
Development of Matlab-Based Software for the Design of the Electric Circuit of Three-Phase Power Transformer

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Abstract: Power transformers are crucial components in electric power systems, as such, it is required that they are built to highest standards of precision and quality and designed for a long life-time. As the average age of these transformers is in the range of 30 to 40 years in many countries, the probability of malfunction is on the rise. This situation is accentuated by the trend of operating transformers closer to their performance limits, adding to their vulnerability if adequate countermeasures are not taken. In this paper, MATLAB-based software was developed for automatic computation of the electric circuit parameters of a three phase power transformer once the input specifications are supplied. A sample design problem was used to demonstrate the effectiveness of the program. The automated computation program was developed using the mathematical models derived for the various parameters to be determined. Apart from its flexibility and speed, the program removed the drudgery involved in the design. In addition, the MATLAB-based software presented in this paper will serve as a useful teaching and laboratory tool for undergraduate courses in transformer design.

Keywords: Transformer, Electric Circuit, Power Transformer, Three Phase, Single Phase, MATLAB

1. Introduction

Over the years, transformers have been used extensively in electric power systems to transfer power by electromagnetic induction between circuits at the same frequency, usually with changed values of voltage and current [1]. Given its importance, transformer design is a big business in the electric power industry. Basically, the aim of transformer design is to obtain the dimensions of all parts of the transformer in order to supply these data to the manufacturer. However, the complexity of transformer design demands reliable and rigorous solution methods. Transformer design is a complex task in which engineers have to ensure that compatibility with the imposed specifications is met, while keeping manufacturing costs low [1], [2] Indeed, it is difficult if at all possible, to meet accurately today's transformer electrical parameters via conventional design techniques [3]. In view of the challenges, an alternative, user-friendly and effective way

for calculating the transformer parameters through the use of software is seriously required. Given that MATLAB is one of the most popular mathematical programs used in engineering analysis, in this paper a MATLAB-based software tool will be developed for the design of the electric circuit of power transformers. In this case, the software tool will make use of the MATLAB Application Program Interface (API) to extend the functionalities of MATLAB application to include the design of the electric circuit of power transformers.

Specifically, this paper presents the design of the electric circuit of power transformers using the MATLAB-based software presented in this paper. Sample design problem is used to demonstrate the effectiveness of the software solution.

2. Review of Related Works

A transformer has been defined by ANSI/IEEE [4] as a static electric device consisting of a winding, or two or more coupled windings, with or without a magnetic core, for

introducing mutual coupling between electric circuits [1]. Transformers operation depends on electromagnetic induction between two stationary coils (the electric circuit) and a magnetic flux of changing magnitude and polarity (the magnetic circuit). In essence, transformers transform electrical energy into magnetic energy, and then back into electrical energy.

Given its importance, transformer design is a big business in the electric power industry. Basically, the aim of transformer design is to obtain the dimensions of all parts of the transformer in order to supply these data to the manufacturer. The transformer design should be carried out based on the specification given, using available materials economically in order to achieve low cost, low weight, small size and good operating performance. The transformer design is worked out using various methods based on accumulated experience realized in different formulas, equations, tables and charts [5]. Transformer design is a complex task in which engineers have to ensure that compatibility with the imposed specifications is met, while keeping manufacturing costs low [1-2]. In addition, in order to compete successfully in the global economy, transformer manufacturers need design software capable of producing manufacturable and optimal designs in a very short time. Over the years, several design procedures for transformers have appeared in many literatures [6-8]. Some of the literatures are targeted at transformer design for teaching and hands-on training purposes [8-10]. Furthermore, other literatures presented the development or the use of various computer programs for transformer design

[6], [11-13].

Specifically, this paper presents the design of the electric circuits of power transformer and the implementation of sample design problem using the MATLAB-based software.

3. Methodology

First mathematical expressions for computing the values of various parameters of the electric circuit of power transformer are derived based on the assumptions that certain design specifications are given. Secondly, the algorithm for automating the computation of those parameters with the use of computer software is developed. Thirdly, MATLAB-based software was developed to read in design specifications as input and then automatically compute and display the various parameters of the electric circuit of power transformer.

