Current Transformer Design Optimization

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Abstract

This paper devises a computer-aided program to design an optimized Current Transformer (CT) not only fulfilling the basic requirements of the user/client but also presents the most economical design. In the first step, basic equations for designing the CT have been set up and a computer program has been developed. Then a numerical optimizing technique i.e. pattern search has been used for determining the most economical design for a certain rating of a CT. To evaluate the workability and practicability, a CT has been designed and manufactured using the results obtained from the program. The results of this work have been then compared with the locally manufactured CT of same rating. Computer application has been developed using MS Excel with background coding in Visual Basic (VB).

Keywords— *Current Transformer, CT Design, Optimization, Computer, Visual Basic,*

I. INTRODUCTION

A CT in many ways differs from a normal transformer. It is connected in series with a circuit, whose current is needed to measure, and its primary and secondary currents are independent of the burden and these currents are of prime interest. The voltage drops are only of interest for determining exciting currents [1] - [3].

There are two types of CTs based on their application in power system [1], [4], [5]:

i. Measuring CT to feed the current to meters / energy meters

ii. Protection CT to feed current to protective relays.

The IEEE papers referred at [2] and [3] published in recent year i.e. 2007 and 2011 respectively, only discusses the performance and behaviour of a current transformer under different operating conditions while the papers at [6] and [7] published fifty years back, provide the basics calculation of CT parameters.

In the forthcoming sections, the basic theory relating to a current transformer, equations involved in the design process and the outline of algorithm employed to obtain the optimized solution will be discussed. In last two sections, the physical and electrical parameters of the CT designed using the developed program shall be compared with the CT manufactured locally to conclude viability of the work-done.

For the purpose of this research work, a 12 kV, 800/5 A metering current transformer of accuracy class 0.5 has been selected. This type of CT is commonly used in 11 kV incoming and outgoing feeders' panel in NTDC/ Distribution Companies' systems. In the first step, design equations for the current transformers have been step up then the numerical optimization technique has been used to obtain the most economical design. The computer application has been developed in a macro enabled EXCEL workbook.

II. BASICS OF CURRENT TRANSFORMER

A. *Working Principle of a Current Transformer*

For a short circuited CT [1], [2], [8], the simplified equivalent model of the CT is:

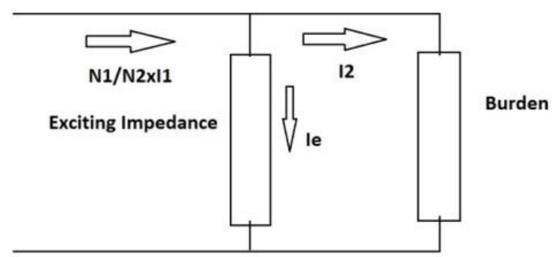


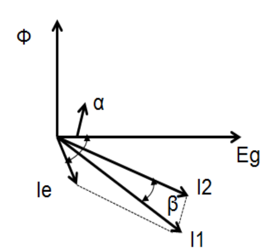
Figure 1: Simplified equivalent model of CT [1].

According to above,

$$I_2 = \frac{N_1}{N_2} I_1 - I_e \tag{1}$$

I_1 = Primary current
I_2 = Secondary current
N_1 = Number of primary turns
N_2 = Number of secondary turns

Also, vector diagram for 1:1 current transformer, describing the relation between current, voltage and flux may be represented as follow:



Eg = Induced Secondary Voltage
Φ = Flux
I1 = Primary Current
I2 = Secondary Current
Ie = Excitation Current
α = angle of excitation current
β = phase angle

Figure 2: Vector diagram showing the relation between current, voltage and flux in a current transformer [9].

B. *Determination of Ratio and Phase Errors*

Ratio and phase error introduced by a CT in the secondary current, are the function of the magnetizing current I_e. The error produced in magnitude is due to the watt loss component of the excitation current I_e and the phase error is proportional to the reactive component of this current.

The phase error being the function of reactive component of the excitation current which varies widely over the current range, take the top priority in the design consideration of the current transformer [8].

A vector diagram between primary and secondary of 1:1 current transformer is shown in Fig. 3 with making two assumptions [1] and [8]:

a) The leakage reactance of the current transformer is neglected

b) The burden is purely resistive.

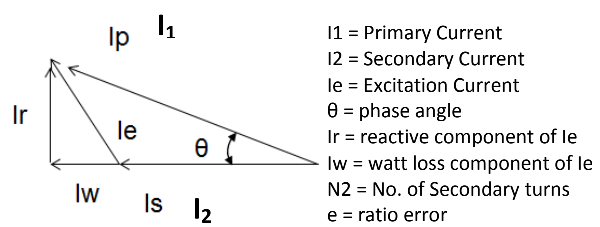


Figure 3: Vector diagram showing relation between primary and secondary current [1] & [8].

