بسم الله الرحمن الرحيم

Losses in Transformer & Reduction Of Losses At Design Stage

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الهندسة الكهربائية

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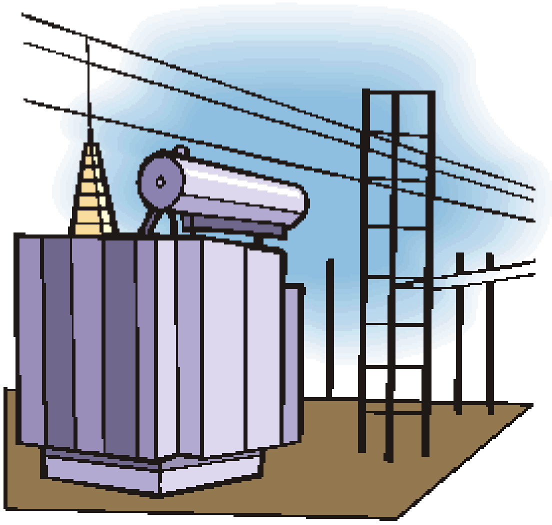


INTRODUCTION

١.١ Background

Distribution transformers are very efficient, with losses of less than ٠.٥% in large units. Smaller units have efficiencies of ٩٧% or above. It is estimated that transformer losses in power distribution networks can exceed ٣% of the total electrical power generated. In India, for an annual electricity consumption of about ٥٠٠ billion kWh, this would come to around ١٥ 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 ١٩٩٦ IEEE Transaction paper documented an almost tripling of transformer losses when feeding ٦٠kW of computer load rather than linear load. Slightly different practices are followed in USA and UK to account for harmonics while selecting transformers.

٢. FUNDAMENTALS

٢.١. 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 ٢.١ shown below explains the above principle

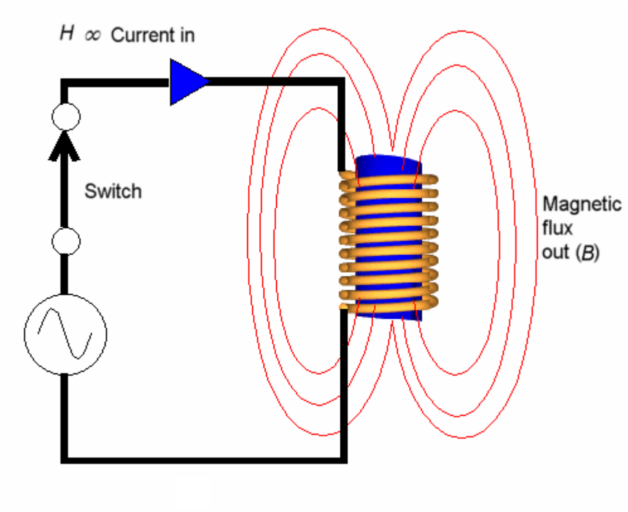
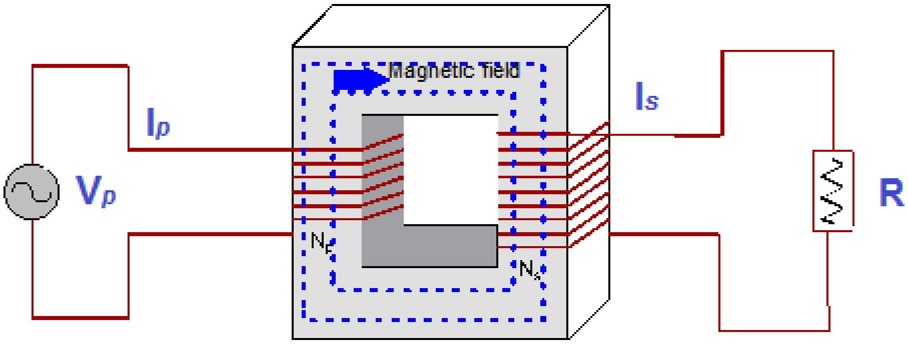


Figure 2-1: Relationship between current, magnetic field strength and flux

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.



$$EMF = Vp = -NpA\frac{\Delta B}{\Delta t} - - - - \text{(١)}$$

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

$$Vs = -NsA\frac{\Delta B}{\Delta t} \text{ ----- (٢)}$$

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The rate of change of flux is the same as that in primary winding. Dividing equation (٢) by (١) gives

$$\frac{Vs}{Vp} = \frac{Ns}{Np}$$

In Figure ٢.٢, 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 ٢.٢, 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