The development of the MATLAB software for designing the electric circuit of power transformers consists of the following:

- the design of different graphical user interfaces (GUIs) for entering the design input parameters
- the design of program to automatically compute and display the remaining parameters of the electric circuit of power transformer based on the mathematical expressions presented in this paper
- aggregating the various GUIs and computation modules into a unified standalone application using the MATLAB deployment tool.

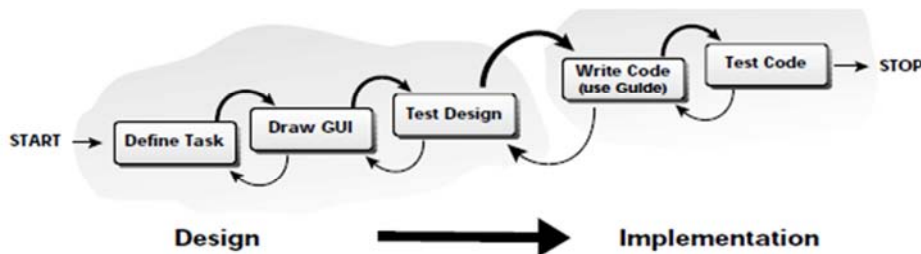


Figure 1. GUI Design and Testing.

In all, the design and implementation of the MATLAB software was done using the MATLAB's GUI development environment, also known as the M-GUIDE. The methodology used for the design and testing of the GUI is given in Figure 1.

3.1. Design Specification

The transformer design begins with the specifications of the transformer to be designed. The specifications give the rating and performance expectation of the transformer. Some useful specifications for the design of electric circuit of power transformer include;

1. Transformer Power rating, S in KVA
2. Frequency, f in Hz
3. Line voltage of the high voltage (HV) winding, V_{inhv}
4. Connection type – star or Delta
5. Percentage impedance, Z%
6. Tapping on the H. V winding, T_{p1} , T_{p2}

Furthermore, in the electric circuit design, it is assumed that some parameters pertaining to the electric circuit of the transformer have been obtained or are give as part of the design specifications; among these parameter are voltage per turn (V_t) iron core cross sectional area (A_i), the window height (H_w), overall core frame height, (H) overall core frame width (W) and diameter of the core limb (D_{sc}).

3.2. Winding Design

The winding consist of the Low Voltage (L. V) and high Voltage (H. V) windings. This paper will consider only disc winding with rectangular conductor.

3.2.1. Low Voltage (L. V) Winding Design

1. Phase voltage (V_{plv}):

$$\text{For star connection } V_{plv} = V_{inlv} / \sqrt{3} \quad (1)$$

$$\text{For delta connection } V_{plv} = V_{lnlv} \quad (2)$$

$$t_{icl v} = t_{icdl v} \times n_{ptlv} \quad (15)$$

Where V_{lnlv} is the line voltage for the low side of the transformer

Height of coil,

2. Number of turn

$$(N_{lv}): N_{lv} = V_{plv} / V_t \quad (3)$$

$$H_{pcl v} = n_{tlylv} \times W_{tcl v} \quad (16)$$

Where V_t is the voltage per turns

Thickness of coil,

$$t_{pcl v} = n_{tlylv} \times t_{icl v} \quad (17)$$

3. Phase current (I_{plv}):

Choose the distance between adjacent coils or disc, $d_{bcl v}$
Height of low voltage winding,

$$\text{For star connection } I_{plv} = S / (\sqrt{3} V_{plv}) \quad (4)$$

$$H_{ndgl v} = (H_{pcl v} \times n_{dcl v}) + (n_{dcl v} - 1) d_{dcl v} \quad (18)$$

$$\text{For delta connection } I_{plv} = S / (3 V_{plv}) \quad (5)$$

Thickness of low voltage winding,

4. Phase current area of the conductor (L. V), a_{lv}

$$a_{lv} = I_{plv} / J_{id} \quad (\text{Choose current density } J_{id} \text{ in } A/mm^2) \quad (6)$$

$$t_{ndgl v} = t_{dcl v} \quad (19)$$

5. L. V conductor dimensions

7. Diameter and Length of Low Voltage Winding

The conductor parameters are obtained as follows;

Choose the distance core and L. V winding, $d_{dcl v}$

(Bare conductor width, W_{bcdlv} bare conductor thickness t_{bcslv} , number of conductors per turn, n_{ptlv} , conductor insulator thickness t_{ins})

