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

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
$R_{T\text{-}op}$ = Resistance at operating temperature
T_{ref} = Standard reference temperature, 75 C

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

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

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, $\dfrac{R_{T-op}}{R_{T-ref}} = \dfrac{234.5 + 100}{234.5 + 75}$ = 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.

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 are 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 are 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 1000 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 1600 kVA transformer causes under loading 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 10.0 lakhs. Hence deliberate over sizing 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 = (Per unit loading as per kW)^2 X Load losses at full load X $\left(\left[\frac{1}{pf}\right]^2 - 1\right)$

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.

3.3. Segregation of non linear 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.

3.4. 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 1°C 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.

3.5. 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

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

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

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

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

3.5.1. 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.

$I = \sqrt{\left(I_1{}^2 + I_2{}^2 + ... + I_n{}^2\right)}$ 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.

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

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

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)	$(I_n/I)^2$	$(I_n/I)^2 xn^2$
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.

3.5.2. 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 = $I^2R + \text{EddyLosses}$ where as Eddy Losses = $(e \times I^2R)$

Hence, 1 = $(I^2R \times (1+e))$

Eddy Losses as a fraction of total load losses = $\left(\frac{e \times I^2R}{I^2R(1+e))}\right)$ = $\left(\frac{e}{(1+e))}\right)$

Eddy Losses at I (100%) = $\left(\frac{e}{1+e}\right)\times\sum_{n=1}^{n}\frac{\left(I_n^2\right)}{I^2}\times n^q$

Since harmonics are expressed as fractions of fundamental,

Eddy Losses = $\left(\frac{e}{1+e}\right)\times\left(\frac{I_1}{I}\right)^2\times\sum_{n=1}^{n}\frac{\left(I_1^2\times1^q+I_3^2\times3^q+\ldots+I_n^2\times n^q\right)}{I_1^2}$

$=\left(\frac{e}{1+e}\right)\times\left(\frac{I_1}{I}\right)^2\times\left(1+\sum_{n=n+2}^{n}\frac{\left(I_1^2\times1^q+I_3^2\times3^q+\ldots+I_n^2\times n^q\right)}{I_1^2}\right)$

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

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

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 3-3: 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		Σ=15.9653

$I_{r.m.s.} = \sqrt{2.1876} = 1.457$.
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

Design changes to reduce transformer losses, just as in a motor, always involve tradeoffs. For example, consider varying the cross-sectional area of the transformer core. An increase tends to lower no-load loss while raising the winding loss. An increase in volts per turn reduces winding loss while increasing the core loss. Variation in conductor area and in the electric and magnetic circuit path lengths will affect efficiency in various ways, always leading the designer to seek a cost-effective balance.

To raise transformer efficiency, core loss has probably drawn the most attention. Core construction permits two important energy-saving features not applicable to industrial motors. First, the inherent colinearity between lamination orientation and the magnetic field direction allows use of grain oriented steel for transformer laminations. That greatly reduces hysteresis loss in the core-the energy required to cyclically realign the "molecular magnets" within the steel, which are randomly positioned in a non-oriented material.

Second, because laminations are sheared or slit in strips rather than being punched with slots, much thinner material can be used in a transformer core than in a rotating machine. Whereas motor laminations are usually 0.014 to 0.025 inch thick, transformer lamination thickness may be as low as 0.006, with 0.009 to 0.012 being common. That lowers eddy current loss.

A further improvement appearing during the 1980's is amorphous core material. Resembling glass more than steel, this lamination material contains no granular structure at all. Laminations only 0.001 inch thick were used in the first mass-produced distribution transformers (25 kVA) manufactured by Westinghouse in 1986. Many similar units have been put in service since then, along with some large power transformers. Typical core loss in such a transformer is only one-third of that in a conventional unit.

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

4.2.1. Losses in Core

Choice of metal is critical for transformer cores, and it's important that good quality magnetic steel be used. There are many grades of steel that can be used for a transformer core. Each grade has an effect on efficiency on a per-kg basis. The choice depends on how you evaluate non-load losses and total owning costs.

Almost all transformer manufacturers today use steel in their cores that provides low losses due to the effects of magnetic hysteresis and eddy currents. To achieve these objectives, high permeability, cold-rolled, grain-oriented, silicon steel is almost always used. Construction of the core utilizes step lap mitered joints and the laminations are carefully stacked.

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

Table 4-1: Evolution of core material

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 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 (up to 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 help 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 densities 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.

4.2.2. Amorphous cores

A new type of liquid-filled transformer introduced commercially in 1986 uses ultra low-loss cores made from amorphous metal; the core losses are between 60% to 70% lower than those for transformers using silicon steel. To date, these transformers have been designed for distribution operation primarily by electric utilities and use wound-cut cores of amorphous metal. Their ratings range from 10kVA through 2500kVA. The reason utilities purchase them, even though they are more expensive than silicon steel core transformers, is because of their high efficiency. The use of amorphous core liquid-filled transformers is now being expanded for use in power applications for industrial and commercial installations. This is especially true in other countries such as Japan.

