

The Application of Computer Programming in Transformer Design

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Abstract

This paper presents a computer-aided design (CAD) of a three-phase core type transformer. The software design platform used is Java. A Java program utilizes a graphical user interface (GUI) to display variations in the electrical parameters of the transformer under design in response to variations in the input voltage alteration. The GUI is designed in such a way as to allow users to enter the transformer ratings. In response, all the necessary parameters required for the design of the transformer are calculated and returned automatically. This would allow the designer to easily predict the output of the transformer at varying input parameters.

Keywords: Computer-aided design, three-phase transformer, core type, graphical user interface, Java program.

1. Introduction

Computer-aided design (CAD) of three-phase transformers is a method by which such transformers are designed with the use of programming software packages among which are C++, Visual Basic, Java, and Matlab[®], to mention but a few. The other method of designing transformers is the manual method, which offers a more laborious process (and comparatively old too) due to its long mathematical calculations which are error prone, time consuming and less effective when compared to the CAD method.

The physical basis of a transformer is the mutual induction between two circuits linked by a common magnetic flux as governed by Faraday's law of electromagnetic induction. It has a magnetic core over which two sets of windings, termed as primary and secondary (high voltage, h.v., and low voltage, l.v.) are suitably placed (Theraja 2005). When one of the windings is connected to alternate current (ac) supply, an electromotive force (e.m.f) is induced in the other winding, which is proportional to the number of turns. The first, coil in which electric energy is fed from the ac

supply mains, is called the primary winding and the other, from which energy is drawn out, is called the secondary winding (Fig. 1).

In this paper, however, the system design would be based wholly on simulations in Java environment. A custom Java program is presented that utilizes a graphical user interface (GUI) to display electrical variations in the parameters of the transformer. It is designed in such a way as to allow the user to enter the parameters under investigation.

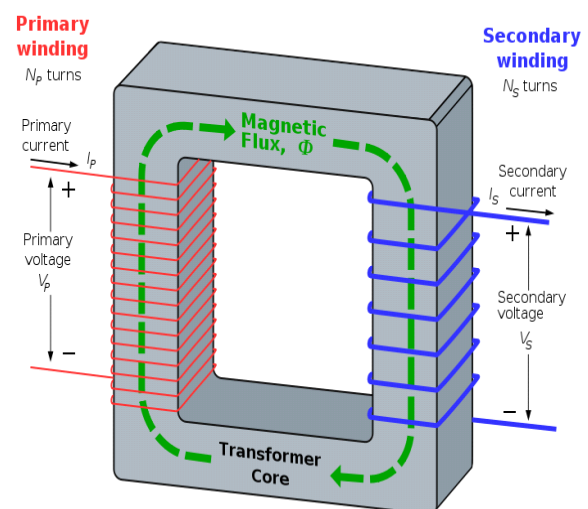


Fig. 1. A simple transformer circuit.

The main reason for GUI utilization is because it makes things simple for the end users of the program. In the absence of GUI, the optional work from the command line interface tends to be quite difficult and frustrating. NetBeans Integrated Developer Environment (IDE) 6.1 of the Java platform is used to write the custom program. The choice of Java stems from its inherent mathematical orientation and easy GUI manipulation. Other software packages like C++ and Visual Basic would have been used instead. These alternative packages also could handle complex mathematical processes that may be encountered in the engineering analysis.

2. Three-Phase Transformer Construction

A three-phase transformer is constructed by winding three single-phase transformers on a single core. These transformers are put into an enclosure which is then filled with dielectric oil. The dielectric oil performs several functions. Since it is a dielectric, a non-conductor of electricity, it provides electrical insulation between the windings and the case. It is also used to help provide cooling and to prevent the formation of moisture, which can deteriorate the winding insulation. All the stages of electric power transmission and distribution make use of three-phase transformers.

