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DEVELOPMENT AND IMPLEMENTATION OF A THREE-PHASE VARIABLE AUTOTRANSFORMER FOR A DETACHABLE MACHINE TRAINER

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ABSTRACT

This paper presents the development and implementation of a Three-Phase Variable Autotransformer (VARIAC) with a rating of 3KVA and voltage supply of 0-380 volts for a Detachable Machine Trainer. This was born out of the fact that the detachable Machine Trainer bought by my Department for conducting series of experiment in the Electrical power Laboratory lack this vital equipment. The variac core was designed and constructed using circular sheet metal laminations to form a toroid core. Each core (3 for the 3-phases) was then stacked together and fitted with a metal shaft which was connected with three carbon brushes to give the output terminals. The output obtained from the autotransformer was then used to run the detachable machine trainer. The design considerations, calculations, implementation and the results obtained are also presented in this paper. The variac has the advantage of being smaller, lighter and cheaper than typical dual-winding transformers.

Keywords: *Autotransformer, Detachable, Machine, Lamination, Variac.*

INTRODUCTION

Electricity is one of the most important blessings that science has given to mankind. It has also become a part of modern life and one cannot think of a world without it. Electricity has many uses in our day to day life(Leshkimi, 2010).It is used for lighting homes, running fans and other domestic appliances like electric stoves, air conditioners and more. In factories, large machines are run with the help of electricity. Essential items like food, cloth, paper and many other items are produced using electricity. Electricity is usually generated, transmitted before it is distributed to the final consumer. During this process, voltage generated is transformed from one level to another through the use of a machine called a

Transformer. The transformer which transforms the voltage has proved to be the easiest means through which voltage can be transformed from one level to another. A transformer is a static or stationary piece of apparatus by means of which electric power in one circuit is transformed into electric power of the same frequency in another circuit. It can raise or lower the voltage in a circuit but with a corresponding increase or decrease in current. The physical basis of a transformer is mutual induction between two circuits linked by a common magnetic flux. In its simplest form it consists of two inductive coils which are electrically separated but magnetically linked through a path of low reluctance (Theraja *et al*., 2008). In fact one of the main advantages of a.c. transmission and distribution is the ease with which an alternating voltage can be increased or decreased by transformers (Bird, 2003). The transformer is a basic and essential equipment for the utilization of electrical energy when provided in alternating current form. It is normally classified as a machine even though it has no rotating parts. The ability of the transformer to be able to transform voltage from one level to another means it can serve different classes of consumers. Since the invention of the first transformer in 1885, transformers have become essential for the transmission, distribution, and utilization of alternating voltage (Bedell, 2010). An Autotransformer is an electrical transformer with only one winding. Autotransformers have the advantages of often being smaller, lighter, and cheaper than typical dual-winding transformers due to the fact that they have only one winding. They are sometimes called Auto step-down transformer (Horowitz *et al.,* 1989). The variable auto-transformer or variac designed and implemented in this paper is a type of autotransformer. It has become generic and commonly referred to as a variable auto-transformer. It is called variable autotransformer because they have the same construction as that of auto-transformers but the auto-transformer has a fixed and tapped secondary that produces a voltage output at a specific level while the variable auto-transformer is designed such that it can be varied continuously over the entire voltage range for which it is designed. For this paper, our design is from 0 to 380V range and a rating of 3Kva. Figure1 shows the block diagram of the variac.

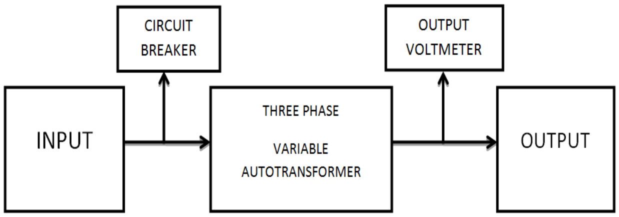

Fig 1. Block diagram of the variac.

MATERIALS AND METHODS

The variac is mainly comprised of toroidal core manufactured using magnetic sheeting with very low loss and high permeability. The variac is also known as a variable autotransformer. It is an extension of the function of the autotransformer. The variac is a special type of transformer, generally having a single winding and a single layer. The top section of the windings is flattened and machined to remove the insulation and provide a smooth surface for the sliding brush that is used to select the voltage needed as shown in Figure 2 (Hemeyer, 2001).

