Simulation, Analytical and Experimental Investigation of Power Distribution Across Step-Up Auto-Transformer Under Linear Loading Conditions

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***Abstract*— This paper presents determining the actual values of the effective resistance and reactance components of a single phase auto-transformers, the measured values of voltages and currents were used for the calculation of R and X components for fundamental frequency of the system. The obtained values are simulated in the PSpice environment and then how the currents, voltages and power are distributed between them is explained based on calculations.**

***Index Terms*— Autotransformer modeling, Autotransformer simulation, Step-up autotransformer, Polarity**

I. INTRODUCTION

Nowadays mathematical modelling of autotransformers has been so important due to its widespread application in different branches of power transmission and distribution systems. Moreover, autotransformers have been applied widely in power factor correction circuits such as fly-back configurations to improve the quality of transmitted power [1]. Exact analysing of a power system intensively depends on the exact modelling and good understanding of function of each subsystem and each element of power system to get an acceptable result for the next planning and designs of power systems. So learning how the elements of circuits work is the basic step to get qualified for the next steps.

A transformer is a stationary device for converting electrical power in an a.c. system at one voltage or current into electrical power at another voltage or current without any changes in frequency. A step-up transformer is a transformer in which the delivered voltage is greater than the supplied voltage. A step-down transformer is one so connected that the delivered voltage is less than that supplied [2].

In ordinary transformers, the two windings are electrically isolated and transmission of power and e.m.f. are induced in the secondary cause of mutual induction. Autotransformer is a kind of transformer in which a part of the winding is common to both the primary and secondary circuits. Autotransformers configuration features electrically connection in two windings and operating on the principle of induction and conduction.

Autotransformers have some performance advantages. They have increased power handling capability, flatter frequency response, lower insertion loss and lower distortion than normal transformers of similar size and cost [3].

The most efficient and effective method of operating a stationary transformer is as an autotransformer. The major drawback of autotransformers is that they do not provide separation between the primary and secondary. This non-insulating feature of the autotransformer should always be remembered; even though a low voltage may be tapped from an autotransformer, the low voltage circuit must be insulated to the same degree as the high voltage side of the transformer. Another drawback is that the autotransformer's impedance is extremely low, and it provides almost no opposition to fault current. Autotransformers are usually primarily for motor staring circuits, where lower voltages are required at the start to reduce the amount of inrush current, and higher voltages are used once the motor is running. Autotransformers are used in power applications where the difference between the primary and secondary voltages is not too great [4].

So many researches and studies have been done on modeling different issues of transformers and autotransformers. A mathematical model of three-winding autotransformer for two different equivalent elements with consideration of the symmetric and asymmetric transformer, constant frequency and skip saturation of the transformer core has been driven [5]. An autotransformer compared to a separate-winding transformer is characterized by small impedances, which can be very small at the neutral

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tap position. For load flow calculations using newton-raphson or current injection algorithm, these features cannot be modelled. A research has proposed a new approach using additional injects for the correct compensation of error in the modelled impedance [6]. Some researchers have been done on the modelling of transformer core nonlinearities in harmonic domain [7].

In this paper a good explanation of autotransformer operation in a simple circuit in the primary and secondary terminals of step-up autotransformers is presented. So many programs in these days are available to simulate and checking the circuits. In this paper, we have used PSpice environment due to its frequent use and easy simulating proses. There exist some researches in modelling of autotransformers. Our modelling in this paper is valid for steady state.

II. Analyses And Results

An ideal diagram of an ordinary transformer is shown in figure 1. It is important to note that the modeling of transformer and auto transformer is with the assumption of transformer being ideal, which means [8][9]:

1. Winding resistances are negligible.
2. All the flux set up by primary links the secondary winding, i.e. all the flux confined to the magnetic core.
3. The core losses (hysteresis and eddy current losses) are negligible.
4. The core has constant permeability, i.e. the magnetization curve for the core is linear.