The construction of three-phase transformers is based on two modes of design: mathematical, or manual, method; and computer-aided design method. Both methods are based on the formula for induced e.m.f. The formula connects the induced voltage, flux and number of turns. Practically, the magnetic flux is predetermined, whilst frequency is already known. So the Volts per turn are derived from Eq. (1) below. By Faraday's laws of electromagnetic induction, there is a mutually induced e.m.f. in the primary coil (Dasgupta 2002):

$$E_P = - T_P d\Phi/dt. \quad (1)$$

Similarly, there is also a mutually induced e.m.f. in the secondary coil:

$$E_S = - T_S d\Phi/dt, \quad (2)$$

where T_P and T_S denote the number of turns in the primary and secondary coils, respectively,

and Φ is the common flux linking both windings.

3. Computer-Aided Design

Computer-aided design (CAD) is the use of computers to assist the design processes. Specialized software packages exist for various purposes: architectural, engineering, electronic, roadway and woven fabric design, to mention but a few. CAD programs usually allow a structure to be built up from several reusable three-dimensional (3D) components and the components (such as gears) may be able to move in relation to one another. It is normally possible to generate engineering drawings to allow the final design to be constructed. Computer-aided design is also the modelling of physical systems on computers, allowing both interactive and automatic analysis of design variants and the expression of designs in a form suitable for manufacturing (CAD 2004, 2013).

4. Design and Implementation

The main aim of designing a transformer is to obtain the information concerning its circuits by using the given specifications and selecting the proper and appropriate materials for each construction part. The said information includes:

- the main dimensions of the magnetic circuit, i.e. core, yoke and window;
- design details of the electrical circuit, i.e. low voltage and high voltage windings;
- performance characteristics, i.e. iron losses, copper losses, hysteresis loss, eddy current loss; and
- cooling system required.

Various design equations can be initiated on the custom Java program upon which the actual design is based. These equations are:

- output equation; and
- equations for e.m.f. and e.m.f. per turn.

5. Design Equations

Computer-aided design of a three-phase transformer, and indeed any transformer, must first begin with mathematical calculations

based on formulae which serve as inputs to the design software. The design equations for initiating the design of the magnetic circuit (main dimensions of core, yoke and window) are shown below.

5.1 Electromotive Force

The e.m.f. induced in the primary winding due to the change of main flux is given by

$$E_1 = - T_1 d\Phi/dt. \tag{3}$$

Also,

$$\Phi = \phi_m \cos(\omega t), \tag{4}$$

thus

$$E_1 = - T_1 d(\phi_m \cos(\omega t))/dt = T_1 \omega \phi_m \sin(\omega t). \tag{5}$$

Hence,

$$E_{1,max} = T_1 \omega \phi_m = T_1 (2\pi f) \phi_m, \tag{6}$$

and the root-mean-square (r.m.s.) value of induced e.m.f. is

$$E_{1,r.m.s.} = T_1 (2\pi f) \phi_m / 2^{1/2} = 4.44 f T_1 \phi_m. \tag{7}$$

Also,

$$E_{1,r.m.s.} = 4.44 f T_1 B_m A_i \text{ Volts.} \tag{8}$$

Similarly, the induced e.m.f. in the secondary winding is

$$E_{2,r.m.s.} = 4.44 f T_2 B_m A_i \text{ Volts.} \tag{9}$$

Hence, the e.m.f. per turn is

$$E_t = 4.44 f \phi_m = 4.44 f B_m A_i \text{ Volts.} \tag{10}$$

In Eqs. (3)-(10): T_1 = number of turns of the primary winding; T_2 = number of turns of the secondary winding; ϕ_m = maximum value of the main flux, Weber; B_m = maximum value of flux density in the core, Tesla; ω = angular frequency of the supply, rad·Hz; f = linear frequency of the supply, Hz; and A_i = net cross-sectional area of the core, m². Let (in kVA)

$$Q = EI \times 10^{-3} = 4.44 f \phi_m TI \times 10^{-3} \\ = 4.44 f \phi_m^2 / r \times 10^{-3}, \tag{11}$$

$$\phi_m / (TI) = r = \text{constant}, \tag{12}$$

$$\phi_m = [(r \times 10^{-3}) / (4.44 f)]^{1/2} (Q)^{1/2}. \tag{13}$$

Then the e.m.f. per turn is given by

$$E_t = 4.44 f [(r \times 10^{-3}) / (4.44 f)]^{1/2} \tag{14}$$

and the kVA rating per phase is

$$kVA_per_phase = VI \times 10^{-3} = VIT/T \times 10^{-3} \\ = E_t IT \times 10^{-3}. \tag{15}$$