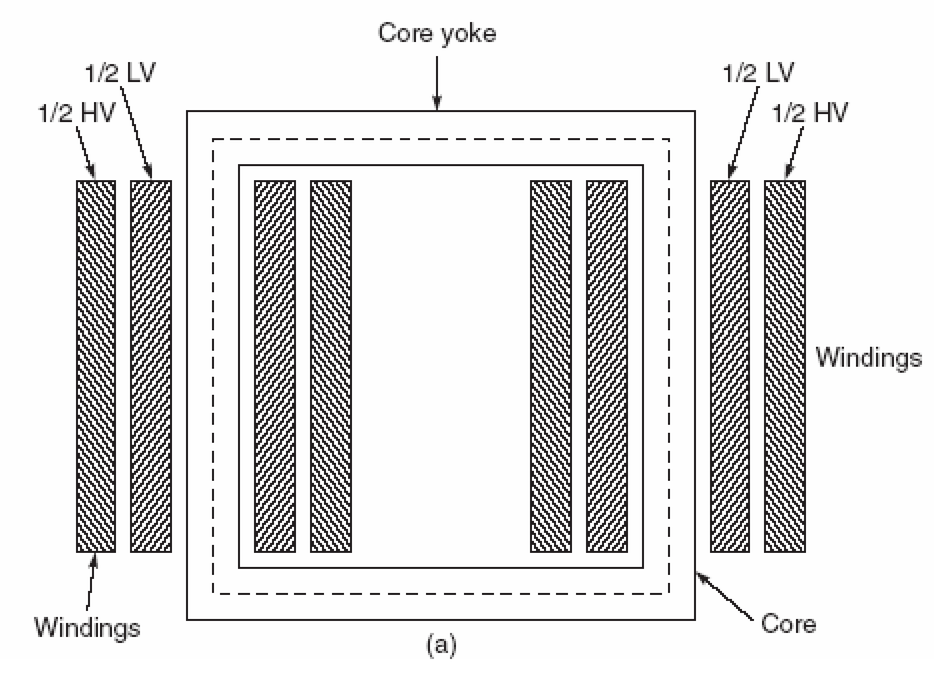

Figure 2-3: Transformer construction

The voltage developed by transformer action is given by

$E = ٤.٤٤ * \mathrm{f} * N * \mathrm{Bmax} * \mathrm{Acore}$

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

$VA = ٤.٤٤ * f * N * B_{max} * A_{core} * J * A_{cond}$

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 ($mm^{٢}$) in the core window; of the conducting material for primary winding. J depends upon heat dissipation and cooling.

٢.٢. Sample calculation

A ٥٠ Hz transformer with ١٠٠٠ turns on primary and ١٠٠ turns on secondary, maximum flux density of ١.٥ Tesla and core area of ٠.٠١ $m^{٢}$. J is taken as ٢ Amps/Sq. mm and A_{cond} as ٣٠ $mm^{٢}$ for this illustration. Voltage developed is given by
In primary winding,
$E_{primary} = ٤.٤٤ \times f \times Np \times B_{max} \times A_{core}$,
= ٤.٤٤ X ٥٠ X ١٠٠٠ X ١.٥ X ٠.٠١
= ٣٣٣٠ Volts
In secondary winding
$E_{secondary} = ٤.٤٤ \times f \times Ns \times B_{max} \times A_{core}$,
= ٤.٤٤ X ٥٠ X ١٠٠ X ١.٥ X ٠.٠١
= ٣٣٣ Volts
Volt-ampere capability is given by the following relationship:
Power rating = ٤.٤٤ x f x Np x B_{max} x A_{core} x J x A_{cond}, X ٠.٠٠١ KVA.
= ٤.٤٤ X ٥٠ X ١٠٠٠ X ١.٥ X ٠.٠١ X ٢ X ٣٠ X ٠.٠٠١
= ٢٠٠ kVA approximately.
Actual Rated KVA = Rated Voltage X Rated Current X $١٠^{-٣}$ for single phase transformers.
Rated KVA =$\sqrt{٣}$ X Rated Line Voltage X Rated Line Current X $١٠^{-٣}$ for three phase transformers.

٢.٣. 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 ١٢ hours on a clock, and a circle consists out of ٣٦٠°, each hour represents ٣٠°.
Thus ١ = ٣٠°, ٢ = ٦٠°, ٣ = ٩٠°, ٦ = ١٨٠° and ١٢ = ٠° or ٣٦٠°.

The minute hand is set on ١٢ 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, ١ = ٣٠° lagging (LV lags HV with ٣٠°) and ١١ = ٣٣٠° lagging or ٣٠° leading (LV leads HV with ٣٠°)

To summarise:

Dd٠: Delta connected HV winding, delta connected LV winding, no phase shift between HV and LV.

Dyn١١: Delta connected HV winding, star connected LV winding with neutral brought out, LV is leading HV with ٣٠°

٨

YNd٥: Star connected HV winding with neutral brought out, delta connected LV winding, LV lags HV with ١٥٠°

٢.٤ 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:

١. The same voltage-ratio
٢. The same per-unit (or percentage) impedance
٣. The same polarity
٤. The same phase-sequence and zero relative phase-displacement

Out of these conditions ٣ and ٤ are absolutely essential and condition ١ must be satisfied to a close degree. There is more latitude with condition ٢, 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 $I^{٢}R$ 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 ٢:١. 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.

٢.٥. Losses in Transformers

The losses in a transformer are as under.
١. Dielectric Loss
٢. Hysteresis Losses in the Core
٣. Eddy current losses in the Core
٤. 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.
٩

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

٢.٥.١. 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).