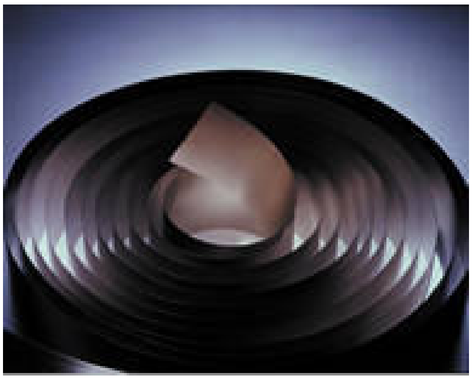

Figure 4-1: Amorphous core -ribbons

Amorphous metal is a new class of material having no crystalline formation. Conventional metals possess crystalline structures in which the atoms form an orderly, repeated, three-dimensional array. Amorphous metals are characterized by a random arrangement of their atoms (because the atomic structure resembles that of glass, the material is sometimes referred to as glassy metal). This atomic structure, along with the difference in the composition and thickness of the metal, accounts for the very low hysteresis and eddy current losses in the new material.

Cost and manufacturing technique are the major obstacles for bringing to the market a broad assortment of amorphous core transformers. The price of these units typically ranges from 15% to 40% higher than that of silicon steel core transformers. To a degree, the price differential is dependent upon which grade of silicon steel the comparison is being made. (The more energy efficient the grade of steel used in the transformer core, the higher the price of the steel.)

At present, amorphous cores are not being applied in dry-type transformers. However, there is continuous developmental work being done on amorphous core transformers, and the use of this special metal in dry-type transformers may become a practical reality sometime in the future.

If you're considering the use of an amorphous core transformer, you should determine the economic trade off; in other words, the price of the unit versus the cost of losses. Losses are especially important when transformers are lightly loaded, such as during the hours from about 9 p.m. to 6 a.m. When lightly loaded, the core loss becomes the largest component of a transformer's total losses. Thus, the cost of electric power at the location where such a transformer is contemplated is a very important factor in carrying out the economic analyses.

Different manufacturers have different capabilities for producing amorphous cores, and recently, some have made substantial advances in making these cores for transformers. The technical difficulties of constructing a core using amorphous steel have restricted the size of transformers using this material. The metal is not easily workable, being very hard and difficult to cut, thin and flimsy, and difficult to obtain in large sheets. However, development of these types of transformers continues; you can expect units larger than 2500kVA being made in the future.

4.3. Minimising Copper losses

The major portion of copper losses is I^2R losses. Using a thicker section of the conductor i.e. selecting a lower current density can reduce the basic I^2R 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.

4.4. Choice of liquid-filled or dry type

Information on the pros and cons of the available types of transformers frequently varies depending upon what information is made available by the manufacturer. Nevertheless, there are certain performance and application characteristics that are almost universally accepted.

Basically, there are two distinct types of transformers: Liquid insulated and cooled (liquid-filled type) and non liquid insulated, air or air/gas cooled (dry type). Also, there are subcategories of each main type.

For liquid-filled transformers, the cooling medium can be conventional mineral oil. There are also wet-type transformers using less flammable liquids, such as high fire point hydrocarbons and silicones.

Liquid-filled transformers are normally more efficient than dry-types, and they usually have a longer life expectancy. Also, liquid is a more efficient cooling medium in reducing hot spot temperatures in the coils. In addition, liquid-filled units have a better overload capability.

There are some drawbacks, however. For example, fire prevention is more important with liquid-type units because of the use of a liquid cooling medium that may catch fire. (Dry-type transformers can catch fire, too.) It's even possible for an improperly protected wet-type transformer to explode. And, depending on the application, liquid-filled transformers may require a containment trough for protection against possible leaks of the fluid.

Arguably, when choosing transformers, the changeover point between dry-types and wet-types is between 500kVA to about 2.5MVA, with dry-types used for the lower ratings and wet-types for the higher ratings. Important factors when choosing what type to use include where the transformer will be installed, such as inside an office building or outside, servicing an industrial load. Dry-type transformers with ratings exceeding 5MVA are available, but the vast majority of the higher-capacity transformers are liquid-filled. For outdoor applications, wet-type transformers are the predominate choice. The flowing table 4.2 shows losses in dry type and oil filled type transformers.

Table 4-2: Comparison of Losses – Oil type and dry type

(Oil Transformer) Losses			Dry Type Transformer Losses		
KVA	**Half Load (w)**	**Full Load (w)**	**KVA**	**Half Load (w)**	**Full Load (w)**
500	2465	4930	500	5000	10000
750	3950	7900	750	7500	15000
1000	4360	8720	1000	8200	16400
1500	6940	13880	1500	11250	22500
2000	8155	16310	2000	13200	26400

5. ECONOMIC ANALYSIS

1.1 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. 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%.

$$PW = \frac{\left((1+i)^n - 1\right)}{i(1+i)^n}$$ where PW is present worth of future cash flows

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} = Purchase Price + Cost of No load loss + Cost of Load loss

Cost of Core loss $_{EFC}$ = A X No load 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.