The ratio of the cross-sectional area of the core and the copper area of the windings will be constant for a particular transformer, i.e.

$$A_i/A_c = \text{constant.} \tag{16}$$

The cross-sectional area of the core is

$$A_i = \phi_m / B_m, \tag{17}$$

and the copper area of the windings is

$$A_c = (\phi_m / (TI)) (\delta / B_m). \tag{18}$$

Thus

$$A_i/A_c = \phi_m / (TI) = r = \text{constant.} \tag{19}$$

The flux density B_m is nearly constant as the current density δ and the substitution for TI from Eq. (19) into Eq. (15) gives

$$kVA_per_phase = E_t (\phi_m / r) \times 10^{-3}, \tag{20}$$

and

$$\phi_m = [(kVA_per_phase) \cdot r / E_t] \times 10^3. \tag{21}$$

The substitution for ϕ_m from Eq. (21) into Eq. (10) gives

$$E_t = 4.44 f r [(kVA_per_phase) / E_t] \times 10^3, \text{ or} \tag{22}$$

$$E_t^2 = (4.44 f r \times 10^3) kVA_per_phase. \tag{23}$$

Hence, the e.m.f. per turn is

$$E_t = k (kVA/3)^{1/2}, \tag{24}$$

where

$$k = (4.44 f r \times 10^3)^{1/2} = \text{constant}, \tag{25}$$

with $k = 0.45$ for 3-phase core type.

The k -factor basically depends on the ratio of the cross-sectional area of the core to the copper cross-sectional area of the windings and will be different for core and shell types of transformers. The k -factor for distribution transformers is less than that of power transformers.

5.2 Window Space Factor (k_w)

The window space factor is defined as the ratio of total area occupied by the copper material of the windings in the window to the window area. The window space in a transformer is occupied by the following materials:

- conducting material of the windings (copper);
- insulating material over the winding conductor;
- insulating material (between the core and l.v. windings, and between the l.v. and h.v. windings); and
- insulating oil.

The window space factor is obtained as follows:

$$k_w = 10 / (30 + kV) \text{ for } (50-200 \text{ kVA}), \tag{26}$$

$$k_w = 12 / (30 + kV) \text{ for } (1,000 \text{ kVA}), \tag{27}$$

where kV is the voltage of the h.v. winding in kilovolts.

5.3 Output Equation for Three-Phase Transformer

Using the equations for e.m.f. per turn, the cross-sectional area of the core can be calculated based on the given specifications. An additional equation is needed to know the dimensions of the frame (core and window) with the given specification via the output.

The output of a 3-phase transformer is

$$Q = 3 V_{ph} I_{ph} \times 10^{-3}$$

$$= 3 \times 4.44 f B_m A_i T_{ph} I_{ph} \times 10^{-3}. \quad (28)$$

For a three-phase transformer in which the window space is occupied by both windings of two phases,

$$Q = 3 V_{ph} I_{ph} \times 10^{-3}$$

$$= 3 \times 4.44 f B_m A_i T_{ph} I_{ph} \times 10^{-3}$$

$$= 3 E_{ph} I_{ph} \times 10^{-3}, \quad (29)$$

and

$$A_W k_W = 2 (a_1 T_1 + a_2 T_2). \quad (30)$$

If

$$a_1 T_1 = a_2 T_2 = a_{ph} T_{ph} \quad (31)$$

and

$$\delta = I/a, \quad (32)$$

then

$$A_W k_W = 2 (a_{ph} T_{ph} + a_{ph} T_{ph}) = 4 I_{ph} T_{ph} / \delta. \quad (33)$$

The substitution for $I_{ph} T_{ph}$ from Eq. (33) into Eq. (29) results in

$$Q = 3 (4.44 f \phi_m I_{ph} \times 10^{-3})$$

$$= 3.33 f B_m \delta K_W A_W A_i \times 10^{-3} \quad (34)$$

The above equations hold for both core type and shell type transformers, where: Q = output (kVA); δ = average value of current density, A/mm²; k_W = window space factor; A_W = net window area; A_i = net cross-sectional area of the iron core; B_m = maximum flux density; and f = linear frequency in Hertz.

