

Transformer Design using MATLAB

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Abstract

Transformer is based on the principal of mutual induction from primary winding to secondary winding due to alternating current. The design calculation of transformer is a hectic process when done manually. Since the calculation is long and interdependent with each steps the occurrence of error is more likely so use of computation system can minimize the error. For this use of MATLAB to have a software to design the transformer providing the design parameter is the main objective of the paper. With the Graphical user interface (GUI) and app designer helps to simplify the process and make it more user friendly which provide space for input values and options to choose. The software make calculation regarding the dimension, efficiency and manufacturing cost of the specified transformer. In addition, the software would be useful for the education and research purpose.

Keywords

App, Efficiency, GUI, MATLAB, Transformer

1. Introduction

Transformer is a crucial component of any electrical system as it allows to work on different voltages level. It is a static device where transfer of energy takes place through the magnetic coupling. When the alternating current is passed through the primary winding then varying magnetic field is produced whose amplitude will depend on the primary voltage, the frequency of the applied voltage, and the number of turns.

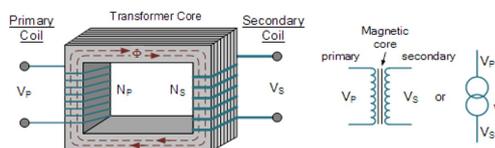


Figure 1: Basic Construction Detail of Transformer

A transformer is based on the principle that energy can be efficiently transferred by magnetic induction from one winding to another winding by a varying magnetic field produced by alternating current. The magnetic circuit or core of a transformer is designed to provide a path for the magnetic field, which is necessary for induction of voltages between the windings. Transformers work on the principle of

Faraday's law of electromagnetic induction [1].

Faraday's law states that "Rate of change of flux linkage with respect to time is directly proportional to the induced EMF in a conductor or coil".

The basic transformer consists of two types of coils:

Primary coil: The coil to which the supply is given is called the primary coil.

Secondary coil: The coil from which the supply is taken is called the secondary coil.

Based on the required output voltage the number of turns in the primary coil and the secondary coil are varied. The processes occurring inside the transformer can be grouped into two:

Magnetic flux is produced in a coil whenever there is a change in current flowing through the coil. Similarly, change in magnetic flux linked with the coil induces EMF in the coil. The first process occurs in the windings of the transformer. When the ac supply is given to the primary winding alternating flux is produced in the coil. The second process occurs in the secondary winding of the transformer. The flux alternating flux produced in the transformer links the

coils in the secondary winding and hence emf is induced in the secondary winding.

Whenever an ac supply is given to the primary coil, flux is produced in the coil. These flux links with the secondary winding thereby inducing emf in the secondary coil. This is the very basic working of the transformer.

The voltage produced in the secondary coil depends mainly on the turn's ratio of the transformer. The relationship between the number of turns and the voltage is given by the following equations [2].

$$N_1/N_2 = V_1/V_2 = I_2/I_1 \quad (1)$$

Where,

N_1 = number of turns in the primary coil of the transformer.

N_2 = number of turns in the secondary coil of the transformer.

V_1 = voltage in the primary coil of the transformer.

V_2 = voltage in the secondary coil of the transformer.

I_1 = current through the primary coil of the transformer.

I_2 = current through the secondary coil of the transformer.

2. System Framework

The paper shows the how automated calculation work can be done in MATLAB with the help of app design. The app developed for design of transformer is shown in figure 2. The program is coded to perform the task. The user enters the data as per their requirement using specified standard design data and then design parameters are calculated automatically. The required data and standard data are shown in figure 3.

2.1 Data input and parameter calculation

The parameter that are determined are:

- a. Winding Design
- b. Window Design
- c. Resistance and reactance
- d. Tank Design
- e. Efficiency

2.2 Windings of transformer

Core type use concentric type of winding i.e. cylindrical, helical, cross-over or disc. In this paper for H.V. and L.V., the area of conductors in primary and the secondary windings is determined after choosing a suitable current density to be used in the windings.

Temperature rise in the windings may become excessive if higher values of current density are chosen and this may cause injury to the insulation. Hence the choice of current density is important in this paper as the $I^2 \times R$ losses and the load at which the maximum efficiency occurs depends on it. For minimum $I^2 \times R$ losses, the value of current density in each of the two windings should be equal. Primary current and secondary current are respectively as:

$$I_1 = \frac{Q \times 10^{-3}}{3V_1} \quad (2)$$

$$I_2 = \frac{Q \times 10^{-3}}{3V_2} \quad \text{OR} \quad \frac{N_1}{N_2} I_1 \quad (3)$$

Sectional area of primary winding and the secondary winding are respectively as:

$$a_1 = \frac{I_1}{\delta} \quad (4)$$

$$a_2 = \frac{I_2}{\delta} \quad (5)$$

Where δ is current the density.