For some typical operating values, let us calculate the TOC_{EFC} for a 1000 kVA , 11 kV/433 V transformer having no load losses of 1500 Watts and load losses of 10000 Watts (at full load).

Purchase price = Rs 8,00,000
Life of equipment, n = 15 years
Inflation rate, a = 4.5%
Interest rate (discounting factor), i = 10%
EL = Cost of Electricity = Rs 4.0 per kWh
HPY = Hours per Year = 8000

Per unit transformer loading (average) = 0.75
Operating temperature = 100 ºC

PW = Present Worth = $\frac{\left((1+i)^n - 1\right)}{i(1+i)^n} = \frac{\left((1+0.1)^{15} - 1\right)}{0.1(1+0.1)^{15}}$ = 7.61

Equivalent first cost of No load losses A = $\frac{\text{PW} \times \text{EL} \times \text{HPY}}{1000} = \frac{7.61 \times 4 \times 8000}{1000}$
= 243.52 Rs/Watt

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

Hence Temperature correction factor, T = 0.9 x 1.0808 +0.1/1.0808 = 1.06523

Equivalent first cost of load losses

B = $A \times p^2 \times T$ = $243.52 \times 0.75^2 \times 1.06523$
= 145. 9152 Rs/Watt

TOC_{EFC} = 800000 + 243.52 x 1500 + 145.9152 x 10000
= Rs 2624432/-

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 **TOC_{EFC}** = (Present depreciated effective cost of old equipment – Salvage value) + A X No load loss + B X Load loss

5.4 Sample Calculations

Total Owning Cost of a 1000 kVA Transformer Using No-load and Load Losses and present worth is estimated below. The calculations for a standard transformer are done in previous section 5.2. Let us now compare a high efficiency 1000 kVA transformer with the standard transformer. Table 5.1 summarises purchase price and losses of two transformers of same rating 1000 kVA.

Table 5-1: Comparison of transformers

Standard Transformer	High-Efficiency Transformer
Purchase price – Rs 8,00,000	Rs 9,50,000
No-load losses - 1500 W	1210 W
Load losses at 100% - 10000 W	7964 W
Load loss at 75% - 6234 W	4215 W

Total Owning Cost of Transformer #1 (standard efficiency)
= Rs 2624432/- as estimated in section 5.2.

Total Owning Cost of transformer #2 (high efficiency):

A = Rs 243.52 / year
B = Rs 145.9152 / year

Total Owning Cost of High-Efficiency transformer
= Rs 9,50,000 + Rs 243.52 x 1210 + Rs 145.9152 x 4215
= Rs 18,69,592
Present Value of Savings with Energy Efficient transformer = Rs 2624432 - Rs 18,69,592
= Rs 7,54,840/-

Note that a high efficiency transformer is having much less Total Owning Cost compared to a standards efficiency transformer in spite of higher investment.

6 CASE STUDIES

6.1 Introduction

There are nine case studies presented in this chapter. Three case studies are from Indian industries and six case studies from international scenario.

The case studies from KEMA, Netherlands 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 is 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 CO_2 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 6-1input 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												

Illustrative Calculations

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

Present worth = $\dfrac{(1+i)^n - 1}{i(1+i)^n}$

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

$$A = \frac{Pw \times EL \times 8760}{1000} = EUR2.46/Watt$$

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

6.2.1 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

6.2.2 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%

6.2.3 Full load losses for Harmonic Loading:

Existing Transformer:

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

= $9500\times(0.9069+5.6\times0.093)$

= 9500×1.42826

= 13568.47 Or 13568 Watts

For Suggested Low Losses transformer

Full 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.

6.2.4 Relative economics for low loss transformers (All Dry type)

The data worked out for 1250 kVA and 1600 kVA are given in Table 6.2 and Table 6.3.

Table 6-2 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 6-3 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 no load losses 2.46 x 2400	= 5904
Present value of Load Loss	= 13568 x 1.04 = EUR 14110
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/annum, 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 %.

6.2.5 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 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 with 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 6.4 summarises the data for dry transformers and oil cooled transformers for future replacement.

Table 6-4 : Outcome 1000 kVA transformer

	Unit	Dry HD 538 transformer	Oil C-C' transformer	Difference
Transformer rating Rated no-load loss Rated load loss	kVA W W	1000 2000 8600	1000 1100 9500	 -900 900
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 Present value no-load loss Present value load loss	EUR EUR EUR	10074 2873 2102	8007 1580 2322	-2067 -1293 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 favored choice and the rate of return is not applicable; since the low loss transformer also happens to have a lower first cost.

Table 6.5 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 6-5: 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 functioning 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) is 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 6.6

Table 6-6: 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 6.7. 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 6-7 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 oil cooled 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 oil cooled 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 6.8 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 6-8: 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 6: 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 takes 200 kVA segregated load.

$$\text{Loss} = 1.66 + (300/500)^2 x6.9 +1.66 + (200/500)^2 \times 6.9 \text{ kW}$$

c) Both are paralleled to take 250 kVA each.

