CHAPTER 1
INTRODUCTION

1.1 GENERAL

The design of electrical machine follows establish and universally accepted physical and mathematical principles, which have been verified by experimental methods, and the knowledge of these principles is often in sufficient to produce correct and economic design. This can only be achieved by correct decisions based upon judgment and intuition through understanding of the subject. The design of electrical machine consists of the solution of many complex and diverse engineering problems and normally these problems are interrelated to a greater or leaser degree. The design presents a mathematically indeterminate problem with many solutions, as the number of equations is less than the number of unknowns. It takes much iteration to arrive at an optimum solution. The iterations require changes in values of variables till both the cost and performance constraints are satisfied. The design if electrical machine is an iterative process wherein the assumed data might have to be varied many tines to obtain the desired design. The program of optimization in electrical machine design eliminates a large number of no- useful combinations of design parameters. The useful parameters are retained and a number of variables are varied to give optimized deign in the region for satisfactory performance [1,2,14].The concepts of two commonly accepted approaches are used in machine design. They are: (1) Analysis method and (2) Synthesis method [2,14].

(1) ANALYSIS METHOD

In this method, the dimensions the designer chooses materials and types of construction and these re presented to the computer as input data. The computer calculates the performance of the machine. The designer examines the performance and makes another choice of the input, if necessary, and the performance is recalculated. This procedure is calculated over again till the performance requirements are satisfied. The analysis method is fairly easy to program, to use and to understand. It results in considerable time saving thereby giving quick returns investments. The programs based upon analysis method are simple but they become the foundations for later day larger and sophisticated programs. The results of analysis methods are highly acceptable by the machine designers [2,14].

(2) **SYNTHESIS METHOD**

In this method, the desired performance is given as input computer. The local decisions required to modify the values of variables to arrive at the desired performance are incorporated in the program as a set of instructions. In this method, the program is not interrupted for the designer to take logical decisions. Synthesis method of design implies designing a machine that satisfies a set of performances indices. By a set of given performance indices, an infinite number of designs can be Produced to satisfy them. Therefore, the synthesis design produces an optimum design. Synthesis without optimization has no meaning [1,2,14].

The synthesis method provide saving in time and in engineering man –hours. Design making is left to the computer itself. It involves too much logical decisions. Formulation of complex program would require the large running time and huge expenditure. So, the synthesis program formulated at high cost can not be used forever. This program has to be changed and up dated keeping in view the changes in materials, manufacturing techniques, performance standards, relative cost of materials, market conditions and the change in the design logic itself. Therefore, a synthesis program requires both additional effort and cost in order that it is updated [2, 14].

1.2 LITRRATURE SURVEY

In high power electrical machine designing, different parameters should be marginally satisfied. Besides, the performances and the requirements of the electrical machine depend on their applications. The performance of the electrical machine, such as efficiency, weight, voltage regulation, no lode current, cost and losses etc., vary according to the rating. International researchers proposed different suggestions [2,4,5,6,7,8,11,12,] to improve the performance of the electrical machine and published their research paper in the international journals and publications. In this thesis, their suggestions and also different modifications have been applied for the further improvement of the

electrical machine. The international researchers examined the effects of electromagnetic shields in the transformer. They proposed that the stray loss, a portion of the total loss, can be reduced if the electromagnetic shields of aluminum are used in the internal walls of the transformer tank. The magnetic material has been permeability and shields by flux shunting mechanism. The currents, induced in high conducting materials. The magnetic field interference can be reduced. The researchers suggested the formula of stray loss analysis recording to the test results. The stray loss is a function of physical geometry of the cores and the windings, voltage class of the transformer and the materials used in the tank construction.. The analysis of shielding shows that stray losses are reduced in the transformer tank when the shield thickness is 10mm for the aluminum.

The iron loss in a transformer includes eddy current loss and hysteresis loss, which depends upon the grade and quality of the laminated core sheet. This iron loss can be considerably reduced. This laminated electrical steel sheet has better quality than others [7, 11]. The present worth analysis and the total annual energy loss saving to justify the economical use of this novel design procedure. Using of aluminum shielding and laminated electrical steel sheet, the overall cost and weight of the transformer may be increased, but a considerable amount of annul energy loss can be saved and the transformer can operate for an extended time period [7,8,11,12].

1.3 OBJECTIVE OF THE THESIS

The objective of the thesis is to develop a mathematical model for the optimal design of electrical machine specially three phase high power transformer for improved performance. Highly nonlinear and non-explicit objective and constrain functions are incorporated in the standard routine,[15, 16] and to give the design solution in a minimum computer time. New suggestions are incorporated in the design program to improve the performances of the electrical machine.

1.4 THESIS ORGANIZATION

This thesis consists of five chapters. As an introductory approach, the thesis objective and literature reviews are presented in chapter 1. General aspects of transformer designing, different part and accessories of transformer are described in chapter 2. General feature and three phase power transformer are presented in chapter 3.general features and different processes of optimization, the techniques applied for the optimum design of transformer are described in chapter 4. Conclusion and recommendation for future work are presented in chapter 5.

CHAPTER 2
TRANSFORMER

2.1 INTRODUCTION

Two categories of transformers are used in power systems. These are (1) Distribution transformer and (2) Power transformer. Distribution transformers, up to a size of about 200KVA, are used to step down the distribution voltage to a standard service voltage. Distribution transformers are kept in all-day operation. They should have small iron losses and full load copper losses, good voltage regulation, small leakage reactance and good all day efficiency. Power transformer, above a rating of 200KVA, are used in generating stations and substations at each end a power transmission line for stepping up or stepping down the voltage. They are put in operation during load periods and are disconnected light load periods [14, 18, 19, 22].

2.2 DEFINITION OF TRANSFORMER

A *transformer* is a device that transfers electrical energy from one circuit to another by electromagnetic induction (transformer action). The electrical energy is always transferred without a change in frequency, but may involve changes in magnitudes of voltage and current. Because a transformer works on the principle of electromagnetic induction, it must be used with an input source voltage that varies in amplitude. A *transformer* is a device in which two circuits are coupled by a magnetic field that is linked to both. There is no conductive connection between the circuits, which may be at arbitrary constant potentials. Only *changes* in one circuit affect the other. The circuits often carry at least approximately sinusoidal currents, and the effect of the transformer is to change the voltages, while transferring power with little loss. The magnetic field coupling the circuits can be in air, but is usually in a ferromagnetic material, the *core*, in which the field can be thousands of times greater than it would be in air, making the transformer efficient and small. The transformer is an honorary electrical "machine" in which the flux changes occur by variation in currents with time, instead of by motion. [7,13]

2.3 OPERATION OF A TRANSFORMER

In its most basic form a transformer consists of:

- A primary coil or winding.
- A secondary coil or winding.
- core that supports the coils or windings.

Refer to the transformer circuit in figure (1) as you read the following explanation: The primary winding is connected to a 50 hertz ac voltage source. The magnetic field (flux) builds up (expands) and collapses (contracts) about the primary winding. The expanding and contracting magnetic field around the primary winding cuts the secondary winding and induces an alternating voltage into the winding. This voltage causes alternating current to flow through the load. The voltage may be stepped up or down depending on the design of the primary and secondary windings.

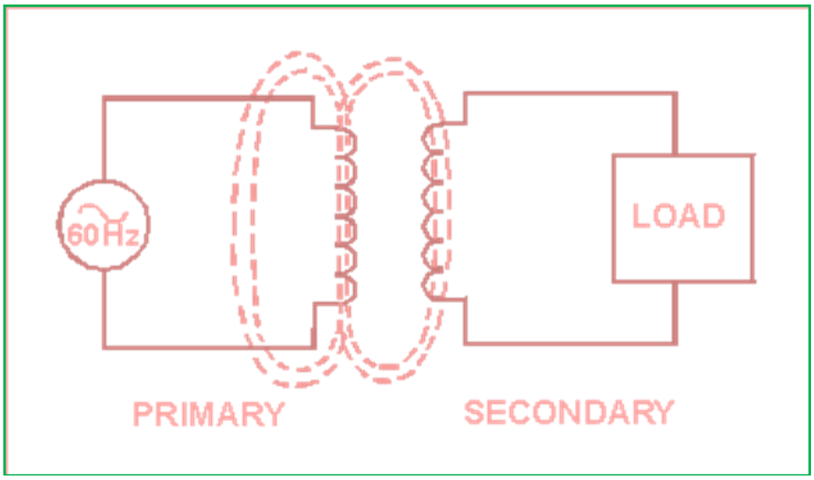


Figure (2.1). - Basic transformer action.

2.4 THE COMPONENTS OF A TRANSFORMER

Two coils of wire (called windings) are wound on some type of core material. In some cases the coils of wire are wound on a cylindrical or rectangular cardboard form. In effect, the core material is air and the transformer is called an *air-core transformer*. Transformers used at low frequencies, such as 50 hertz and 400 hertz, require a core of low-reluctance magnetic material, usually iron. This type of transformer is called an *iron-core transformer***.** Most power transformers are of the iron-core type. The principle parts of a transformer and their functions are:

- The *core*, which provides a path for the magnetic lines of flux.
- The *primary winding*, which receives energy from the ac source.
- The *secondary winding*, which receives energy from the primary winding and delivers it to the load.
- The *enclosure*, which protects the above components from dirt, moisture, and mechanical damage.

(i) **Core**:

The composition of a transformer core depends on such factors as voltage, current, and frequency. Size limitations and construction costs are also factors to be considered. Commonly used core materials are air, soft iron, and steel. Each of these materials is suitable for particular applications and unsuitable for others. Generally, air-core transformers are used when the voltage source has a high frequency (above 20 kHz). Iron-core transformers are usually used when the source frequency is low (below 20 kHz). A soft-iron-core transformer is very useful where the transformer must be physically small, yet efficient. The iron-core transformer provides better power transfer than does the air-core transformer. A transformer whose core is constructed of laminated sheets of steel dissipates heat readily; thus it provides for the efficient transfer of power. The majority of transformers you will encounter in Navy equipment contain laminated-steel cores. These steel laminations (see figure 2) are insulated with a non conducting material, such as varnish, and then formed into a core. It takes about 50 such laminations to make a core an inch thick. The purpose of the laminations is to reduce certain losses which will be discussed later in this part. An important point to remember is that the most efficient transformer core is one that offers the best path for the most lines of flux with the least loss in magnetic and electrical energy.

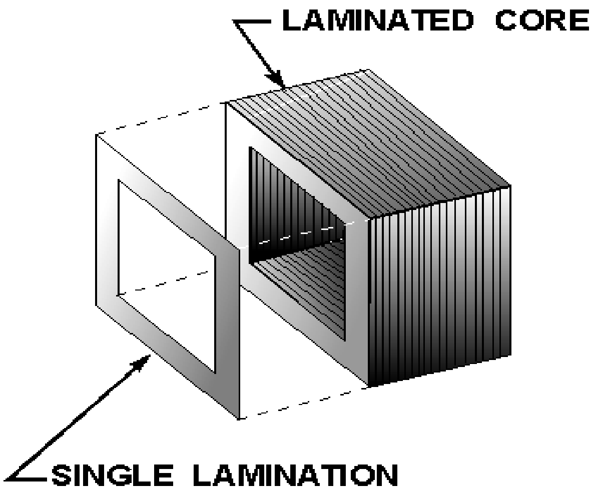


Figure (2.2). - Hollow-core construction.

(ii)**Transformer Windings:**

As stated above, the transformer consists of two coils called windings which are wrapped around a core. The transformer operates when a source of ac voltage is connected to one of the windings and a load device is connected to the other. The winding that is connected to the source is called the *primary winding*. The winding that is connected to the load is called the *secondary winding*. (Note: In this part the terms "primary winding" and "primary" are used interchangeably; the term: "secondary winding" and "secondary" are also used interchangeably.) Figure (5) shows an exploded view of a shell-type transformer. The primary is wound in layers directly on a rectangular cardboard form.

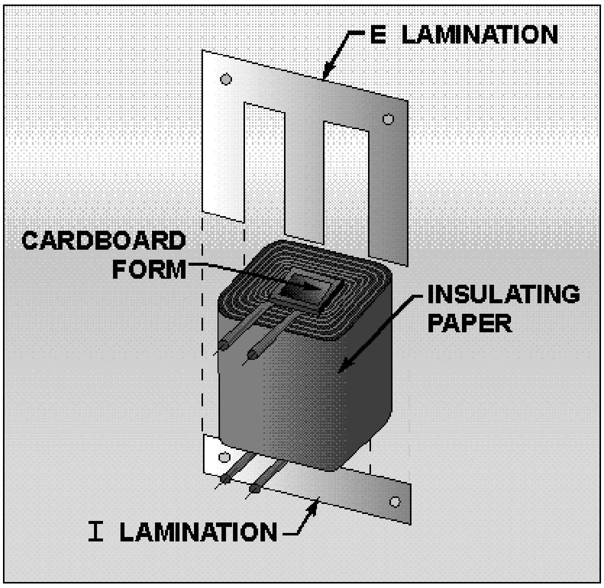


Figure (2.3). - Exploded view of shell-type transformer construction.