٢.٥.٢. 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 ٢.٤ for a typical BH Loop.
Figure 2- ٤ for a typical BH Loop.

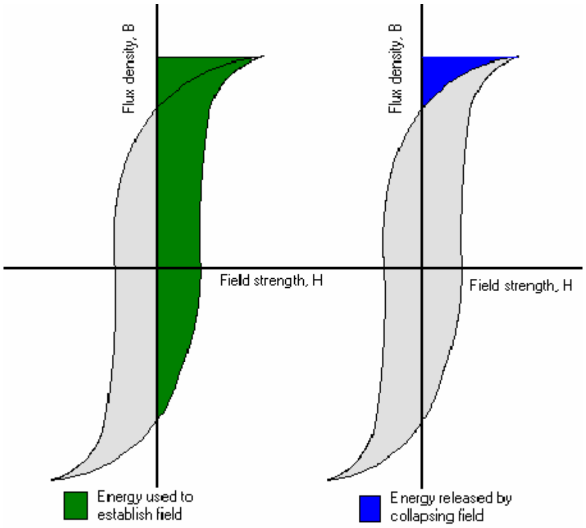

Figure 2-4: B-H Loop

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 ٥٠% of the constant core losses for CRGO (Cold Rolled Grain Oriented) sheet steel with normal design practice.
Hysteresis Losses,

$$W_h = K_h \cdot f \cdot B_m^{١.٦} \text{ Watts/Kg.}$$

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

٢.٥.٣. 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 ٢.٥ below for a comparison of solid iron core and a laminated iron core.
Fig. ٢.٥B shows a solid core, which is split up by laminations of thickness '$d_{١}$' and depth $d_{٢}$ as shown in C. This is shown pictorially in ٢.٥ A.

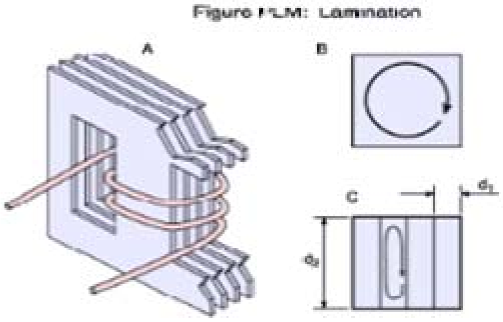

Figure 2-5 Core lamination to reduce eddy current losses

Eddy Losses,

$$W_e\ K_e\ B_m\ f\ t_{٢} = \cdot\cdot\cdot \text{ Watts/Kg.}$$

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 ٠.٣٥ 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 ٥٠% of the core losses.

٢.٥.٤. Resistive losses in the windings

These represent the main component of the load dependent or the variable losses, designated as $I^{٢}R$ 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.

$$R = \frac{\mathrm{p}L}{A}$$

Where R = Winding resistance, Ω
p = Resistivity in Ohms - mm^{٢}/m.
L = Length of conductor in metres
A = Area of cross section of the conductor, mm^{٢}

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

$$R_l = R_o * \left[\frac{T_l + ٢٣٥}{T_o + ٢٣٥}\right]$$ The constant ٢٣٥ is for Copper. For Aluminums, use ٢٢٥ or ٢٢٧

for Alloyed Aluminums

Where $R_{٠}$ = Winding resistance at temperature $T_{٠}$, 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.

٢.٥.٥. 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 (٥٠ 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 ٥% to ١٥%. Detailed subdivision is available only from design data. It can be taken as ١٠% 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 ٠.٨ 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.

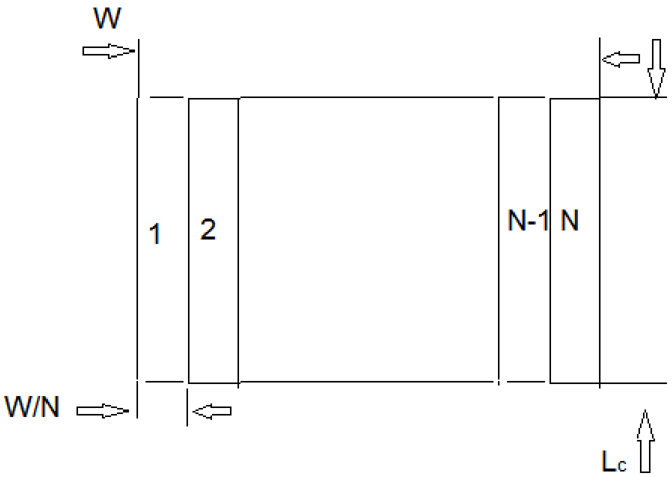

Figure 2-6: Sectionalised transformer winding – Schematic

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

$$K_e = ١ + [aW/N]^{٤} * \frac{N^{٢}}{٩}$$

Where $a = \sqrt{\frac{\pi * ٤\pi * ١٠^{-٧} * f * Lc}{p * L}}$

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 ٦٠ °C, $a = 100 * \sqrt{\frac{L_c}{L}}$ ρ= ٢ X $١٠^{-٨}$ Ohm-metres

If W' is in cm, W = W'/١٠٠

Hence $\alpha W/N \approx W' * \sqrt{\frac{L_C}{L}}$, α^4 is thus proportional to $f^{٢}$

As the number of subdivisions increase, W’ becomes smaller and Ke comes nearer to ١; but always above ١. 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.