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

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

Operation at higher loads during lean season:

a) Two paralleled transformers

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

b) Only one transformer is energized

$$\text{Losses} = 1.66 \times (0.25)^2 \times 6.9 = 2.09 \text{ kW at 25\% load}$$
$$\text{Losses} = 1.66 \times (0.05)^2 \times 6.9 = 1.68 \text{ kW at 5\% load}$$

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.

6.9 Case Study 7: Steel Mill (India)

INTESCO-Bhoruka has implemented an energy efficiency project at Bhoruka Steel's Karnataka mini-mill. The project is designed to reduce energy costs, and increase plant productivity. The company's energy costs have increased due to power shortages and low voltage levels causing inefficient operation of its melting and casting operations. The $265,000 project involves the installation of a highly-efficient 25 MVA transformer to replace two older and smaller transformers.

Energy consumption profile:

Energy use at the plant is comprised of consumption at the steel melting shop, the wire rod mill, and inherent transformer losses. The steel melting shop has a 30-ton GEC electric arc furnace. When power quality is good, specific energy consumption averages between 550 kWh and 650 kWh per ton. With poor power quality, consumption can increase up to 700 kWh for the same product mix. By improving the voltage quality under this project, it was expected that specific consumption would be reduced by 30-35 kWh per ton.

The wire rod mill produces wire rods from 5 mm to 16 mm in diameter. The average specific energy consumption during good voltage conditions is about 200 kWh per ton. As the drive systems at the mill already have in-built automatic voltage regulators, there was not expected to be any substantial reduction in energy usage as a result of the project.

Energy saving measure

Prior to the energy efficiency project, the power from the grid was being tapped through two-12.5 MVA, 66/11KV transformers. Each transformer had a load loss factor of 10-12 kWh per ton, for a total of 20-25 kWh per ton. Installation of the new transformer was expected to slash load loss by half (to a total of 10-12 kWh per ton).

In sum, the total savings per ton of steel produced was expected to reach 40 units per ton, with the majority coming from the savings in the steel melting shop (75% of the savings).

Project Savings (in kWh per Ton of Steel Produced)

Steel Melting Shop	30
Wire Rod Mill	0
Transformer Losses	10
Total	40

Project Implementation

In order to solve the voltage problem, it was proposed to replace the two 12.5 MVA transformers with a single 66/11 KV 25 MVA **transformer** fitted with an on-load tap changer. The new 25 MVA **transformer** can handle large fluctuations in incoming voltage, resulting in **energy** savings. These changes would reduce load losses and reduce **energy** consumption during production. The new 25 MVA **transformer** installed by INTESCO- Bhoruka was expected to reduce energy consumption per unit of steel produced by as much as 8%. Construction of the project began in May 1994, and was completed in September. Commissioned in October 1994, the upgraded plant is already running eight "heats" per day, up from five per day previously. (A heat is the process of melting steel in an arc furnace in preparation for casting.) The annual **energy** savings is estimated at 1.8 million KWh.

The total cost of the project is about $265,000 (Rs. 82.6 lakhs) and the combination of improved **energy** efficiency and productivity is expected to save Bhoruka Steel about $115,000 per year (Rs. 36 lakhs). The project has a simple payback on investment of 2.3 years

6.10 Case Study-8: Automobile Plant (India)

A leading automobile manufacturer has main incomer at 132 kV. This voltage is stepped down to 11 kV. From 11 kV to 433 V, plant has several transformers located in eight substations. During an energy audit, loading on transformers located at various substations was analyzed. In few of the cases it was observed that some transformers are grossly under loaded (around 10-20%) and the scope exists to shift or distribute this load to other transformer in the substation. This would also ensure optimum level of loading. While achieving optimum loading, the standby transformers at various substations were suggested to be kept open on H.T side to save no-load losses. Also an operating schedule was proposed to alternate the transformer operation weekly so as to keep them in good health. In sub station # 1, one transformer was kept as stand by. This hot standby transformer can be kept open (Energy savings 0.45 lakh per annum)

In sub station # 3, transformers #1 and #2 were drastically under loaded (i.e, 20% and 15% respectively). Loads of transformer # 2 was transferred to Transformer # 1 and Transformer # 2 was switched off (Energy savings 0.37 lakh kWh/year) In sub station # 7, transformers # 2 and # 3 were drastically under loaded (i.e, 10% and 25% respectively). Loads of transformer # 2 was transferred to Transformer # 2 and Transformer # 2 was switched off (Energy savings 0.42 lakh kWh/year) In substation # 8, keeping hot standby transformer open, resulted in energy saving of 0.45 lakh kWh per year.