Now we can use round conductors or strip conductors. For this, the IS codes and ICC (Indian Cable Company) table can be referred.

Number of primary turns for %tapping = $T_2 \times E_1$ required E_2 with tapping.

2.3 Specification of Core and frame

Core type transformer generally uses rectangular or stepped core. Also core type distribution and small and medium power transformer uses rectangular core. The ratio of depth to width of the core varies between 1.4 to 2. Square core is used when circular coils are required for high voltage distribution transformer. On circular coils forces by excessive leakage flux due to short circuit are radial and there is no tendency for the coils to change its shape. As the size of transformer increases it become wasteful to use rectangular coils

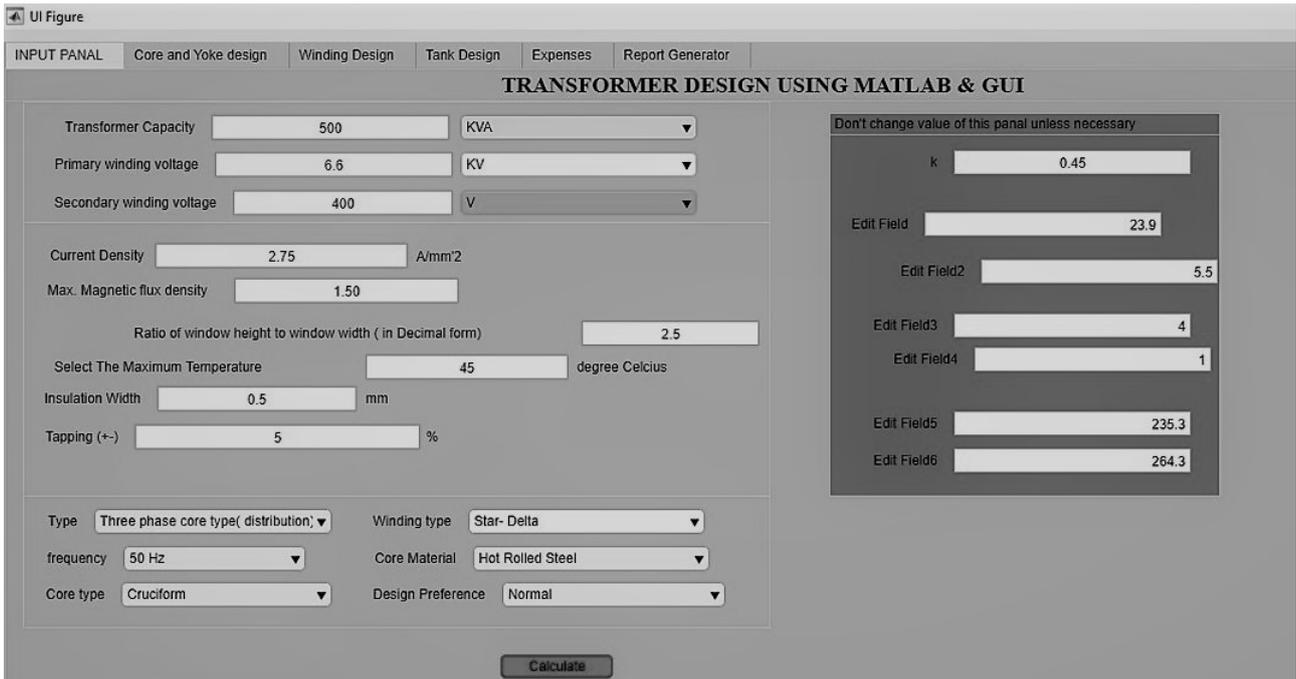


Figure 2: MATLAB GUI APP

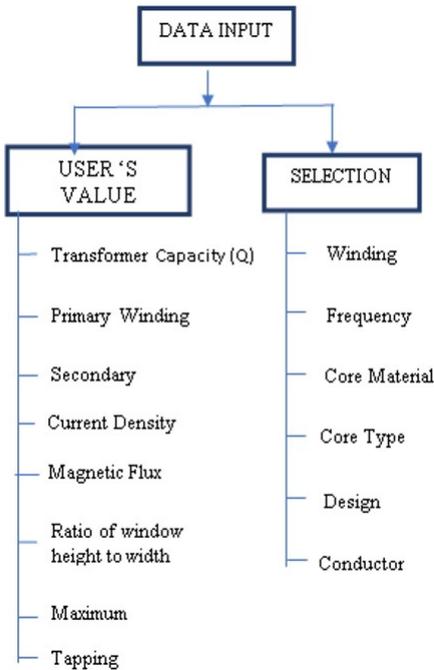


Figure 3: Input Data for the Model

following relation [1].

$$A_i = \frac{flux_{max}}{B_m} \tag{7}$$

Where $flux_{max}$ is the maximum flux which is given by following relation.