٢.٥.٦ 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** $^{٠.٨}$**,** 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

٣. TRANSFORMER OPERATIONS

٣.١ Variation of losses during operation

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

٣.١.١. Variation of losses with loading level

$$\% \text{ Efficiency} = \frac{\text{Output} * ١٠٠}{\text{Output} + \text{Losses}}$$

$$= \frac{\text{P} * \text{ kVA rating} * \text{ p.f.} * ١٠٠٠ * ١٠٠}{\text{P} * \text{ kVA rating} * \text{ p.f.} * ١٠٠٠ * ١٠٠ + \text{N.L} + \text{L.L} * \text{P}^{٢} * \text{T}}$$

Where,
p = per unit loading
N.L. = No load losses in Watts
L.L. = Load losses in Watts at full load, at ٧٥ °C
T = Temperature correction factor
p.f. = Load power factor

The basic D.C. resistance copper losses are assumed to be ٩٠% of the load losses. Eddy current losses (in conductors) are assumed to be ١٠% of the load losses. Basic $I^{٢}R$ losses increase with temperature, while eddy losses decreases with increase in temperature. Thus, ٩٠% of the load losses vary directly with rise in temperature and ١٠% 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.

$$\frac{\boldsymbol{R_T} - \text{op}}{\boldsymbol{R_T} - \text{ref}} = \frac{\boldsymbol{F} + \boldsymbol{T_{amb}} + \boldsymbol{T_{rise}}}{\boldsymbol{F} + \boldsymbol{T_{ref}}}$$

Where F= ٢٣٤.٥ for Copper,
= ٢٢٥ for Aluminium
= ٢٢٧ for alloyed Aluminium
$R_{T\text{-op}}$ = Resistance at operating temperature
T_{ref} = Standard reference temperature, ٧٥ C

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

$$= \boldsymbol{0.9} * \left(\frac{\boldsymbol{R_T} - \boldsymbol{_{op}}}{\boldsymbol{R_T} - \boldsymbol{_{ref}}}\right) + \boldsymbol{0.1}\left(\frac{\boldsymbol{R_T} - \boldsymbol{_{ref}}}{\boldsymbol{R_T} - \boldsymbol{_{op}}}\right)$$

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

If operating temperature is ١٠٠ C, $\left(\frac{R_{T-op}}{R_{T-ref}}\right) = \frac{234.5+100}{234.5+5} = \mathbf{1.0808}$

Hence $T = ٠.٩ * ١.٠٨٠٨ + \frac{٠.١}{١.٠٨٠٨} = ١.٠٦٥٢٣$

٣.١.٢. 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.

٣.١.٣. Variation in Load Losses

About ٩٠%of the load losses as measured by short circuit test are due to $I^٢R$ losses in the windings. They vary with the square of the current and also with winding temperature.

$$\text{Load Losses} = (\text{Per Unit Loading})^٢ * \text{Load losses at full load} * \left(\frac{\mathrm{F} + \mathrm{T_{op}}}{\mathrm{F} + \mathrm{T_{ref}}}\right)$$

F = Temperature coefficient = ٢٣٤.٥ for Copper and ٢٢٧ for Aluminium.

T_{ref} = ٧٥ °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 $I^٢R$ losses. In addition, the major increase comes from the variation in eddy current losses in the windings (Usually ٥ to ١٠% of the total load losses), which vary with the square of the frequency.

٣.٢. 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 ٥٠% load.

٣.٢.١. 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 ٥٠% load. Such a situation can lead to lower than ٢٥% 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 ١٥ to ٢٠% growth
- ١٠ to ١٥% margin for non-linear loads
- Availability of standard rating

Generally, ٣٠ to ٥٠% 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 ٥.

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 ٧٥ C. They have to be corrected to expected site operating temperature. Basic I۲R 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 ٢٠. Details of K factor evaluation are given in section ٣.٤ of this chapter. This will need derating of ١٢% for ١٠% nonlinear load to about ٢٧% for ٤٠% 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 minimized

٣.٢.٢. Energy Saving by Under-utilisation of transformers

Table ٣.١ summarises the variation in losses and efficiency for a ١٠٠٠ kVA transformer and also shows the difference in losses by using a ١٦٠٠ kVA transformer for the same. The ١٠٠٠ kVA transformer has a no load loss of ١٧٠٠ watts and load loss of ١٠٥٠٠ Watts at ١٠٠% load. The corresponding figures for ١٦٠٠ kVA transformer are ٢٦٠٠ Watts and ١٧٠٠٠ Watts respectively. Loading is by linear loads. Temperatures assumed equal.