In the transformer shown in the cutaway view in figure (6), the primary consists of many turns of relatively small wire. The wire is coated with varnish so that each turn of the winding is insulated from every other turn. In a transformer designed for high-voltage applications, sheets of insulating material, such as paper, are placed between the layers of windings to provide additional insulation.

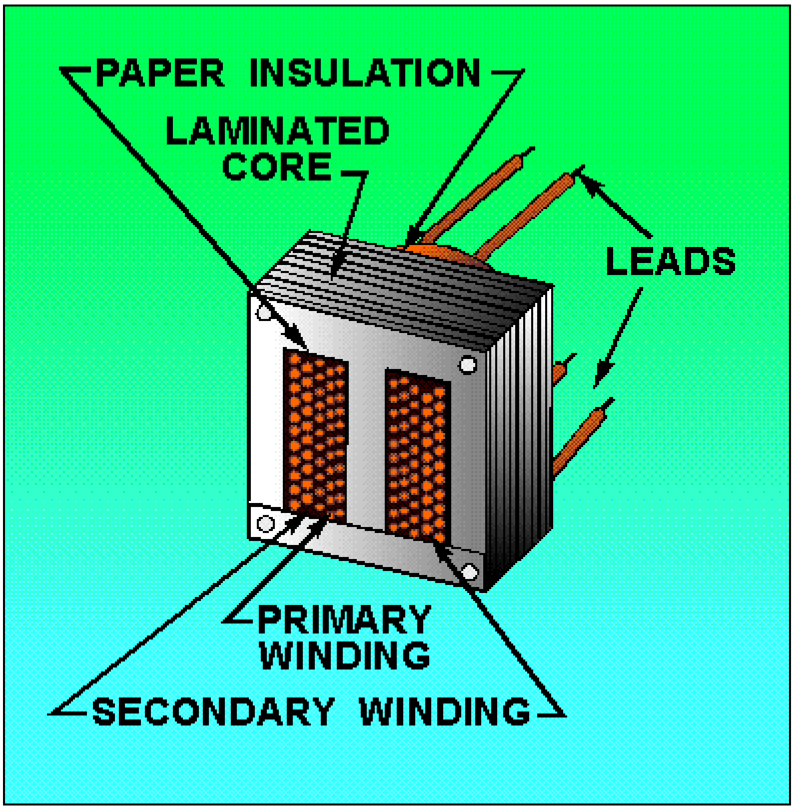


Figure (2.4). - Cutaway view of shell-type core with windings.

When the primary winding is completely wound, it is wrapped in insulating paper or cloth. The secondary winding is then wound on top of the primary winding. After the secondary winding is complete, it too is covered with insulating paper. Next, the E and I sections of the iron core are inserted into and around the windings as shown.

The leads from the windings are normally brought out through a hole in the enclosure of the transformer. Sometimes, terminals may be provided on the enclosure for connections to the windings. The figure shows four leads, two from the primary and two from the secondary. These leads are to be connected to the source and load, respectively.

2.5 TYPES OF TRANSFORMER

According to working principle:

(a) Step up transformer
(b) Step down transformer

According to core:

(a) Core type transformer
(b) Shell type transformer
(c) Spiral type transformer

According to establishment:

(a) Indoor type transformer.
(b) Outdoor type transformer.
(c) Pole mounted transformer.
(d) Underground transformer.

According to frequency:

(a) Audio frequency transformer.
(b) Radio frequency transformer.

According to phase:

(a) Single phase transformer.
(b) Poly phase transformer.

Core Type Transformers

There are two main shapes of cores used in laminated-steel-core transformers. One is the CORE Type, so named because the core is shaped with a hollow square through the center. Figure 5-2illustrates this shape of core. Notice that the core is made up of many laminations of steel.

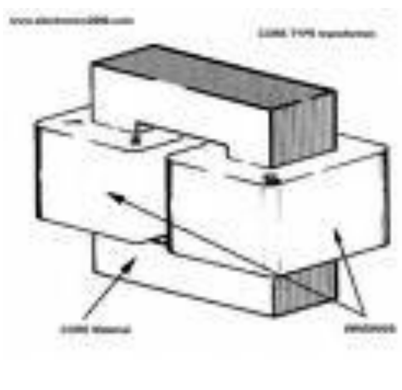


Figure (2.5). Core- type core construction.

Shell-Core Transformers

The most popular and efficient transformer core is the SHELL CORE, as illustrated in figure (4). As shown, each layer of the core consists of E- and I-shaped sections of metal. These sections are butted together to form the laminations. The laminations are insulated from each other and then pressed together to form the core.

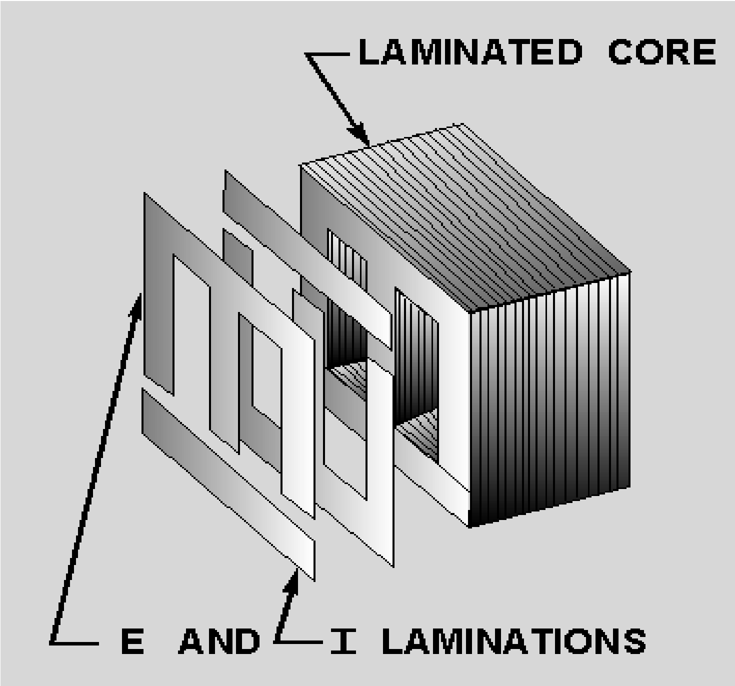


Figure (2.6): Shell-type core construction.

EQUIVALENT CIRCUIT OF TRANSFORMER:

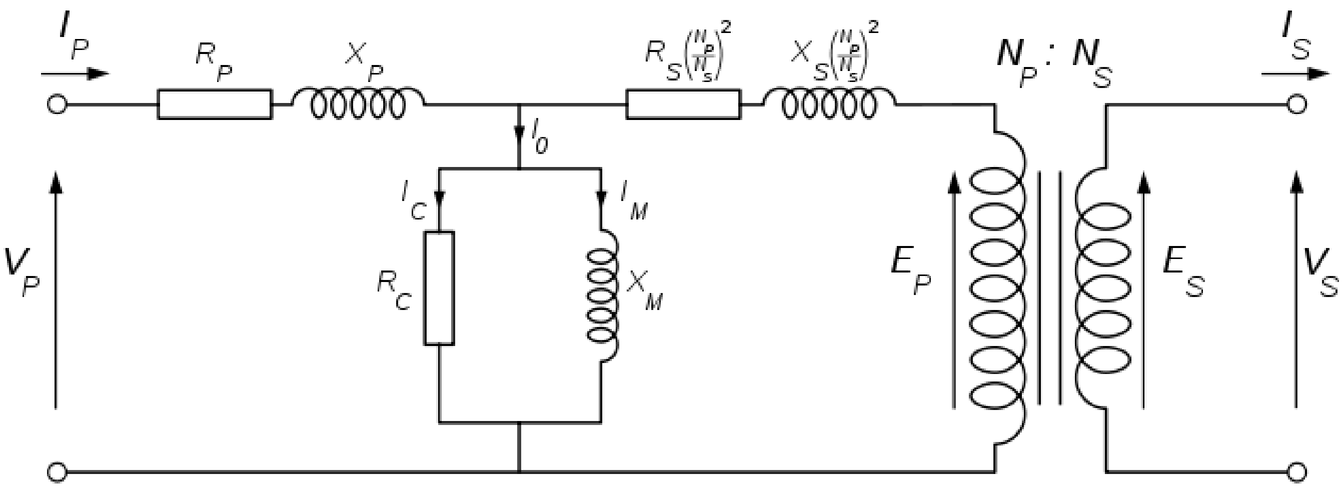


Figure (2.7): Equivalent circuit of Transformer

2.6 IDEAL ATRANSFORMER S AND NO-LOAD CONDITION

2.6.1 Ideal Transformer

An Ideal transformer is lossless transformer which changes the voltage in one level to another level without changing the frequency.

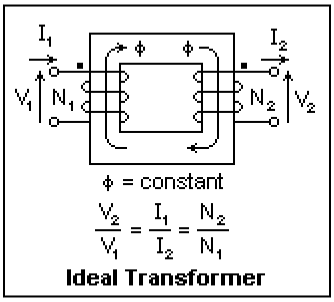


Figure (2.8): Ideal Transformer

Most transformers with iron cores can be considered as *ideal* when you use them. An ideal transformer has no losses, an aim that is closely attained in practice, so the energy transfer from the primary circuit to the secondary circuit is perfect. The diagram represents such a transformer, showing the core with magnetic flux φ, the primary winding of N_1 turns, and the secondary winding of N_2 turns. The reference directions for the voltages and currents at the terminals are shown. All of these quantities are to be considered as phasor amplitudes, varying sinusoidally with time. Note the dots at one or the other of the terminals of each winding. Currents entering the dotted terminals produce flux in the same direction, the direction shown.

The current and voltage ratios are equal to the turns ratio. This means that the power factor (cosine of the phase angle), and the power, are the same at input (primary) and output (secondary).The mutual flux φ is the means of transfer of energy from primary to secondary, and links both windings. In an ideal transformer, this flux requires negligibly small ampere-turns to produce it, so the net ampere-turns, primary plus secondary, is about zero. When a current is drawn from the secondary in the positive direction, ampere-turns decrease substantially. This must be matched by an equal increase in primary ampere-turns, which is caused by an increase in the current entering the primary in the positive direction. In this way, the back-emf of the primary (the voltage induced in it by the flux φ) equals the voltage applied to the primary, as it must. This fundamental explanation of the operation of a transformer must be clearly understood before proceeding further.

2.6.2 No Load Condition

We know that a transformer is capable of supplying voltages which are usually higher or lower than the source voltage. This is accomplished through mutual induction, which takes place when the changing magnetic field produced by the primary voltage cuts the secondary winding.

A no-load condition is said to exist when a voltage is applied to the primary, but no load is connected to the secondary, as illustrated by figure (8). Because of the open switch, there is no current flowing in the secondary winding.

With the switch open and an ac voltage applied to the primary, there is, however, a very small amount of current called *exciting current* flowing in the primary. Essentially, what the exciting current does is "excite" the coil of the primary to create a magnetic field. The amount of exciting current is determined by three factors: (1) the amount of voltage applied (E_a), (2) the resistance (R) of the primary coil's wire and core losses, and (3) the X_L which is dependent on the frequency of the exciting current. These last two factors are controlled by transformer design.

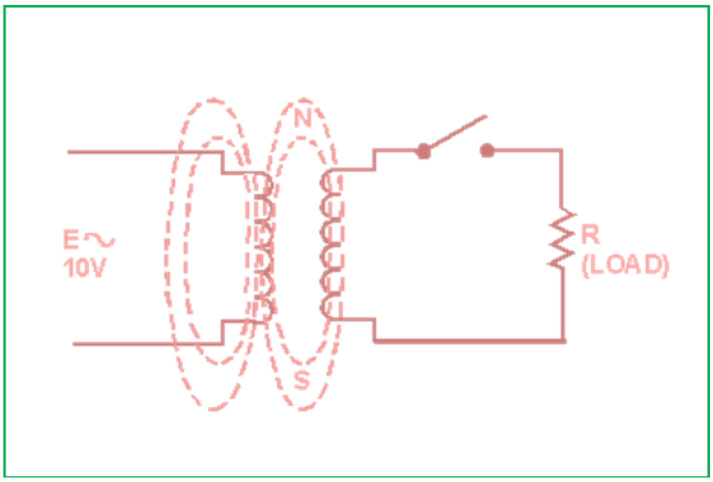
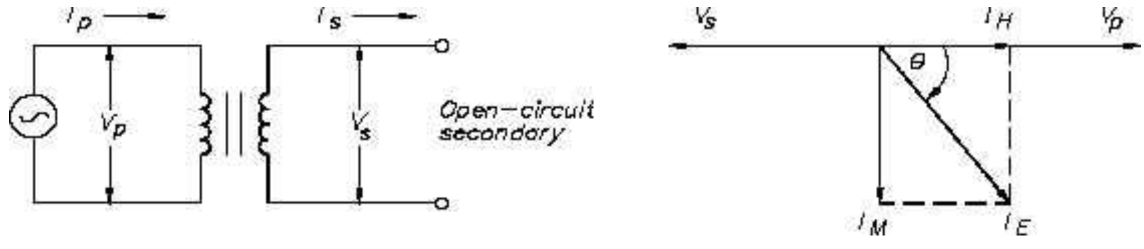


Figure (2.9): Transformer under no-load conditions.