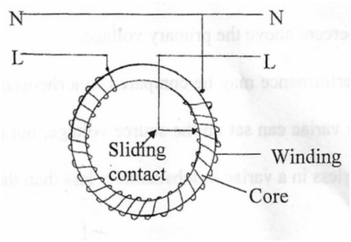

Fig. 2. Winding diagram of a variac

In this design of the variac, certain parameters and details were used as divide to achieving the overall objective. These parameters will either be specified or determined using appropriate formulae and equations. The variac which is also known as a variable auto-transformer as the name suggests is also a transformer. Hence there are very little differences in the specifications when compared with the conventional transformer. For this paper, the details which are known are as stated below:

Power rating	3KVA
Input (primary) voltage	415V
Output (secondary) voltage	(0-380) V
Frequency of supply voltage	50Hz

Number of phases Three phase
Type of cooling Natural air
Transformer type Auto-transformer
Tapings Variable

(a)CORE AND WINDING ANALYSIS

Determination of Voltage per Turn

To design a three phase variac means to design three individual variac which is mounted on one stem with a central and uniform knob to vary the voltage on each core so that we can achieve a balanced three phase voltage. Therefore in doing the calculations we have to do our calculation for single phase since all the phases are equal. Therefore to find the value of voltage that will be induced in each turn for a single phase, the voltage per turn can be obtained using equation 3.1.

$V/t = \frac{E}{N}$ - - 1

Where: E = E.m.f. induced in the winding
N = number of turns

But $E = 4.44fN\Phi_m$ -- 2

(e.m.f equation of a transformer)

Where, f = frequency of supply voltage 60Hz
N = Number of turns
E = Induced e.m.f in the winding (volt)
Φ_m=Maximum flux linking the winding and the core (in Weber)

Substituting equation (2) into equation (1)

$$V/t = \frac{4.44 fN\Phi_m}{N}$$

$V/t = 4.44 f\Phi_m$ - 3

Also,

$V/t = C\sqrt{KVA}$ - 4

The value of C ranges from 0.45-1.0 for power transformers (shell core), (Bingh, 1985)

A value of 0.55 was used for the purpose of this paper.

KVA = 3KVA
:. $V/t = 0.55\sqrt{3}$
V/t = 0.55 x 1.732
V/t = 0.95

Determination of area of core

The area of core is the area without air gap in the lamination. This can be obtained from equation 3.

$V/t = 4.44 f\Phi_m$ - - - 5

Where: V/t = voltage per turn = 0.95
f = frequency of supply = 50Hz

Φ_m = maximum flux ?

$\Phi_m = B_m A$ - - 6

A = Area of core = ?

Substituting equation (3.6) into (3.5)

V/t = 4.44fB_mA - 7

B_m = 1.55 (standard value for autotransformer) (Bingh, 1985)

$$A = \frac{V/t}{4.44 f\, B_m}$$

$$A = \frac{0.95}{4.44 \times 50 \times 1.55}$$

$$A = \frac{0.95}{344.1}$$

$A = 0.002760825 \text{m}^2$

$A = 27.61 \text{cm}^2$

Assuming space factor of 0.91

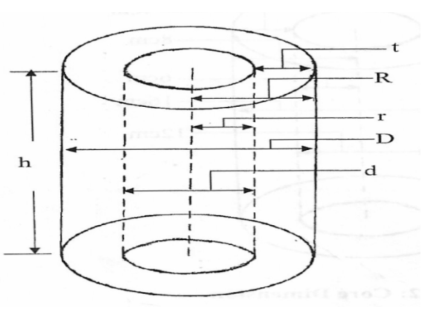

Fig 3: Core Parameter

Where,

D = External diameter
d = Internal diameter
R = External radius
r = Internal radius
h = Height
t = Thickness

$$A = \frac{27.61}{0.91}$$

$A = 30.3 \text{cm}^2$

$A = 31 \text{cm}^2$

Calculation of Core Parameters

The design of the variac requires that a toroid core be used in order to make continuous varying of output voltage easy. In doing the analysis, the toroid core is seen as a solid cylinder with its various dimensions as shown in figure 2.When the toroid core is to be analyzed, it is best if it is seen as a solid cylinder. Fig. 3. shows the diagram of a core with its various dimensions

