

Design Aspects of Core Components of Stabilizer Transformer of given Power Rating



S. Saratchandra Singh, Anish Thingujam, M.S.P. Subathra, S. Sanathoi Singh

Abstract: *There are wide ranges of transformers for voltage stabilizer. The autotransformers used in the voltage stabilizers are designed and constructed under design specifications of standard assumptions. In this work, core components of autotransformer are designed using power rating as only input parameter, nevertheless, taking into consideration of standard assumptions. The bounded area of the flux of magnetic field forms basis for core area of electromagnetic induction of transformer. The core area of the electromagnetic induction and window area of transformer for housing copper windings, thus, have linkage with power rating and e.m.f equation of the transformer. Accordingly, we establish a relationship, in the form of equation, between core area and window area. The product of core area and window is equated to the numerical value of the product that has been determined from the power rating and standard assumptions of other design parameters. With the help of proportional relationship, standard as well as from aspect of desired look of the transformer, between length and breadth of the core area and similarly for window area, the dimensions of the core components of the transformer are designed. The designed parameters are tested for feasibility and a transformer under the designed parameters is constructed to validate the experimental result with the theoretical values of the parameters of the transformer. This design is used to determine accurate dimensions of core components of transformer of desired power rating and desired look. This design aspect minimizes waste of core material in fabrication of core components and help in proper lamination of components such as E & I of the transformer.*

Keywords: *Autotransformer, core area, core components, e.m.f equation, power rating, window area.*

I. INTRODUCTION

We often experience power failures and voltage problems in our daily life. In such situations, sometimes we experience breakdown of electrical appliances within our home. The use of voltage stabilizer with appliances like refrigerators, television, music system, washing machine, and so on, is very common as it protects the appliances from voltage fluctuation to certain extent. The specific purpose behind use of voltage stabilizer [2] is to protect the devices against voltage fluctuations.

The electrical appliances are designed to operate under a specific voltage range to give desired performance. Voltage stabilizer regulates the voltage if the supply voltage varies or fluctuates over a given range. The voltage stabilizer detects input voltage conditions and correspondingly brings the output voltage to a permissible range before it feeds to the load.

In other words, the purpose of voltage stabilizer is not for providing a constant voltage output and instead it operates the load in an acceptable range of voltage, for instance, with tolerance of $\pm 10\%$ of the rated voltage [4]. The main components of voltage stabilizer are transformer, relays, and electronic circuit. These components are set to perform specific tasks and in addition, they are designed to work in a coordinated way so that the output voltage is brought to desired voltage range. The electronic circuit senses the input voltage and if the input voltage is within predefined range, it operates an appropriate relay from amongst the relays provided at different tapping positions in the input winding of the transformer. The voltage obtained with the operation of relay is fed into transformer as input voltage supply. The transformer adds more voltage if input voltage is below the desired output voltage range and on the other hand the transformer reduces voltage if input voltage is higher than the desired output voltage range. There are wide ranges of transformer in the market. Manufactures of transformers for the stabilizers adopt different approaches in design of the transformers. In this work, we design transformers from the aspects of power ratings of the transformers.

II. BACKGROUND AND LITERATURE REVIEW

Autotransformer [3] is an electrical transformer where primary and secondary windings share same common single winding (as opposed to isolation transformers with two separate windings). It is one winding transformer. It is small, lighter and provides greater voltage stability and tolerances [3]. In autotransformer, a single winding is used and it does functions of both primary and secondary windings. An important characteristic of transformer is that it does not and cannot change frequency even though it can adjust voltage. Frequency, on the other hand, in most cases is irrelevant to the proper operation of appliances. We consider autotransformer for the design purpose in this work and primary objective is to design core components of transformer such as bobin, E, I, and so on, from given power rating of the transformer so that we can construct transformer of desired power rating. The power rating is considered as the only given parameter in design of the transformer components and it is also used to derive other design parameters,

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which are required for the design of the components and the transformer. The bobin, E, I are some of the components of transformer and these components have closer linkage with the core area of electromagnetic induction and window area where the copper windings are housed. The core area and window do have linkage with length of copper wire, diameter of the copper wire.