(a) No-load condition (b) Phasor diagram

This very small amount of exciting current serves two functions:

- Most of the exciting energy is used to maintain the magnetic field of the primary.
- A small amount of energy is used to overcome the resistance of the wire and core losses which are dissipated in the form of heat (power loss).

Exciting current will flow in the primary winding at all times to maintain this magnetic field, but no transfer of energy will take place as long as the secondary circuit is open.

2.7 TRANSFORMER RATIO

2.7.1 Turns and Voltage Ratio

The total voltage induced into the secondary winding of a transformer is determined mainly by the ratio of the number of turns in the primary to the number of turns in the secondary, and by the amount of voltage applied to the primary. Refer to figure (10). Part (A) of the figure shows a transformer whose primary consists of ten turns of wire and whose secondary consists of a single turn of wire. You know that as lines of flux generated by the primary expand and collapse, they cut both the ten turns of the primary and the single turn of the secondary. Since the length of the wire in the secondary is approximately the same as the length of the wire in each turn in the primary.[15]

emf induced into the secondary will be the same as the emf induced into each turn in the primary. This means that if the voltage applied to the primary winding is 10 volts, the counter emf in the primary is almost 10 volts. Thus, each turn in the primary will have an induced counter emf of approximately one-tenth of the total applied voltage, or one volt. Since the same flux lines cut the turns in both the secondary and the primary, each turn will have an emf of one volt induced into it. The transformer in part (A) of figure 5-10 has only one turn in the secondary, thus, the emf across the secondary is one volt.

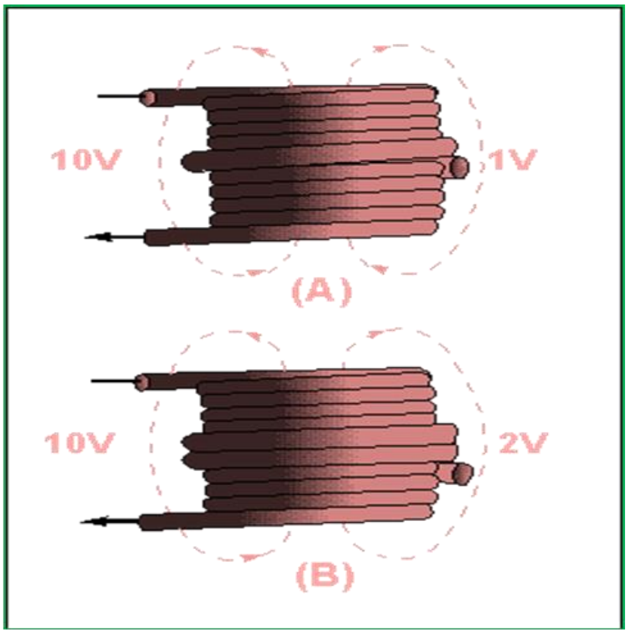


Figure (2.10): Transformer turns and voltage ratios.

The transformer represented in part (B) of figure (10)
has a ten-turn primary and a two-turn secondary. Since the flux induces one volt per turn, the total voltage across the secondary is two volts. Notice that the volts per turn are the same for both primary and secondary windings.
Since the counter emf in the primary is equal (or almost) to the applied voltage, a proportion may be set up to express the value of the voltage induced in terms of the voltage applied to the primary and the number of turns in each winding. This proportion also shows the relationship between the number of turns in each winding and the voltage across each winding. This proportion is expressed by the equation:

$$\frac{E_S}{E_P} = \frac{N_S}{N_P}$$

Where:

N_P = number of turns in the primary
E_P = voltage applied to the primary
E_S = voltage induced in the secondary
N_S = number of turns in the secondary

Notice the equation shows that the ratio of secondary voltage to primary voltage is equal to the ratio of secondary turns to primary turns.
The equation can be written as:

$$E_P N_S = E_S N_P$$

The following formulas are derived from the above equation:

Transposing for E_S: $$E_S = \frac{E_S N_P}{N_P}$$

Transposing for E_P: $$E_P = \frac{E_S N_P}{N_S}$$

The transformer in each of the above problems has fewer turns in the secondary than in the primary. As a result, there is less voltage across the secondary than across the primary. A transformer in which the voltage across the secondary is less than the voltage across the primary is called a *step-down* transformer.

The ratio of a four-to-one step-down transformer is written as 4:1. A transformer that has fewer turns in the primary than in the secondary will produce a greater voltage across the secondary than the voltage applied to the primary. A transformer in which the voltage across the secondary is greater than the voltage applied to the primary is called a *step-up* transformer. The ratio of a one-to-four step-up transformer should be written as 1:4. Notice in the two ratios that the value of the primary winding is always stated first.

2.7.2 Turns and Current Ratio

The number of flux lines developed in a core is proportional to the magnetizing force *(in ampere-turns)* of the primary and secondary windings. The ampere-turn (I X N) is a measure of magneto motive force; it is defined as the magneto motive force developed by one ampere of current flowing in a coil of one turn. The flux which exists in the core of a transformer surrounds both the primary and secondary windings. Since the flux is the same for both windings, the ampere-turns in both the primary and secondary windings must be the same.[8,18].

Therefore:

$$I_P N_P = I_S N_S$$

Where:

$I_P N_P$ = ampere − turns in the primary winding

$I_S N_S$ = ampere − turns in the secondary winding

By dividing both sides of the equation by $I_P N_S$, you obtain:

$$\frac{N_P}{N_S} = \frac{I_S}{I_P}$$

Since: $$\frac{E_S}{E_P} = \frac{N_S}{N_P}$$

Then: $$\frac{E_P}{E_S} = \frac{N_P}{N_S}$$

And: $$\frac{E_P}{E_S} = \frac{I_S}{I_P}$$

Where:

E_P = voltage applied to the primary in volts

E_S = voltage across the secondary in volts

I_P = current in the primary in amperes

I_S = current in the secondary in amperes

Notice the equations show the current ratio to be the inverse of the turns ratio and the voltage ratio. This means, a transformer having less turns in the secondary than in the primary would step down the voltage, but would step up the current. The turns ratio indicates the amount by which the transformer increases or decreases the voltage applied to the primary. For example, if the secondary of a transformer has two times as many turns as the primary, the voltage induced into the secondary will be two times the voltage across the primary. If the secondary has one-half as many turns as the primary, the voltage across the secondary will be one-half the voltage across the primary. However, the turns ratio and the current ratio of a transformer have an inverse relationship. Thus, a 1:2 step-up transformer will have one-half the current in the secondary as in the primary. A 2:1 step-down transformer will have twice the current in the secondary as in the primary.

2.8 TRANSFORMER LOSSES

Practical power transformers, although highly efficient, are not perfect devices. Small power transformers used in electrical equipment have an 80 to 90 percent efficiency range, while large, commercial power line transformers may have efficiencies exceeding 98 percent. The total power loss in a transformer is a combination of three types of losses. One loss is due to the dc resistance in the primary and secondary windings. This loss is called *copper* loss or I^2R loss. [6,9]

The two other losses are due to *eddy currents* and to *hysteresis* in the core of the transformer. Copper loss, eddy-current loss, and Hysteresis loss result in undesirable conversion of electrical energy into heat energy.

2.8.1 Copper Loss

Whenever current flows in a conductor, power is dissipated in the resistance of the conductor in the form of heat. The amount of power dissipated by the conductor is directly proportional to the resistance of the wire, and to the square of the current through it. The greater the value of resistance or current, the greater is the power dissipated. The primary and secondary windings of a transformer are usually made of low-resistance copper wire. The resistance of a given winding is a function of the diameter of the wire and its length. Copper loss can be minimized by using the proper diameter wire. Large diameter wire is required for high-current windings, whereas small diameter wire can be used for low-current windings.

2.8.2 Eddy-Current Loss

The core of a transformer is usually constructed of some type of ferromagnetic material because it is a good conductor of magnetic lines of flux. Whenever the primary of an iron-core transformer is energized by an alternating-current source, a fluctuating magnetic field is produced. This magnetic field cuts the conducting core material and induces a voltage into it. The induced voltage causes random currents to flow through the core which dissipates power in the form of heat. These undesirable currents are called eddy currents**.** To minimize the loss resulting from eddy currents, transformer cores are laminated. Since the thin, insulated laminations do not provide an easy path for current, eddy-current losses are greatly reduced.

2.8.3 Hysteresis Loss

When a magnetic field is passed through a core, the core material becomes magnetized. To become magnetized, the domains within the core must align themselves with the external field. If the direction of the field is reversed, the domains must turn so that their poles are aligned with the new direction of the external field.

Power transformers normally operate from either 50 Hz, or 400 Hz alternating current. Each tiny domain must realign itself twice during each cycle, or a total of 100 times a second when 50 Hz alternating current is used. The energy used to turn each domain is dissipated as heat within the iron core. This loss, called *hysteresis loss*, can be thought of as resulting from molecular friction. Hysteresis loss can be held to a small value by proper choice of core materials.

2.9 TRANSFORMER RATINGS AND TRANSFORMER EFFICIENCY

2.9.1 Transformer Ratings

When a transformer is to be used in a circuit, more than just the turns ratio must be considered. The voltage, current, and power-handling capabilities of the primary and secondary windings must also be considered. The maximum voltage that can safely be applied to any winding is determined by the type and thickness of the insulation used. When a better (and thicker) insulation is used between the windings, a higher maximum voltage can be applied to the windings. The maximum current that can be carried by a transformer winding is determined by the diameter of the wire used for the winding. If current is excessive in a winding, a higher than ordinary amount of power will be dissipated by the winding in the form of heat. This heat may be sufficiently high to cause the insulation around the wire to break down. If this happens, the transformer may be permanently damaged. The power-handling capacity of a transformer is dependent upon its ability to dissipate heat. If the heat can safely be removed, the power-handling capacity of the transformer can be increased. This is sometimes accomplished by immersing the transformer in oil, or by the use of cooling fins. The power-handling capacity of a transformer is measured in either the volt-ampere unit or the watt unit.

Two common power generator frequencies (50 hertz and 400 hertz) have been mentioned, but the effect of varying frequency has not been discussed. If the frequency applied to a transformer is increased, the inductive reactance of the windings is increased, causing a greater ac voltage drop across the windings and a lesser voltage drop across the load. However, an increase in the frequency applied to a transformer should not damage it. But, if the frequency applied to the transformer is decreased, the reactance of the windings is decreased and the current through the transformer winding is increased. If the decrease in frequency is enough, the resulting increase in current will damage the transformer. For this reason a transformer may be used at frequencies above its normal operating frequency, but not below that frequency.

2.9.2 Transformer Efficiency

To compute the efficiency of a transformer, the input power to and the output power from the transformer must be known. The input power is equal to the product of the voltage applied to the primary and the current in the primary. The output power is equal to the product of the voltage across the secondary and the current in the secondary. The difference between the input power and the output power represents a power loss. You can calculate the percentage of efficiency of a transformer by using the standard efficiency formula shown below:

$$\text{Efficiency (in \%)} = \frac{P_{out}}{P_{in}} \times 100$$

Where:

P_{out} = total output power delivered to the load

P_{in} = total input power

2.10 DESIGN OF INSULATION

The arrangements of core, winding and insulation and the design of insulation in transformer depend upon the following considerations: (1) Electrical considerations, (2) Mechanical considerations and (3) Thermal considerations of the transformer during steady state and transient conditions [14, 16]. The winding voltages produce an electrostatic field in the dielectric. Therefore, dielectric stress is produced in the insulation. The current in the windings set up a magnetic field in order to increase the electromagnetic forces in the windings. Therefore, mechanical stress is produced in the insulation. Losses in transformer produce temperature rise. As a result, thermal stress is produced in the insulation [14].

2.10.1 Types of insulation of a transformer

(a) Insulation between winding and core, (b) Insulation between winding of same phases, (c) Insulation between turns, coils and layers,(d) Insulation relative to tank, (e) Insulation between phases (f) Insulation relative to tank i. e, insulation between oil-ducts, barriers and windings [14,18].

Basically, pressboards, paper, wood strips, synthetic resin bonded paper (s.r.b.p) cylinder are used as insulating material in transformer design. Pressboards, wood strips or s.r.b.p. cylinders are used between the low voltage and high voltage winding and between windings and core [14, 11,].

2.10.2 Choice of the current density and conductors

The number of turn per phase in high voltage winding must be to even to ensure the symmetry of the winding. A suitable current density should be chosen in order to determine the area of copper conductors in primary and secondary windings and can limit the local heating and efficiency [14, 22]. Higher current density causes excessive temperature rise in the windings, injury to the insulation and higher copper loss. Higher current density results in smaller conductor area, higher conductor resistance, higher copper loss and lower copper cost. Smaller current density causes higher conductor area, lower conductor resistance, lowers copper loss and higher copper cost [14, 17]. Current densities in different transformer [14, 16]:

(a) For distribution and small power transformer, self –oil-cooled up to 50KVA, current density should be 1.1-2.3 Amp/mm, (b) For large power transformer, self-oil-cooled air blast type current density should 2.2-3.2 Amp/mm and (c) For large power transformer, forced circulation of oil or water-cooling, current density should be 5.4-6.2 Amp/mm.