Annual Total energy savings, 1.69 lakh KWh
Annual Cost savings, Rs. 5.9 lakh
Cost of Implementation Nil
Simple payback period, Immediate

6.11 Case Study -9: Improving Reliability and availability

A lot of industries (e.g. chemical) are interested in a reliable power supply, as an unforeseen interruption of the power supply may have severe consequences. First there is the economical damage if there is a shutdown, which leads to loss of production until the process has restarted. But also there can be damage of the installation. Next to the direct damage, long outages may cause pollution and human safety problems.

To reduce the risks of an outage, it is possible to have two transformers in redundancy. This means if one transformer fails, the other transformer will carry the full load, and there will be no interruption of the power and/or shutdown of the factory.

For this case study, the economical cost when an unforeseen outage occurs is a necessary input figure. The costs of outages are very hard to determine, for this given situation it is presumed that outage of the electricity will cause a shutdown of the factory, whereby each hour outage is equal to Euro 10.000,=.

The MTBF (mean time between failures) for a transformer is presumed to be 40 years. The MTTR (mean time to repair) or time to replace a failed transformer is 8 hours. This means that the average outage frequency equals 0,025 per year and the average outage duration equals 12 minutes per year. If there is redundancy the average outage frequency equals $1{,}14 \times 10^{-6}$ per year, while the average outage duration equals $2{,}7 \times 10^{-4}$ minutes per year. This means the chance that both parallel transformers having a failure at the same time is very small compared to the outage of one transformer.

The choice for the designer to use one transformer (2500 kVA) or two transformers (1600 kVA) can now be quantified. Presuming the load is 1500 kVA; the 2500 kVA transformer loading is 60%, while the loading of the 1600 kVA transformer is 47% when both transformers are in parallel. The total annual losses for both options are given in table 6.9

Table 6-9: electricity losses over a year

2500 kVA Transformer	Oil C-C'	Oil D-D'	Dry HD 538	Dry Low loss
No load kWh/yr.	21900	18615	37668	36179
Load kWh/yr.	69379	58972	56765	47083
Total kWh/yr.	91279	77587	94433	83262
2x 1600 kVA Transformer	Oil C-C'	Oil D-D'	Dry HD 538	Dry Low loss
No load kWh/yr.	29784	25316	49056	46778
Load kWh/yr.	54182	46054	38702	36186
Total kWh/yr.	83966	71370	87758	82964

If the economic life time is estimated at 10 years, and the electricity price Euro 70,= per MWh, the following costs are expected in these 10 years (see table 6.10).

Table 6-10: Costs over 10 years.

2500 kVA Transformer	Oil C-C'	Oil D-D'	Dry HD 538	Dry Low loss
Purchase price [Euro]	24897	29402	25527	27494
Cost of no load [Euro]	15330	13030	26368	25325
Cost of load [Euro]	48565	41280	39736	32958
Cost of outage [Euro]	20000	20000	20000	20000
Total cost [Euro]	*108792*	*103712*	*111631*	*105777*
2x 1600 kVA Transformer	Oil C-C'	Oil D-D'	Dry HD 538	Dry Low loss
Purchase price [Euro]	27340	35774	35902	38146
Cost of no load [Euro]	20849	17721	34339	32745
Cost of load [Euro]	37927	32238	27091	25330
Cost of outage [Euro]	<1	<1	<1	<1
Total cost [Euro]	*86117*	*85734*	*97333*	*96222*

From table 6.10, it can be seen that the costs of outage are having influence on the total costs over 10 years. If the costs of outage are neglected, the designer would probably have chosen for a single 2500 kVA oil-transformer type D-D' or a dry transformer with lower losses than given in the HD 428.

However if the average costs of an outage are taken in account, the designer will probably order two 1600 kVA transformers. However, the two 1600 kVA transformers will also need an installation more than the 2500 kVA transformer, which is not taken in account in this case study. Nevertheless, it is clear that redundancy of transformers is preferred anyway for situations were shutdown of a process causes pollution or safety risks.

6.12 Case study-10: Use of Amorphous Core Transformers

This case study describes the choice of amorphous core distribution transformers in place of conventional silicon steel core transformers.

A very large amorphous iron three-phase distribution transformer has been built and installed in the European Union at an engine plant at Waterford in Ireland in 1998. The 1.6MVA transformer is the first to be designed specifically for the European industrial market. The load losses are 18.2kW, the no-load losses are as low as 384W, compared to 1,700W for a HD 428 C-C' transformer. With no-load losses up to 80% lower than a conventional silicon core transformer, and the payback period is 3 years. The transformer has increased the site's power capacity by 40%, while providing dramatically lower losses than a conventional transformer.'

At an average loading of 70%, the AMDT will use 13.3GWh less energy a year than a conventional transformer. With a price premium of £2,500 over a standard transformer, the AMDT should pay for itself in about three years at current Irish power prices - and continue to make savings over its 20-30-year life.

The 20kV/400V transformer, completed by Pauwels International, is the first AMDT to target European industrial customers.

ANNEXURE-1: GUIDELINES FOR INSTALLING TRANSFORMERS

When your transformer arrives on site, various procedures should be carried out to assure successful operation.