The relationship between core area and magnetic flux is taken as an aspect for the design purpose. The nature of induced e.m.f discovered by Faraday and law of nature of self-induction are important nature of laws that help develop the design concepts of the core components. Whenever flux of magnetic field through an area bounded by a closed conducting loop changes, an e.m.f is produced in the loop and its magnitude is equal to the rate of change of the flux linkages. The e.m.f is given by, $e = \frac{d\phi}{dt}$, where, $\phi = \int \vec{B} \cdot d\vec{S}$ is the flux of the magnetic field, \vec{B} through the area, $d\vec{S}$. According to principle of self-induction, when a current is established in a closed conducting loop, it produces a magnetic field. This magnetic field has its flux through the area bounded by the loop. If the current changes with time, the flux through the loop changes and hence an e.m.f is induced in the loop. The e.m.f is induced in the coil due to the change of its own flux linked with it. If current through the closed conducting loop is changed, then the flux linked with its own turns also changes. The magnetic field at any point due to a current is proportional to the current. The e.m.f induced in the coil when the current in the coil changes, is given by, $e = N \frac{d\phi}{dt}$, where N is number of turns of the coil. The principle of self-induction, the magnetic flux and bounded area have built design aspects for core area and window area of the transformer. The relationship of the induced e.m.f, bounded area, magnetic flux is established by E.M.F equation of the transformer.

A. EMF Equation of Transformer

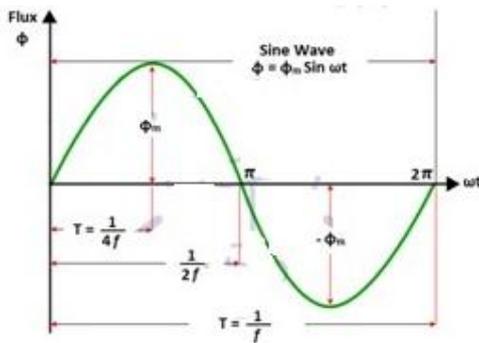


Figure 1: EMF Equation

Lets,

N_1 = Number of turns in primary windings.

N_2 = Number of turns in second windings.

Φ_m = Maximum flux in the core, in Weber, ($\Phi_m = B_m \cdot A_c$)

f = Frequency of A.C input in Hz.

Induced e.m. f. in a coil of N turns is given by

$$e = N \frac{d\phi}{dt} \text{ volts (or webers/sec)}$$

As shown in the Fig. 1, flux increases from its zero value to maximum value ϕ_m in one quarter of the cycle, i.e. in $1/4f$ second.

Therefore,

average induced e.m.f,

$$\begin{aligned} V_{av} \text{ or } E_{av} &= \frac{1}{T} \int_0^T e dt \\ &= 4f \int_0^{\phi_m} N d\phi \\ &= 4f N \Phi_m \text{ Weber/Sec or Volt} \\ &= 4f N A_c B_m \end{aligned}$$

where, A_c is cross sectional area of the coil and B_m is maximum flux density linked with the coil.

If k_f is form factor of transformer, then $k_f = \frac{V_{RMS}}{V_{AV}}$, therefore, $V_{RMS} = 4 k_f f N A_c B$ -- (1)

III. METHODOLOGY

In the design of the transformer, output power rating of the transformer is considered as the main design parameter. From power rating and e.m.f equation of the transformer,