For above vector diagram;

$$sin\theta = \frac{I_r}{I_1} \quad (2)$$

$$i.e. \quad \theta = sin^{-1}\frac{I_r}{I_1} \quad (3)$$

However, in actual θ is so small that [8]

$$\theta \approx \frac{I_r}{I_1} (radian) \quad (4)$$

Also

$$I_1 = \sqrt{[(N]_2 I_2 + I_w)^2 + Ir^2} \quad (5)$$

Since θ is so small, hence the approximation [8]

$$I_1 \approx N_2 I_2 + I_w \quad (6)$$

and the ratio error as

$$e = \frac{I_w}{I_1} \text{ x } 100 \ (\%) \quad (7)$$

III. CURRENT TRANSFORMER DESIGNING

The designing process of a CT consists of the following step:

A. Core Design

It is first and the most essential design parameter of a CT. Ratio and phase errors of a CT are directly dependent on this.

For toroidal cores, following three parameters are selected by the designer:

i) Internal diameter of the core (ID)

ii) Outer diameter of the core (OD)

iii) Step thickness or axial height of the core (HT)

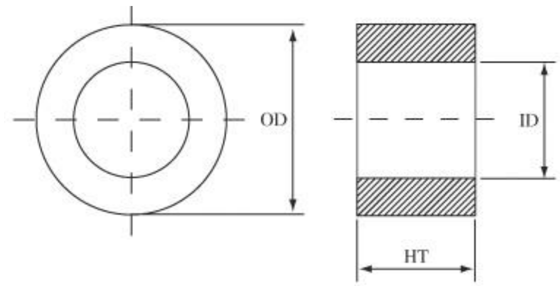


Figure 4: Geometry of toroidal core

The selection of internal diameter (ID) of the core is function of primary conductor size and Insulation class of CT.

B. Winding Design

The designing of winding in the case of CTs is quite straight forward and easy task as the maximum current flowing through the secondary winding is independent of VA burden on the current transformer.

The normally used secondary current ratings are of 1 A or 5 A, therefore, selection of the conductor depends upon the type of insulation used i.e. oil type or cast resin and the short circuit current capability of CT.

C. Error Calculation

After finalizing the core and winding design, the ratio and phase error shall be calculated for the designed core-coil assembly. The results should meet the error limits mentioned in the IEC 60044-1. The steps involved in the calculation are:

i. Calculation of secondary induced emf E_{si}(V):

$$E_{si} = I_s \text{ x } \square \quad (8)$$

where

Z is total secondary impedance

$$Z = \sqrt{(R_b + R_{wind})^2 + X_b^2} \quad (9)$$

Where

R_b = Resistance of Burden in Ohm

R_{wind} = Resistance of Winding at 75°C

X_b= reactance of Burden in ohm

ii. Determination of Flux density B_m(T) required to induce E_{si}

$$B_m = \frac{E_{si}}{4.44 \text{ x } f \text{ x } N_2 \text{ x } A_{core}} \quad (10)$$

Where

f = frequency in Hz

N_2 = number of secondary turns

A_{core} = core area in mm^2

iii. Calculation of reactive and watt loss current

The reactive (H_r) and watt-loss (H_w) component of magnetizing force necessary to induce the flux density B_m can be obtained from the magnetizing curve of the core and consequently the I_r and I_w can be found as under:

$I_r = H_r \text{ x } L_m$ & $I_w = H_w \text{ x } L_m$ (11)

Where L_m = mean length of core in m.

iv. Determination of Ratio and phase errors

The error then calculated using equations (4) and (7).

D. Calculation of Instrument Security Factory (ISF)/ Accuracy Limit Factor (ALF)

The instrument primary current limit of metering CT is the value primary current beyond which CT core becomes saturated while the accuracy limit primary current of protection CT is the value of primary current up to which CT does not saturate. The ISF or ALF can be found using following relations:

i. Calculation of secondary limiting EMF and corresponding flux density:

E_{limit} = ISF x I_s x Z or ALF x I_s x Z (12)

$$B_m = \frac{E_{limit}}{4.44 \text{ x } f \text{ x } N_2 \text{ x } A_{core}} \quad (13)$$

ii. Determination of I_e(A) and subsequently calculation of ISF/ALF:

$I_e = H_o \text{ x } L_m$ (14)

For measuring core:

$$\frac{I_e}{(I_2 \ x \ ISF)} \ x \ 100 \geq 10 \quad (15)$$

For protection core:

$$\frac{I_e}{(I_2 \ x \ ALF)} \ x \ 100 \leq composite \ error \quad (16)$$

IV. METHODOLOGY

Since it has been discussed in the above section, the core design is the first and the most important step as it directly affects the ratio and phase errors, therefore independent variables which affect the CT performance are ID, OD and HT. Other variable may be the diameter of the secondary conductor, but this does not have much effect on the performance of CTs. Only core design parameters have been considered while writing the optimization code.