Table 3-1: Comparison of transformer losses

	١٠٠٠ kVA, No load losses = ١٧٠٠ W				١٦٠٠ kVA. No load losses = ٢٦٠٠ W		Difference in losses, W
Per unitload	Load losses, W	Total losses,W	Output, kW	Efficiency, %	Load losses, W	otal losses, W	
٠.١	١٠٥	١٨٠٥	١٠٠	٩٨.٢٣	٦٠	٢٦٦٠	٨٦١
٠.٢	٤٢٠	٢١٢٠	٢٠٠	٩٨.٩٥	٢٦٥	٢٨٦٥	٧٤٥
٠.٣	٩٤٥	٢٦٤٥	٣٠٠	٩٩.١٣	٥٩٧	٣١٩٧	٥٥٢
٠.٤	١٦٨٠	٣٣٨٠	٤٠٠	٩٩.١٦	١٠٦٢	٣٦٦٢	٢٨٢
٠.٥	٢٦٢٥	٤٣٢٥	٥٠٠	٩٩.١٤	١٦٦٠	٤٢٦٧	-٥٨
٠.٦	٣٧٨٠	٥٤٨٠	٦٠٠	٩٩.٠٩	٢٣٩٠	٤٩٩٠	-٤٩٠
٠.٧	٥١٤٥	٦٨٤٥	٧٠٠	٩٩.٠٣	٣٢٥٨	٥٨٥٣	-٩٩٢
٠.٨	٦٧٢٠	٨٤٢٠	٨٠٠	٩٨.٩٦	٤٢٥٠	٦٨٥٠	-١٥٧٠
٠.٩	٨٥٠٥	١٠٢٠٥	٩٠٠	٩٨.٨٨	٥٣٧٩	٧٩٧٩	-٢٢٢٦
١	١٠٥٠٠	١٢٢٠٠	١٠٠٠	٩٨.٧٨	٦٦٤٠	٩٢٤٠	-٢٩٦٠

The efficiency of ١٠٠٠ kVA transformer is maximum at about ٤٠% load. Using ١٦٠٠ kVA transformer causes under loading for ١٠٠٠ 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 ٥٠% load, there is saving which is ٢.٩٦ kW at ١٠٠٠ kW load.

The saving by using a ١٦٠٠ kVA transformer in place of a ١٠٠٠ kVA transformer at ١٠٠٠ kW load for ٨٧٦٠ hours/annum is ٢٥٩٦٠ kWh/year. @Rs ٥.٠ /kWh, this is worth Rs ١.٢٩ lakhs. The extra first cost would be around Rs ١٠.٠ lakhs. Hence deliberate over sizing is not economically viable.

٣.٢.٣. Reduction of losses due to improvement of power factor

Transformer load losses vary as square of current. Industrial power factor vary from ٠.٦ to ٠.٨. Thus the loads tend to draw ٦٠% to ٢٥% 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)^{٢} X Load losses at full load X $\left(\left(\frac{١}{PF}\right)^{٢} + ١\right)$

Thus, if p.f is ٠.٨ and it is improved to unity, the saving will be ٥٦.٢٥% 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.

٣.٣. 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.

٣.٤. 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 ١°C rise in operating temperature gives about ٠.٤% rise in load losses. A reference temperature of ٧٥ °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.

٣.٥. 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 ٦١٣٧٨-١ ‘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 typetransformers.
The alternative approaches for power distribution transformers using K-Factor and Factor-K are given later. As per IEC ٦١٣٧٨-١, the total load losses with current harmonics are given as under

$$P_T = P_{DC١} * \left(\frac{I_L}{I_١}\right)^٢ + P_{WE١} - \left[\sum_{١}^{n}\left(\frac{I_n}{I_١}\right)^٢ * n^٢\right] + (P_{CE١} + P_{SE١}) * \left[\sum_{١}^{n}\left(\frac{I_n}{I_١}\right)^٢ * n^{٠.٨}\right]$$

$$I_L^٢ = \sum_{١}^{n} I_n^٢$$

$P_{DC١}$= Basic copper losses for fundamental frequency
$P_{WE١}$= Winding eddy losses for fundamental
$P_{CE١}$ = Eddy losses in structural parts due to current leads for fundamental
١ ٧
$P_{SE١}$ = Eddy losses in structural parts for fundamental
I_n = Current for harmonic order n
$I_١$ = Fundamental current
$P_{CE١}$ and $P_{SE١}$ are not applicable to dry type transformers

٣.٥.١. 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.

$$K = \sum_{n=١}^{٢} I_n^٢ * n^٢$$

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 = ١ for resistance heating, motors, distribution transformers etc.
K = ٤ for welders Induction heaters, Fluorescent lights
K = ١٣ For Telecommunication equipment.
K = ٢٠ for main frame computers, variable speed drives and desktop computers.

The eddy losses in conductors are assumed to vary as$(I_n/I)^٢$ X$n^٢$
where I is the total r.m.s. current and is assumed to be ١٠٠ % i.e. rated value.