2.10.3 Selection of proper type of winding

The winding in transformer design should have the desired electrical characteristics and adequate mechanical strength.

(1) High voltage winding

Following types of winding and conductor are used in high voltage side:

(a) Cylindrical winding with circular conductor or (b)Crossover winding with circular or small rectangular conductor are used in transformer up to 1000KVA, 33KV and (c) Continuous disc type winding with rectangular conductors are used in transformer rating 200HVA to MVA range, 11KV and above [14, 21, 22] .

(2) Low voltage winding

Following types of winding and conductor are used in low voltage side [14, 22]: Cylindrical winding with rectangular conductor are used in transformer up to 8000KVA, 433V.Helical with rectangular conductors are used in transformer rating: MVA range, 15-33KV and Continuous disc type winding is used in 8 MVA transformer, According to the sizes of the conductors and the transformer, a number of parallel paths can be used to arrange the conductors in low voltage and high voltage winding.

2.11 TRANSFORMER CORE AND YOKE

2.11.1 Transformer Core

The transformer core is a closed magnetic circuit. The mutual flux passes through the core and links with both the windings. The core is built of high permeable cold rolled grain oriented laminated silicon steel sheet (contains 3-5 % silicon) of 0.3-0.35 mm thickness to give low no-load loss, low noise level and low magnetizing current. The core is annealed at the high temperature (800° C) to relieve mechanical stress and to fix into designed shape [14,20]. Cold rolled grain oriented (CRGO) laminated steel sheet of 0.3 mm thickness allows higher flux densities up to 1.8 Wb/m^2. The increased value of fix density reduces the weight of core and windings [9,14].

2.11.2 Choice of Flux Density in Core

The value of flu density in the core determines the core area. Higher flu density means smaller core area, smaller iron cost, smaller mean length of turn of copper winding and smaller conductor cost. But, higher flux density causes higher iron loss, larger magnetizing and objectionable harmonics. The choice of the magnetic flux density depends upon the service condition of the transformer. The value of magnetic flux density should be low in order to keep the iron loss low [14, 19].

(i)Maximum flux density for hot rolled silicon steel
Bm =1.1-1.5 Wb/m^2 for distribution transformer
Bm =1.25–1.45 Wb/m^2 for power transformer

(ii) Maximum flux density for cold rolled silicon steel
Bm = 1.55 WB/m^2 for transformer unto 132KV
Bm = 1.7 Wb/m^2 for transformer unto 275KV
Bm = 1.7 Wb/m^2 for 400KV and generator transformer

(iii) Maximum flux density according to transformer size
Bm = 1.1-1.35 Wb/m² for KVA transformer rating
Bm = 1.5-1.85 WB/m² for MVA transformer rating

2.11.3 Cross-section of core

Small core type transformers have rectangular section limbs with rectangular coils. In large capacity transformers, circular core is used for the economic use of core material. The windings around the circular core have minimum mean length of conductor terns. Thus, both the weight and costs of the conductors can be reduced [14]. In modern transformers, multiple steps are used in core assembly to increase the net sectional area and to reduce (i) The mean length of term, (ii) The cost of conductor materials, (iii) I^2R losses and (iv) Iron losses. In large size core type three-phase transformer, multiple strips of laminated steel sheets are interleaved at a time in a specific manner. As a result, mechanical imbalance of the magnetic circuit assembly can be minimized. The interleaving at the lamination joints should be done carefully to reduce the magnetizing current [7, 14].

2.11.4 Transformer Yoke

The cross -section of the yoke is made about 15%to 25% greater than that of the core in transformer using hot rolled steel. This reduces the flux density in the yoke. The reduced flux density reduces the magnetizing current and iron losses [14]. There are no windings around the yoke. The larger cross-section of yoke reduces the no load current and iron losses. In order to simplify the core construction and to minimize the labor cost, the yoke cross –section need reduces the not to be multi-stepped. The yoke provides additional space along the height for location of the tapping of winding [14]. Yoke stepping equalizes the flux density distribution in the core and reduces the additional iron losses. Yokes with rectangular cross –section are used for small capacity transformer and yokes with cruciform and stepped cross –section are used for large capacity transformers. Yoke laminations are clamped between steel frames with core clamping bolts and the frames also support the winding through end blocks and rings. The construction ensures reduces the magnetizing current and iron losses [14].

CHAPTER 3
HIGH POWER TRANSFORMER

3.1 POWER TRANSFORMER

Power transformers are used to supply voltages to the various circuits in electrical equipment. These transformers have two or more windings wound on a laminated iron core. The number of windings and the turns per winding depend upon the voltages that the transformer is to supply. Their coefficient of coupling is 0.95 or more. You can usually distinguish between the high-voltage and low-voltage windings in a power transformer by measuring the resistance. The low-voltage winding usually carries the higher current and therefore has the larger diameter wire. This means that its resistance is less than the resistance of the high-voltage winding, which normally carries less current and therefore may be constructed of smaller diameter wire.

So far you have learned about transformers that have but one secondary winding. The typical power transformer has several secondary windings, each providing a different voltage. The schematic symbol for a typical power-supply transformer is shown in figure 5-12. For any given voltage across the primary, the voltage across each of the secondary windings is determined by the number of turns in each secondary. A winding may be center-tapped like the secondary 350 volt winding shown in the figure. To center tap a winding means to connect a wire to the center of the coil, so that between this center tap and either terminal of the winding there appears one-half of the voltage developed across the entire winding. Most power transformers have colored leads so that it is easy to distinguish between the various windings to which they are connected. Carefully examine the figure which also illustrates the color code for a typical power transformer. Usually, red is used to indicate the high-voltage leads, but it is possible for a manufacturer to use some other colors.

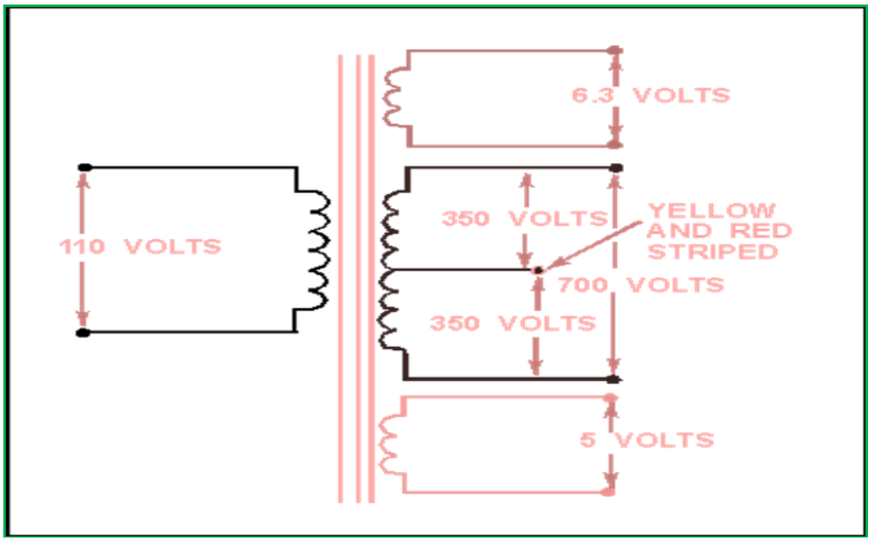


Figure (3.1): Schematic diagram of a typical power transformer.

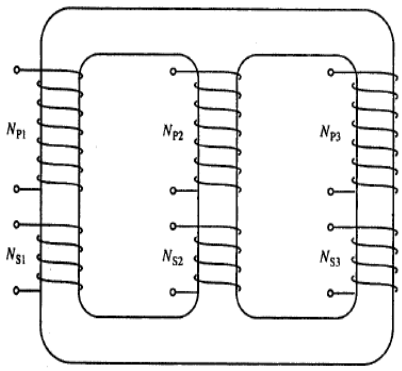
There are many types of power transformers. They range in size from the huge transformers weighing several tons-used in power substations of commercial power companies-to very small ones weighing as little as a few ounces-used in electronic equipment.

3.2 THREE PHASE POWER TRANSFORMER

A three phase transformer, there is a three-legged iron core as shown below. Each leg has a respective primary and secondary winding. Most power is distributed in the form of three-phase AC. Therefore, before proceeding any further you should understand what is meant by three phase power. Basically, the power company generators produce electricity by rotating (3) coils or windings through a magnetic field within the generator. These coils or windings are spaced 120 degrees apart. As they rotate through the magnetic field they generate power which is then sent out on three (3) lines as in three-phase power. ***3 phase transformer*** must have (3) coils or windings connected in the proper sequence in order to match the incoming power and therefore transform the power company voltage to the level of voltage we need and maintain the proper phasing or polarity.

In a ***three-phase transformer***, there is a three-legged iron core as shown below.

Each leg has a respective primary and secondary winding.



Figure(3.2) : Three Phase Transformer

The three primary windings (P1, P2, P3) will be connected at the factory to provide the proper sequence (or correct polarity) required and will be in a configuration known as Delta. The three secondary windings (S1, S2, S3) will also be connected at the factory to provide the proper sequence (or correct polarity) required. However, the secondary windings, depending on our voltage requirements, will be in either Delta or a Wye configuration.

3.3 CONECTION OF THREE PHASE TRANSFORMER

The windings of primary and secondary (in any construction) can be connected in either a wye (Y) or delta (Δ). This provides a total of 4 possible connections for three phase transformer (if Neutral is not grounded):

(a) Wye-wye Y-Y

(b) Wye-delta Y-Δ

(c) Delta-wye Δ-Y

(d) Delta-Delta Δ-Δ

3.3.1 Wye and Wye Connection

In Y-Y connection, primary voltage on each phase is $V_{\varphi P}=V_{LP}/\sqrt{3}$ Primary phase voltage is related to secondary phase voltage by turns ratio of transformer

Phase voltage of secondary is related to Line voltage of secondary by VLS=√3 VφS

Overall the voltage ratio of transformer is:

$$\frac{V_{LP}}{V_{LS}} = \frac{\sqrt{3}V_{\varphi P}}{\sqrt{3}V_{\varphi S}} = a$$

A Y/Y connection for the primary and secondary windings of a three-phase transformer is shown in the figure below. The line-to-line voltage on each side of the three-phase transformer is √3 times the nominal voltage of the single-phase transformer. The main advantage of Y/Y connection is that we have access to the neutral terminal on each side and it can be grounded if desired. Without grounding the neutral terminals, the Y/Y operation satisfactory only when the three-phase load is balanced. The electrical insulation is stressed only to about 58% of the line voltage in a Y-connected transformer.(4:225)

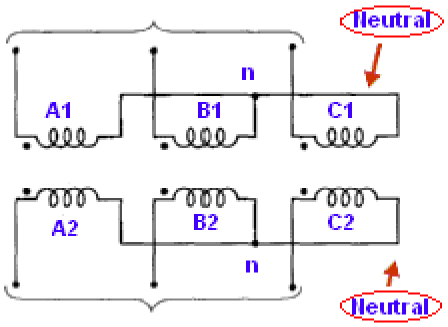


Figure (3.3): Y/Y connected three-phase transformer.

3.3.2 Wye-Delta Connection

VLP=√3 VφP, while : VLS= VφS
Voltage ratio of each phase : VφP/ VφS=a
VLP/ VLS= √3 VφP/ VφS= √3 a ← Y-Δ

This connection as shown in figure below is very suitable for step-down applications. The secondary winding current is about 58% of the load current. On the primary side the voltages are from line to neutral, whereas the voltages are from line to line on the secondary side. Therefore, the voltage and the current in the primary are out of phase with the voltage and the current in the secondary. In a Y/Δ connection the distortion in the waveform of the induced voltages is not as drastic as it is in a Y/Y-connected transformer when the neutral is not connected to the ground the reason is that the distorted currents in the primary give rise to a circulating current in the Δ-connected secondary.(4:256)

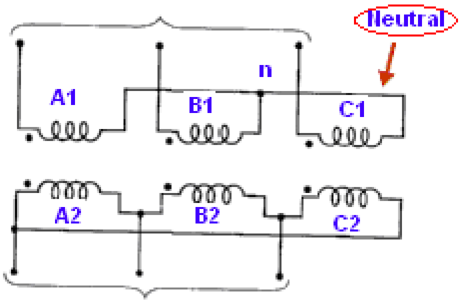


Figure (3.4): Y/ Δ connected three-phase transformer.