The algorithm used for the optimization uses the basic blueprint of pattern search [10]. The flow chart of the working of the algorithm is shown below:

Step-1: **Input** data

⇩

Step-2: **Estimate** an initial design and stores it as optimum solution and corresponding material cost as minimum cost

⇩

Step-3: **Generate** discrete sets of each independent variable using some step value X=*{…,x_i+Δ, x_i, x_i-Δ,…}*

⇩

Step-4: **Using** discrete sets of Step-3, generate unique combinations independent variables

⇩

Step-5: **Do** design calculations for each combination

⇩

Step-6: **Find** the combination giving minimum cost and meeting requirement

⇩

Step-7: **while** *material cost obtained in Step-6 <>material cost of Step-2* material cost obtained in Step-6 is new optimum solution and go to Step-3

⇩

Step-8: **Output** the result

V. SIMULATION

Algorithm has been developed using macros of MS EXCEL. The macro consists of three Sub routine. First sub routine returns the initial solution, second Sub routine do the calculations of the combinations while in third Sub routine, main code is implemented. The graphical user interface has been developed using worksheets of MS EXCEL.

As it mentioned in above sections, we have selected the CT having characteristics as mentioned below:

i. Transformation ratio = 800 A / 5 A
ii. Type of CT = Metering (cast resin Box Type)
iii. Voltage class = 12kV
iv. Accuracy class = 0.5
v. Instrument security factor = 10
v. Short time withstand current = 12.5kA

In order to obtain the results from the program developed, following steps are performed:

Step1: The above data is entered in the worksheet name “Input”. Also the other necessary inputs like clearance, size of primary conductor, rate of copper and core are also entered.

Step2: After providing the necessary inputs, push the button “Run optimization”, and the ‘opt’ worksheet is appeared on which different calculation are being done by the main code.

Step3: When the program finds the optimum solution, it terminates the loop and the ‘output’ sheet appears.

The snapshot of ‘output’ sheet is shown below:

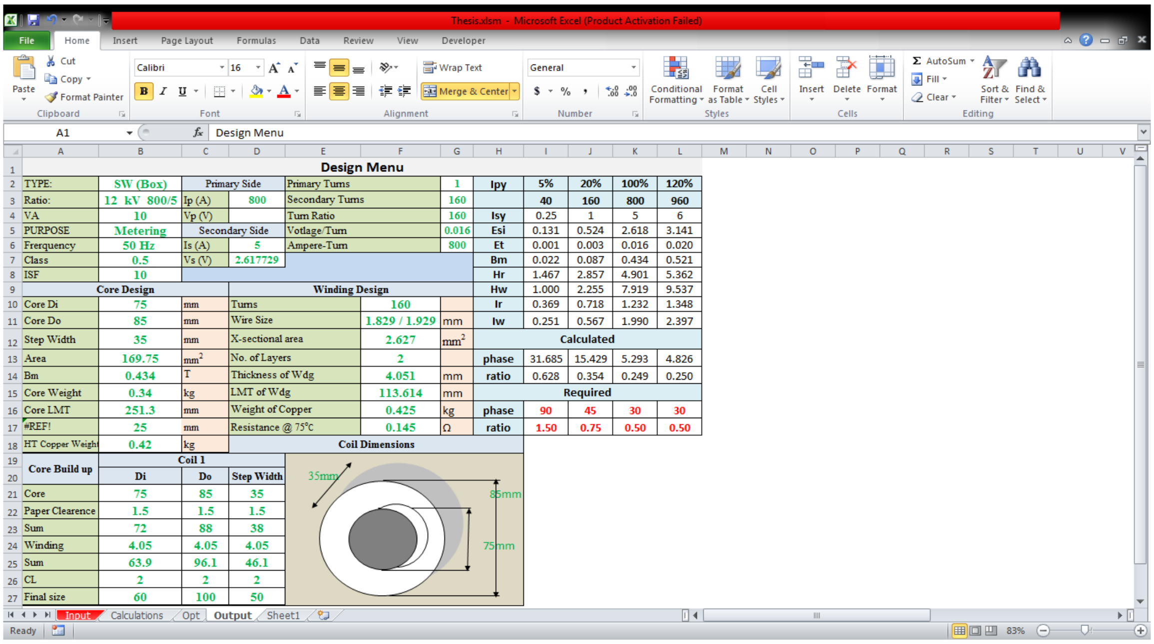


Figure 5: Snapshot of “Output” Worksheet

The output result obtained using this program is as under:

