Extraction of Electrical Power Transformer Parameters

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Abstract

In this paper the VISUAL BASIC language is used to design an interactive program that helps in understanding of transformers theory, as well as demonstrating its internal construction, getting its operating characteristics and the equivalent circuit elements. The program helps in minimizing the computational time especially in case of complicated hand calculation and facilitates an easy way for explaining extracting the transformer parameters.

Keywords: *Power Transformer, Transformer Parameters, virtual Lab.*

1. Introduction

The huge leap in the science and technology ruled that innovation modern methods and forms of teaching process, accessibility of the information in shortest possible time and interesting. These modern methods are to exploit the possibilities of computer programming to build virtualized environment that helps to assimilating the basic elements of the curriculum with ease away from the crippling complexity. Also to introduce the spirit of the courses that are characterized by a kind of immobility, need ability to a large imagine and complex calculations to analyze large amount of variables and to draw conclusions on them. For programming such functions the high level languages such as BASIC, VISUAL BASIC, C, C+, C++ ... etc were used.

2. Ideal Transformer and Voltage Ratio

A power transformer normally consists of a pair of windings the set of windings connected to the source side of the transformer are called primary windings, and those connected to the load are named secondary windings. They are linked by a magnetic circuit or core. When an alternating voltage is applied to the primary windings, a current will flow which sets up an alternating magneto-motive force (m.m.f). Hence an alternating flux is developed in the core, which in turn induces electromagnetic force (e.m.f) in both windings. In the primary winding this is the 'back e.m.f.' and, if the transformer were perfect, it would oppose the primary applied voltage to the extent that no current would flow. In reality, the current which flows is the transformer (magnetizing current). In the secondary winding the induced e.m.f. is the secondary open-circuit voltage. If a load is connected to the secondary winding which permits the flow of secondary current, then this current creates a demagnetizing m.m.f. thus destroying the balance between primary applied voltage and back e.m.f. To restore the balance an increased primary current must be drawn from the supply to provide an exactly equivalent m.m.f. so that equilibrium is once again established. Since there is no difference between the voltage induced in the primary or the secondary winding, then the total voltage induced in each of the windings by the common flux must be proportional to the number of turns. Thus the well known relationship is established that: [1]

$$E_p \big/ E_s = N_p \big/ N_s \ldots\ldots\ldots\ldots\ldots (1)$$

The ratio of the ampere-turns balance;

$$I_p N_p = I_s N_s \quad \dots\dots\dots\dots\dots \text{ (2)}$$

The relationship between the induced voltage (e) and the flux (Φ) is given by reference to Faraday's law which states that its magnitude is proportional to the rate of change of flux linkage, and Lenz's law which is normally expressed in the form; [2, 3]

$$e = -N(\frac{d\Phi}{dt}) \quad \dots\dots\dots\dots\dots\dots.\dots \text{ (3)}$$

But for practical transformer, it can be shown that the voltage induced per turn is,

$$E = KN\Phi_m f = 4.44N\Phi_m f \dots\dots\dots\dots\dots \text{ (4)}$$

Where $K = \frac{2\Pi}{\sqrt{2}} = 4.44$; for sinusoidal voltage.

For design calculations the designer is more interested in volts per turn and flux density in the core rather than total flux, so the expression is;

$$E/N = 4.44B_m Af \quad \dots\dots\dots\dots.\dots \text{ (5)}$$

For practical designs B_m set by the core material and the operating conditions for the transformer, a selected from a range of cross-sections related to the standard range of core sizes, whilst frequency **f** is dictated by the customer's system. It is then an easy matter to determine the number of turns in each winding from the specified voltage of the winding [2].

Transformer losses may be divided into two main types. The losses which vary with load current and that vary with the core flux.

Since the load current is not constant during normal operation the winding I^2R losses will vary. Under normal conditions, the core flux will remain approximately constant, so the losses which vary with the core flux will be approximately constant independent of the load. These losses include stray losses due to e.m.f induced by stray field in adjacent conductors. These will be a loss due to the resistance of each winding, so the total winding loss is:

$$Pc = I_p^2 R_p + I_s^2 R_s = I_s^2 (R_s + R_p^{'}) \dots\dots\dots \text{ (7)}$$

The core losses are divided into two parts, the hystersis loss (P_h) and eddy current losses (P_e) [2, 3].