3.3.3 Delta-Wye Connection

In Δ-Y primary line voltage is equal to primary phase voltage VLP=VφP, in secondary VLS=√3VφS

Line to line voltage ratio ;

VLP/ VLS = VφP/ [√3 VφS]=a/√3 ← Δ-Y

This connection has the same advantages & phase shifts as Y- Δ

And Secondary voltage lags primary voltage by 30◦ with abc phase sequence. This connection as shown in figure below is proper for a step-up application. However, this connection is now being exploited to satisfy the requirements of both three-phase and the single-phase loads. In this case, we use a four-wire secondary. The single-phase loads are taken care of by the three line-to-neutral circuits. An attempt is invariably made to distribute the single-phase loads almost equally among three-phases.(4:256)

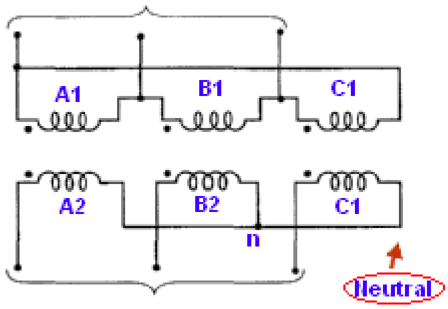


Figure (3.5) : Δ/Y connected three-phase transformer.

3.3.4 Delta-Delta Connection

In Δ-Δ connection VLP= VφP and VLS= VφS

Voltage ratio : VLP/VLS= VφP / VφS =a ← Δ-Δ

This configuration has no phase shift and there is no concern about unbalanced loads or harmonics. As shown below the three transformers with the primary and secondary windings connected as Δ/Δ. The line-to-line voltage on either side is equal to the corresponding phase voltage. Therefore, this arrangement is useful when the voltages are not very high. The advantage of this connection is that even under unbalanced loads the three-phase load voltages remain substantially equal. This disadvantage of Δ/Δ connection is the absence of a neutral terminal on either side. Another drawback is that the electrical insulation is stressed to the line voltage. Therefore, a Δ-connection winding requires more expensive insulation than a Y-connected winding for the same power rating.(4:255)

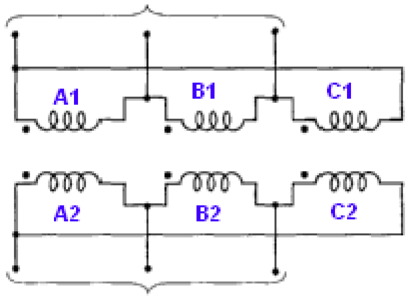


Figure (3.6): Δ/Δ connected three-phase transformer.

Three phase transformers are important equipments in power systems and power plants. When a three-phase transformer is energized, the inrush current due to flux saturation causes a stress impact to the transformer. As a result, the differential relays are applied to design the protective system of a three-phase transformer. This protective system can distinguish inrush current from fault current.

CHAPTER 4

OPTIMUM DESIGN OF TRANSFORMER

4.1 INTRODUCTION

Process optimization is the discipline of adjusting a process so as to optimize some specified set of parameters without violating some constraint. The most common goals are minimizing cost, maximizing throughput, and/or efficiency. This is one of the major quantitative tools in industrial decision making. In chemical engineering terms, a process is typically a set of equipment arranged, controlled, and operated in a particular way, to produce a product. The product must meet certain specifications, such as a certain production rate, product quality, and cost. When optimizing a process, the goal is to maximize one or more of the process specifications, while keeping all others within their constraints.

4.2 DEFINITION OF OPTIMIZATION

Finding an alternative with the most cost effective or highest achievable performance under the given constraints, by maximizing desired factors and minimizing undesired ones. In comparison, maximization means trying to attain the highest or maximum result or outcome without regard to cost or expense. Practice of optimization is restricted by the lack of full information, and the lack of time to evaluate what information is available (see bounded reality for details). In computer simulation (modeling) of business problems, optimization is achieved usually by using linear programming techniques of operations research.

Optimization theory is the study of the *external* values of a function: its minima and maxima. Topics in this theory range from conditions for the existence of a unique external value to methods---both analytic and numeric---for finding the external values and for what values of the independent variables the function attains its extremes. In this book, minimizing an error criterion is an essential step toward deriving optimal signal processing algorithms. An appendix summarizing the key results of optimization theory is essential to understand optimal algorithms.

In mathematics and computer science, *optimization*, or *mathematical programming*, refers to choosing the best element from some set of available alternatives. In the simplest case, this means solving problems in which one seeks to minimize or maximize a real function by systematically choosing the values of real or integer variables from within an allowed set. This formulation, using a scalar, real-valued objective function, is probably the simplest example; the generalization of optimization theory and techniques to other formulations comprises a large area of applied mathematics. More generally, it means finding "best available" values of some objective function given a defined domain, including a variety of different types of objective functions and different types of domains.

4.3 AREAS OF OPTIMIZATION

Fundamentally, there are three parameters that can be adjusted to affect optimal performance. These are:

- Equipment optimization

The first step is to verify that the existing equipment is being used to its fullest advantage by examining operating data to identify equipment bottlenecks.

- Operating procedures

Operating procedures may vary widely from person-to-person or from shift-to-shift. Automation of the plant can help significantly. But automation will be of no help if the operators take control and run the plant in manual.

- Control optimization

In a typical processing plant, such as a chemical plant or oil refinery, there are hundreds or even thousands of control loops. Each control loop is responsible for controlling one part of the process, such as maintaining a temperature, level, or flow. If the control loop is not properly designed and tuned, the process runs below its optimum. The process will be more expensive to operate, and equipment will wear out prematurely. For each control loop to run optimally, identification of sensor, valve, and tuning problems is important. It has been well documented that over 35% of control loops typically have problems.

The process of continuously monitoring and optimizing the entire plant is sometimes called performance supervision.

4.4 GENERAL PROCEDURE OF OPTIMIZATION

The general objective of the optimization is to choose a set of values of the independent variables, subject to various restrictions, which will produce the desired optimum response for the particular problem under examination [1, 2,14]

The general procedure or approach of optimization is listed below:

(1) Define a suitable objective for the problem under examination.
(2) Examine the restrictions imposed upon the problem by external agencies.
(3) Choose a system or systems for study.
(4) Examine the structure of each system and the inter-relationship of the system elements and streams.
(5) Construct a model for the system. This is the technical design stage, which allows the objective to be defined in terms of the system variables.
(6) Examine and define the internal restriction placed on the system variables.
(7) Carry out the simulation by expressing the objective in terms of the system variables, using the system model. This is the objective function.
(8) Analyze the problem and reduce it to its essential features. This reduction is necessary in many cases to allow optimization to be attempted.
(9) Verify that the proposed model in fact describes the system being studied.
(10) Determine the optimum solution for the system and discuss the nature of the optimum conditions.
(11) Repeat this procedure until a satisfactory result is found.

4.5 OPTIMIZATION METHODS $f(a,Y)$

In the above we introduced functions of the form $f(a,Y)$ which measure the fit of a model instance with **n** parameters a to some set of data Y. We are interested in the optimal choice of parameters, those which give the best fit to the data. This involves finding the optimum (maximum or minimum) of the function $f(a,Y)$ with respect to a. For notational simplicity we will use $f(a) = f(a,Y)$. Since any maximum of $f(a)$ is a minimum of f $-f(a)$ we will only consider minimization. Formally $\mathbf{a}$ is a minimum point of $f(a)$ if there exists a region about a of radius ϵ such that

$$f(\mathbf{a}+\mathbf{x}) > f(\mathbf{a}) \quad \forall \quad |\mathbf{x}| < \epsilon$$

The maxima and minima of a function can either be *global* (the highest or lowest value over the whole region of interest) or *local* (the highest or lowest value over some small neighbourhood). We are usually most interested in finding the global optimum (such as the model parameters which give the best match to some image data), but this can be very difficult. Often a problem will have many local optima (perhaps caused by image noise or clutter) which means that locating the single global optima can be tricky. The most suitable methods to locate minima depend upon the nature of the function we are dealing with. There are two broad classes of algorithms.

- *Local* minimizers that, given a point in a `valley' of the function, locate the lowest point on the valley.
- *Global* minimizers that range over a region of parameter space attempting to find the bottom of the deepest valley.

If a good estimate of the position of the minimum exists we need only use a local minimizer to improve it and find the optimum choice of parameters. If no such estimate exists some global method must be used. The simplest would be to generate a set of possible start points, locally optimize each and choose the best. However, this may not be the most efficient approach. Often an application will require both local and global methods. For instance, in a tracking problem initializing a model on the first frame may require a global search, but subsequent frames would only require a local search about the current best estimate. The choice of which local minimization technique to use will depend upon

- Whether a is one or many-dimensional,

- Whether can $f(a)$ be differentiated efficiently,
- How noisy $f(a)$is.

4.5.1 Linear Programming

Linear programming (LP) is a mathematical method for determining the way to achieve the best outcome (such as maximum profit or lowest cost) in a given mathematical model for some list of requirements represented as linear equations.

More formally, linear programming is a technique for the optimization of a linear objective function, subject to linear equality and linear inequality constraints. Given a polyhedron (for example, a polygon), and a real-valued affine function defined on this polyhedron, a linear programming method will find a point on the polyhedron where this function has the smallest (or largest) value if such point exists, by searching through the polyhedron vertices.

Linear programs are problems that can be expressed in canonical form:

Maximize $\boldsymbol{C^T X}$
Subject to $\mathbf{Ax} \leq \boldsymbol{b}$

Where **x** represents the vector of variables (to be determined), **c** and **b** are vectors of (known) coefficients and **A** is a (known) matrix of coefficients. The expression to be maximized or minimized is called the objective function ($\boldsymbol{C^T X}$ in this case). The equations $\mathbf{Ax} \leq \boldsymbol{b}$ are the constraints which specify a convex polytope over which the objective function is to be optimized.

Linear programming can be applied to various fields of study. It is used most extensively in business and economics, but can also be utilized for some engineering problems. Industries that use linear programming models include transportation, energy, telecommunications, and manufacturing. It has proved useful in modeling diverse types of problems in planning, routing, scheduling, assignment, and design.

Standard form is the usual and most intuitive form of describing a linear programming problem. It consists of the following three parts:

- A **linear function to be maximized**

  e.g. maximize $c_1x_1 + c_2x_2$
- **Problem constraints** of the following form

  e.g. $a_{11}x_1 + a_{12}x_2 \leq b_1$
  $a_{21}x_1 + a_{22}x_2 \leq b_2$
  $a_{31}x_1 + a_{32}x_2 \leq b_3$

- **Non-negative variables**

  e.g $x_1 \geq 0$
  $x_2 \geq 0$

The problem is usually expressed in *matrix form*, and then becomes:

maximize $\boldsymbol{C^T X}$

subject to $\mathbf{A}\mathbf{x} \leq \boldsymbol{b}, \mathbf{x} \geq \mathbf{0}$

Other forms, such as minimization problems, problems with constraints on alternative forms, as well as problems involving negative variables can always be rewritten into an equivalent problem in standard form.

4.5.2 Non –Linear Programming

An *NP-optimization problem* (NPO) is an optimization problem with the following additional conditions. [2] Note that the below referred polynomials are functions of the size of the respective functions' inputs, not the size of some implicit set of input instances.

- the size of every feasible solution $y \in f(x)$ is poly nominally bounded in the size of the given instance x,
- the languages $\{x \mid x \in 1\}$ and $\{(x, y) \mid y \in f(x)\}$ can be recognized in polynomial time, and
- *m* is polynomial-time computable.

This implies that the corresponding decision problem is in NP. In computer science, interesting optimization problems usually have the above properties and are therefore NPO problems. A problem is additionally called a P-optimization (PO) problem, if there exists an algorithm which finds optimal solutions in polynomial time. Often, when dealing with the class NPO, one is interested in optimization problems for which the decision versions are NP-hard. Note that hardness relations are always with respect to some reduction. Due to the connection between approximation algorithms and computational optimization problems, reductions which preserve approximation in some respect are for this subject preferred than the usual Turing and Karp reductions. An example of such a reduction would be the L-reduction. For this reason, optimization problems with NP-complete decision versions are not necessarily called NPO-complete.[3]

NPO is divided into the following subclasses according to their approximability

- *NPO(I)*: Equals FPTAS. Contains the Knapsack problem.
- *NPO(II)*: Equals PTAS. Contains the Makespan scheduling problem.
- *NPO(III)*: :The class of NPO problems that have polynomial-time algorithms which computes solutions with a cost at most c times the optimal cost (for minimization problems) or a cost at least $1 / c$ of the optimal cost (for maximization problems). In Hromkovic's book, excluded from this class are all NPO(II)-problems save if P=NP. Without the exclusion, equals APX. Contains MAX-SAT and metric TSP.
- *NPO(IV)*: :The class of NPO problems with polynomial-time algorithms approximating the optimal solution by a ratio that is polynomial in a logarithm of the size of the input. In Hromkovic's book, excluded from this class are all NPO(III)-problems save if P=NP. Contains the set cover problem.
- *NPO(V)*: :The class of NPO problems with polynomial-time algorithms approximating the optimal solution by a ratio bounded by some function on n. In Hromkovic's book, excluded from this class are all NPO(IV)-problems save if P=NP. Contains the TSP and Max Clique problems.

Another class of interest is NPOPB, NPO with poly-nominally bounded cost functions. Problems with this condition have many desirable properties.

4.5.3 Quadratic programming

Quadratic programming (QP) is a special type of mathematical optimization problem. It is the problem of optimizing (minimizing or maximizing) a quadratic function of several variables subject to linear constraints on these variables.