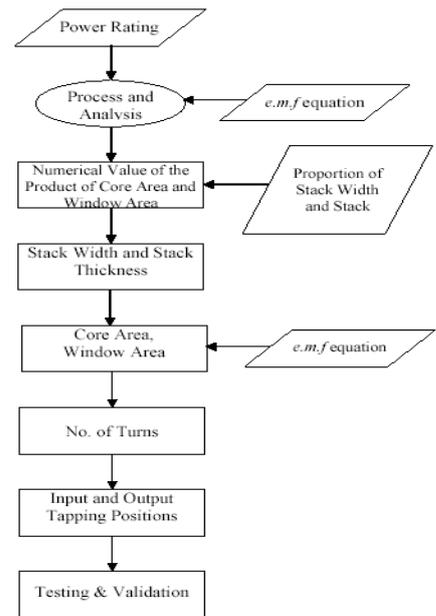


Figure 2: Flow Chart for Design and Testing

we derive other design parameters of the transformer. Flow-chart for determination of the design parameters and testing & validation of the transformer is illustrated in Figure 2. The core area can be expressed in terms of stack width, a and similarly window area can also be expressed in terms of stack width. The window area where copper windings are housed is expressed as product of $0.5a$ and $1.5a$, that is, $window\ area = 0.5a \times 1.5a$. The gross cross sectional area, on the other hand,

is expressed as product of stack width and gross stack thickness, that is, gross cross sectional area, $A_{cg} = a \times b_g$. There is no standard proportional relationship between stack width and gross stack thickness, however, in order to have apparent look of the transformer, we can take value of gross stack thickness as 1.5 times or 1.6 times of stack width.

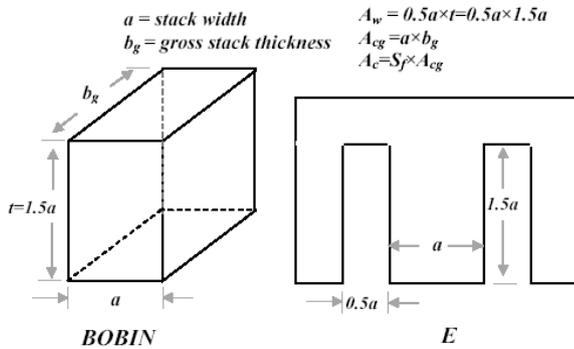


Figure 3: Bobin and E

Thus, gross cross sectional area and window area of the transformer can be represented in terms of stack width, a . From power rating and e.m.f equation of the transformer, we can determine numerical value of the product of core area and window area, and this numerical value is used to determine value of stack width.



Figure 4 : E and BOBIN

With the value of stack width, the sizes of the components such as **E** and **Bobin** are determined.

A. Stack Width and Stack Thickness

If N number of turns of the coil fills up K_w times the window area A_w , then

$$K_w \cdot A_w = N \cdot a_s$$

where,

a_s is cross sectional area of copper wire, $A_w = a \times t = 0.5a \times 1.5a = 0.75a^2$ (in which a is stack width) and N is number of turns.

Let, N_1 = number of turns of the primary windings and N_2 = number of turns of the secondary windings, then

$$K_w \cdot A_w = N_1 \cdot a_1 + N_2 \cdot a_2 \quad \text{-- (2)}$$

Again, if J is the current density in the coil, then

$$a_1 = \frac{I_1}{J}$$

and, $a_2 = \frac{I_2}{J}$, then

$$K_w \cdot A_w \cdot J = N_1 \cdot I_1 + N_2 \cdot I_2 \quad \text{-- (3)}$$

From Eqn. 1 and 3, we have

$$K_w \cdot A_w \cdot J = \frac{V_1 \cdot I_1}{4K_f f A_c B} + \frac{V_2 \cdot I_2}{4K_f f A_c B}$$

$$= \frac{P_1 + P_2}{4K_f f A_c B}$$

Therefore,

$$A_w \cdot A_c = \frac{P_2 \left(1 + \frac{P_1}{P_2}\right)}{4K_f f A_c K_w J B}$$

$$= \frac{P_2 \left(1 + \frac{1}{\frac{P_2}{P_1}}\right)}{4K_f f K_w J B}$$

If

$$P_1 = \text{Input power, } P_i$$

$$P_2 = \text{Output power, } P_o$$

Then,

$$A_c \cdot A_w = \frac{P_o \left(1 + \frac{1}{\frac{P_o}{P_i}}\right)}{4K_f f K_w J B}$$

$$= \frac{P_o \left(1 + \frac{1}{\eta}\right)}{4K_f f K_w J B} \quad \text{-- (4)}$$

where, $A_c = a \times b$ is the actual cross-sectional area of the core which is required for power transmission of power rating, P_o ; a is stack width and b is stack thickness. The other parameters to be used in Eqn. 4 are $K_w = 0.3$ to 0.7 , $f = 50$ Hz, $J = 3$ to 5 A/mm², $B = 0.9$ to 1.3 Tesla.