A. The Importance of Polarity

An understanding of polarity is essential to correctly construct three-phase transformer banks and to properly parallel single or three-phase transformers with existing electrical systems. A knowledge of polarity is also required to connect potential and current transformers to power metering devices and protective relays. Transformer polarity refers to the relative direction of the induced voltages between the high voltage terminals and the low voltage terminals [10].

To insure correct wiring, polarity marks are shown on connection diagrams. The polarity mark is usually shown as a round dot, on or adjacent to terminals. An ideal transformer circuit as a controlled source is shown Figure 1.

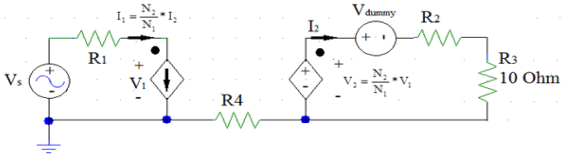


Fig. 1. Ideal transformer equivalent circuit.

B. Case Study

For a step-up autotransformer supplied with a sinusoidal voltage and loaded with a linear load, Figure 2. shows the circuit schematic of a step-up autotransformer. The relations between primary and secondary voltages and currents of a step-up autotransformer are as below:

$$\frac{V_1}{V_2} = \frac{\pm N_1}{\pm N_1 \pm N_2} \qquad (1)$$

$$\frac{I_1}{I_2} = -\left(\frac{\pm N_1 \pm N_2}{\pm N_1}\right) \qquad (2)$$

Which N_1 and N_2 are winding portions of primary and secondary windings. If dot mark is on the positive head of each terminal, then the positive sign is used for winding portion number of the terminals in voltage equation (1), otherwise the negative one is used.

For current equation (2), if the current direction is getting in the dot mark then the positive sign is used, and if the current gets out of the dot mark, the negative sign is used for appropriate winding portion.

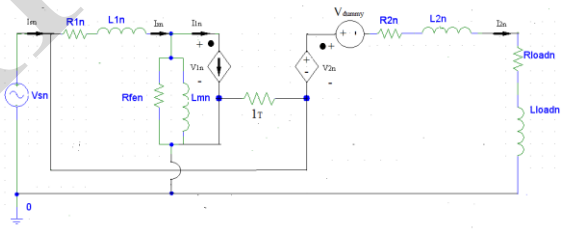


Fig. 2. Equivalent circuit of the step-up auto-transformer

For a normal transformer, excitation current (I_e), core current (I_{fe}), magnetization current (I_m) and core voltage (V_c) is obtained by using primary and secondary winding parameters. Primary and secondary winding resistances R_1, R_2 and leakage reactances X_1, X_2 vary with harmonic frequencies. In this paper only fundamental frequency values were considered. In order to use the measurements together with analytical calculation methods, the parameters R_1, X_1, R_2, X_2 are assumed to be known or can be determined for fundamental frequency [11]. In fig. 1 the equivalent circuit diagram of a normal transformer is shown.

For this circuit the active power equation can be written as below [12]:

$$V_1.I_1.\mathrm{Cos}(\varphi_{v1} - \varphi_{i1}) = R_1.I_1^2 + P_{fe} + R_2.u^2.(I_2^2/u^2) + V_2.I_2.\mathrm{Cos}(\varphi_{v2} - \varphi_{i2})$$

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In this way we can say that:

$$P_{fe} = V_1.I_1.\text{Cos}(\varphi_{v1} - \varphi_{i1}) - R_1.I_1^2 - R_2.u^2.(I_2^2/u^2) - V_2.I_2.\text{Cos}(\varphi_{v2} - \varphi_{i2})$$

Where V_1 and I_1 are input voltage and input current, R_1 and R_2 primary and secondary winding resistance, and X_1 and X_2 primary and secondary leakage reactances, respectively. Vector value of input voltage and current were measured directly, and the calculation of active power was done using mentioned equations. This values also were used for calculation of reactive power as follow:

$$V_1.I_1.\text{Sin}(\varphi_{v1} - \varphi_{i1}) = X_1.I_1^2 + Q_m + X_2.u^2.(I_2^2/u^2) + V_2.I_2.\text{Sin}(\varphi_{v2} - \varphi_{i2})$$