The quadratic programming problem can be formulated as:

Assume **x** belongs to R^n space. The *n*×*n* matrix *Q* is symmetric, and **c** is any *n*×1 vector.Minimize (with respect to **x**) $f(x) = \frac{1}{2}x^T Q_x + C^T$ subject to one or more constraints of the form:

Ax $\leq b$(inequality constraint)
Ex=d (equality constraint)

where x^T indicates the vector transpose of X . The notation Ax $\leq b$ means that every entry of the vector *Ax* is less than or equal to the corresponding entry of the vector **b**. If Q is a positive semidefinite matrix, then $f(x)$ is a convex function. In this case the quadratic program has a global minimizer if there exists at least one vector **x** satisfying the constraints and $f(x)$ is bounded below on the feasible region. If the matrix *Q* is positive definite then this global minimizer is unique. If Q is zero, then the problem becomes a linear program. From optimization theory, a necessary condition for a point to be a global minimizer is for it to satisfy the Karush–Kuhn–Tucker conditions. These conditions are also sufficient when $f(x)$ is convex.

4.5.4 Quasi-Newton Method

One of the first problems to which Sir Isaac Newton applied calculus was the optimization of a function. He observed that the extremium of a function is characterized by its derivatives being equal to zero. For example, for the ordinary least squares problem

$$f(B) = y^t y € 2Bx^t y + B^t x^t xB$$

is a multivariate quadratic function of a vector of coefficients. The extremum, i.e., the
value of B for which $f(B)$ is either maximum or minimum, is found by setting the derivative of $f(B)$

$$f'(B) = -2x'y + x'xB$$

with respect to B to zero and solving for B

$$B_m = (x^t x)^{-1} x^t y$$

Finding such an extremum for non quadratic functions is not so easy. In general a simple closed form solution is not available as it is in the least squares problem. For this kind of problem Newton proposed an iterative solution: first we look at a local quadratic approximation to the nonlinear function and find its extremum, and then generate a new local approximation and so on. For the local approximation we use a Taylor series approximation about some given point x˙k on the function's surface,

$$f(x) = f(x_m) + f'(x_m)(x - x_m) + \frac{1}{2}(x - x_m)f''(x_m)(x - x_m)$$

In the same manner as above we calculate the derivatives, set to zero, and solve for x:

$$f'(x) = f'(x_m) + f''(x_m)(x - x_m) = 0$$

$$x = x_m - [f''(x_m)]^{-1} f'(x_m)$$

If the function is quadratic, we arrive at the extremum in a singel step, i.e., x is the
solution. If the function is not quadratic, we must solve for the solution iteratively, that is we set xm equal to x and compute a new x

$$x_{m+1} = x_m - \delta_m$$

where $\delta_m = [f''(x_m)]^{-1} f'(x_m) = H^{-1}_m g_m$

is called the direction. The direction is a vector describing a segment of a path from the starting point to the solution were the inverse of the Hessian, H_m determines the “angle” of the direction and the gradient, g_m determines its “size”. When the approximation is good, the Hessian is well-conditioned and the convergence quadratic (Dennis and Schnabel, 1989, Theorem 2.1.1) which roughly speaking means that the number of places of accuracy doubles at each step (Gill, Murray, and Wright, 1981). Quite often, however, the function being optimized is not particularly well behaved in the region of x˙m. This point might be far from the optimum and the surface in that region might be poorly approximated by the quadratic function. An additional step is introduced in the iterations to deal with this. The Newton step is re-defined as $x_{m+1} = x_m - \alpha_m \delta_m$ where α_m is called the step length. The step length is determined by a local optimization of the function, called a line search, that is given the direction and the starting point $f\ (x_m - \alpha_m \delta_m)$ is a scalar function of the step length. Depending on the type of line search, this function will be either minimized or some value of α_m is found such that $f\ (x_m - \alpha_m \delta_m)) < f(x_m)$. The Newton method is simple and straightforward to describe, but there are a number of issues that arise in actual application. The first issue devolves from the fact that a function for computing an analytical Hessian is almost hever available.

Since a function for computing the Hessian used in computing the direction is rarely available, attention has focused on computing it numerically. The calculation of the Hessian is very expensive computationally, however, and efforts were made to find away to produce the Hessian more cheaply. The critical insight from which came thecurrent quasi-Newton methods was made by Broyden (1969): use informatoin from thecurrent iteration to compute the new Hessian.

Let

$s_k = x_{m+1} - x_m = \alpha_m \delta_m$ be the change in the parameters in the current iteration, and $\eta_m = g_{m+1} - g_m$ be the change in the gradients. Then a natural estimate of the Hessian at the next iteration H_{m+1} would be the solution of the system of linear equations $H_{m+1} s_m = eta_m$

that is, H_{m+1} is the ratio of the change in the gradient to the change in the parameters. This is called the quasi-Newton condition. There are many solutions to this set of equations. Broyden suggested a solution in the form of a secand update

$$H_{m+1} = H_m + uv^t$$

Further work has developed other types of secant updates, the most important of which are the dfp (for Davidon, 1959, and Fletcher and Powell, 1963), and the BFGS (for Broyden, 1969, Fletcher, 1970, Goldfarb, 1970, and Shanno, 1970). The BFGS is generally regarded as the best performing method:

$$H_{m+1} = H_m + \frac{\eta_m \eta^t m}{s_m \eta^t m} - \frac{H_m s_m s^t m H_m}{s^t m H_m s_m}$$

$$= H_m + \frac{\eta_m \eta^t{}_m}{s_m \eta^t{}_m} - \frac{g_m g^t{}_m}{\delta^t{}_m g_m}$$

taking advantage of the fact that $H_m s_m = \alpha_m H_m \delta_m = \alpha_m g_m$. The BFGS method is used in the *gauss* function *qnewton*. However, the update is made to the Cholesky factorization of *H* rather than to the Hessian itself, that is to *R* where

$H = R^t R$. In Q newton *H* itself is not computed anywhere in the iterations. The direction δm is computed using *cholsol*, that is as a solution to

$R^t{}_m R_m \delta m = g_m$ Where R_m and g_m are its arguments, and R_m is the Cholesky factorization of H_m. Then R_{m+1} is computed as an update and a down date to R_m using the gauss Functions cholup and choldn.

4.5.5 Advantages for selection of quasi-Newton Method

The method of constructing Hk completely eliminates the needs for evaluating second derivatives and performing matrix inversions and yet sequence of convergence to the minimum point X*. Furthermore, the matrix Hk can be improved at each iteration converges to j. Quasi-Newton Method has been chosen for optimal design of electrical machine for the following reasons [1]:

(1) The Quasi-Newton method ensures to find out the local minimum of a solution.
(2) The method can be made to converge to the minimum point.
(3) It will find the minimum in less number of steps and requires less computation time to solve a problem and find out the minimum point in all cases.
(4) It is usually avoids the convergence to a saddle point or a minimum. It is the most powerful minimization method.
(5) It has the fast convergence ability and gives a global minimum.
(6) It can be handle a more number of independent design variables and constraints.
(7) It has the ability to converge a large design problem.
(8) This method completely eliminates the need for evaluating second derivatives and performing matrix inversions and yet sequence of convergence to the minimum point.

(9) The matrix can be improved at each iteration to achieve convergence.

(10) In machine design problem, the objective functions as well as the constraint function are highly nonlinear. An electrical machine design problem contains a number of design variables and constraints.

So, method the Quasi-Newton is a very efficient superior to handle more number of design variables and constraints of an electrical machine design problem. So, in the machine design problem, we will minimize the effective cost of electrical machine by using the Quasi-Newton method. By this optimization process, we can design an electrical machine having optimum effective cost and efficient performance [1].

4.6 OPTIMUM DESIGN OF A TRANSFORMER

4.6.1 Introduction

It is well known that many important phenomena in power transformers are strongly connected with leakage field distribution which, in turn, depends on the ratio of distances of tank wall at and core limb ac from the inter winding gap, respectively, and also on the thickness d of the screen covering the tank wall . In fact, the stray flux in the inter winding gap is almost constant, only the flux to the core and the flux to the tank wall vary, when tank distance or screen are changed .In particular, in the case of electromagnetic screens, the screening effect gives rise to a conflict of design objectives: on one hand, the flux entering into the core limb is increased with respect to the flux into the tank wall; on the other hand, axial forces and additional losses from the radial component of flux density in the LV winding are increased too. Moreover, when distance between windings and tank increases, power losses in tank decrease, but volume and cost of the whole device are increased in turn. Moving from this background, the shape design of the screen could be tackled in a systematic way in terms of the identification of the non-dominated solutions, namely the set of solutions such that no decrease of an objective is possible without a simultaneous increase of the other objectives specifically, the inverse problem could be stated e.g. as follows: starting from a set of feasible geometries, identify the corresponding non-dominated geometries, such that power losses are minimum and tank volume is minimum too (two-objective shape design).

In the case of a single screen, three design variables can be selected, namely: radial position, height and thickness of the screen itself. In order to meet the requirement of a rapid-design method for industrial environment, the following computational scheme is adopted: given a prototype transformer, a sequence of fast magnetic analyses, based on reluctance-network method, is performed first, by varying the design variables in the feasible design space. Then, the solutions so obtained are sorted in the objective space according to the definition of non-dominated solutions. As a result, an approximation of the set of best-compromise design is identified without the use of a time-consuming optimization algorithm linked e.g. to a finite-element solver.

4.6.2 Transformer Design

(i)Core loss

• Inclusion of core loss
• Selection of operating flux density to optimize total loss

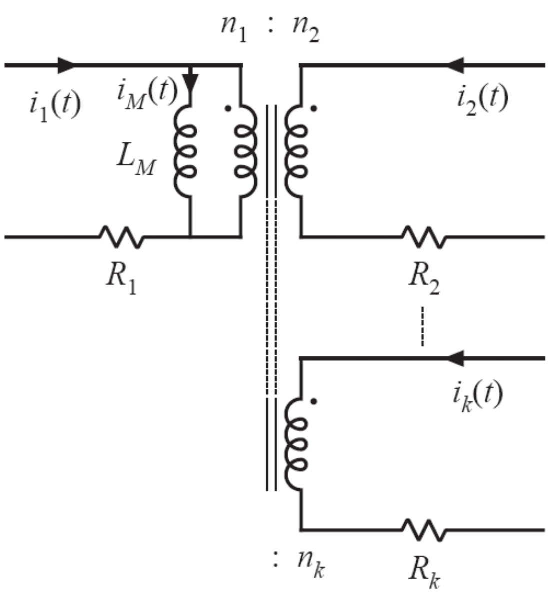


Figure (4.1): Transformer Core.

• Multiple winding design: as in the coupled-inductor case, allocate the available window area among several windings
• A transformer design procedure
• How switching frequency affects transformer size

Core loss, $P_{fe} = K_{fe}(\Delta B)^{\beta} A_c l_m$

ΔB is the peak value of the ac component of $B(t)$, i.e., the peak ac flux density So increasing ΔB causes core loss to increase rapidly. Flux density $B(t)$ is related to the applied winding voltage according to Faraday's Law. Denote the volt seconds applied to the primary winding during the positive portion of $v_1(t)$ as λ_1:

$$\lambda_1 = \int_{t_1}^{t_2} v_1(t)dt$$

This causes the flux to change from its negative peak to its positive peak. From Faraday's law, the peak value of the ac component of flux density is

$$\Delta B = \frac{\lambda_1}{2n_1 A_c}$$

To attain a given flux density, the primary turns should be chosen according to

$$n_1 = \frac{\lambda_1}{2\Delta B A_c}$$

(ii)Copper loss

Allocate window area between windings in optimum manner, as described in previous section. Total copper loss is then equal to

$$P_{cu} = \frac{\rho(MLT)n_1^2 I_{tot}^2}{W_A K_u}$$

with

$$I_{tot} = \sum_{j=1}^{k} \frac{n_j}{n_1} I_j$$

Eliminate *n*1, using result of previous slide:

$$P_{cu} = \left(\frac{\rho \lambda_1^2 I_{tot}^2}{4K_u}\right)\left(\frac{(MLT)}{W_A A_c^2}\right)\left(\frac{1}{\Delta B}\right)^2$$

: Note that copper loss decreases rapidly as ΔB is increased

(iii)Total power loss

$$P_{tot} = P_{cu} + P_{fe}$$

There is a value of ΔB that minimizes the total power loss

$$P_{tot} = P_{fe} + P_{cu}$$

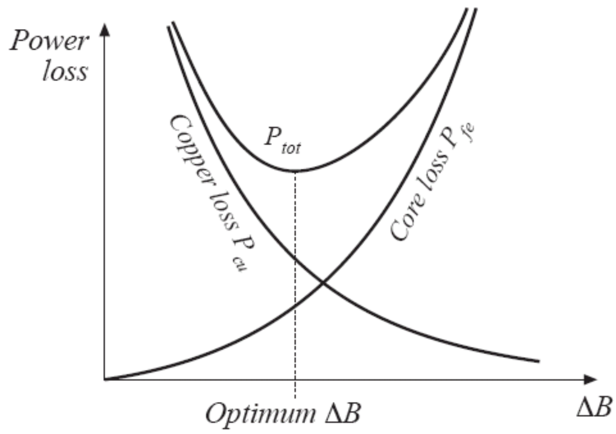


Figure (4.2): Power losses Vs Flux density

$$P_{fe} = K_{fe}(\Delta B)^{\beta} A_c \ell_m$$

$$P_{cu} = \left(\frac{\rho \lambda_1^2 I_{tot}^2}{4K_u}\right)\left(\frac{(MLT)}{W_A A_c^2}\right)\left(\frac{1}{\Delta B}\right)^2$$ Optimum flux density ΔB