5.4 Current Density δ

The highest temperature rise in the transformer is seen to occur in the high voltage windings, and as such the current density to be used for copper windings is limited due to local heating. A high current density is therefore chosen to allow for reduced cross-sectional area thereby reducing the cost of design since the cost of copper is reduced. However, with high current density there is a high resistance of the windings resulting in increased copper losses leading to reduced efficiency and increasing the temperature of the transformer.

The current density of the h.v. windings should be taken higher compared to that of the l.v. windings because the cooling conditions are better in the h.v. winding and the high internal temperature of the winding may cause deterioration of the insulation of the windings. The following values may be used as average current density for l.v. and h.v. winding (Agarwal 2002):

- small distribution transformers, oil immersed, self-cooled - 1.5 to 2.6 A/mm²;
- medium and large transformers, oil immersed and air blast - 2.4 to 3.4 A/mm²; and
- large transformers, oil immersed - 5.4 to 6.3 A/mm².

5.5 Specific Magnetic Loading (Flux Density B_m)

The choice of flux density in the core is basically dependent on the steel grades used for the core and yoke. Normally, the two types of steel used in construction of the core and yoke are hot rolled silicon steel and cold rolled grain oriented steel (Mittle and Mittal 1996).

5.6 Typical Values of B_m

Typical values of B_m using hot rolled silicon steel are: within the range 1.1-1.4 Tesla for power transformers; and within the range 1.2-1.3 Tesla for distribution transformers. Also, typical values of B_m using cold rolled grain oriented silicon steel are: within the range 1.5-1.7 Tesla for power transformers; and within the range 0.4-1.5 Tesla for distribution transformers.

5.7 Main Dimensions of Magnetic Circuit

The main dimensions of a core type transformer consist of:

- diameter of the circumscribed circle, d , around the stepped core which depends on the kVA rating of the transformer.
- length of the core, L , which is equal to the height of the window (h_w).
- centre-to-centre distance, D , between the cores which depends on the width of the window (W_w) and the diameter of the circumscribed circle and also to some extent on the number of steps in the core.

The net cross-sectional area of the core, A_i , can be found using Eqs. (10) and (23). Hence, the diameter of the circumscribed circle can be calculated for various values of the stepped cores:

$$A_i = kd^2. \tag{35}$$

5.8 Main Dimensions of Windows

The window area is determined from Eq. (34) in which the average current density, δ , is also based on the kVA rating and the h.v./l.v. winding. Since the area of the window is

$$A_W = L(D - d), \tag{36}$$

where D is the centre-to-centre distance between the cores and the width of the window is given by

$$b_W = D - d, \tag{37}$$

then the height of the window, L , can be assumed to vary from 2.5 to 4.0 times the width of the window,

$$L/(D - d) = 2.5 \text{ to } 4.0. \tag{38}$$

From the above, the width and height of the window can be calculated using Eqs. (37) and (38).

6. Main Dimensions of the Yoke

The overall length, W , the width of the yoke and the height of the yoke are shown in Fig. 2. The overall length of the yoke is $W = 2D + 0.9d$ (3-phase, 3-stepped). (39)

The sectional area of the yoke (A_y) can be 10 to 15% larger than the core section in order to reduce the flux density in the yoke section which in turn reduces the magnetizing current and iron losses occurring in the yoke (Mittle and Mittal 1996).

Therefore, the sectional area of yoke is

$$A_y = 1.15 \text{ to } 1.25 A_i, \tag{40}$$

the width of the yoke is

$$b_y = 0.6 d \text{ (m)}, \tag{41}$$

and the height of the yoke is

$$h_y = A_y / b_y \text{ (m)}. \tag{42}$$

From the above, the dimensions of the yoke can be calculated using Eqs. (41) and (42).