The inside diameter or L. V coil, $d_{ilv} = \text{core diameter} + 2 (d_{dcl v})$

$$D_{ilv} = D_{sc} + 2 (d_{dcl v}) \quad (20)$$

Area of the bare conductor,

Outside diameter of L. V coil (d_{olv}):

$$a_{bcdlv} = (W_{bcdlv}) (t_{bcslv}) (n_{ptlv}) \quad (7)$$

$$d_{olv} = d_{ilv} + 2 (t_{ndgv}) \quad (21)$$

With the insulation on the conductor, dimension becomes
Insulated conductor width,

Mean diameter of L. V winding (d_{mlv}):

$$W_{icdlv} = W_{bcdlv} + t_{ins} \quad (8)$$

$$d_{mlv} = d_{ilv} + t_{ndglv} \quad (22)$$

Insulated conductor thickness, t_{icdlv} :

Mean length of L. V winding L_{mlv} :

$$t_{icdlv} = t_{bcslv} + t_{ins} \quad (9)$$

$$L_{mlv} = \pi (d_{mlv}) \quad (23)$$

Area of insulated conductor, a_{icdlv} :

$$a_{icdlv} = W_{icdlv} (t_{icdlv}) (n_{ptlv}) \quad (10)$$

3.2.2. High Voltage Winding Design

1. Phase voltage (V_{phv}):

$$\text{For star connection } V_{phv} = V_{lnhv} / \sqrt{3} \quad (24)$$

$$\text{For delta connection } V_{phv} = V_{lnhv} \quad (25)$$

Since the dimension of the conductor are chosen, the area of the conductor, a_{bcdlv} may be different from the area, a_{lv} computed earlier, hence, the current density will change. The actual current density is given as

Where V_{lnhv} is the line voltage of the high voltage side of the transformer

2. Number of turns (N_{hv}):

$$J_{ic} = I_{plv} / a_{bcdlv} \quad (11)$$

$$N_{hv} = V_{phv} / V_t \quad (26)$$

6. Disc winding of L. V winding

3. Phase current (I_{phv}): for star connection,

Choose the number of disc (or coil) n_{dclv}

$$I_{phv} = S / (\sqrt{3} V_{phv}) \quad (27)$$

The number of turn per disc,

For delta connection,

$$n_{tdclv} = N_{lv} / n_{dclv} \quad (12)$$

$$I_{phv} = S / (3 V_{phv}) \quad (28)$$

Choose the number of layers per disc, n_{lylv}

Number of turns per layer per disc, n_{tlylv} :

$$n_{tlylv} = n_{tdclv} / n_{lylv} \quad (13)$$

4. Cross sectional area of the conductor (a_{hv}):

$$a_{nv} = I_{phv} / J_{id} \quad (29)$$

The dimensions of each turn of the coil are as follows;

Width of each turn of coil

$$W_{tclv} = W_{icdlv} \quad (14)$$

Thickness of each turn of coil,

5. Conductor dimension: The conductor used is rectangular, choose the appropriate conductor dimensions and number of conductors. The conductor parameters are as follows, bare conductor width, W_{bcdhv} , bar conductor thickness, t_{bcdhv} , number of conductor stripes per turn, n_{pthv} ,

Area of bare conductor, a_{bcdhv} :

$$a_{bcdhv} = W_{bcdhv} \times t_{bcdhv} \times n_{pthv} \quad (30)$$

Choose the conductor and hence the insulator thickness, t_{ins} .
With the insulation on the conductor, the dimensions become:

Insulated conductor width, W_{icdhv} :

$$W_{icdhv} = W_{bcdhv} + t_{ins} \quad (31)$$

Insulated conductor thickness, t_{icdhv} :

$$t_{icdhv} = t_{bcdhv} + t_{ins} \quad (32)$$

Area of insulated conductor a_{icdhv} :

$$a_{icdhv} = t_{icdhv} \times n_{pthv} \quad (33)$$

6. Disc winding design for the H. V Winding

Choose the number of disc (coil) n_{dchv} ,

The number of turn per disc, n_{tdchv} :

$$n_{tdchv} = N_{hv} / n_{dchv} \quad (34)$$

Choose the number of layers per disc, n_{lyhv}

The number of turns per layer per disc, n_{tlyhv} :