The gross cross sectional area A_{cg} of transformer of power rating, P_o is given by

$$A_{cg} = \frac{A_c}{S_f} \quad \text{-- (5)}$$

where, S_f is stacking factor and it is normally taken as 0.8 . The value of A_{cg} is generally determined for a given power rating and it is used for calculation of stack thickness, b_g . To have an apparent look of the transformer the gross stack thickness b_g in terms of stack width a can be expressed as

$$b_g = 1.5a \text{ (or } b_g = 1.6a).$$

With given stack width a , we can calculate gross stack thickness b_g

$$b_g = \frac{A_{cg}}{a} \quad \text{-- (6)}$$

From Eqn (5) and (6)

$$A_{cg} = \frac{A_c}{S_f}$$

$$\Rightarrow a \times b_g = \frac{a \times b}{0.8}$$

$$\Rightarrow b = 1.2a \quad \text{-- (7)}$$

B. Estimation of Stack Width

In Eqn. (4), we take values of other design parameters as-

- i. rated output power, P_o
- ii. efficiency of the transformer, η
- iii. form factor, $K_f = 1.1$
- iv. window factor, $K_w = 0.3$ to 0.7
- v. frequency, $f = 50$ Hz
- vi. magnetic field, $B = 0.9$ to 1.3 Tesla
- vii. current density, $J = 3$ to 5 A/mm²

With the given rated output power, P_o (in VA) we can determine the current, $I \left(= \frac{P_o}{V_o} \right)$.

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With output current, I_o and current density, J (to be chosen from 3 to 5A/mm²) we can determine cross-sectional area, a_{so} of the copper wire. The standard wire from SWG table corresponding to a_{so} is to be chosen for output windings. We have to use similar process for selecting wire size of cross sectional area, a_{si} for input windings. From Eqn (4), we can calculate the value of $A_c \times A_w$ and let the value of $A_c \times A_w$ be represented by x .

Then,

$$\begin{aligned} A_c \times A_w &= x \\ \Rightarrow A_c \times 0.75a^2 &= x \quad [A_w = 0.5a \times 1.5a = 0.75a^2] \\ \Rightarrow S_f \times A_{cg} &= \frac{x}{0.75a^2} \\ \Rightarrow 0.8 \times A_{cg} &= \frac{x}{0.75a^2} \\ \Rightarrow a \times b_g &= \frac{x}{0.8 \times 0.75a^2} \\ \Rightarrow a &= \sqrt[4]{\frac{x}{0.9}} \end{aligned}$$

With the value of $A_c \times A_w$ ($=x$) obtained from Eqn. 4, we can determine value of stack width.

C. Number of Turn per Volt

From Equation 1,

$$N = \frac{E}{4f A_c B k_f} \quad \text{then}$$

$$\text{Turn per Volt, } T_V = \frac{10^4}{4f A_c B K_f} \quad ,$$

where, $f= 50 \text{ Hz}$, unit of $B= 1 \text{ Tesla} = 10^4 \text{ Weber/cm}^2$,
Form factor, $k_f= 1.1$

In calculating N for power transformers, we should take $B= 1.3 \text{ Tesla}$ and $k_f=1$ (for sine wave) for primary winding and $B= 1 \text{ Tesla}$ and $k_f=1.1$ for secondary winding.