6.1 Stacking Factor

The stacking factor determines the area of arrangement of the laminations forming the cores (Mittle and Mittal 1996):

$$A_i = k_s A_{gi}, \tag{43}$$

where: k_s = stacking factor which is between 0.85 to 0.9; A_{gi} is the gross iron area of the core; and A_i is the net area of the core. For a square section (Fig. 3a), $A_{gi} = a^2 = (0.71 d)^2 = 0.5 d^2$, and $A_i = 0.9 \cdot 0.5 d^2 = 0.45 d^2$, where the iron factor = 0.9. For two steps (Fig. 3b), $A_i = 0.56 d^2$, for three steps, $A_i = 0.6 d^2$, and for four steps, $A_i = 0.62 d^2$.

6.2 Design of Windings

The following primary requirements are necessary for the proper design of the l.v. and h.v. windings of the transformer:

- ability to withstand electric stress;
- ability to withstand voltage surges due to switching and atmospheric disturbances;
- ability to withstand electromagnetic forces;
- percentage impedance within tolerable limits;
- temperature rise not exceeding the specified limit; and
- minimum cost of the windings.

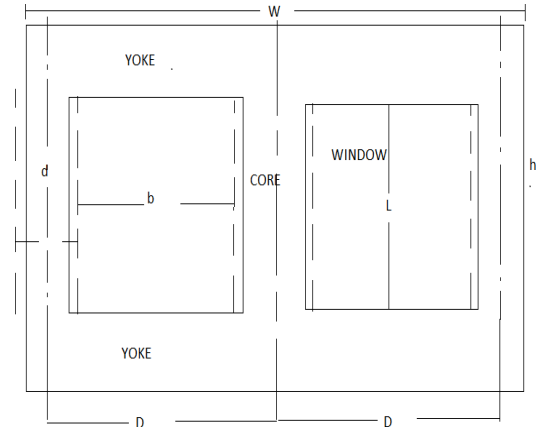


Fig. 2. Core, yoke and window depictions.

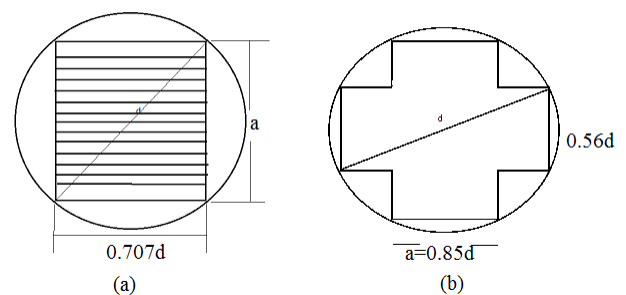


Fig. 3. Cross sections of: (a) a square core; and (b) a two-stepped core.

6.3 Design of Low Voltage Winding

The number of turns per phase is

$$T_{l.v.} = V_{l.v.} / E_t, \quad (44)$$

the current in the l.v. winding is

$$I_{l.v.} = [(kVA_{per_phase} \times 1,000) / (V_{ph\ l.v.})] \text{ (Amps)}, \quad (45)$$

and the cross-sectional area of the conductor is

$$a_{l.v.} = I_{l.v.} / \delta_1 \text{ (mm}^2\text{)}, \quad (46)$$

where: $T_{l.v.}$ = number of turns in the l.v. winding per phase; $V_{l.v.}$ = voltage rating of the l.v. winding per phase; $I_{l.v.}$ = current rating of the l.v. winding; and δ_1 = current density in the l.v. winding.

6.4 Design of High Voltage Windings

The number of turns per phase is

$$T_{h.v.} = T_{l.v.} V_{h.v.} / V_{l.v.}, \quad (47)$$

the current in the h.v. winding is

$$I_{h.v.} = [(kVA_{per_phase} \times 1,000) / (V_{ph\ h.v.})] \text{ (Amps)}, \quad (48)$$

and the cross-sectional area of the conductor is

$$a_{h.v.} = I_{h.v.} / \delta_2 \text{ (mm}^2\text{)}, \quad (49)$$

where: $T_{h.v.}$ = number of turns in the h.v. winding per phase; $V_{h.v.}$ = voltage rating of the h.v. winding per phase; $I_{h.v.}$ = current rating of the h.v. winding; and δ_2 = current density in the h.v. winding.