$$n_{tlyhv} = n_{tdchv} / n_{lyhv} \quad (35)$$

The dimensions of the each turn of the coil are as follows

$$\text{Width of each turn of coil, } W_{tchv} = W_{icdhv} \quad (36)$$

$$\text{Thickness of each coil, } t_{tchv} = t_{icdhv} \times n_{pthv} \quad (37)$$

$$\text{Height of coil, } H_{pchv} = n_{tlyhv} \times W_{tchv} \quad (38)$$

$$\text{Thickness of coil } t_{pchv} = n_{lyhv} \times t_{tchv} \quad (39)$$

Choose the distance between adjacent coils (or discs) d_{bchv}

Height of high voltage winding, H_{ndghv} :

$$H_{ndghv} = (H_{pchv} \times n_{dchv}) + (n_{dchv} - 1) d_{bchv} \quad (40)$$

Thickness of high voltage winding, t_{ndghv} :

$$t_{ndghv} = t_{pchv} \quad (41)$$

7. Diameter and length of high voltage winding

Choose the distance between the low voltage winding and the high voltage winding, d_{lvhv}

Inside diameter of high voltage winding,

$$d_{ihv} = d_{olv} + 2 (d_{lvhv}) \quad (42)$$

Outside diameter of high voltage winding, d_{ohv} :

$$d_{ohv} = d_{ilv} + 2 (t_{ndghv}) \quad (43)$$

Mean diameter of high voltage winding, d_{mhv} :

$$d_{mhv} = d_{ohv} + t_{ndghv} \quad (44)$$

Mean length of H. V coil, L_{mhv} :

$$L_{mhv} = \pi d_{mhv} \quad (45)$$

3.3. Percentage Reactance (X_{pct}) and Percentage Resistance (R_{pct})

Average length of turn L_{mt} :

$$L_{mt} = (L_{mlv} + L_{mhv}) / 2 \quad (46)$$

Ampere turn,

$$A_{in} = I_{plv} \times N_{lv} \quad (47)$$

Mean height of turn, H_{mt} :

$$H_{mt} = (H_{ndglv} + H_{ndghv}) / 2 \quad (48)$$

Percentage resistance, X_{pet} :

$$X_{pet} = A_{in} (2\pi f \mu_0 L_{mt}) (d_{lvhv} + (t_{ndglv} + t_{ndghv})) \quad (49)$$

Where, $\mu_0 = 4\pi \times 10^{-7}$

$\rho_{20} = 0.01724 \text{ ohm/mm}^2/\text{m}$, $\alpha_{20} = 0.00393$

At the temperature of T_{mp} °C, ρ_{Tmp} is given as

$$\rho_{Tmp} = \rho_{20} (1 + \alpha_{20} (T_{mp} - 20)) \quad (50)$$

Resistance of the low voltage winding,

$$R_{ndglv} = (\rho_{Tmp} \times L_{mlv} \times N_{lv}) / (a_{lv} \times 1000) \quad (51)$$

Resistance of the high voltage winding,

$$R_{ndghv} = (\rho_{Tmp} \times L_{mhv} \times N_{hv}) / (a_{lv} \times 1000) \quad (52)$$

Ratio of transformation,

$$k_{hlv} = V_{phv} / V_{plv} \quad (53)$$

Equivalent resistance referred to high voltage side,

$$R_{rhv} = R_{ndghv} + R_{ndglv} (K_{hlv})^2 \quad (54)$$

Percentage resistance,

$$R_{pct} = (I_{phv} \times R_{rhv}) / V_{phv} \quad (55)$$

3.4. Percentage Impedance (Z_{pct}) and Core Loss

$$Z_{pct} = \sqrt{((X_{pct})^2 + (R_{pct})^2)} \quad (56)$$

$$\text{Volume of iron, } V_i = A_i (2W + 3H) \quad (57)$$

Where A_i is cross sectional area of iron, H is the overall core frame height, W is the overall core frame width and A_i , W and H are given in the design specification

$$\text{Weight of iron, } W_i = (V_i \times \rho_i) \quad (58)$$

where density of iron, ρ_i is given as

Choose core loss per kilogram of iron (K_{Lkg}), K_{Lkg}

$$\text{Core loss } L_{cor} = W_i \times K_{Lkg} \quad (59)$$

3.5. Weight of Copper and Copper Loss, L_{cpc}

Read Magnetizing Volt-ampere per kilogram (K_{vakg})