D. Current Density, J

It is an important parameter and standard value of it must be within 3 to 5 A/mm². In other words, from perspective of design, the ratio of the current (in Amps) and cross sectional area (in mm²) of the wire must be taken in the range of 3 to 5, because a value beyond 5 may damage the coil due to overload.

For example, if a transformer of rating $P_o= 500 \text{ VA}$ draws a current of 10A, then a standard enameled copper wire of 12 SWG of cross sectional area, $a_s= 2.642 \text{ mm}^2$ can carry current density, J of 3.8A/mm², which is within standard value of 3 to 5 A/mm².

Therefore,

$$J = \frac{10}{a_s} \text{ A/mm}^2 = 3.8 \text{ A/mm}^2$$

where, a_s is cross sectional area of the copper wire. For power rating, $P_s= 500 \text{ VA}$, $V_s= 230 \text{ V AC}$, the current is 2.2A and cross sectional area of the size, a_{so} is given by $2.2/J \text{ mm}^2$.

E. Determination of Weight of Copper

Lets,

N_i = No. of input winding

N_o = No. of output winding, wherever applicable

N_c = No. of charging winding, wherever applicable

Then,

Weight of copper

$$= \frac{N_i a_{si} + N_o a_{so} + N_c a_{sc}}{10^3} \times S_g \times L \quad \text{grams}$$

where,

a_{si} is cross-sectional area of input coil

a_{so} is cross-sectional area of output coil

a_{sc} is cross-sectional area of charging coil

S_g is specific gravity of copper in gm/cc

L is mean perimeter of core cross section in mm

F. Design Feasibility

Let $A_c = a \times b$ be actual core cross-sectional area of a given transformer of power rating, P_o . And let N_i , N_o and N_c be no. of input winding, no. of output winding and no. of charging winding respectively. The basic concept of feasibility is to see if these three windings, wherever applicable, fit into window gap which has an area, $A_w = 0.5a \times 1.5a = 0.75a^2$. If it fits then the design could be considered as feasible. The steps for the feasibility check could be as follows-

- i. calculate cross sectional areas of coils such as a_{si} , a_{so} and a_{sc}
- ii. take window factor, $K_w = 0.3 \text{ to } 0.7$ and see if $K_w \cdot A_w \geq (N_i a_{si} + N_o a_{so} + N_c a_{sc})$ -- (8)

IV. DESIGN, CONSTRUCTION AND VALIDATION

We design a transformer of power rating, $P_o= 500\text{VA}$ as per design aspects of this work and the transformer is constructed using the design specifications, primarily to validate the result.

Given parameters:

Output power, $P_o= 500 \text{ VA}$

Presumption:

Efficiency, $\eta = 0.9$

Frequency, $f= 50 \text{ Hz}$

Magnetic Field, $B=1.3 \text{ Tesla}$

Window Factor, $K_w = 0.3$

Form Factor, $K_f = 1.1$

Current Density, $J= 4\text{A/mm}^2$

Input Power and Window Area:

$$\text{Input power, } P_i = \frac{P_o}{\eta} = \frac{500}{0.9} \text{ VA} = 555 \text{ VA}$$

Let a (in cm) be stack width, then, Window Area,

$$A_w = 0.5a \times 1.5a = 0.75a^2$$

Determination of Core Area:

$$\begin{aligned} A_c \cdot A_w &= \frac{P_o \left(1 + \frac{1}{\eta}\right)}{4 K_f f K_w J B} \\ &= \frac{500 \times \left(1 + \frac{1}{0.9}\right)}{4 \times 1.1 \times 50 \times 0.3 \times 4 \times 1.3} \times 100 \\ &= 307.56 \text{ cm}^4 \end{aligned}$$

$$\Rightarrow A_c \times A_w = 307.56$$

$$\Rightarrow (S_f \times A_{cg}) \times (0.5a \times 1.5a) = 307.56$$

$$\Rightarrow 0.8 \times a \times 1.5a \times 0.75a^2 = 307.56$$

$$\Rightarrow a = 4.2 \text{ cm}$$

Then,

$$b_g = 1.5a$$

$$= 6.3 \text{ cm (} b_g \text{ is taken as } 1.5a)$$

$$A_c \times A_w = 307.56$$

$$\Rightarrow A_c \times 0.5a \times 1.5a = 307.56 \quad (a = 4.2 \text{ cm})$$

$$\Rightarrow A_c = 23.24 \text{ cm}^2$$

Calculation of Total Number of Turns and Turn per Volt for determination of tapping positions:

In calculation of actual number of turns such as Total Number of Turns for the A.