6.5 Hysteresis Loss

Hysteresis loss occurs in the magnetic frame and depends on the area of hysteresis loop of the magnetic material used for the magnetic frame, which depends on:

- the flux density at which the material is being worked;
- the volume of the core and yoke; and
- the frequency of the magnetic flux.

The hysteresis loss is given by an empirical formula:

$$P_h = \eta V f (B_{max})^n \text{ Watts}, \quad (50)$$

where η is a constant known as Steimetz's coefficient and its value is 275 and 500 for silicon and sheet steel, respectively; V is the volume of the core in m^3 ; $(B_{max})^n$ is the maximum flux density in Tesla; and n is Steimetz's exponent which varies from 1.6 to 2.5.

6.6 Eddy Current Loss

This loss depends on the thickness of the laminations of the core and yoke, t , the

frequency of the flux, the maximum flux density in the core and yoke $(B_{max})^n$ and the quality of the material for the magnetic frame:

eddy current loss = $k B_{max}^2 f^2 t^2$ V Watts.

$$(51)$$

6.7 Copper Losses

The copper losses occur in the areas that carry current and consist of the copper materials, i.e. the l.v. and h.v. windings:

copper loss in the l.v. winding = $I_2^2 r_2$ Watts,

$$(52)$$

copper loss in the h.v. winding = $I_1^2 r_1$ Watts,

$$(53)$$

where r_1 and r_2 are the resistances in the respective windings.

6.8 Iron Losses

The iron loss in the yoke is

$$l_y = B_y N_y A_y L \times 7.55 \times 10^{-3} \text{ kg}\cdot\text{cm}^{-3}, \quad (54)$$

and the iron loss in the core is

$$l_c = B_c N_c A_y L \times 7.55 \times 10^{-3} \text{ kg}\cdot\text{cm}^{-3}, \quad (55)$$

where

$$B_c = B_y (A_y/A_i), \quad (56)$$

and the total iron losses are

$$l_t = l_y + l_c. \quad (57)$$

6.9 Cooling

Various forms of cooling methods are given below depending on the size and type of the transformer:

- air-natural and air-blast cooled (AN and AB): used for small transformers of ratings up to 10 kVA.
- oil-immersed, self-cooled: used for small, medium and large transformers of ratings up to 50 MVA as the entire piece is immersed into a tank filled with oil. The tank dissipates heat to the surroundings by the various modes of heat exchange in addition to having fins or radiators.
- oil-immersed, water-cooled: Used for transformers up to 50 MVA and it is much cheaper than the ones with fins but the water is dangerous for the insulation, hence it is least preferred.
- oil immersed, forced-air cooled: supports rating up to 75 MVA but economically supports 50 MVA (NAPTIN 2009).

6.10 Choice of Assumed Values of Design Parameters

The design parameters are assigned the following assumed values:

- frequency, $f = 50$ Hertz;
- specific magnetic loading, $B_m = 1.5$ Tesla;
- current density, $\delta = 2.5 \text{ A/mm}^2 = 2.5 \times 10^6 \text{ A/m}^2$;
- window space factor, $k_w = 0.34$;
- k -factor, $k = 0.90$;
- height of window, $L = 0.75$ m;
- thickness of lamination sheets, $t = 0.3$ mm;
- Steinmetz's exponent, $n = 2.5$;
- Steinmetz's coefficient, $\eta = 275$;
- l.v. winding current density, $\delta_1 = 2.5 \text{ A/mm}^2$;
- h.v. winding current density, $\delta_2 = 2.3 \text{ A/mm}^2$;
- l.v. winding resistance, $r_1 = 7.65 \text{ } \Omega$; and
- h.v. winding resistance, $r_2 = 0.0081 \text{ } \Omega$.

7. Results and Discussion

The graphical user interface is the final product of the design implementation (Fig. 4). After the formulae have been obtained, the program is run to activate the GUI as shown in Fig. 5. The specified inputs (kVA ratings, h.v. and l.v. values) are fed appropriately into the GUI with a high degree of precision.