Magnetizing volt-ampere, M_{VA}

$$M_{VA} = W_i \times (K_{vakg}) \quad (60)$$

Weight of L. V winding

$$W_{ivcp}=(\rho_{cp}\times N_{iv}\times L_{mLV} a_{LV})/ (100\times 1000) \quad (61)$$

Where ρ_{cp} is the density of copper is given as
Weight of L. V winding

$$W_{hvcp}=(\rho_{cp}\times N_{hv}\times L_{mhv} a_{Hv})/ (100\times 1000) \quad (62)$$

Total weight of copper,

$$W_{thlcp}=3 (W_{hvcp}+W_{ivcp}) \quad (63)$$

$$L_{cpp}=3 (R_{rhv}) (I_{phv})^2 \quad (64)$$

Add 7% due to stray load loss, then

$$L_{cpp}=1.07 (3 (R_{rhv}) (I_{phv})^2) \quad (65)$$

Total Loss, L_{icp} is given as;

$$L_{icp}=L_{cor}+L_{cpp} \quad (66)$$

3.6. Efficiency and Regulation at Unity Power Factor

1. Efficiency on full load, Eff_1 :

$$Eff_1=(S\times 10^3)/(S\times 10^3+L_{icp})100\% \quad (67)$$

2. Efficiency at $\frac{3}{4}$ full load at unity power factor, Eff_2
Copper loss at $\frac{3}{4}$ full load:

$$L_{cpp3/4}=(3/4)^2\times L_{cpp} \quad (68)$$

Total loss at $\frac{3}{4}$ full load:

$$L_{icp3/4}=L_{cor}+L_{cpp3/4} \quad (69)$$

Efficiency at $\frac{3}{4}$ full load:

$$Eff_2=(((3/4) S\times 10^3) / ((3/4) (S\times 10^3)+L_{icp3/4})) 100\% \quad (70)$$

3. Efficiency at $\frac{1}{2}$ full load at unity power factor, Eff_3
Copper loss at $\frac{1}{2}$ full load

$$L_{cpp1/2}=(1/2)^2\times L_{cpp} \quad (71)$$

Total loss at $\frac{1}{2}$ full load,

$$L_{icp1/2}=L_{cor}+L_{cpp1/2} \quad (72)$$

Efficiency at $\frac{1}{2}$ full load,

$$Eff_3=(((1/2) S\times 10^3)/(1/2) (S\times 10^3)+L_{icp1/2}))100\% \quad (73)$$

1. Regulation at unity power factor, Reg_1

$$E=\sqrt{((1+(R_{pct}/100)^2+(X_{pct}/100)^2)} \quad (74)$$

Thus,

$$Reg_1=(E - 1) 100\% \quad (75)$$

2. Regulation at 0.8 power factor, $Reg_{0.8}$

$$Reg_{0.8}=0.8R_{pct}+0.6X_{pct} \quad (76)$$

3.7. Other Parameters

Core Loss Current, (I_{ci}) is given as;

$$I_{ci}=L_{cor} / (3V_{phv}) \quad (77)$$

Magnetizing Current, I_{mi} is given as;

$$I_{mi}=M_{VA}/ (3V_{phv}) \quad (78)$$

No Load Current, I_{0l} is given as;

$$I_{0l}=\sqrt{(I_{mi}^2+I_{ci}^2)} \quad (79)$$

Tapping on the High Voltage Side is given as;

The tapping are given as percentage of the H. V winding, example $t_{p1}\%$, $t_{p2}\%$, $t_{p3}\%$ then the number of turns for each of the tapping are given as N_{phv1} , N_{phv2} , N_{phv3} , where

$$N_{phv1}=N_{phv}\times(t_{p1}/100)$$

$$N_{phv2}=N_{phv}\times(t_{p2}/100)$$

$$N_{phv3}=N_{phv}\times(t_{p3}/100) \quad (80)$$

4. Algorithm for Designing the Electric Circuit of 3-phase Power Transformer

4.1. Design Specifications

Obtain the values of the following parameters from the given design specifications

1. Power rating, S in KVA
2. Frequency, f in Hz
3. Line voltage of the high voltage (H. V) winding, V_{inhv}
4. Line voltage of the low voltage (L. V) winding, V_{inlv}
5. Connection types –delta or star
6. Percentage impedance
7. Tapping on the H. V winding