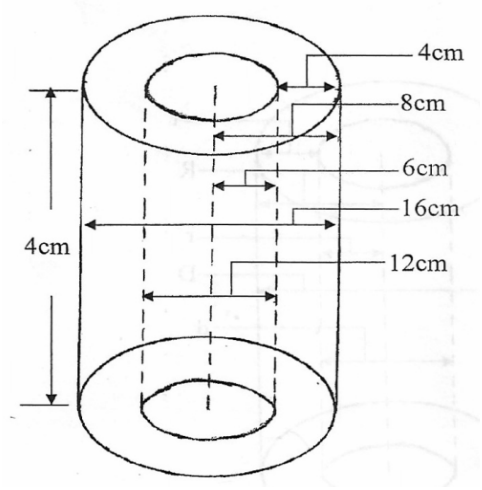

Fig 4: Core Dimension

Figure 4 shows the diagrammatic view of the core dimension of the toroid core used in the design.

Determination of Number of Turns

To calculate for the number of turns we use a single phase assumption to represent each winding which is between line to neutral(230v) and at the end of each of the winding, the three different coils were connected in WYE to get the three phase which is (400v) line to line voltage for the three phase variac.

Therefore,

$$V/t = \frac{V_S}{N_S} \quad - \quad 8$$

Where: V/t = voltage per turn = 0.95

V_s= Secondary (maximum output) voltage = 230V line to neutral

N_s = Secondary number of turns

$\therefore N_s = \frac{V_s}{V_t}$

$N_s = \frac{230}{0.95} = 242.10$

N_s = 243 turns

Determination of Number of Turns for Output Voltage Levels

Using $V/t = \frac{V}{N}$

$N = \frac{V}{V/_t}$

Where, V/t = Voltage per turn

V = Output voltage level

N=Number of turns

For 20v,

$N = \frac{20v}{0.95} = 21.1 \approx 21$ turns,

For 40v,

$N = \frac{40v}{0.95} = 42.1 \approx 42$ turns

For 60v,

$N = \frac{60v}{0.95} = 63.1 \approx 63$turns,

For 80v,

$N = \frac{80v}{0.95} = 84.2 \approx 84$turns

For 100v,

$N = \frac{100v}{0.95} = 105.3 \approx$ 105turns,

For 120v,

$N = \frac{120v}{0.95} = 126.3 \approx 126$ turns

For 140v,

$N = \frac{140v}{0.95} = 147.4 \approx$ 147turns,

For 160v,

$N = \frac{160v}{0.95} = 168.4 \approx$ 168turns

For 180v,

$N = \frac{180v}{0.95} = 189.5 \approx$ 190turns,

For 200v,

$N = \frac{200v}{0.95} = 210.5 \approx$ 211turns

For 220v,

$N = \frac{220v}{0.95} = 231.5 \approx$ 236turns,

For 240v,

$N = \frac{240v}{0.95} = 252.6 \approx$ 253turns

Determination of Conductor Size

It is necessary to know the size of wire to use for the winding because the wire needs to be able to carry the maximum current drawn by the electrical equipment with the rated power. The size of the conductor will be obtained from conductor size table after finding cross-sectional area and diameter of the conductor.

To find cross-sectional area

Using $J = \frac{I}{A}$

$\therefore A = \frac{I}{J}$ - - 9

Where: A = cross-sectional area of conductor (in mm^2)

J = Current density (in Amm^2)

I = Current (in Amperes, A)

The range of current density of a transformer influences the size. Various classes of transformer have their current density conductor value. The current density for auto-transformer ranges from 3.7Amm^{-2} to 5.0Amm^{-2}. Hence, a current density of 4.37Amm^{-2} will be used.

i.e. J = 4.37Amm^{-2}

Using $I = \frac{kVA}{V\sqrt{3}}$ - - - 10

$I = \frac{3 * 10^3}{230\sqrt{3}}$

I = 7.53A

$\therefore I \approx 8.0A$.

Substituting I and J into equation (9)

$A = \frac{8.0}{4.37}$

A = 1.83mm^2

Determination of Diameter of the Conductor

Using $A = \frac{\pi d^2}{4}$ - 11

Where, A = Cross-sectional area of the conductor (in mm^2)

d = diameter of conductor (in mm)

π =Constant=3.142

Therefore from equation (11)

$d^2 = \frac{4A}{\pi}$

$d = \sqrt{\frac{4A}{\pi}}$

Recall A = 1.83mm^2

$d = \sqrt{\frac{4 * 1.83}{3.142}}$

$d = \sqrt{\frac{7.32}{3.142}}$

$d = \sqrt{2.33}$

d = 1.526mm

Based on the calculated values of 'd' and 'A', it would have been appropriate to choose any of the gauge. However, considering the current carrying capacity, gauge (8) is more appropriate because its current carrying capacity is slightly above the rated current calculated.