The steel specimen is subjected to an alternating flux; the hystersis loss per cycle is proportional to the area of the loop and therefore, the hystersis loss is**:**

$$P_h = K_h f B_m^n \text{ w/m}^3 \dots\dots\dots\dots\dots \text{ (8)}$$

n = coefficient empirically found in the range 1.6 to 2.

The eddy current loss is due to flow of eddy current in core then high resistance lamination effectively reduces the eddy current loss to small operation. The eddy current loss is proportional to the sequence of the frequency. The total core loss Pi is:

$$P_i = P_h + p_e = K_h f B_m^n + K_e f^2 B_m^2 \dots\dots\dots\dots (9)$$

Provided that B_m and f are constant the core losses should be constant. For B_m to be constant; the magnetizing current and the applied voltage must be constant [3].

3. Determination of Transformer Parameters

For the purposes here we concentrate on the test methods and the experimental set-up of the traditionally accepted electrical equivalent circuit for a power transformer in steady-state shown in

Fig.1. This particular equivalent circuit's parameters are referred to primary side. The phasor diagram of simplified equivalent circuit of transformer is shown in fig.2, [2,3,4,5].
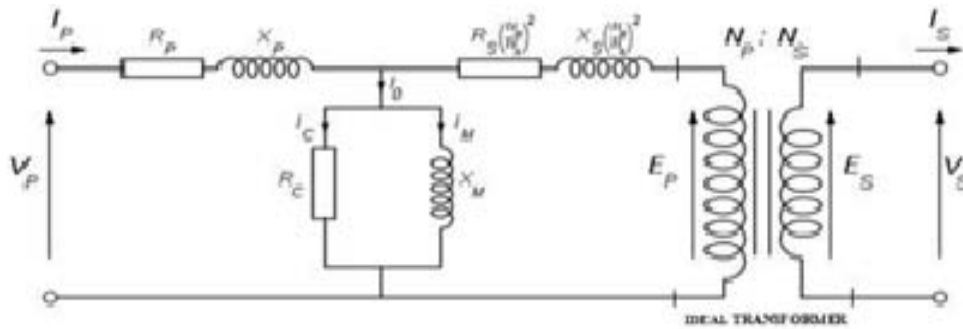

Fig.1: Power Transformer Steady-state Equivalent Circuit
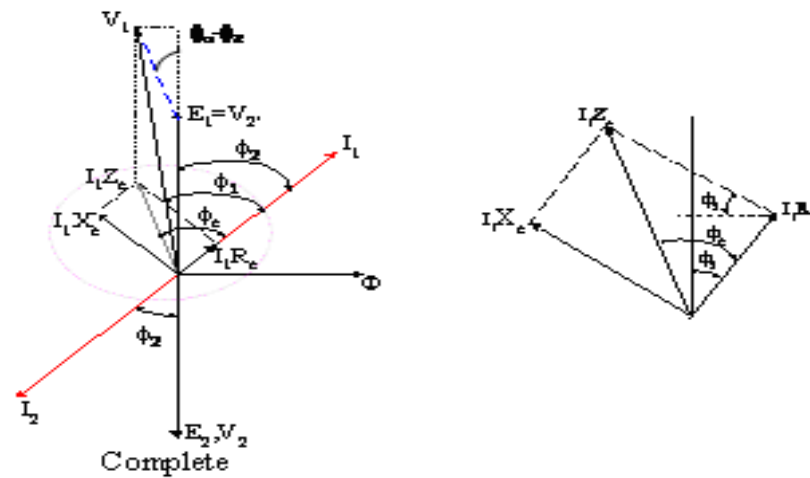

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Fig. 2: Phasor Diagram of Simplified Equivalent Circuit of Transformer

It is important to note that for a typical power transformer the ratio of the parallel combination of the common leg impedances to the total impedance of either winding will exceed 200.