4.2. Low Voltage (L. V) Winding Design (Disc Winding)

4.2.1. L. V Voltage and Current Parameters

1. Compute L. V phase voltage, V_{plv} using $V_{plv}=V_{inlv}/\sqrt{3}$ for star connection or $V_{plv}=V_{inlv}$ for delta connection
2. Compute L. V phase current, I_{plv} using $I_{plv}=S/(\sqrt{3} V_{plv})$ for star or $I_{plv}=S/(3 V_{plv})$ for delta connection

4.2.2. Low Voltage Conductor Parameter

1. Compute the number of turns in L. V winding, N_{lv} form $N_{lv}=V_{plv}/V_t$
2. Choose current density, J_{id}
3. Compute cross sectional area of L. V conductor a_{lv} from $a_{lv}=I_{plv}/J_{id}$
4. The winding type is disc and conductor is rectangular. look at the standard wire gauge table and choose cable stripe that can handle the L. V phase current I_{plv} . If one stripe cannot handle it then two or more conductors stripe can be chosen and combined where n_{ptlv} is the number of conductor so chosen from the table, read the width of the bare conductor stripe W_{bcdlv} and the thickness of the conductors, t_{bcdlv}

5. Compute the area of the bare conductor stripe a_{bcdlv} from $a_{bcdlv}=(W_{bcdlv})(t_{bcdlv})(n_{ptlv})$
6. Choose conductor insulator thickness, t_{ins}
7. Compute insulated conductor width, W_{icdlv} from $W_{icdlv}=W_{bcdlv}+t_{ins}$
8. Compute insulate conductor thickness, t_{icdlv} from $t_{icdlv}=t_{bcdlv}+t_{ins}$
9. Compute insulated conductor area, a_{icdlv} from $a_{icdlv}=W_{icdlv}(t_{icdlv})(n_{ptlv})$
10. Compute actual current density J_{ic} from $J_{ic}=I_{plv}/a_{bcdlv}$

4.2.3. L. V Disc Winding Parameter

1. Choose number of disc, n_{dclv}
2. Compute number of turns per disc, n_{tdclv} from $n_{tdclv}=N_{lv}/n_{dclv}$
3. Choose number of layers per disc, n_{lylv}
4. Compute number of layers per disc, n_{tlylv} from $n_{tlylv}=n_{tdclv}/n_{lylv}$
5. Compute width of each turn of coil, W_{tclv} from $W_{tclv}=W_{icdlv}$
6. Compute thickness of each turn of coil t_{tclv} from $t_{tclv}=t_{icdlv}\times n_{ptlv}$
7. Compute height of each coil, H_{pclv} from $H_{pclv}=n_{tlylv}\times W_{tclv}$
8. Compute thickness of each coil, t_{pclv} from $t_{pclv}=n_{lylv}\times t_{tclv}$
9. Choose the distance between adjacent coil, or disc, d_{bclv}
10. Compute height of L. V winding, H_{ndglv} from $H_{ndglv}=(H_{pclv}\times n_{dclv})+(n_{dclv}-1)d_{bclv}$
11. Compute thickness of L. V winding, t_{ndglv} from $t_{ndglv}=t_{dclv}$
12. Choose the distance between core limb and L. V winding, d_{clv}
13. Compute inside diameter of L. V coil, d_{ilv} from $d_{ilv}=D_{sc}+2(d_{clv})$
14. Compute inside diameter of L. V coil, d_{olv} from $d_{olv}=d_{ilv}+2(t_{ndgv})$
15. Compute mean diameter of L. V winding, d_{mlv} from $d_{mlv}=d_{olv}+t_{ndglv}$
16. Compute mean length of L. V winding L_{mlv} from $L_{mlv}=\pi(d_{mlv})$

4.2.4. High Voltage Winding Design

1. Compute H. V phase voltage, V_{phv} from $V_{phv}=V_{lnhv}/\sqrt{3}$ for star connection or $V_{phv}=V_{lnhv}$ for delta connection
2. Compute H. V phase current I_{phv} from $I_{phv}=S/(\sqrt{3}V_{phv})$ for star and $I_{phv}=S/(3V_{phv})$ for delta