$I = \sqrt{I_١^٢ + I_٢^٢ \ldots\ldots\ldots I_n^٢}$ Where $I_١$ is taken as ١. Now, since I is defined, loss variation is taken as

$(I_n/I)^{٢}$ $Xn^{٢}$ including fundamental.

K is ratio of Eddy losses at ١٠٠ % current with harmonics and Eddy losses at ١٠٠ % current with fundamental.

$$K = \sum_{n=١}^{n} \left[\frac{I_n}{I}\right]^{٢} * n^{٢}$$

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 ١٠ %. Copper losses are then assumed to be the balance ٩٠ %.
Total load losses at ١٠٠ % load = (٠.٩ + ٠.١ x K)
If K = ١١, eddy losses at ١٠٠% load with this harmonic pattern are ١١ times the eddy losses at fundamental.
Total load losses at ١٠٠% load = ٠.٩ + ١.١ = ٢
Total load losses at x% load = x_2 x ٢.

If total load losses are assumed to be ١٠٠% or ١ for same temperature rise, then $x^{٢}$= ١/K =١/٢. x = $١/K^{٠.٥}$ or ٧٠.٧%. Thus the transformer can work at ٧٠% 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	In/I١	(In/I١)^{٢}	(In/I)	(In/I)^{٢}	(In/I)^{٢}xn^{٢}
١	١	١	١	٠.٦٧٦١	٠.٤٥٧١	٠.٤٥٧١
٣	٠.٨٢	٠.٨٢	٠.٦٧٢٤	٠.٥٥٤٤	٠.٣٠٧٣	٢.٧٦٦٣
٥	٠.٥٨	٠.٥٨	٠.٣٣٦٤	٠.٣٩٢١	٠.١٥٣٨	٣.٨٤٤٤
٧	٠.٣٨	٠.٣٨	٠.١٤٤٤	٠.٢٥٦٩	٠.٠٦٦٠	٣.٢٣٤٤
٩	٠.١٨	٠.١٨	٠.٠٣٢٤	٠.١٢١٧	٠.٠١٤٨	١.٢٠٠٠
١١	٠.٠٤٥	٠.٠٤٥	٠.٠٠٢٠	٠.٠٣٠٤	٠.٠٠٠٩	٠.١١٢٠
Total r.m.s	١.٤٧٩					
Sum			٢.١٨٧٦			١١.٦١٣٨

$I_{r.m.s.} = \sqrt{٢.١٨٧٦}$ =١.٤٧٩ =I. K-Factor is given by last column. K factor = ١١.٦١٨
A K١٣ rated transformer is recommended for this load.

٣.٥.٢. European Practice- ‘Factor K’

The European practice as defined in BS ٧٨٢١ Part ٤ and HD ٥٣٨.٣.S١ defines a derating factor for a given transformer by a ‘Factor-K’.

$$K = \left[١ + \frac{e}{١ + e} \left(\frac{I_١}{I} \right)^٢ * \sum_{n+٢}^{N} n^q * \left(\frac{I_n}{I_١} \right)^٢ \right]^{٠.٥}$$

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
= ١.٧ for round / rectangular section
= ١.٥ for foil type low voltage winding.
I = R.M.S. value of the current including all harmonics

$$= \left(\sum_{n=١}^{n=N} I_n^٢ \right)^{٠.٥}$$

The objective is to estimate the total load losses at ١٠٠% current, when that current contains harmonics. The base current is thus I the r.m.s. current which is ١٠٠%. 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. ١.

١ = $I^٢R$+ EddyLosses where as Eddy Losses = $(e\, I^٢R)$

$$\text{Eddy Losses as a fraction of total load losses} = \left[\frac{e * I^٢R}{I^٢R(١ + e)} \right] = \left[\frac{e}{(١ + e)} \right]$$

$$\text{Eddy Losses at I (١٠٠\%)} = \left(\frac{e}{١ + e} \right) * \sum_{n=١}^{n} \frac{(I_n^٢)}{I^٢} * n^q$$

Since harmonics are expressed as fractions of fundamental,

$$\text{Eddy Losses } = \left(\frac{e}{e + ١} \right) * \left(\frac{I_١}{I} \right)^٢ * \sum_{n=١}^{n} \frac{\left(I_١^٢ + ١^q + I_٣^٢ + ٣^q \ldots\ldots\ldots. + I_n^٢ + n^q \right)}{I_١^٢}$$

$$= \left(\frac{e}{e+١} \right) * \left(\frac{I_١}{I} \right)^٢ * \left(١ + \sum\nolimits_{n=n+٢}^{n} \frac{\left(I_١^٢+١^q+I_٣^٢+٣^q \ldots\ldots\ldots +I_n^٢+n^q \right)}{I_١^٢} \right)$$

$I = I_١^٢ + I_H^٢$ where $I_H^٢$ equals the sum of squares for harmonics, but excluding fundamental.

$$\text{Total losses } = I^٢R + \left(\frac{e}{e + ١} \right) * \left(\frac{I_١^٢ + I_H^٢}{I^٢} \right) - \left(\frac{e}{e + ١} \right) * \left(\frac{I_H^٢}{I^٢} \right) + \left(\frac{e}{e + ١} \right) * \left(\frac{I_١}{I} \right)^٢ * \sum_{n=n+٢}^{n} \left(\frac{I_n}{I_١} \right)^٢ * n^q$$

If the term for $I_H^{٢}$ is neglected, there is an error on safe side with a total deviation of only ٢% to ٤% depending upon I_H, since e/ ١+ e itself is about ٩% to ١٠% of total losses at fundamental. The addition to eddy losses may be ١٠ to ١٥ times due to harmonics. The first two terms equal the total losses at fundamental and thus equals ١.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 > ١ and thus covers harmonics only. At *X*% load, Load Losses = X_2 K^{٢} and since new load losses should be equal to ١,
X= ١/K .