Given that

$$P_{tot} = P_{fe} + P_{cu}$$

Then, at the ΔB that minimizes *Ptot*, we can write

$$\frac{dP_{tot}}{d(\Delta B)} = \frac{dP_{fe}}{d(\Delta B)} + \frac{dP_{cu}}{d(\Delta B)} = 0$$

Optimum does not necessarily occur where *Pfe* = *Pcu*. Rather, itoccurs where

$$\frac{dP_{fe}}{d(\Delta B)} = -\frac{dP_{cu}}{d(\Delta B)}$$

(iv) Derivatives of core and copper loss

$$P_{fe} = K_{fe}(\Delta B)^{\beta} A_c \ell_m \qquad P_{cu} = \left(\frac{\rho \lambda_1^2 I_{tot}^2}{4K_u}\right)\left(\frac{(MLT)}{W_A A_c^2}\right)\left(\frac{1}{\Delta B}\right)^2$$

$$\frac{dP_{fe}}{d(\Delta B)} = \beta K_{fe}(\Delta B)^{(\beta-1)} A_c \ell_m \qquad \frac{dP_{cu}}{d(\Delta B)} = -2\left(\frac{\rho \lambda_1^2 I_{tot}^2}{4K_u}\right)\left(\frac{(MLT)}{W_A A_c^2}\right)(\Delta B)^{-3}$$

Now, substitute into $\frac{dP_{fe}}{d(\Delta B)} = -\frac{dP_{cu}}{d(\Delta B)}$ and solve for ΔB:

$$\Delta B = \left[\frac{\rho \lambda_1^2 I_{tot}^2}{2K_u} \frac{(MLT)}{W_A A_c^3 \ell_m} \frac{1}{\beta K_{fe}}\right]^{\left(\frac{1}{\beta+2}\right)}$$

Optimum ΔB for a given core and application

Substitute optimum ΔB into expressions for P_{cu} and P_{fe}. The total loss is:

$$P_{tot} = \left[A_c \ell_m K_{fe}\right]^{\left(\frac{2}{\beta+2}\right)} \left[\frac{\rho \lambda_1^2 I_{tot}^2}{4K_u} \frac{(MLT)}{W_A A_c^2}\right]^{\left(\frac{\beta}{\beta+2}\right)} \left[\left(\frac{\beta}{2}\right)^{-\left(\frac{\beta}{\beta+2}\right)} + \left(\frac{\beta}{2}\right)^{\left(\frac{2}{\beta+2}\right)}\right]$$

Rearrange as follows:

$$\frac{W_A (A_c)^{(2(\beta-1)/\beta)}}{(MLT)\ell_m^{(2/\beta)}} \left[\left(\frac{\beta}{2}\right)^{-\left(\frac{\beta}{\beta+2}\right)} + \left(\frac{\beta}{2}\right)^{\left(\frac{2}{\beta+2}\right)}\right]^{-\left(\frac{\beta+2}{\beta}\right)} = \frac{\rho \lambda_1^2 I_{tot}^2 K_{fe}^{(2/\beta)}}{4K_u (P_{tot})^{((\beta+2)/\beta)}}$$

Left side: term depend on core geometry

Right side: terms depend on specification of the application

Define

$$K_{gfe} = \frac{W_A (A_c)^{(2(\beta-1)/\beta)}}{(MLT)\ell^{(2/\beta)}} \left[\left(\frac{\beta}{2}\right)^{-\left(\frac{\beta}{\beta+2}\right)} + \left(\frac{\beta}{2}\right)^{\left(\frac{2}{\beta+2}\right)} \right]^{-\left(\frac{\beta+2}{\beta}\right)}$$

Select a core that $K_{gfe} \geq \frac{\rho \lambda_1^2 I_{tot}^2 K_{fe}^{(2/\beta)}}{4K_u (P_{tot})^{((\beta+2)/\beta)}}$ satisfies

Kgfe is similar to the *Kg* geometrical constant

• *Kg* is used when *Bmax* is specified

• *Kgfe* is used when ΔB is to be chosen to minimize total loss

4.7 STEP BY STEP TRANSFORMER DESIGNS PROCEDURE

The following quantities are specified using the units noted:

Wire effective resistivity	ρ	(Ω-cm)
Total rms winding current, ref to pri	I_{tot}	(A)
Desired turns ratios	n_2/n_1, n_3/n_1, etc.	
Applied pri volt-sec	λ_1	(V-sec)
Allowed total power dissipation	P_{tot}	(W)
Winding fill factor	K_u	
Core loss exponent	β	
Core loss coefficient	K_{fe}	(W/cm^3T^β)

Other quantities and their dimensions:

Core cross-sectional area	A_c	(cm^2)
Core window area	W_A	(cm^2)
Mean length per turn	MLT	(cm)
Magnetic path length	ℓ_e	(cm)
Wire areas	$A_{w1}, \ldots$	(cm^2)
Peak ac flux density	ΔB	(T)

Step-1: Determine core size:

$$K_{gfe} \geq \frac{\rho \lambda_1^2 I_{tot}^2 K_{fe}^{(2/\beta)}}{4K_u (P_{tot})^{((\beta+2)/\beta)}} 10^8$$

Select a core that satisfies this inequality.

It may be possible to reduce the core size by choosing a core material that has lower loss, i.e., lower *Kfe*.

Step-2: Evaluate peak ac flux density:

$$\Delta B = \left[10^8 \frac{\rho \lambda_1^2 I_{tot}^2}{2K_u} \frac{(MLT)}{W_A A_c^3 \ell_m} \frac{1}{\beta K_{fe}}\right]^{\left(\frac{1}{\beta+2}\right)}$$

At this point, one should check whether the saturation flux density is exceeded. If the core operates with a flux dc bias B_{dc}, then $\Delta B + B_{dc}$ should be less than the saturation flux density B_{sat}.
If the core will saturate, then there are two choices:
• Specify ΔB using the *Kg* method of Chapter 14, or
• Choose a core material having greater core loss, then repeat steps 1 and 2

Step-3 and 4: Evaluate turns

$$n_1 = \frac{\lambda_1}{2\Delta B A_c} 10^4$$

Choose secondary turns according to desired turns ratios:

$$n_2 = n_1 \left(\frac{n_2}{n_1}\right)$$
$$n_3 = n_1 \left(\frac{n_3}{n_1}\right)$$

Step-5 and 6: Choose wire sizes

Fraction of window area assigned to each winding:

$$\alpha_1 = \frac{n_1 I_1}{n_1 I_{tot}}$$
$$\alpha_2 = \frac{n_2 I_2}{n_1 I_{tot}}$$
$$\vdots$$
$$\alpha_k = \frac{n_k I_k}{n_1 I_{tot}}$$

Choose wire sizes according to:

$$A_{w1} \le \frac{\alpha_1 K_u W_A}{n_1}$$
$$A_{w2} \le \frac{\alpha_2 K_u W_A}{n_2}$$

4.8 IMPROVEMENT ACHIEVED IN TRANSFORMER DESIGN

(i) Losses and Temperature Rise

Transformer loss is sometimes limited directly by the need to achieve required overall power supply efficiency. More often, transformer losses are limited by a maximum “hot spot” temperature rise at the core surface inside the center of the windings. Temperature rise (°C) equals thermal resistance (°C/Watt) time’s power loss (Watts).

$$\Delta T = R_T \times P_L$$

Ultimately, the appropriate core size for the application is the smallest core that will handle the required power with losses that are acceptable in terms of transformer temperature rise or power supply efficiency. Ultimately, the appropriate core size for the application is the smallest core that will handle the required power with losses that are acceptable in terms of transformer temperature rise or power supply efficiency.

(ii)Temperature Rise Limit

In consumer or industrial applications, a transformer temperature rise of 40-50°C may be acceptable, resulting in a maximum internal temperature of 100°C. However, it may be wiser to use the next size larger core to obtain reduced temperature rise and reduced losses for better power supply efficiency.

(ii) Losses

Losses are difficult to predict with accuracy. Core loss data from core manufacturers is not always dependable, partly because measurements are made under sinusoidal drive conditions. Low frequency winding losses are easy to calculate, but high frequency eddy current losses are difficult to determine accurately, because of the high frequency harmonic content of the switched rectangular current wave shape. Section 3 discusses this problem extensively. Computer software can greatly ease the difficulty of calculating the winding losses, including high order harmonics.

(iv) Thermal Resistance

Temperature rise depends not only upon transformer losses, but also upon the thermal resistance, RT (°C/Watt), from the external ambient to the central hot spot. Thermal resistance is a key parameter, unfortunately very difficult to define with a reasonable degree of accuracy. It has two main components: internal thermal resistance RI between the heat sources (core and windings) and the transformer surface, and the external thermal resistance RE from the surface to the external ambient. Internal thermal resistance depends greatly upon the physical construction. It is difficult to quantify because the heat sources are distributed throughout the transformer. R**I** from surface to internal hot spot is not relevant because very little heat is actually generated at that point. Most of the heat generated in the core (other than in toroids) is near the transformer surface. Heat generated within the winding is distributed from the surface to the internal core. Although copper has very low thermal resistance, electrical insulation and voids raises the RT within the winding. This is a design area where expertise and experience is very helpful. Fortunately, internal thermal resistance is considerably smaller than external RE (except with high velocity forced air cooling), and while R**I** shouldn't be ignored, it usually is not critically important compared with RE. External RE is mainly a function of air convection across the surface of the transformer–either natural convection or forced air. RE with natural convection cooling depends greatly upon how the transformer is mounted and impediments to air flow in its vicinity. A transformer mounted on a horizontal surface and surrounded by tall components, or mounted in a relatively small enclosure will have considerably greater RE than if it were mounted on a vertical surface, benefiting from the "chimney effect". With forced air cooling, RE can be driven down to a very small value, depending on air velocity, in which case internal RI becomes the primary concern. With forced air cooling, thermal resistance and temperature rise often become irrelevant, because an absolute loss limit to achieve power supply efficiency goals becomes dominant. For the average situation with natural convection cooling, a crude "rule of thumb" can be used:

$$R_E = \frac{800°\text{C - cm}^2 \text{ / Watt}}{A_S \text{ in cm}^2} \quad °\text{C / Watt}$$

Where AS is the total surface area of the transformer, excluding the mounting surface. Calculating AS is time-consuming, but another rule of thumb simplifies this, as well. For a given class of cores, such as E-E cores in the ETD or EC series, the relative proportions are quite similar for all core sizes. Thus for all cores in the ETD or EC series, the usable surface area, AS, is approximately 22 times the winding window area, AW. Combining this with the equation above enables the window area, AW, from the core data sheet, to be used to directly calculate the external thermal resistance:

$$R_E = \frac{36}{A_W \text{ in cm}^2} \quad \text{°C / Watt}$$

For pot cores or PQ cores, window areas are proportionately smaller, and not as consistent. AS/AW may range from 25 to 50, so that RE may range from 16/AW to 32/AW °C/W.

(v) Winding losses:

In buck-derived regulators, peak secondary current equals load current and peak primary current equals load current divided by the turns ratio:

$$I_{Spk} = I_L \;\; ; \;\; I_{Ppk} = I_L / n$$

Peak currents are independent of VIN. But at constant peak currents (constant load), *rms current squared (and I2R loss) is proportional to duty cycle D and inversely proportional to VIN.*. (With constant peak current, high order harmonics depend mostly on switching transitions and do not vary significantly with D.) *In buck-derived regulators, winding loss is always greatest at low VIN.*

(vi) Balancing Core and Winding Losses

At SMPS operating frequencies, when the core is usually loss-limited, not saturation limited, total losses are at a broad minimum when core losses are approximately equal to or a little less than winding losses. Likewise, winding losses are at a minimum and well distributed by making the rms current density approximately equal in all windings. With a bridge or half-bridge primary, which has good winding utilization, and center-tapped secondaries which have poor utilization, rms current densities will be approximately equalized when the primary conductor cross-section area is 40% and the secondaries 60% of the available area. In most other cases, primary and secondary conductor areas should be 50%/50%, including: Forward converter (single-ended primary/ secondary SE/SE), C.T. primary/C.T. secondary, bridge-half bridge primary/bridge secondary. The above allocations can be impossible to achieve because the number of turns in each winding must be an integral number. In a low voltage secondary, 1.5 turns may be required for optimum balance between core and winding losses. With one turn, the flux swing and core loss may be much too large; with two turns the winding loss becomes too great. At either extreme, it may be impossible to meet temperature rise or absolute loss limits. A larger core may be required to resolve this problem.