I. The open circuit and short circuit tests

The open-circuit test run at rated voltage and yields the following quantities:

The I²R losses on open circuit may be neglected, the no load input is the normal core loss then the values of R_c and X_m in the parallel exciting circuit as in fig.1 can be calculated.

$$R_C = \frac{V_{OC}^2}{P_{OC}} = \frac{V_{OC}}{I_{OC}} \text{ Ohms} \ldots\ldots\ldots\ldots\ldots (10)$$

The reactance X_m can be found by determining the reactive part of the test quantities. Thus, the power factor is:

$$pf = \frac{P_{OC}}{V_{OC}I_{OC}} \ldots\ldots\ldots\ldots\ldots (1\,1)$$

$$Q = \sqrt{S^2 - P^2} \qquad \ldots\ldots\ldots\ldots\ldots (1\,2)$$

$$I_m = I_{OC}\sin(\cos^{-1} pf) \qquad \ldots\ldots\ldots\ldots (13)$$

Where; I_m is the magnetization current of the transformer in ampere.

$$X_m = \frac{V_{OC}^2}{I_m} = \frac{V_{OC}^2}{Q_{OC}} \quad \text{Ohms} \qquad \dots\dots\dots\dots\dots (14)$$

Where X_m; is the magnetization reactance.

In the short circuit test; one winding is short circuited and the voltage applied to other is gradually raised from zero until full load current flows. This run at rated current and provides the values of the applied voltage, Input short-circuits current and the input power; the equivalent impedance seen as:

$$Z = R_p + R_s' + j(X_p + X_{s2}') = R_{eq} + X_{eq} = \frac{V_{SC}}{I_{SC}} \quad \dots(15)$$

Since the parallel combination of the common leg impedance is very large, the majority of the input short-circuits current passes through only the winding impedances. Therefore, the core losses are negligible and the following is true [2].

$$R_{eq} = \frac{P_{SC}}{I_{SC}^2} \qquad \dots\dots\dots\dots\dots\dots\dots\dots (16)$$

$$X_{eq} = \sqrt{Z_{eq}^2 - R_{eq}^2} \qquad \dots\dots\dots\dots\dots\dots (17)$$

$$R_1, R_2 = \frac{R_{eq}}{2} \quad \text{and} \quad X_1, X_2 = \frac{X_{eq}}{2} \dots\dots\dots\dots (18)$$

In the absence of more definitive information, the components of R_{eq} and X_{eq} are split equally between the two sides of the transformer. This completes the development necessary to derive the steady-state equivalent circuit from the test data.

II. Transformer Efficiency and Regulation

The performance of the device can be checked by comparing the output with respect to the input.

$$Efficiency, \eta = \frac{OutputPower}{InputPower} * 100\%$$

$$= \frac{P_{out}}{P_{out} + P_{losses}} * 100\% = \frac{V_2 I_2 \cos\theta}{V_2 I_2 \cos\theta + P_c + P_{cu}} * 100\% \qquad \dots\dots (19)$$

$$\eta_{(fulload)} = \frac{VI \cos\theta}{VI \cos\theta + P_c + P_{cu}} * 100\%$$

$$\eta_{(loadn)} = \frac{nVI \cos\theta}{nVI \cos\theta + P_c + n^2 P_{cu}} * 100\% \qquad \dots\dots (20)$$

Where:

If ½ load, hence $\eta = ½$, ¼ load, $\eta = ¼$, 90% of full load, $\eta = 0.9$. In this case, $P_{cu} = P_{sc}$ & $P_c = P_{oc.}$

Equivalent Circuit Regulations method is used. In which, the parameters are referred to primary or secondary.

$$V.R = \frac{I_1 [R_{01} \cos\theta_{p.f} \pm X_{01} \sin\theta_{p.f}]}{V_1} \times 100\% \qquad \dots\dots (21)$$

If referred to primary side

$$V.R = \frac{I_2 \left[R_{02} \cos\theta_{p.f} \pm X_{02} \sin\theta_{p.f} \right]}{V_2} \times 100\% \qquad\qquad \text{..... (22)}$$

4. The Proposed Program

Microsoft Visual Basic 6.0 has been used to design a small size program for designing laboratory simulator unit of transformers. This program is developed three Multiple Document Interface (MDI) forms. Two of them are open and short circuits tests, and the equivalent circuit parameters of transformers [6, 7, 8, 9, 10].

I.   Running Simulator Program

Simulator A Form, run to derive the equivalent circuit type of transformer. Fig 4 shows the equivalent circuit of single phase referred to primary, equivalent circuit referred to secondary.

Simulator B Form, which contains open circuit and short circuit test and transformer performance, including the losses, efficiency and voltage regulation. This accomplished through a short circuit and open circuit test. The input is the basic information for transformer as voltage ratings (secondary and primary), apparent power and power factor in the basic information recorded in program.