Typical calculation (taking *q* as ١.٧ and assuming that eddy current loss at fundamental as ١٠% of resistive loss i.e. e= ٠.١) is given below

Table 3-3: Estimation of Factor K

Harmonic No.	RMS Current	In/I١	(In/I١)^{٢}	N^q	N^q (In/I)^{٢}
١	١	١	١	١	١
٣	٠.٨٢	٠.٨٢	٠.٦٧٢٤	٦.٤٧٣	٤.٣٥٢٥
٥	٠.٥٨	٠.٥٨	٠.٣٣٦٤	١٥.٤٢٦	٥.١٨٩٣
٧	٠.٣٨	٠.٣٨	٠.١٤٤٤	٢٧.٣٣٢	٣.٩٤٦٧
٩	٠.١٨	٠.١٨	٠.٠٣٢٤	٤١.٩٠٠	١.٣٥٧٦
١١	٠.٠٤٥	٠.٠٤٥	٠.٠٠٢٠	٥٨.٩٣٤	٠.١١٩٣
Sum			٢.١٨٧٦		$\sum$ = ١٥.٩٦٥٣

$I_{r.m.s.}$ =√ ٢.١٨٧٦ = ١.٤٧٩
K^{٢} = ١ + (٠.١/ ١.١) x (١/١.٤٧٩)^{٢} x (١٥.٩٦٥٣ –١) =١.٦٢٢
K = ١.٢٧٣٥
Transformer derating factor **=** ١/K = ١/١.٢٧٣٥x ١٠٠ = ٧٨.٠٥%

٤. REDUCTION OF LOSSES AT DESIGN STAGE

٤.١. 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 ٠.٠١٤ to ٠.٠٢٥ inch thick, transformer lamination thickness may be as low as ٠.٠٠٦, with ٠.٠٠٩ to ٠.٠١٢ being common. That lowers eddy current loss.

A further improvement appearing during the ١٩٨٠'s is amorphous core material. Resembling glass more than steel, this lamination material contains no granular structure at all. Laminations only ٠.٠٠١ inch thick were used in the first mass-produced distribution transformers (٢٥ kVA) manufactured by Westinghouse in ١٩٨٦. 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

١. Using more material
٢. Better material
٣. New Material
٤. Improved distribution of materials
٥. 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.

٤.٢. Minimising Iron Losses

٤.٢.١. 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 ٥٠hz)
١٩١٠	Warm rolled FeSi	٠.٣٥	٢ (١.٥T)
١٩٥٠	Cold rolled CRGO	٠.٣٥	١ (١.٥T)
١٩٦٠	Cold rolled CRGO	٠.٣	٠.٩ (١.٥T)
١٩٦٥	Cold rolled CRGO	٠.٢٧	٠.٨٤ (١.٥T)
١٩٧٥	Amorphous metal	٠.٠٣	٠.٢ (١.٣T)
١٩٨٠	Cold rolled CRGO	٠.٢٣	٠.٧٥ (١.٥T)
١٩٨٥	Cold rolled CRGO	٠.١٨	٠.٦٧ (١.٥T)

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 ٢٥% 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 ١.٥ 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.

٤.٢.٢. Amorphous cores

A new type of liquid-filled transformer introduced commercially in ١٩٨٦ uses ultra low-loss cores made from amorphous metal; the core losses are between ٦٠% to ٧٠% 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 ١٠kVA through ٢٥٠٠kVA. 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.
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 ١٥% to ٤٠% 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 ٩ p.m. to ٦ 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 ٢٥٠٠kVA being made in the future.

٤.٣. Minimising Copper losses

The major portion of copper losses is $I^٢R$ losses. Using a thicker section of the conductor i.e. selecting a lower current density can reduce the basic $I^٢R$ 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 $I^٢R$ and minimum eddy current losses for a given design and specified harmonic loading.