C primary winding, N_{ACP} and Charging Winding, N_{ACCHG} wherever applicable, the actual core cross sectional area, A_c is used. If the maximum input voltage, V_1 is 260V, then the number of turns for this 260V is given by-

$$N_{ACP} = \frac{E \times 10^4}{4 \times k_f \times A_c \times B \times f}$$

$$= \frac{260 \times 10^4}{4 \times 1.1 \times 23.24 \times 1.3 \times 50}$$

$$= 391 \text{ turns}$$

$$T_{VAC} = \frac{\text{Total No. of Turns}}{\text{Maximum Input Voltage}}$$

$$= 391/260 = 1.5 \text{ Turns per Volt}$$

Determination of tapping position for the desired output voltage:

The desired output voltage is derived from the copper winding (the single winding, as it does not have secondary winding) by tapping from it. The number of turns (say N_2) for the tapping position of the desired output voltage (say V_2) serves as secondary winding. Number of turns, N_2 at this tapping position corresponding to V_2 (say, 230V if desired output voltage is 230V) is calculated from maximum input voltage, V_1 (260V in this case) and its corresponding number of turns, N_1 (391 turns in this case).

$$\frac{N_1}{V_1} = \frac{N_2}{V_2}$$

$$\Rightarrow \frac{391}{260} = \frac{N_2}{230}$$

$$\Rightarrow N_2 = 345$$

This output tapping position is named as 4th tapping position and it is the point from where output voltage is to be taken. It also serves as input position for the input of voltage range 200 -230V.

Determination of input tapping positions for input voltages of varying ranges:

The other input tapping positions are determined with reference to output tapping position which has $N_2=345$ turns, $V_2=230V$.

3rd tapping position-

$$N_2=345, V_2= 230V$$

$$\frac{N_1}{V_1} = \frac{N_2}{V_2}$$

$$\Rightarrow \frac{N_1}{200} = \frac{345}{230}$$

$$\Rightarrow N_1 = 300$$

The 3rd tapping is input position for the input of voltage range 175-200V.

2nd tapping position-

$$N_2=345, V_2= 230V$$

$$\frac{N_1}{V_1} = \frac{N_2}{V_2}$$

$$\Rightarrow \frac{N_1}{175} = \frac{345}{230}$$

$$\Rightarrow N_1 = 262$$

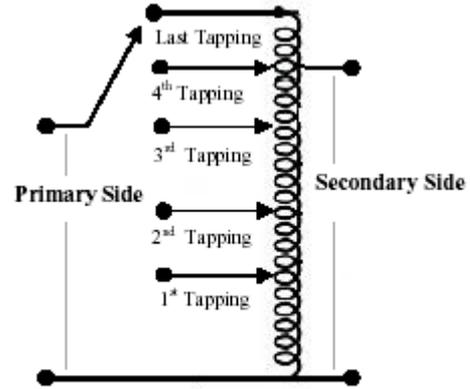


Fig.5: Tapping Positions

The 2nd tapping is input position for the input of voltage range 150-175V.

1st tapping position-

$$N_2=345, V_2= 230V$$

$$\frac{N_1}{V_1} = \frac{N_2}{V_2}$$

$$\Rightarrow N_1 = 225$$

The 1st tapping is input position for the input of voltage range 120-150V.