Computation is done for all dimensions of the core diagram and a detailed table can be displayed with the graphical user interface. A specified input of 1,000 kVA, 6,600/440 Volts is shown in Fig. 6. The resultant diagram of the core dimensions is shown in Fig. 7. The computer-aided design of a three-phase transformer is greatly affected by some of the assumed parameters such as the window space factor, the specific magnetic loading, the k -factor, the current density, Steinmetz's coefficient, etc. This is because these values are either chosen from a table corresponding to approximate kVA ratings or calculated in accordance with the voltage ratings of the windings and the type of steel material.

7.1 Window Space Factor

If two transformers of the same kVA rating are designed for voltage (a) 110 kV (b)

330 kV, then the space in the window needed for the insulation will be more for the transformer with the 330 kV compared to the 110 kV. As such space available in the window for copper of the windings will be less in the case of transformer of 330 kV. Hence the window space factor decreases as the voltage of the h.v. winding increases (Kulkarni and Khaparde 2004).

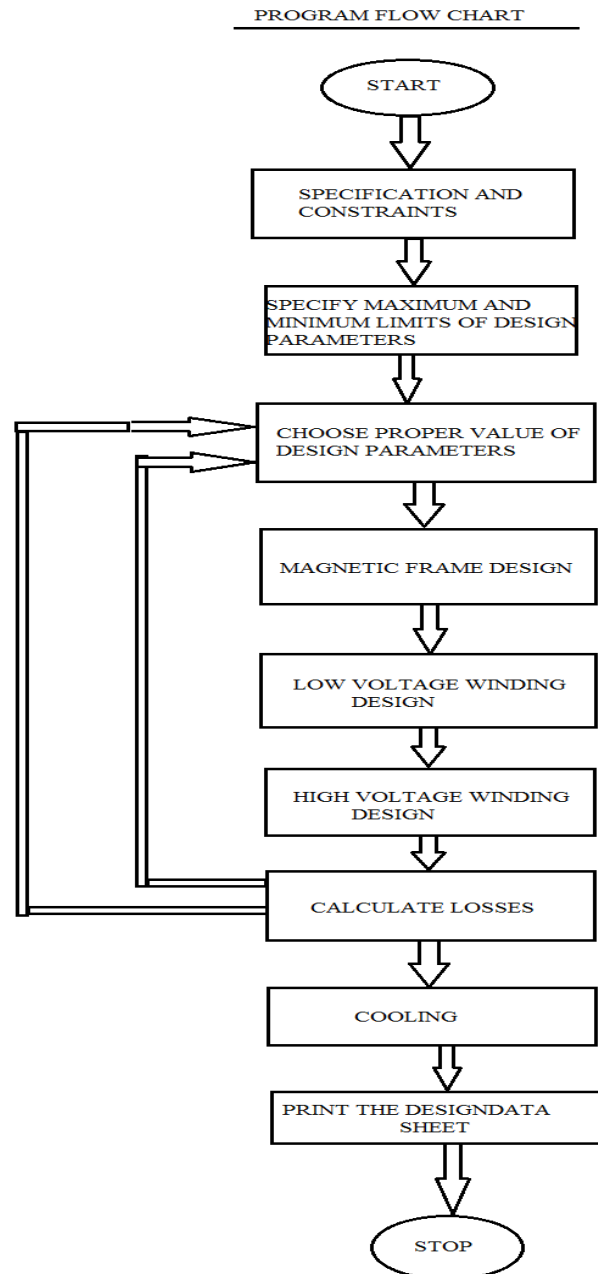


Fig. 4. Flow chart for design implementation.



Fig. 5. Graphical user interface (GUI) for general transformer properties (Shadrack 2010).

Electrical Quantity	Value
Power Rating	1000.0kVA
Secondary Voltage	440.0 Volts
Primary Voltage	6600.0 Volts
Emf per turn	8.58099 V
Cross-Sectional Area of Core	0.02577 m ²
Frequency	50 Hz
Specific Magnetic Loading	1.5 Tesla
k factor	0.6
Window Area	5.33479 m ²
Width of window	0.25 m
Core Distance	0.366 meters
Current density	2.5 A/mm ²
Window space factor	0.34
Height of window	0.75 m
Length of yoke	1.09122 m
Area of yoke	0.02963 m ²
Width of yoke	1.30435 m
Height of yoke	0.16151 m
Secondary Turns	29.6043 turns/phase
Secondary Current	1,312.1597 amp
Secondary Conductor Size	570.50422 m ²
Secondary Current Density	2.3 A/mm ²
Primary Turns	769.14231 turns/phase
Primary Current	50.50505 amp

Fig. 6. Table of results displayed with the GUI.