Through the open and short circuit buttons in test-circuit frame the parameters can be calculated. For specified transformer performance the losses, efficiency and voltage regulation data can be given as a report or printed format.
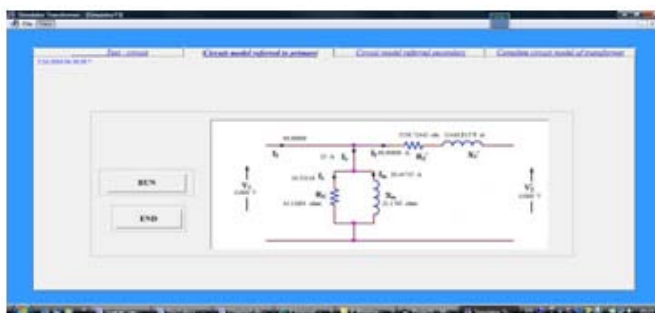

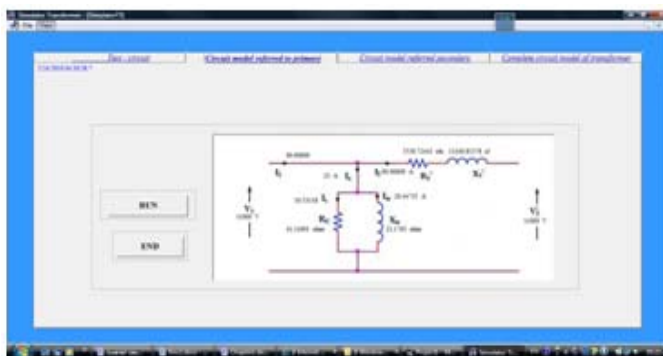**Fig.4.a Illustrates Equivalent circuit Referred to Primary.**

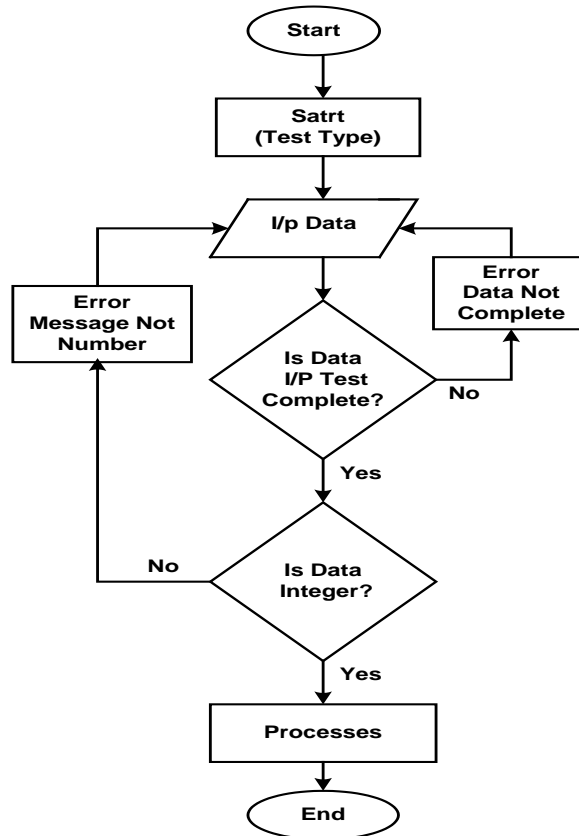

Fig.4.b Illustrates Equivalent Circuit Referred to Secondary.