It is worthy of note that the conductor used is a copper conductor. Copper conductor was chosen because it has the highest electrical conduction rating of all non-precious metals and high tensile strength which enables it resist 20cm stretching and breaking.

Determination of Copper Loss (I^2R)

Copper loss is given by;

$P_{in} = I^2R$ - - - 12

This is used to find the power loss in the winding due to current flow through the resistance of the conductor. It normally occurs in the form of heat. This term is used regardless of the material the conductor is made of. Hence it is also called wind age loss. Equation (13) was used to find the resistance.

$R = \frac{\ell L}{A}$ - 13

R = resistance of the conductor (for the entire length) in (ohms) = 3

I = Current flowing in winding in (A) = 8A

Where

ℓ = resistivity of copper conductor = $1.72 \times 10^{-8}\Omega/m$

L = length of conductor in (m)

A = Cross-sectional area of conductor = $1.83mm^2 = (1.83 \times 10^{-6})$ m

To find length of conductor

L = Mean turn of coil (m) X number of turns (N)

L=2(h+t) x N - - 14

N = 243 turns

h = height of core = 4cm = 0.04m

t = thickness of core = 4cm = 0.04m

:. L=2(0.04+0.04)x243

L = 2 (0.08) x 243

L = 38.9m

Substitutingℓ, L and A into equation (13) yields,

$R = \frac{1.72*10^{-8}* 38.9}{1.83*10^{-6}}$

$R = 36.562 \times 10^{-2}$

$R = 0.3656\Omega$

Substituting R and I into equation (12), we get,

$P_{in} = 8.0^2 \times 0.3656$

$P_{in} = 64 \times 0.3656$

$P_{in} = 23.4$ watts

This means that 23.4watts will be lost in the form of heat in the copper winding of each of the coils in the variac i.e coil A, B C representing the three individual phase.

Determination of impedance of the VARIAC

The impedance is given by;

$Z = \sqrt{R^2 + X^2}$ - - - - 14

Where

R = Resistance of the conductor = 0.3656Ω

X = Reactance of the inductor? (Ω)

To find the reactance of the inductor,

$$X = \frac{2.01NfM_a IW_e \times 10^{-6}}{2L_e} \qquad - \quad 15$$

Where

N = Number of turns = 243turns

f = Frequency of supply = 50HƵ

Ma = Average of the mean turns of the winding = $\frac{243}{2}$ = 121.5$turns$

I = Current = 8A

We = Effective width of the core = 4cm

Le = Effective length of conductor = 47.2m = 4720cm

$$\therefore X = \frac{2.01 \times 50 \times 243 \times 121.5 \times 4 \times 10^{-6}}{2 \times 4720}$$

$$X = \frac{11.869}{9440}$$

X = 0.00126Ω

Substituting X and R into equation (14)

$$Ƶ = \sqrt{(0.3656^2) + (0.00126^2)}$$

$$Ƶ = \sqrt{0.11077 + 0.000001588}$$

$$Ƶ = \sqrt{0.1107715876}$$

Ƶ = 0.3656Ω

Voltage drop caused by impedance that will be on each of the separate coil will be:

V_z = IZ - (16)

V_z = 13 x 0.3656

V_z = 4.3267 (which is negligible compared to the maximum voltage)

VOLTMETER SELECTION

The voltmeter selected to serve as voltage indicating instrument is the moving iron type with the following features.

Voltage range	0 – 450V
Accuracy	0.3 to 5.0V
Limits	Reads r.m.s value on an even scale

This is chosen because it is Robust and has a high torque/weight ratio with less frictional error.

IMPEMENTATION OF THE VARIAC DESIGN

The implementation of the design presented in this paper is broken into two parts viz: the electrical part and mechanical part which is the casing.