4.2.5. High Voltage Conductor Parameter

1. Compute the number of turns in H. V winding, N_{hn} from $N_{hv}=V_{phv}/V_t$
 2. Compute cross sectional area of H. V conductor a_{hv} from $a_{hv}=I_{phv}/J_{id}$
- From the standard wire gauge table choose appropriate size of conductor and number of conductor stripe that can handle the given current I_{phv} . Let n_{pthv} be the choose number of conductor strips. Then read the width of the bare conductor stripe, w_{bcdlv} read the thickness of the bare conductor stripe, t_{bcdhv}
3. Compute area of bare conductor, a_{bcdhv} from

4. Choose the conductor insulator thickness, t_{ins}
5. Compute width of insulated conductor, W_{icdhv} from $W_{icdhv}=W_{bcdhv}+t_{ins}$
6. Compute thickness of insulated conductor, t_{icdhv} from $t_{icdhv}=t_{bcdhv}+t_{ins}$
7. Compute area of insulated conductor, a_{icdhv} from $a_{icdhv}=W_{icdhv}\times t_{icdhv}\times n_{pthv}$

4.2.6. H. V Disc Winding Parameter

1. Choose number of disc, n_{dchv}
2. Compute number of turns per disc, n_{tdchv} from $n_{tdchv}=N_{hv}/n_{dchv}$
3. Choose number of layers per disc, n_{lyhv}
4. Compute number of turns per disc, n_{tlyhv} from $n_{tlyhv}=n_{tdchv}/n_{lyhv}$
5. Compute width of each turn of coil, W_{tchv} from $W_{tchv}=W_{icdhv}$
6. Compute thickness of each turn of coil, t_{tchv} from $t_{tchv}=t_{icdhv}\times n_{pthv}$
7. Compute height of coil, H_{pchv} from $H_{pchv}=n_{tlyhv}\times W_{tchv}$
8. Compute thickness of coil, t_{pchv} from $t_{pchv}=n_{lyhv}\times t_{tchv}$
9. Choose the distance between adjacent coil (or disc), d_{bchv}
10. Compute height of H. V winding, H_{ndghv} from $H_{ndghv}=(H_{pchv}\times n_{dchv})+(n_{dchv}-1)d_{bchv}$
11. Compute thickness of winding, t_{ndghv} from $t_{ndghv}=t_{pchv}$
12. Choose the distance between H. V winding and the H. N winding, d_{lvhv}
13. Compute inside diameter of H. V winding, d_{ihv} from $d_{ihv}=d_{sc}+2(d_{lvhv})$
14. Compute inside diameter of H. V winding, d_{ohv} from $d_{ohv}=d_{ihv}+2(t_{ndghv})$
15. Compute mean diameter of H. V winding, d_{mhv} from $d_{mhv}=d_{ohv}+t_{ndghv}$
16. Compute mean length of H. V coil, L_{mhv} from $L_{mhv}=\pi d_{mhv}$

4.3. Percentage Impedance

1. Compute average length of turn, L_{mt} from $L_{mt}=(L_{mlv}+L_{mhv})/2$
2. Compute ampere turn, A_{tn} from $A_{tn}=I_{plv}\times N_{lv}$
3. Compute mean height of turn, H_{mt} from $H_{mt}=(H_{ndglv}+H_{ndghv})/2$
4. Compute percentage reactance, X_{pet} from $X_{pet}=A_{tn}(2\pi f\mu_0 L_{mt})(d_{lvhv}+(t_{ndglv}+t_{ndghv}))$
5. Compute resistance of L. V winding, R_{ndglv} from $R_{ndglv}=(\rho_{Timp}\times L_{mlv}\times N_{lv})/(a_{lv}\times 1000)$
6. Compute resistance of H. V winding, R_{ndghv} from $R_{ndghv}=(\rho_{Timp}\times L_{mhv}\times N_{hv})/(a_{hv}\times 1000)$
7. Compute ratio of transformation, K_{hlv} from $k_{hlv}=V_{phv}/V_{plv}$
8. Compute equivalent resistance referred to H. V side, R_{rhv} from $R_{rhv}=R_{ndghv}+R_{ndglv}(K_{hlv})^2$
9. Compute percentage impedance Z_{pct} from $Z_{pct}=\sqrt{((X_{pet})^2+(R_{pct})^2)}$