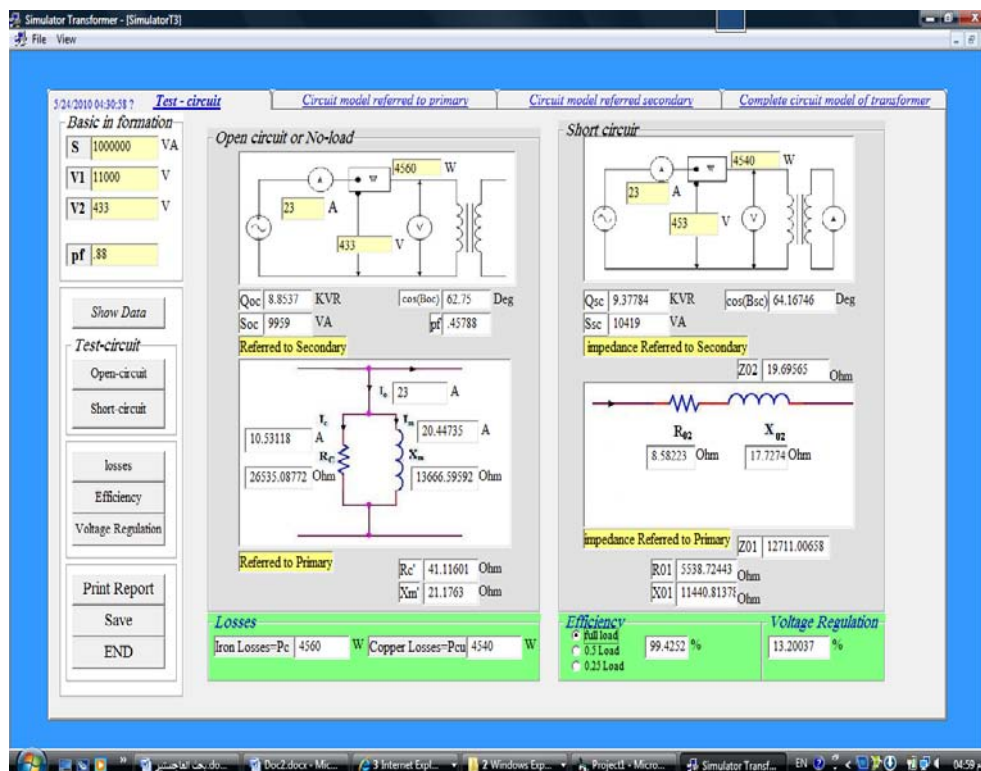**Fig.5 Flow Chart Illustrates Calculation of Parameters in Simulator B.**

Fig.6. Window for Calculating the Transformer Parameters

II. *Program Verification*

This section compares the calculated equivalent circuit parameter with obtained by simulation program. The transformer used for this experiment are rated (11- 0.433kV, 1000kVA). This transformer manufactured by *Sudanese Egyptian Electrical Industries –SUDATRAF*.

Use the 433 V and the 631 V voltage range settings for the open circuit and short circuit test respectively.

For open circuit test; the secondary must be disconnected for the open circuit-test, while applying rated voltage, 433 V, from the Single-Phase AC source to the primary side of the transformer. Records of power, current and voltage are shown in table 4.1.

Table (1) values of open circuit test.

Power	Current	Voltage
1.520 KW	15 A	433 V

For short circuit test; the short-circuit test is run with the secondary jumper connected. by SLOWLY increasing the single-phase AC source from the zero setting until a 53 Amp reading is achieved. Allow a little time for the system to stabilize, and then records of power, current, and voltage are in table2.

Table (2) values of short circuit test

Power	Current	Voltage
9.910KW	52.26A	631V

Table (3) Equivalent Circuit Values (in ohms) as calculated manually:

Values referred to	Primary	Secondary
Series Resistance ($R_{1,2}$)	3241.77	3.628
Series Reactance ($X_{1,2}$)	7432.167	11.516
Shunt Magnetizing (X_m)	29.7	19161.83
Shunt Core Loss(R_c)	123.35	79605.26

The program has ability to analyze data of open and short circuit test of transformer; which is a main target of the program. As well as, possibility of giving excitation current, magnetizing current and core-losses.

II. Simulation program Report

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Analysis report of a Single-Phase Transformer

Basic Information Voltage and Power

Primary (Line -V)		Scondary (Line -V)		Apparent power	
11000	volts	433	volts	1000000	VA

Test Data

	Short Circuit Values	Open Circuit Values	
Voltage	631	433	volts
Current	52.26	15	ampere
Power	9910	1520	watts

Equivalent Circuit Values (in ohms)

Values referred to	Primary Side	Scondary Side
Series Resistance (R1,2)	2341.771	3.6286
Series Reactance (X1,2)	7432.1686	11.5161
Shunt Magnetizing (Xm)	29.6912	19161.8336
Shunt Core Loss (Rc)	123.348	79605.2632
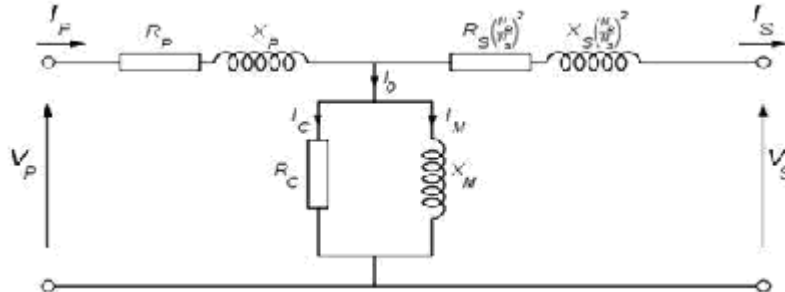
Loesses