Electrical Part

The electrical segment comprises mainly of the magnetic core and coils used in the implementation. The first step was to construct the toroidal core which is simply a solid cylindrical core. After the core had been prepared, a suitable length of wire was wound on short length of finely shaped stick (short enough to pass through the internal diameter). One end of the wire was placed on the core with about 60mm allowed to be free to serve as one leadoff the winding. Taking the number of turns of the winding into consideration, the wire was wound manually and carefully around the cores one after the other for the separate phases. After each turn; the stick was passed through the internal diameter of the core. While winding, it was ensured that the wire was perfectly aligned with each turn, wound firmly and held in place so that the winding will not slack. This process was continued until the number of turns required to give the maximum voltage was obtained. The two leads where brought with 60mm allowed to be free for both leads. After winding the coils on the Cores, vanish was applied to the completed winding. This was done to make the winding firm so that the turns will not move out of position when the brush is moving over it or due to vibration around the variac.

After the core has been cased, there is no telling how much hazard will be caused to the operator if the leads of the winding come in contact with the casing. In order to prevent this from happening the leads were covered with sleeve up to the point where it is connected to output and input devices.

Three brush holder of length 6cm each which already have carbon brushes fixed to them was bought in the market for the cores. The carbon brushes were then filed at the bottom such that it can run smoothly on the winding, contacting the appropriate number of turns per volt at every time it moves. Knowing the length of the brush holder, the distance from the center point of the core to the part on the top of the winding where the brush rests, we then marked the point and the insulation was scraped evenly to allow the carbon brush to make good contact with windings.

A connector was then used to receive the output and input leads.

The Mechanical Part (Casing)

We used the stem of a damaged three phase variac to carry our individual cores placing them one on top the other to cover the three in one stem as shown in Fig 5. Then finally a blackpaspect glass was attached to the metal sheet using screws and the paspect glass served as the base where the connector which was carrying the input and output lead was seated.

Fig 5: The Variac showing the individual cores stacked upright.

The casing was then sprayed with red ABRO paint to bring out the beauty of the constructed job. Fig 6 shows the complete picture of the finished work.

Fig 6: The Completed Variac showing external connections to the components

MODE OF OPERATION

Alternating current of 240V is supplied to the windings of coil a, b and c respectively. It then create a magnetic field around the individual cores a, b and c and magnetic flux is set up in the cores as shown in Fig 7. This flux is alternating and links with the terminating part of the winding such that e.m.f is induced in each turn as the flux cuts across it. When the carbon brush is rotated, it makes contact with a part of the winding individually on the separate cores uniformly such that the output voltage at any point in time is the voltage selected by the brush contact on each of the three phase winding which corresponds to value of voltage per turn. The output voltage at every point in time can be checked using a digital volt meter connected across the output terminal i.e. between phases.

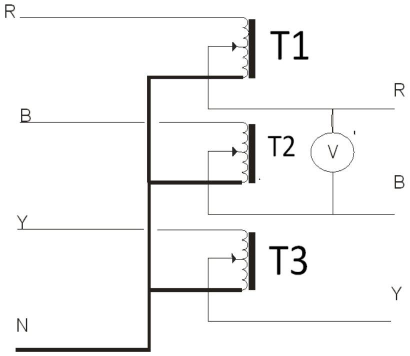

Fig 7: Circuit Diagram

TEST, RESULTS AND OBSERVATION

The system was powered with a three phase supply voltage on the input and varying the knob to get different voltages at the output.

Table 1 shows the values of voltage, current and speed respectively of the detachable machine trainer when used with the variable autotransformer (Variac) to conduct a test in the electrical power Laboratory of my Department.

Table 1. Values for Voltage, Current and Speed

VOLTAGE (V)	CURRENT (I)	SPEED (RPM)
0	0	0
20	0.82	0
40	1.12	260
60	1.62	820
80	2.2	1860
100	2.8	2260

Figure 8 through 10 show the speed/voltage, current/voltage and speed/current characteristics respectively of the detachable machine trainer when used with the variable autotransformer (variac).