Table 1 PHYSICAL DIMENSION AND WEIGHTS

Dimensions in mm	ID	OD	HT
	75	85	35
	ID_final	OD_final	HT_final
	60	100	50
Weights in kg	Wcore	Wcond	Wcore+coil
	0.35	0.422	0.772

Table 2 Errors calculation

Ip	5%	20%	100%	120%
	40A	160A	800A	960A
Is	0.25A	1A	5A	6A
CALCULATED				
Phase	31.748’	15.463’	5.304’	4.839’
Ratio	0.628%	0.356%	0.250%	0.251%
REQUIRED				
Phase	90’	45’	30’	30’
Ratio	1.50%	0.75%	0.50%	0.50%

VI. VERIFICATION OF RESULTS & COMPARISON

Based upon output results, the core coil assembly of the CT was manufactured and tested using the CT accuracy test equipment in order to ascertain the viability of the devised program for real world implementation.

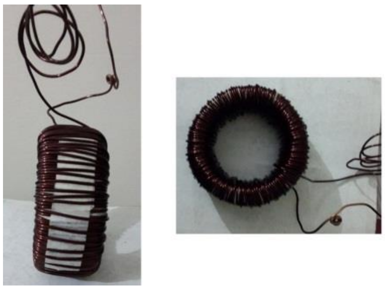


Figure 6: Picture of designed CT core and coil assembly

The physical dimensions and results of manufactured core coil assembly are summarized below:

Table 3 Physical Dimension and weights

Dimensions in mm	ID	OD	HT
	75	85	35
	ID_final	OD_final	HT_final
	62.4	106.3	43
Weights in kg	Wcore	Wcond	Wcore+coil
	0.40	0.43	0.830

The graphical representation of ratio and phase errors’ allowable limit, their calculated and measured value are shown Figure 7 & 8.

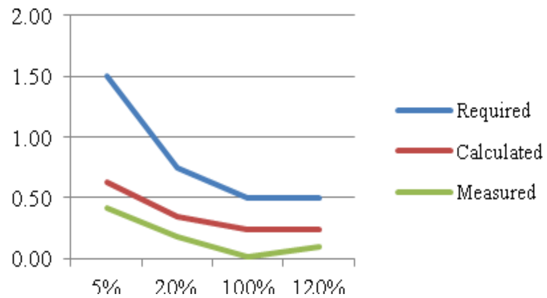


Figure 7: Percentage rated primary current Vs % Ratio error

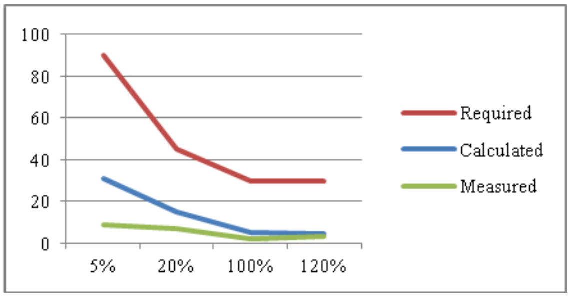


Figure 8: Percentage rated primary Current Vs % Phase error

The weights and material cost of the designed CT has been compared with the CT of same type manufactured locally. The comparison showed that the cost of designed CT's core coil assembly is 80% less than the locally manufactured CT. The summary of the comparison made is shown below:

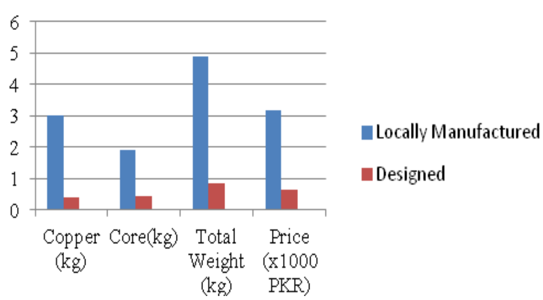


Figure 9: Graphical representation of weight and Price Comparison

It should also be noted that above comparison only considers the saving in secondary core coil assembly cost. The saving in primary conductor and volume of epoxy resin has not been considered in the comparison. If these are also taken into consideration, it may be established that the designed CT is not only economical but also it provides saving in volume/ space.

VII. CONCLUSION

The devised computer aided program for the designing of CT is not only easy and time saving but also provides the best economical design possible keeping in view all the practical constraints. The results obtained by using this program not only conform to experimental data but also provides economical solution as the saving in the copper and core is 85 % and 75 % respectively as compared to the locally manufactured CT which results in the cost of reduction of more than 80%.

The program developed can be improved by considering the industrial practices and also by including other features which are not included in this work like consideration of insulating resin and primary turn selections and its size and their consideration in selection of optimal solution. This program with slight change can also be applicable for protection type current transformer.

This paper is based upon the Master's thesis submitted in the Eletrical Engineering Department University Of Engineering And Technology Lahore.

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