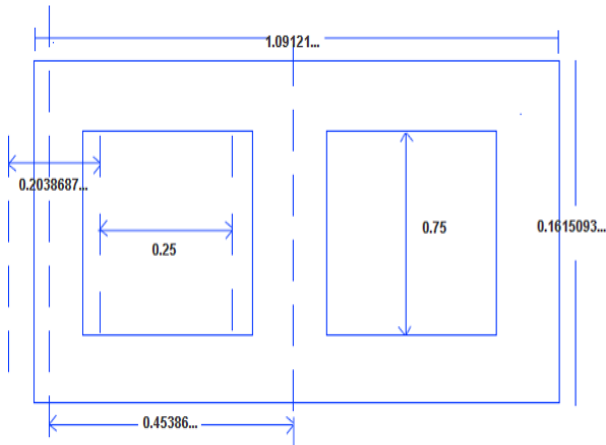


Fig. 7. Diagram of the core dimensions.

7.2 Flux Density

There are certain advantages that result from choosing higher values of flux density in the core. These advantages are:

- Reduction of core section for same output;
- Reduction of transformer weight; and
- Reduction in the overall cost of the transformer;

These advantages clearly indicate that the higher flux density is chosen to achieve an economically designed transformer with a reduced size.

7.3 Disadvantages with High Flux Density

Apparently, the following disadvantages are associated with high flux density:

- increased magnetizing current (large Ampere turns requirement);
- higher no-load losses;
- saturation of magnetic material;
- lower efficiency (because of higher no-load losses); and
- higher temperature rise due to increase of no-load losses.

7.4 Specific Magnetic Loading

Since the cooling conditions are different in the l.v. and h.v. windings, the l.v. winding being an inner winding has power cooling conditions compared to the h.v. windings, which is an outer winding. Hence, comparatively lower value of current density should be assumed for the l.v. winding.

7.5 Choice of Conductor Type

Cross-over type, cylindrical type with circular conductor, and continuous disc type

are generally used for h.v. winding. The type of winding to be used is first selected, depending on the rating of the transformer and design limitations. The conductor section is selected depending upon the type of winding, i.e. rectangular or circular. Generally, for small and medium transformers with comparatively lesser conductor section, circular conductors are used. For large transformers, rectangular conductors are preferred because of their higher current ratings.

Electrical grade insulating paper (EGIP) is used for covering the bare conductor. This is due to the following EGIP qualities:

- flexibility;
- easy to use;
- higher insulation with lesser thickness;
- high resistance to oil;
- reasonable heat resistance; and
- low chloride impurities.

7.6 Choice of Copper or Aluminium as Winding Material

The choice of using copper or aluminium as winding material generally depends on the end users and most power utilities need transformers up to 250 kVA / 11 kV with aluminium windings because of its wide availability and economy in cost. Due to some limitations in the inherent properties of aluminium, higher rating transformers are made with copper winding. Also, 22-kV and 33-kV distribution transformers are always made with copper winding only because of its low conductivity. An aluminium conductor occupies almost double the volume than that of a copper winding and hence an aluminium wound transformer always looks bigger in size than a copper wound transformer of the same kVA rating.

8. Conclusion and Recommendations

The computer-aided design is a useful developmental tool that opens up new techniques for designing static electrical machines. It saves time and reduces potential errors to a minimum level as compared with the manual mathematical approach which has apparent limitations. Due to the variety of assumed parameters such as specific magnetic

loading, current density, window space factor, k -factor, height of window, thickness of lamination sheets, Steinmentz's exponent, Steinmentz's coefficient, l.v. winding current density, h.v. winding current density, l.v. winding resistance, and h.v. winding resistance for which certain limits are given, the choice of values could be slightly different from designer to designer resulting in slightly different dimensions. The computer-aided design of transformers is quite a specialized topic and as such more work needs to be done (by engineers, programmers and scholars of the academia) to improve upon its efficiency and capabilities.

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