A. Design Specification of Voltage Ranges

Input				Output			
No. of Turns, N1 (Input)	Voltage, V1 (Input)	Input Tapping Position	Input Voltage Range for the tapping position	No. of Turns, N2 (Output)	Voltage, V2 (Output)	Output Tapping Position	Output Voltage Range
391	260	5th	>230-260	345	230	4th	202-230
345	230	4th	>200-230	345	230	4th	200-230
300	200	3rd	>175-200	345	230	4th	201-230
262	175	2nd	>150-175	345	230	4th	198-230
225	150	1st	>120-150	345	230	4th	184-230

Table 1: Input and Output Voltage Ranges of the Design

The transformer designed as per specifications stated above has to produce the output voltages (voltage ranges) corresponding to the input voltage (voltage ranges) as illustrated in Table 1. The theoretical/expected value may differ, because of standard assumption, from the actual to the extent of 5 to 10 percent. The expected and actual output of the voltages at various inputs and output tapping positions are illustrated in the Table-2.

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Input				
Experiment No.	No. of Turns, N1 (Input)	Actual Input Voltage, V1	Input Tapping Position	Input Voltage Range for the tapping position
1	391	252	5th	>230-260
2	300	185	3rd	>175-200
3	391	169	5th	>230-260

Output				
Experiment No.	No. of Turns, N2 (Output)	Expected Output, V2E	Actual Output, V2A	Output Tapping Position
1	345	222	217	4th
2	345	212	208	4th
3	345	149	144	4th

Result		
Experiment	Difference V2E-V2A	Variations
1	5	2.25%
2	4	1.89%
3	5	2.25%

Table 2: Validation of Result

B. Design Feasibility

$P_0=500VA$, Voltage, $V_0=230V$, therefore, Current, $I_0=2.2A$, Current density as per presumption in Eqn. 4, $J=4 A/mm^2$, Window factor as per presumption in Eqn. 4, $K_w = 0.3$

Cross sectional area of the copper wire, $a_s = I/J = 0.55mm^2$ and for this value of a_s , we can take copper wire of 24 SWG. Maximum No. of turns, $N = 391$

Then for Copper Wire of 24 SWG,

$$N \times a_s = 391 \times 0.55mm^2 = 2.2 cm^2$$

$$K_w \times A_w = 0.3 \times 0.75 \times 4.2 \times 4.2 cm^2 = 3.9 cm^2$$

Theoretical condition for design feasibility as per Eqn. 8	Results		SWG of Copper Wire	Feasibility
	$K_w \times A_w$	$N \times a_s$		
$K_w \times A_w \geq N \times a_s$	$3.9 cm^2$	$2.2 cm^2$	24 SWG	Feasible as $K_w \times A_w > N \times a_s$

Table 3: Condition for Feasibility of Design

For Copper Wire of 19 SWG,

$$a_s = 1.016mm^2, \text{ then current } I = a_s \times J \approx 4A$$

$$N \times a_s = 391 \times 1.016mm^2 = 3.9cm^2$$

$$K_w \times A_w = 3.9 cm^2$$

In the above design, we can even use copper wire of 19 SWG, which has cross sectional area of $1.016 mm^2$, as design value of $K_w \times A_w \geq$ experimental value of $N \times a_s$.

V. CONCLUSION

There are some standard proportional relationships among parameters, such as length, width, and thickness of the core components of transformer, for example, the parameter such as length, thickness are constant multiple of the width. Nevertheless, the important aspect here is to find value of

the width, which is further used to determine other parameters. The proportional relationship, except standard proportion for certain parameters, may vary and under this condition we can also determine dimensions of the core components from perspective of desired look of the transformer. The flux of the electromagnetic field and its bounded area are important parameters for *e.m.f* equation of transformer. In addition, from the *e.m.f* equation, desired power rating of the transformer and proportional relationship among the length, width, thickness of the core components, we can determine, for example, the value of width, in other words, stack width in this work. Thus, with given power rating we can design accurate dimensions of the core components of transformer. This work gives a fair idea as to how to design core components of transformer economically and yet based on the size, desired look of the stabilizer we can do pre-fabrication planning for dimensions of the core components of the transformer.

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