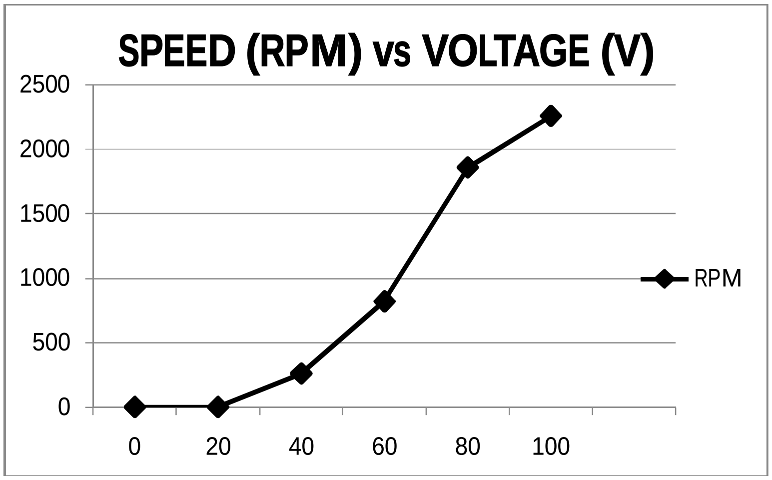

Fig 8: Speed / Voltage Characteristics

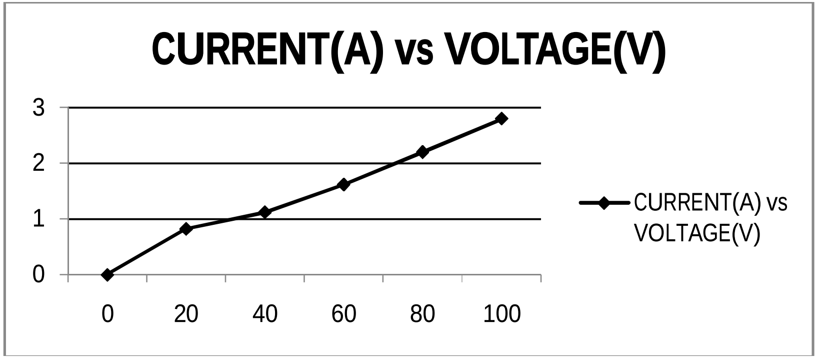

Fig 9: Current / Voltage Characteristics

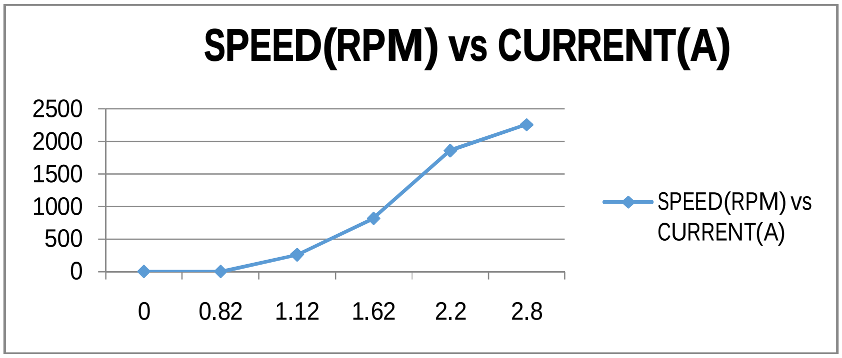

Fig 10: Speed (RPM / Current (I) Characteristics

After the implementation, it was observed that as the knob was being varied, the output voltage also varied. If we vary the knob by increasing the number of turns, we observed that the output voltage also increases but if we vary the knob by reducing the number of turns the output voltage also decreases. In doing this, care was taken not to vary the voltage above maximum or below minimum value by forcing the knob. We also ensured that the power rating of the equipment to be powered by the variac was known so as not to exceed the power rating of the variac.

CONCLUSION

After all necessary procedures have been keenly followed to achieve the design of the three phases 3KVA variac, it was successfully implemented. The problem of getting a variac to operate the deterchable machine trainer to perform experiment in the Electrical Power Laboratory was therefore solved.

REFERENCES

1. Leshkimi (2010), "The Importance of Electricity", Young World, (pp. 1-3).
2. Theraja, B. L., (2012),"A Textbook of Electrical Technology", S. Chand & Company Ltd, New Delhi, (pp. 1116-1119).
3. Bird J.,(2003), "Electrical Circuit Theory and Technology", Newness Publications Jordan Hill, Oxford, (pp315-347).
4. Bedell F., (2011), "History of AC waveform, Its Determination and Standardization", Retrieved September 15, 2017 from Wikipedia:https://en.wikipedia.org/wiki/Transformer.
5. Paul Horowitz and Winfield Hill, (1989), "The Art of Electronics Second Edition", Cambridge University Press, Cambridge MA, (pp 58-65).
6. Hemeyer (2001*), "Second Maxwell-Equation (Faraday's Law)"* in Section 2 – Basics, Retrieved September19, 2017, from Wikipedia: https://en.wikipedia.org/wiki/Transformer