Iron Losses=Pc	1520	W	Copper Losses=Pcu	9910		W
Efficiency						
FllL Load 99.825 %	0.5 Load 100	%		0.25 Load	99	%

Voltage Regulation 4.3114 %   Power factor 0.99

5. Discussions and Conclusions

For the parameters of transformer (R_C, X_m, X_1, X_2, R_1, R_2) the simulation and manual report results show small deviation from each other. This due to the fact that the simulation is always considered being the ideal situation, while the practical results include some unseen minor effects. In this paper, the concept of the generating magnetic flux theory, transition and (open/short) circuit tests all are easily demonstrated through interactive VISUAL BASIC programming. The program has the ability to link between mathematical equations to infer the characteristics of transformers and deriving equivalent circuit along with the possibility of giving the report on the electrical elements of the transformer. The program developed when compared with manually calculated parameters of transformer, it varies in error from 0.05ppm for shunt core loss resistance of the secondary side to maximum error of 296ppm for the shunt magnetizing reactance of the primary side.

References:
[1] Martin J. Heathcote, *"The J & P Transformer Book – A practical Technology of the Power Transformer-"* Welfth edition © Reed Educational and Professional Publishing Ltd 1998.
[2] Del Toro, Vincent. "*Electromechanical Devices for Energy Conversion and Control Systems*", Prentice-Hall, Inc 1968.
[3] James H. Harlow, "*Electric power transformer engineering*" CRC Press LLC, 2004.
[4] http://fullnet.com/~tomg/gooteesp.htm; Modeling a Power Transformer Directly from Measurements.
[5] Vivek Pahwa And Dr. K. S. Sandhu; Modelling and Simulation of Single-phase Transformer Including the Flux Saturation Effect; *NSC 2008, December 17-19, 2008; (821-825).*
[6] Byrons.Gottfried, Ph.D**.** *"Schaum's Outline of Theory and Problems of Programming with VISUAL BASIC"* McGraw-Hill Companies; 2001.
[7] Michael Halvoeson, *"Microsoft VISUAL BASIC2008"*, 2008.
[8] Steven Holzner, *"Visual Basic 6 Black Book"*, Coriolis Group; 1998.
[9] Lou Tylee, *"Learn Visual Basic 6.0"*, KIDware 1998.
[10]Luc Vouligny; Power Transformer Simulation Laboratory for Proactive Maintenance. IOSsoft ; Usedrs Conference 2012.

List of Symbols used:

Φm	The maximum value of total flux linking the turn	Webers
f	The supply frequency………………………	(Hz)
B_m	Maximum value of flux density in the core	Tesla
A	Nett cross-sectional area of the core………	mm2
I_{OC}	Exciting current as read by ammeter of open circuit test	A
V_{OC}	Applied voltage as read by voltmeter of open circuit test	V
P_{oc}	Power as measured with wattmeter of open circuit test	W
V_{SC}	Applied voltage as read by voltmeter of short circuit test	V
I_{SC}	Input short-circuits current as read by ammeter of short circuit test	A
P_{SC}	Input power as read by wattmeter of short circuit test	W
R_C	Core resistance…………………………….	Ohm
X_m	Magnetism reactance………………………	Ohm
R_P , X_P	Primary winding resistance and leakage reactance …….	Ohm
R_S, X_S	2nd winding resistance & leakage reactance	Ohm
V_P, V_S	Primary supply & 2nd (load) voltages ……	V
E_P, E_S	Primary & Secondary winding voltages…..	V
I_c, I_m	Core current & Magnetizing current……..	A
I_1, I_2	Primary & 2nd winding current…………..	A
I_1'	Primary winding current…………………...	A
Io	No load current…..……………………..	A
Q	Reactive power of open test in……………	KAVR
P	Active power in …………………………...	kW
S	Apparent power in ………………………..	kVA
N_1, N_2	Turns Number of primary& second winding	turn