The successful operation of a transformer is dependent on proper installation as well as on good design and manufacture. The instructions mentioned in the manufacturer manual or in Standards shall be followed to ensure adequate safety to personnel and equipment.

This section will provide general guidelines for installing and testing both dry-type and liquid-filled transformers for placement into service.

Standard transformer tests performed for each unit include the following:

- Ratio, for voltage relationship;
- Polarity for single- and 3-phase units (because single-phase transformers are sometimes connected in parallel and sometimes in a 3-phase bank);
- Phase relationship for 3-phase units (important when two or more transformers are operated in parallel);
- Excitation current, which relates to efficiency and verifies that core design is correct;
- No-load core loss, which also relates to efficiency and correct core design;
- Resistance, for calculating winding temperature
- Impedance (via short circuit testing), which provides information needed for breaker and/or fuse sizing and interrupting rating and for coordinating relaying schemes;
- Load loss, which again directly relates to the transformer's efficiency;
- Regulation, which determines voltage drop when load is applied; and
- Applied and induced potentials, which verify dielectric strength.

There are additional tests that may be applicable, depending upon how and where the transformer will be used. The additional tests that can be conducted include the following:

- Impulse (where lightning and switching surges are prevalent);
- Sound (important for applications in residential and office areas and that can be used as comparison with future sound tests to reveal any core problems);
- Temperature rise of the coils, which helps ensure that design limits will not be exceeded;
- Corona for medium voltage (MV) and high-voltage (HV) units, which helps determine if the insulation system is functioning properly;
- Insulation resistance (meg-ohmmeter testing), which determines dryness of insulation and is often done after delivery to serve as a benchmark for comparison against future readings; and
- Insulation power factor, which is done at initial installation and every few years thereafter to help determine the aging process of the insulation.

Site considerations

When planning the installation, the location is selected, that complies with all safety codes yet does not interfere with the normal movement of personnel, equipment, and material. The location should not expose the transformer to possible damage from cranes, trucks, or moving equipment.

Preliminary inspection upon receipt of transformer

When received, a transformer should be inspected for damage during shipment. Examination should be made before removing it from the railroad car or truck, and, if any damage is evident or any indication of rough handling is visible, a claim should be filed with the carrier at once and the manufacturer notified. Subsequently, covers or panels should be removed and an internal inspection should be made for damage or displacement of parts, loose or broken connections, dirt or foreign material, and for the presence of water or moisture. If the transformer is moved or if it is stored before installation, this inspection should be repeated before placing the transformer in service.

Plan for the prevention of contaminants

Develop a procedure for inventory of all tools, hardware, and any other objects used in the inspection, assembly, and testing of the transformer. A check sheet should be used to record all items, and verification should be made that these items have been properly accounted for upon completion of work.

Making connections that work

The connections shall be made, between the transformer's terminals and the incoming and outgoing conductors, carefully following the instructions given on the nameplate or on the connection diagram. Check all of the tap jumpers for proper location and for tightness. Re-tighten all cable retaining bolts after the first 30 days of service. Before working on the connections make sure all safety precautions have been taken. Arrangements shall be made to adequately support the incoming/outgoing connecting cables, so that there is no mechanical stress imposed on transformer bushings and connections. Such stress could cause a bushing to crack or a connection to fail.

Controlling sound level

All transformers, when energized, produce an audible noise. Although there are no moving parts in a transformer, the core does generate sound. In the presence of a magnetic field, the core laminations elongate and contract. These periodic mechanical movements create sound vibrations with a fundamental frequency of 120 Hz and harmonics derivatives of this fundamental.

The location of a transformer relates directly to how noticeable its sound level appears. For example, if the transformer is installed in a quiet hallway, a definite hum will be noticed. If the unit is installed in a location it shares with other equipment such as motors, pumps, or compressors, the transformer hum will go unnoticed. Some applications require a reduced sound level, such as a large unit in a commercial building with people working close to it. Occasionally, the installation of some method of sound abatement will be called for.

Make sure the transformer is grounded

Grounding is necessary to remove static charges that may accumulate and also is needed as a protection should the transformer windings accidentally come in contact with the core or enclosure (or tank for wet types).

Note that for MV transformers, the secondary neutral is sometimes grounded through an impedance.

Ensure that all grounding or bonding systems meet NEC and local codes.

Final inspection and testing

Once the transformer has been located on its permanent site, a thorough final inspection should be made before any assembly is accomplished and the unit is energized. Before energizing the unit, it's very important that all personnel installing the transformer are alerted, that lethal voltages will be present inside the transformer enclosure as well as at all connection points. The installation of conductors should be performed only by personnel qualified and experienced in high-voltage equipment. Personnel should be instructed that should any service work be required to the unit, the lines that power the transformer must be opened and appropriate safety locks and tags applied.

A careful examination should be made to ensure that all electrical connections have been properly carried out and that the correct ratio exists between the low and high-voltage windings. For this test, apply a low-voltage (240V or 480V) to the high-voltage winding and measure the output at the low-voltage winding. However, for low-voltage (600V and below) transformers, this is not practical. Here, a transformer turns ratio indicator should be used to measure the ratio.