That results in:

$$Q_m = V_1.I_1.\text{Sin}(\varphi_{v1} - \varphi_{i1}) - X_1.I_1^2 - X_2.I_2^2 - V_2.I_2.\text{Sin}(\varphi_{v2} - \varphi_{i2})$$

Combining the equations of active and reactive power gives,

$$\text{tg}\varphi = \frac{Q_m}{P_{fe}}$$

so, therefore Cosφ can be obtained. Appropriate equations for core voltage V_c and excitation current I_e can be explained as below:

$$V_c = V_s - (R_1 + j.X_1).I_1$$

$$I_e = \frac{P_{fe}}{V_c.\text{Cos}\varphi}$$

From equations, the following core and magnetizing currents are obtained as follow is serial core resistance which are converted to parallel resistance later.

$$P_{fe} = R_{fes}.I_e^2$$

$$R_{fes} = \frac{P_{fe}}{I_e^2}$$

$$R_{fep} = \frac{R_{fes}^2 + X_{ms}^2}{R_{fes}^2}$$

$$I_{fep} = \frac{V_c}{R_{fep}}$$

$$Q_m = X_{ms}.I_e^2$$

$$X_{ms} = \frac{Q_m}{I_e^2}$$

$$X_{mp} = \frac{R_{fes}^2 + X_{ms}^2}{X_{ms}^2}$$

$$I_{mp} = \frac{V_c}{X_{mp}}$$

Experimental, Analytical and Simulation Results:
In fig. 3, schematic circuit diagram of step-up auto-transformer in PSpice environment. For the step-up auto-transformer configuration, the input and output voltages and currents are as:

$V_1 = 80{,}89 \angle 0$ v, $I_1 = 2.509 \angle -3{,}23$ A,

$V_2 = 16{,}99 \angle -3.29$ v $I_2 = 9{,}924 \angle -2{,}08$ A.

the obtained values of resistances and reactances of transformers calculated by the mentioned method were:
$R_{fe} = 4130{,}298\ \Omega$, $X_m = 1528{,}428\ \Omega$,

The calculations of active and reactive power of transformer result in:

$P_{fe1} = 1{,}336$ W, $Q_m = 3{,}61$VAr,

The excitation current of each transformer calculated as:

I_e=52 mA

The calculated value of core current and magnetization current of each transformer are:

I_{fep}=18 mA, I_{mp}=50 mA.

As it can be seen the results of the calculated power and simulated power are the same.

In figure 3. a step-up circuit is shown. In figure 4 simulated active power P_{fe1} and reactive power Q_{m1} and in figure 5, the waveforms of simulated active power P_{cu1} and P_{cu2}, and reactive power Q_{cu1} and Q_{cu2} of autotransformer is presented As it can be seen, the calculated results are the same as the simulated results.

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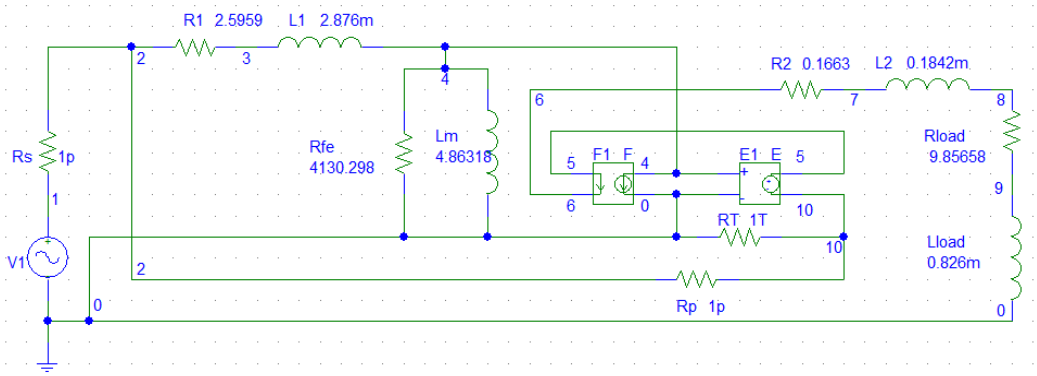