$$flux_{max} = \frac{E_t}{4.44 \times f} \tag{8}$$

The gross core area (A_{gi}) is given by following relation.

$$A_{gi} = \frac{A_i}{k} \tag{9}$$

Where, k_i is the stacking factor
 K_w is the window space factor, it is the ratio of the copper area in the window of the total window area, it depends upon the relative amount of the insulation and copper provided which in turn depends upon the voltage rating and output of transformer.

hence in this paper, we used stepped core.

$$E_t = k \times \sqrt{Q} \tag{6}$$

Where,

E_t is the voltage per turn

Q is the rating of transformer

A_i is the net core area required which is obtained by

$$K_w = \frac{8}{30 + KV} \tag{10}$$

Diameter of circumscribing circle,

$$D = \sqrt{\frac{A_i}{.56}} \tag{11}$$

The net core area required is obtained as:

$$A_i = 0.56 \times D_2 \quad (12)$$

Finally, the output of the transformer is given by the following relation:

$$Q = 3.33 \times f \times B_m \times \delta \times A_w \times A_i \quad (13)$$

Where, A_w is the area of the window defined as:

$$A_w = H_w \times W_w \quad (14)$$

H_w and W_w is the height and width of window respectively. The distance between adjacent core centers is defined and given as [1]:

$$\begin{aligned} d &= W_w + D \\ A_y &= (1.25 \text{ to } 1.5) * A_i \end{aligned} \quad (15)$$

Where, A_y is the area of yoke. Area of the yoke is 15 to 25% larger than that of the core for hot rolled steel transformer, but of the same area as core in cold rolled grain oriented steel transformer.

$$W = 2 \times d + a \quad (16)$$

Where, d is the distance between adjacent core centers. Height of yoke is given as:

$$H_y = \frac{A_y}{D_y} \quad (17)$$

H is the height of the frame and H_y is the height of the yoke.

$$H = H_w + 2 \times H_y, \quad (18)$$

The width of the frame is given as:

$$W = (2 \times d) + s \quad (19)$$

Where, s is the width of laminations.

2.4 Losses and Efficiency

The total losses decrease if the frequency increased and the applied voltage is kept constant, hence with increased frequency we can afford to have more $I_2 \times R$ loss and thus for the same loss the rating of the transformer can be increased.

The total loss in the transformer constitute core loss and the copper loss given by:

$$\text{Total losses} = \text{Core loss} + I_2 \times R \text{ loss} \quad (20)$$

The copper loss depends on the loading and thus is a variable loss. It is calculate as:

$$\text{Total } I_2 \times R \text{ loss} = [3 \times I_2 \times R + \text{stray loss}] \quad (21)$$

Where, stray losses is taken around 15% of $I_2 \times R$ losses. However, core loss is constant loss that is independent on the loading and is given as:

$$\text{Total Core loss} = [\text{losses in limb} + \text{losses in yoke}] \quad (22)$$

Now, the efficiency of the transformer could be calculated as the ratio of actual output power to the actual input power calculated as:

$$\text{Efficiency} = \frac{\text{output}}{\text{output} + \text{loss}} \quad (23)$$

The loading at which the maximum efficiency occurs is $\sqrt{\frac{P_i}{P_c}}$ percent of full load. No load current I_0 consists of two components, magnetizing component I_m and wattage component I_l ,

$$I_0 = \sqrt{\frac{I_m^2}{I_l^2}} \quad (24)$$

Total magnetizing mmf is given as:

$$T_{mmf} = 2 \times ATC \times l_c + 2 \times aty \times l_y \quad (25)$$

where,

aty is magnetizing mmf in the yoke.

2.5 Specification of Tank

Tank bodies of the transformers are made up from rolled steel plates which are fabricated to form the container. Small tanks are welded from steel plates while larger ones are assembled from boiler plates. Tanks are provided with lifting lugs, small transformers have cooling tubes let into the vertical sides, but large transformers require separate banks of cooling tubes. Such transformers have plain tanks with provision for pipes and valves to direct and control the oil flow. Stray load losses and cost should be considered. The tank should be strong enough to withstand stresses produced by jacking and lifting. The size of the tank is taken large enough to accommodate cores, winding's, internal connections and also must the requisite clearance between the winding's and the walls. The temperature rises as calculated with plain tanks exceeds the specified limit, but it brought down by the provision of tubes, it increases the dissipation area.

Height of the tank is calculated as [3]:

$$= (H + h)/1000 \quad (26)$$

Where, h is clearance between assembled transformer and the tank,

H is height of the frame

Width of the Tank (in meters) is calculated as:

$$W_t = (2 * D + d_{out} + 2 * l)/1000 \quad (27)$$

Where, d_{out} is outside diameter of High Voltage winding

Length of the Tank is calculated as:

$$L_t = (d_{out} + 2 * l)/1000 \quad (28)$$

Where, l is clearance on each side between winding and tank along the width. Clearance along the length of the transformer i.e. l is greater than that along the width of the transformer this is because additional space is needed along the length to accommodate tapping. Z is the clearance between high voltage winding and tank.