٤.٤. 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 wettype 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 ٥٠٠kVA to about ٢.٥MVA, 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 ٥MVA 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 ٤.٢ 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)
٥٠٠	٢٤٥٦	٤٩٣٠	٥٠٠	٥٠٠٠	١٠٠٠٠
٧٥٠	٣٩٥٠	٧٩٠٠	٧٥٠	٧٥٠٠	١٥٠٠٠
١٠٠٠	٤٣٦٠	٨٧٢٠	١٠٠٠	٨٢٠٠	١٦٤٠٠
١٥٠٠	٦٩٤٠	١٣٨٨٠	١٥٠٠	١١٢٥٠	٢٢٥٠٠
٢٠٠٠	٨١٥٥	١٦٣١٠	٢٠٠٠	١٣٢٠٠	٢٦٤٠٠

٥. ECONOMIC ANALYSIS

٥.١ 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 ٩٠.٩١ is invested at an annual interest of ١٠%, it will yield ٩٠.٩١x (١+١٠/١٠٠) = Rs ١٠٠/- at the end of one year. Hence the present worth of Rs ١٠٠ after one year is Rs ٩٠.٩١/- , if the annual rate of interest is ١٠%.

$PW = \frac{((١+i)^n-١)}{i(١+i)^n}$ 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 ١٠ to ١٥ 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.

٥.٢ 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

$$= \frac{PW+EL+HPY}{١٠٠٠}$$

PW = Present worth, explained in previous section ٥.١
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
= $A*P^{٢}*T$
p = Per Unit load on transformer
T = Temperature correction factor, details of calculation given in section ٣.١.١.

For some typical operating values, let us calculate the TOC_{EFC} for a ١٠٠٠ kVA , ١١ kV/٤٣٣ V transformer having no load losses of ١٥٠٠ Watts and load losses of ١٠٠٠٠ Watts (at full load).

Purchase price = Rs ٨,٠٠,٠٠٠
Life of equipment, n = ١٥ years
Inflation rate, a = ٤.٥%
Interest rate (discounting factor), i = ١٠%
EL = Cost of Electricity = Rs ٤.٠ per kWh
HPY = Hours per Year = ٨٠٠٠
Per unit transformer loading (average) = ٠.٧٥
Operating temperature = ١٠٠ °C

$$PW = \text{Present Worth} = \frac{((١+i)^{n}-١)}{i(١+i)^{n}} = \frac{((١+٠,١)^{١٥}-١)}{٠.١(١+٠.١)^{١٥}} = ٧.٦١$$

Equivalent first cost of No load losses $= \frac{PW+EL+HPY}{١٠٠٠} = \frac{٧.٦١+٤+٨٠٠٠}{١٠٠٠}$
= ٢٤٣.٥٢ Rs/Watt

If operating temperature is ١٠٠ °C, $\frac{R_{T-op}}{R_{T-reF}} = \frac{٢٣٤.٥+١٠٠}{٢٣٤.٥+٧٥} = ١.٠٨٠٨$
Hence Temperature correction factor, T = ٠.٩ x ١.٠٨٠٨ +٠.١/١.٠٨٠٨ = ١.٠٦٥٢٣

Equivalent first cost of load losses
B = $A*p^{٢}*T$ = ٢٤٣.٥٢* $٠.٧٥^{٢}$ *١.٠٦٥٢٣
= ١٤٥. ٩١٥٢ Rs/Watt
TOC_{EFC} = ٨٠٠٠٠٠ + ٢٤٣.٥٢ x ١٥٠٠ + ١٤٥.٩١٥٢ x ١٠٠٠٠
= Rs ٢٦٢٤٤٣٢/-

٥.٣ 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 $\textbf{TOC}_{\textbf{EFC}}$ = (Present depreciated effective cost of old equipment – Salvage value) + A X No load loss +B X Load loss

٥.٤ Sample Calculations

Total Owning Cost of a ١٠٠٠ 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 ٥.٢. Let us now compare a high efficiency ١٠٠٠ kVA transformer with the standard transformer. Table ٥.١ summarises purchase price and losses of two transformers of same rating ١٠٠٠ kVA.

Table 5-1: Comparison of transformers

Standard Transformer	High-Efficiency Transformer
Purchase price – Rs ٨,٠٠,٠٠٠	Rs ٩,٥٠,٠٠٠
No-load losses - ١٥٠٠ W	١٢١٠ W
Load losses at ١٠٠% - ١٠٠٠٠ W	٧٩٦٤ W
Load loss at ٧٥% - ٦٢٣٤ W	٤٢١٥ W

Total Owning Cost of Transformer #١ (standard efficiency)
= Rs ٢٦٢٤٤٣٢/- as estimated in section ٥.٢.
Total Owning Cost of transformer #٢ (high efficiency):
A = Rs ٢٤٣.٥٢ / year
B = Rs ١٤٥.٩١٥٢ / year

Total Owning Cost of High-Efficiency transformer
= Rs ٩,٥٠,٠٠٠ + Rs ٢٤٣.٥٢ x ١٢١٠ + Rs ١٤٥.٩١٥٢ x ٤٢١٥
= Rs ١٨,٦٩,٥٩٢
Present Value of Savings with Energy Efficient transformer = Rs ٢٦٢٤٤٣٢ - Rs ١٨,٦٩,٥٩٢
= Rs ٧,٥٤,٨٤٠/-
Note that a high efficiency transformer is having much less Total Owning Cost compared to a standards efficiency transformer in spite of higher investment.