Fig. 3. Simulation of Normal Auto-transformer in Pspice Environment

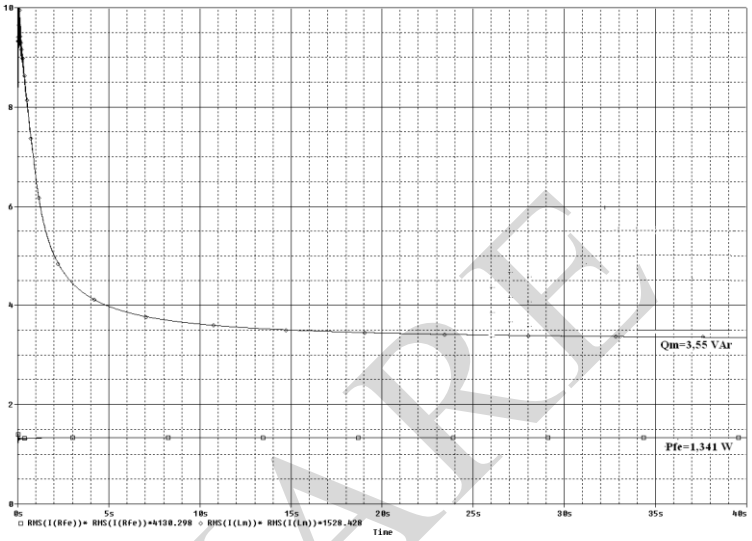


Fig.4. Simulated active power Pfe1 and reactive power Qm1 auto-transformer.

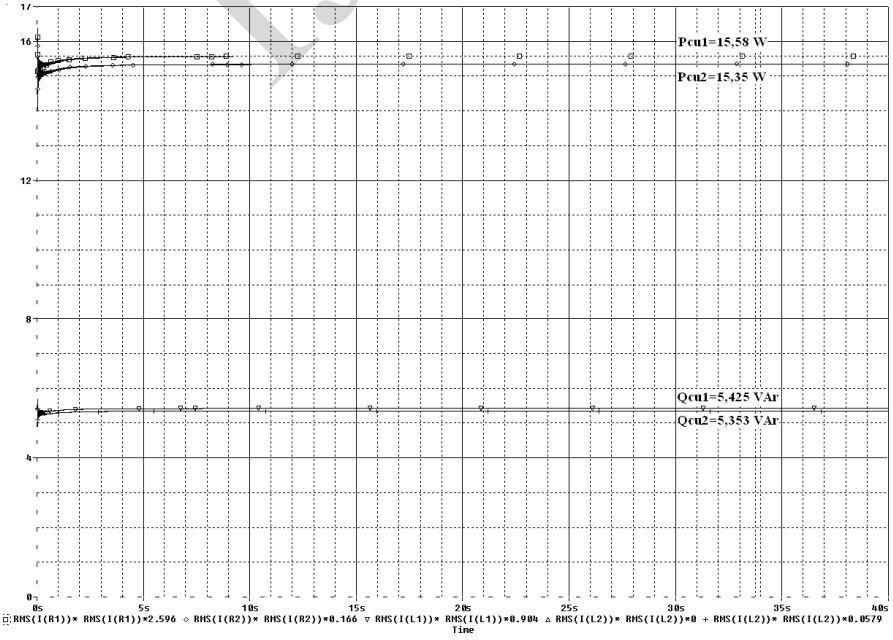


Fig.5. Simulated active power Pcu1 and Pcu2, and reactive power Qcu1 and Qcu2 of autotransformer.

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III. Conclusion

In this paper the equivalent circuit diagram of a single phase normal autotransformer with its appropriate active and reactive power equations was presented. By direct measurement of voltages and currents of a single phase normal autotransformer, the impedances and reactances of transformers and also the active and reactive power P_{fe1} and reactive power Q_m , P_{cu1} and Q_{cu1} and Q_{cu2} , P_{cu2} have been calculated and then the calculated values has been used in the simulated circuit and all the results have been validated As it can be seen, the calculated results are the same as the simulated results and practical measured values.

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