Total loss dissipating surface of the tank

$$S_t = 2 * (W_t + L_t) * H_t \quad (29)$$

Temperature rise within tubes is given as:

$$\theta = TL_{fl} / (S_t * S_L) \quad (30)$$

If the value of the θ is below 35°C then plain tank is sufficient for cooling and no extra tubes are required for cooling of the transformer.

3. Results and Discussion

The software works well without any error when checked using the standard data and calculation. The calculation sample for one set of data has been examined and presented here. However, the output has been very well verified for different transformer types and categories.

These apps are supposed to meet the basic standard of NEA, for maintaining the maximum efficiency of at least 97.5 % on the transformer.

We have found from several entry of input of transformer varying size and voltage level. And from the output we can conclude that use of transformer with high power rating and high level of voltage in both primary and secondary winding would be more economical and power efficient than that of number of small transformers in parallel sharing equal amount of

Table 1: Transformer Design Input Panel

Transformer Capacity	25 kVA
Primary Winding Voltage	11 kV
Secondary Winding Voltage	400 V
Current Density	22 A/mm ²
Maximum Magnetic Flux Density	150
Ratio of Window height to window width	2.5
Selection of maximum allowable temperature	45 ^o C
Insulation Width	0.5 mm
Tapping(±)	5%
pf	0.8
Type	Three phase core type (oil)
Winding Type	Star-Delta
Frequency	50 Hz
Core material	Cold Rolled Steel
Core type	Cruciform
Design Preference	Normal
Transformer oil type	Naphtha based
Output Constant (k)	0.45

Table 2: Tank Design Output Panel

Height of tank	850 mm
Width of tank	350 mm
Length of tank	800 mm
Temperature rise	26.18 °C
Wall area of each tube	1.649 × 10 ⁵ mm ²
Number of tubes	0
Cooling type	

power.

Similarly, use of Three Phase transformers seems to be more practical economically and in terms of power efficiency then that of using Single phase transformer. For the same power supply, three phase transformers are around 2% more efficient then single phase transformer, which is much significant [4].

Designing of Power Transformer is made to operate in maximum efficiency near full load and Distribution transformer is made to operate in maximum efficiency near its half load.

Use of Cold rolled steel is more preferable in core material than Hot rolled steel. Being produced in mass production we find there is not so much price margin. Therefore, use of Cold rolled Steel has more advantage

Table 3: Winding Design Output Panel

Primary Winding type		Delta	
Secondary Winding type		Star	
High Voltage Specifications		Low Voltage Specifications	
Winding	Primary	Winding	Secondary
Number of turns	4889 turns	Number of turns	103
With tapping	5133	Number of parallel conductor	1
Number of layer	20	Low voltage current	36.08 A
High Voltage current	0.7576	Current Density	2.062 A/mm ²
Current Density	0 A/mm ²	Area of conductor	17.5 mm ²
Area of conductor	0.5027 mm ²	Thickness of conductor	2.5 mm
Axial height	32.5 mm	Width of conductor	7 mm
Number of coils	8	Axial height	88.33 mm
Radial Width	25.2	Radial width	23.5 mm
Outside diameter	240 mm	Outside diameter	159.8 mm
Inside diameter	189.6 mm	Inside diameter	112.8 mm

Table 4: Loss and Efficiency Output Panel

Losses(Watt)		Efficiency	
Copper loss	442.7	Full load efficiency	97.5 %
Stray loss with Cu loss	509.1	Half load efficiency	97.98 %
Loss across limb	46.22	Maximum efficiency occurs at	50.66 % of full load
Loss across yoke	84.43		
Total core loss	130.6		
Total loss	639.8		

on designing of transformer. Similarly, the output that

Table 5: Resistance and Reactance Output

Resistance	257.1 Ω
Resistance in p.u	0.01771
Reactance	2695 Ω
Reactance in p.u	0.1856
Impedance in p.u	0.1865
Regulation	0.1255
Insulation type	F

the program generates is the cost that in occur during the manufacturing process.

With these output the user can also have the design parameter data in report generation section. The report is available in .pdf or doc. format so that the user can print for the desired use.

4. Conclusion

To analyze the transformer parameter coding is done in MATLAB software. Application was developed with the friendly GUI to take the input which is processed by the program coded giving the design parameters and efficiency as the output. This system can be used for preliminary design of transformer for manufacturing.

The software couldn't be used for the manufacturing process as the specification and parameters are within limited range up to 500 kVA. The program can be improvised to accommodate the need and the demand also. The mere purpose of the project is to make it as an educational tool.

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