(vii) Window Utilization

As a reminder:
Safety isolation requirements impose minimum dimensional limits for creep age and insulation thickness which can waste a high percentage of window area, especially in a small transformer. A bobbin also reduces the area available for windings. Triple insulated wire satisfies the insulation thickness requirement and eliminates the core page requirement. It is worth considering, especially for small transformers where core page distances take up a large percentage of window area. In the reduced window area that is available for the windings, much of the actual winding area is taken up by voids between round wires and by wire insulation. In a winding consisting of many turns of single, round, insulated wires, only 70 - 75% of the area available for that winding is likely to be conductor metal -- “copper”. With Litz wire, the copper area is reduced further. For every level of twisting , an additional 0.75 factor (approximate) applies. For example, with Litz wire 7 strands of 7 strands (49 total wires), the copper area would be .75•.75•.75 = 42% of the area available for that winding. On the other hand, a winding consisting of layers (turns) of copper foil or strap, there are no voids, only the insulation between turns. Winding area utilization could be as much as 80 - 90% copper area.

(viii) Frequency

There are several meanings to the term “frequency” in switching power supply applications, and it is easy for confusion to arise. In this paper, “switching frequency”, fS, is defined as the frequency at which switch drive pulses are generated. It is the frequency seen by the output filter, the frequency of the output ripple and input ripple current, and is an important concept in control loop design. In a single-ended power circuit such as the forward converter, the power switch, the transformer, and the output rectifier all operate at the switching frequency and there is no confusion. The transformer frequency and the switching frequency are the same. “Clock frequency” is the frequency of clock pulses generated in the control IC. Usually, the switching frequency is the same as the clock frequency, but not always. Occasionally, the control IC may divide the clock frequency to obtain a lower switching frequency.

It is not unusual for a push-pull control IC to be used in a single-ended forward converter application, where only one of the two switch drivers is used, to guarantee 50% max. duty cycle. In this case the switching frequency is half the clock frequency. Confusion often arises with push-pull topologies. Think of the push-pull power circuit as a 2:1 frequency divider, with the transformer and the individual switches and individual rectifiers operating at a "transformer frequency", fT, which is one-half of the switching frequency. Collectively, the switches and rectifiers operate at the switching frequency, but the transformer operates at the transformer frequency. Some designers define switching frequency" as the frequency that the individual switch and the transformer operate at, but this requires redefining the term "switching frequency" when dealing with output ripple and in control loop design.

(xi) Restrictions on Number of Turns

Choices regarding the number of turns and turns ratios are often severely limited by low voltage secondaries. For a 5 Volt output the alternatives might be a 1-turn or a 2-turn secondary–a 2 to 1 step in the number of turns in every winding. For the same size core and window, this doubles the current density in the windings and accordingly increases the loss. Choices may be further restricted when there are multiple low voltage secondary. For example, a 2.5 to 1 turns ratio may be desirable between a 12 Volt and a 5 Volt output. This is easily accomplished with a 2-turn 5V secondary and a 5-turn 12V winding. But if the 5V secondary has only 1 turn, the only choice for the 12V secondary is 3 turns, which may result in excessive linear post-regulator loss. This problem could be handled by the use of fractional turns – see reference (R6). There are no hard and fast rules to follow in establishing the optimum turns for each winding, but there is some general guidance.

First, define the ideal turns *ratios* between windings that will achieve the desired output voltages with the normal VIND established earlier. Later, when a specific core has been tentatively selected, the turns ratios will translate into specific turns, but these are not likely to be the integral numbers required in practice. It then becomes a juggling act, testing several approaches, before reaching the best compromise with integral turns. The lowest voltage secondary usually dominates this process, because with small numbers the jumps between integral turns are a larger percentage. Especially if the lowest voltage output has the greatest load power, which is often the case, the lowest voltage secondary is rounded up or down to the nearest integral. Rounding down will increase core loss, rounding up will increase winding loss. If the increased loss is unacceptable, a different core must be used that will require less adjustment to reach an integral number of turns. The low voltage output is usually regulated by the main control loop. Higher voltage secondary's can be rounded up to the next integral with less difficulty because they have more turns. However, it is unlikely that accuracy or load regulation will be acceptable, requiring linear or switched post-regulation. Since the primary is usually higher voltage, the primary turns can usually be set to achieve the desired turns ratio without difficulty. Once the turns have been established, the initial calculations must be redefined.

(x) Flux Walking

Faraday's Law states that the flux through a winding is equal to the integral volt-seconds per turn. This requires that the voltage across any winding of any magnetic device must average zero over a period of time. The smallest dc voltage component in an applied ac waveform will slowly but inevitably "walk" the flux into saturation. In a low frequency mains transformer, the resistance of the primary winding is usually sufficient to control this problem. As a small dc voltage component pushes the flux slowly toward saturation, the magnetizing current becomes asymmetrical. The increasing dc component of the magnetizing current causes an IR drop in the winding which eventually cancels the dc voltage component of the drive waveform, hopefully well short of saturation. In a high frequency switch mode power supply, a push-pull driver will theoretically apply equal and opposite volt-seconds to the windings during alternate switching periods, thus "resetting" the core (bringing the flux and the magnetizing current back to its starting point). But there are usually small volt second asymmetries in the driving waveform due to inequalities in MOSFET RDSon or switching speeds. The resulting small dc component will cause the flux to "walk". The high frequency transformer, with relatively few primary turns, has extremely low dc resistance, and the IR drop from the dc magnetizing current component is usually not sufficient to cancel the volt-second asymmetry until the core reaches saturation. Flux walking is not a problem with the forward converter. When the switch turns off, the transformer magnetizing current causes the voltage to backswing, usually into a clamp.

The reverse voltage causes the magnetizing current to decrease back to zero, from whence it started. The reverse volt-seconds will exactly equal the volt-seconds when the switch was ON. Thus the forward converter automatically resets itself (assuming sufficient reset time is allowed, by limiting the maximum duty cycle). The flux walking problem is a serious concern with any push-pull topology (bridge, half-bridge or push-pull CT), when using voltage mode control. One solution is to put a *small* gap in series with the core. This will raise the magnetizing current so that the IR drop in the circuit resistances will be able to offset the dc asymmetry in the drive waveform. But the increased magnetizing current represents increased energy in the mutual inductance which usually ends up in a snubbed or clamp, increasing circuit losses. A more elegant solution to the asymmetry problem is an automatic benefit of using current mode control (peak or average CMC). As the dc flux starts to walk in one direction due to volt-second drive asymmetry, the peak magnetizing current becomes progressively asymmetrical in alternate switching periods. However, current mode control senses current and turns off the switches at the same peak current level in each switching period, so that ON times are alternately lengthened and shortened. The initial volt-second asymmetry is thereby corrected, peak magnetizing currents are approximately equal in both directions, and flux walking is minimized. However, with the half-bridge topology this creates a new problem. When current mode control corrects the volt-second inequality by shortening and lengthening alternate pulse widths, an ampere-second (charge) inequality is created in alternate switching periods.

This is of no consequence in full bridge or push-pull center-tap circuits, but in the half-bridge, the charge inequality causes the capacitor divider voltage to walk toward the positive or negative rail. As the capacitor divider voltage moves away from the mid-point, the volt-second unbalance is made worse, resulting in further pulse width correction by the current mode control. A runaway situation exists, and the voltage will walk (or run) to one of the rails. This problem is corrected by adding a pair of diodes and a low-power winding to the transformer, as detailed in the Unitrode Applications Handbook.

(xi) Core Selection: Material

Select a core material appropriate for the desired *transformer* frequency. With power ferrites, higher frequency materials have higher resistivity, hence lower eddy current losses. However, the permeability is generally lower, resulting in greater magnetizing current, which must be dealt with in snobbery and clamps. With metal alloy cores, the higher frequency materials have higher resistivity and require very thin laminations. Although saturation flux density is usually very much greater than with ferrite materials, this is usually irrelevant because flux swing is severely limited by eddy current losses. Ferrite is the best choice in transformer applications except for mechanical ruggedness.

(xii) Core Selection: Shape

The window configuration is extremely important. The window should be as wide as possible to maximize winding breadth and minimize the number of layers. This results in minimized Rac and leakage inductance. Also, with a wide window, the fixed core page allowance dimension has less impact. With a wider window, less winding height is required, and the window area can be better utilized. Pot cores and PQ cores have small window area in relation to core size, and the window shape is almost square. The core page allowance wastes a large fraction of the window area, and the winding breadth is far from optimum. These cores are not as well suited for high frequency SMPS applications. One advantage of pot cores and PQ cores is that they provide better magnetic shielding than E-E cores, reducing EMI propagation. EC, ETD, LP cores are all E-E core shapes. They have large window area in relation to core size, and the window has the desirable wide configuration. Toroidal cores, properly wound, must have all windings distributed uniformly around the entire core.

Thus the winding breadth is essentially the circumference of the core, resulting in the lowest possible leakage inductance and minimizing the number of winding layers. There is no creepage allowance because there is no end to the windings. (But there is a problem bringing the leads out.) Stray magnetic flux and EMI propagation are also very low. The big problem with toroidal cores is the winding difficulty, especially with the shapes and gauge of conductors used in SMPS transformers. How can a 1- turn secondary be spread around the entire toroid? Automatic winding is virtually impossible. For this reason, toroidal shapes are seldom used in SMPS transformers. Planar cores with their low profile are becoming more popular as SMPS frequencies progressively increase. Planar cores introduce a new set of unique problems which are beyond the scope of this discussion. Be assured that Faraday's and Ampere's Laws still apply, but in a planar core, flux density and field intensity change considerably throughout the important regions, making calculation much more difficult.

(xiii) Core Selection: Size

A novice in the art of transformer design usually needs some guidance in making an initial estimate of the core size appropriate for the application requirements. One widely used method, with many variations, is based on the core Area Product, obtained by multiplying the core magnetic cross-section area by the window area available for the winding. There are many variables involved in estimating the appropriate core size. Core power handling capability does not scale linearly with area product or with core volume. A larger transformer must operate at a lower power density because heat dissipating surface area increases less than heat-producing volume. The thermal environment is difficult to evaluate accurately, whether by forced air or natural convection. Some core manufacturers no longer provide area product information on their data sheets, often substituting their own methodology to make an initial core size choice for various applications. The following formula provides a crude indication of the area product required:

$$AP = A_W A_E = \left(\frac{P_O}{K \, \Delta B \, f_T} \right)^{4/3} \quad cm^4$$

Where:
- PO = Power Output
- ΔB = Flux density swing, Tesla
- fT = *Transformer* operating frequency
- K = .014 (Forward converter,PPCT)
  = .017 (Bridge, half bridge)

This formula is based on current density of 420A/cm2 in the windings, and assumes a window utilization of 40% copper. At low frequencies, the flux swing is limited by saturation, but above 50kHz (ferrite), ΔB is usually limited by core losses. Use the ΔB value that results in a core loss of 100mW/cm3 (2 times the "flux density" given in the core loss curves). These initial estimates of core size are not very accurate, but they do reduce the number of trial solutions that might otherwise be required. In the final analysis, the validity of the design should be checked with a prototype transformer operated in the circuit and the environment of the application, with the hot spot temperature rise measured by means of a thermocouple cemented to the center of the center post.

(xvi) Reduce eddy current and hysteresis loss

The iron loss in transformer includes eddy current and hysteresis loss, which depends upon the grade and quality of the laminated core sheet. This iron loss can be considerably reduced by using 0.3mm grain oriented laminated high quality electrical steel sheet in core design. Using of aluminum shielding and laminated electrical steel sheet, the overall cost and weight of the transformer may be increased, but a considerable amount of annul energy loss can be saved and the transformer can operate for an extended time period.[7,8,11,12].

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

The objective of this thesis is to optimize the electrical machine design of high power transformer induction motor of improved performance. The design involves obtaining the shape and size of machines satisfying the required specification and restrictions. The problem is first to formulated as a nonlinear programming problem expressing the objective and constrained function in terms of the specific independent variables. Novelties are applied in the design for further improvement of the machine. Then it is converted in to sequence of optimization problem by Quasi Newton Method.

In novel design procedure of transformer, (i.e. the application of aluminum shielding on transformer tank and the use of thin laminated electrical steel sheet for core construction), the overall performance of transformer (such as efficiency, temperature, rise etc.) but the overall weight and the cost of transformer have been increased. A large amount of annual energy can be saved which can balance the increase in the manufacturing cost of the transformer. So, novel procedure causes a large advantage in the transformer designing.

For transformer, the operating cost throughout the rated lifetime or extended lifetime in novel design procedure is lower than that of the conventional design procedure. So, the novel design procedure is preferable to operate a transformer over a long period of time.

In novel design procedure of induction motor (i.e. application of inverter driven induction motor concept, modification of stator and motor dimensions.) the performance of the motor (i.e. improved efficiency and power factor, starting torque, lower motor weight, motor cost and satisfactory noise level) can be improved. So, the novel design procedure of induction motor is preferable to conventional design procedure.

5.2 Recommendations for Future Work

(i) To design higher rating of machine, constraint values should be changed.

(ii) Application of proposed novel designing, performance of the machine can be improved.

(iii) Further improvement can be achieved by selecting other or multiple objective functions (i.e. machine weight or efficiency or both).

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