4.4. Transformer Losses

1. Compute volume of iron, V_i from $V_i=A_i(2W+3H)$

2. Compute weight of iron, W_i from $W_i=(V_i \times \rho_i)$
3. Compute core loss, L_{cor} from $L_{cor}=W_i \times K_{Lkg}$
4. Compute magnetizing volt ampere, M_{VA} from $M_{VA}=W_i (K_{vakg})$
5. Compute weight of L. V winding, W_{lvc} from $W_{lvc}=(\rho_{cp} \times N_{lv} \times L_{mlv} a_{lv}) / (100 \times 1000)$
6. Compute weight H. V winding, W_{hvc} from $W_{hvc}=(\rho_{cp} \times N_{hv} \times L_{m hv} a_{hv}) / (100 \times 1000)$
7. Compute total weight copper loss, W_{thlcp} from $W_{thlcp}=3 (W_{hvc}+W_{lvc})$
8. Compute copper loss, L_{cpp} from $L_{cpp}=3 (R_{rhv}) (I_{phv})^2$
9. Compute total loss, L_{icp} from $L_{icp}=L_{cor}+L_{cpp}$

4.5. Efficiency of the Transformer

1. Compute efficiency at full load, Eff_1 from $Eff_1=(S \times 10^3) / (S \times 10^3 + L_{icp}) 100\%$
2. Compute copper loss at $3/4$ full load, $L_{cpp3/4}$ from $L_{cpp3/4}=(3/4)^2 \times L_{cpp}$
3. Compute total loss at $3/4$ full load, $L_{icp3/4}$ from $L_{icp3/4}=L_{cor}+L_{cpp3/4}$
4. Compute efficiency at $3/4$ full load, Eff_2 from $Eff_2=((3/4) S \times 10^3 / ((3/4) (S \times 10^3) + L_{icp3/4})) 100\%$
5. Compute copper loss at $1/2$ full load, $L_{cpp1/2}$ from $L_{cpp1/2}=(1/2)^2 \times L_{cpp}$
6. Compute total loss at $1/2$ full load, $L_{icp1/2}$ from $L_{icp1/2}=L_{cor}+L_{cpp1/2}$
7. Compute efficiency at $1/2$ full load, Eff_3 from $Eff_3=((1/2) S \times 10^3) / ((1/2) (S \times 10^3) + L_{icp1/2}) 100\%$

4.6. Regulation

1. Compute regulation at unity power factor, Reg_1 from $Reg_1=(E - 1) 100\%$
2. Compute regulation at 0.8 power factor, $Reg_{0.8}$ from $Reg_{0.8}=0.8R_{pct}+0.6X_{pct}$
3. Compute core loss current I_{ci} from $I_{ci}=L_{cor} / (3V_{phv})$
4. Compute magnetizing current I_{mi} from $I_{mi}=M_{VA} / (3V_{phv})$
5. Compute no load current I_{0i} from $\sqrt{I_{mi}^2+I_{ci}^2}$
6. Compute tapping on H. V winding, N_{phv1} from $N_{phv1}=N_{phv} \times (t_{p1}/100)$ and N_{phv2} from $N_{phv2}=N_{phv} \times (t_{p2}/100)$

5. Conclusion and Recommendation

5.1. Conclusion

In this paper, a standalone program was developed in MATLAB for the design of the electric circuit of a 3-phase power transformer. Mathematical models were developed for all the parameters to be computed and then a design algorithm was developed. Based on the mathematical models and algorithm the MATLAB-based software was developed and then a sample design problem was used to demonstrate how the program can be used. The ideas presented in the paper are extracts from undergraduate students' hands-on projects. The simplicity of the mathematical models and the modular nature of the program make them relevant for teaching and hands-on training on power transformer design. It is also easy to upgrade the programs to accommodate the design of other

kinds of transformers and the use of other design methodologies and also for incorporating optimization issues in the program.

5.2. Recommendation for Further Works

The scope of this paper covers only the design of the electric circuit of 3-phase power transformers. In particular, the design considered disc winding with rectangular conductors only. Further work is needed to cover other types of transformers and other form of winding layouts and conductor shapes. Also, design optimization was not considered in this paper. However, the modular nature of the program makes provision for the program to be easily upgraded to include the optimization module. Consequently, further work is required to develop the mathematical models and program codes for those additional modules.

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