Any control circuits, if any, should be checked to make sure they function correctly. These include the operation of fans, motors, thermal relays, and other auxiliary devices. Correct fan rotation should be visually verified as well as by checking indicator lights if they are installed. Also, a one-minute, 1200V insulation resistance test of the control circuits shall be done. (If the power transformer has CT circuits, they should be closed.)

All windings should be checked for continuity. An insulation resistance test shall be carried out to make certain that no windings are grounded.

Applying the load

Before energizing a 3-phase transformer, arrangement for monitoring the voltages and currents on the low-voltage side shall be done. Then, without connecting the load, energize the transformer. The magnitude of the voltages shown (line-to-ground and line-to-line) should be very similar. If this is not the case, de-energize the transformer and contact the manufacturer before proceeding further.

Next, connect the load and energize the transformer. While monitoring the voltages and currents, gradually increase the load in a stepped or gradual application until full load is reached. Both the voltages and currents should change in a similar fashion. If this does not happen, de-energize the transformer and contact the manufacturer.

The maximum continuous load a transformer can handle is indicated on its nameplate.

Adjustment for correct tap setting

After installation, check the output voltage of the transformer. This should be done at some safe access point near or at the load. Never attempt to check the output voltage at the transformer. Dangerous high voltage will be present within the transformer enclosure.

When changing taps, the same changes must be made for all phases. Consult the transformer diagrammatic nameplate for information on what tap must be used to correct for extra high or extra low incoming line voltage. The same adjustment should be made to compensate for voltage drop in the output due to long cable runs. When the load-side voltage is low, tap connections below 100% of line voltage must be used to raise the load voltage. If the load-side voltage is high, tap connections above 100% of line voltage must be used to lower the load voltage.

ANNEXURE-2: MAINTENANCE GUIDELINES

Following specific checking and maintenance guidelines as well as conducting routine inspections will help ensure the prolonged life and increased reliability of a dry-type transformer.

The frequency of periodic checks will depend on the degree of atmospheric contamination and the type of load applied to the transformer.

Routine checks and resultant maintenance

SI No	Inspection Frequency	Items to be inspected	Inspection Notes	Action required if inspection shows unsatisfactory conditions
1.01	Hourly	Ambient Temperature	-	-
1.02	Hourly	Oil & Winding Temperature	Check that temperature rise is reasonable	Shutdown the transformer and investigate if either is persistently higher than normal
1.03	Hourly	Load (Amperes) and Voltage	Check against rated figures	Shutdown the transformer and investigate if either is persistently higher than normal
2.01	Daily	Oil level in transformer	Check against transformer oil level	If low, top up with dry oil examine transformer for leaks
2.02	Daily	Oil level in bushing	-	-
2.03	Daily	Leakage of water into cooler	-	-
2.04	Daily	Relief diaphragm	-	Replace if cracked or broken-
2.05	Daily	Dehydrating breather	Check that air passages are free. Check colour of active agent	If silica gel is pink, change by spare charge. The old charge may be reactivated for use again.
3.01	Quarterly	Bushing	Examine for cracks and dirt deposits	Clean or replace
3.02	Quarterly	Oil in transformer	Check for dielectric strength & water content	Take suitable action
3.03	Quarterly	Cooler fan bearings, motors and operating mechanisms	Lubricate bearings, check gear boxes, examine contacts,	Replace burnt or worn contact or other parts

			check manual control and interlocks	
3.04	Quarterly	OLTC	Check oil in OLTC driving mechanism	-
4.01	Yearly	Oil in transformer	Check for acidity and sludge	Filter or replace
4.02	Yearly	Oil filled bushing	Test oil	Filter or replace
4.03	Yearly	Gasket Joints	-	Tighten the bolts evenly to avoib uneven pressure
4.04	Yearly	Cable boxes	Check for sealing arrangements for filling holes.	Replace gasket, if leaking
4.05	Yearly	Surge Diverter and gaps	Examine for cracks and dirt deposits	Clean or replace
4.06	Yearly	Relays, alarms & control circuits	Examine relays and alarm contacts, their operation, fuses etc. Test relays	Clean the components and replace contacts & fuses, if required.
4.07	Yearly	Earth resistance	-	Take suitable action, if earth resistance is high

IR testing:

The transformer should be de-energized and electrically isolated with all terminals of each winding shorted together. The windings not being tested should be grounded. The meg-ohmmeter should be applied between each winding and ground (high voltage to ground and low voltage to ground) and between each set of windings (high voltage to low voltage). The meg-ohm values along with the description of the instrument, voltage level, humidity, and temperature should be recorded for future reference.

The minimum megaohm value for a winding should be 200 times the rated voltage of the winding divided by 1000. For example, a winding rated at 13.2kV would have a minimum acceptable value of 2640 megaohms ([13,200V x 200] / 1000). If previously recorded readings taken under similar conditions are more than 50% higher, the transformer should be thoroughly inspected, with acceptance tests performed before reenergizing.

Turns ratio testing:

The transformer turn ratio is the number of turns in the high voltage winding divided by the number of turns in the low voltage winding. This ratio is also equal to the rated phase voltage of the high voltage winding being measured divided by the rated phase voltage of the low voltage winding being measured.

Transformer turns ratio measurements are best made with specialized instruments that include detailed connection and operating instructions. The measured turns ratio should be within 0.5% of the calculated turns ratio. Ratios outside this limit may be the result of winding damage, which has shorted or opened some winding turns.

Insulation PF testing:

Insulation PF is the ratio of the power dissipated in the resistive component of the insulation system, when tested under an applied AC voltage, divided by the total AC power dissipated. A perfect insulation would have no resistive current and the PF would be zero. As insulation PF increases, the concern for the integrity of the insulation does also. The PF of insulation systems of different vintages and manufacturers of transformers varies over a wide range (from under 1% to as high as 20%). As such, it's important that you establish a historic record for each transformer and use good judgment in analyzing the data for significant variations.

Acceptance testing

Acceptance tests are those tests made at the time of installation of the unit or following a service interruption to demonstrate the serviceability of the transformer. This testing also applies to dry-type units. The acceptance tests should include IR testing, insulation PF measurement, and turns ratio testing, all as described under periodic tests. In addition, winding resistance measurements should be made and excitation current testing done.

Winding resistance measurement:

Accurate measurement of the resistance between winding terminals can give an indication of winding damage, which can cause changes to some or all of the winding conductors. Such damage might result from a transient winding fault that cleared; localized overheating that opened some of the strands of a multi-strand winding conductor; or short circuiting of some of the winding conductors.

Sometimes, conductor strands will burn open like a fuse, decreasing the conductor cross section and resulting in an increase in resistance. Occasionally, there may be turn-to-turn shorts causing a current bypass in part of the winding; this usually results in a decrease of resistance.

To conduct this test, the transformer is de-energized and disconnected from all external circuit connections. A sensitive bridge or micro-ohmmeter capable of measuring in the micro-ohm range (for the secondary winding) and up to 20 ohms (for the primary winding) must be used. These values may be compared with original test data corrected for temperature variations between the factory values and the field measurement or they may be compared with prior maintenance measurements. On any single test, the measured values for each phase on a 3-phase transformer should be within 5% of the other phases.

Excitation current measurement:

The excitation current is the amperage drawn by each primary coil, with a voltage applied to the input terminals of the primary and the secondary or output terminals open-circuited. For this test, the transformer is disconnected from all external circuit connections. With most transformers, the reduced voltage applied to the primary winding coils may be from a single-phase 120V supply. The voltage should be applied to each phase in succession, with the applied voltage and current measured and recorded.

If there is a defect in the winding, or in the magnetic circuit that is circulating a fault current, there will be a noticeable increase in the excitation current. There is normally a difference between the excitation current in the primary coil on the center leg compared to that in the primary coils on the other legs; thus, it's preferable to have established benchmark readings for comparison.

Variation in current versus prior readings should not exceed 5%. On any single test, the current and voltage readings of the primary windings for each of the phases should be within 15% of each other.

Applied voltage testing:

The applied voltage test is more commonly referred to as the "hi-pot test." This test is performed by connecting all terminals of each individual winding together and applying a voltage between windings as well as from each winding to ground, in separate tests. Untested windings are grounded during each application of voltage.

This test should be used with caution as it can cause insulation failure. It should be regarded as a proof test to be conducted when there has been an event or pattern in the transformer's operating history that makes its insulation integrity suspect.

DC applied voltage tests are often conducted in the field because DC test sets are smaller and more readily available than AC applied voltage sets. With DC tests, the leakage current can be measured and is often taken as a quantitative measure. However, DC leakage current can vary considerably from test to test because of creepage across the complex surfaces between windings and between windings and ground.

The use of AC voltage is preferable since the transformer insulation structures were designed, constructed, and tested with the application of AC voltage intended.

Impedance testing:

An impedance test may be useful in evaluating the condition of transformer windings, specifically for detecting mechanical damage following rough shipment or a service fault on the output side that caused high fault currents to flow through the transformer windings. Mechanical distortion of the windings will cause a change in their impedance. To maximize the effectiveness of this test, a measurement should be taken during the transformer's initial installation to establish a benchmark value.

An impedance test is performed by electrically connecting the secondary terminals together with a conductor capable of carrying at least 10% of the line current and applying a reduced voltage to the primary windings. This is easily accomplished by applying a single-phase voltage to each phase in succession. The applied voltage is measured at the primary terminals and the current measured in each line.

These values shall be recorded and then calculate the ratio of voltage to current for each phase. This ratio should be within 2% for each phase and should not vary more than 2% between tests. A variation of more than 2% indicates the possibility of mechanical distortion of the winding conductors, which should be investigated as soon as possible.

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