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Simulation, Analytical and Experimental Investigation of Power Distribution Across Two Parallel-Connected Transformers

KEYWORDS: Paralleled transformers, Power distribution, transformer impedance

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ABSTRACT *This paper presents determining the actual values of the effective resistance and reactance components of two single phase parallel-connected 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.*

1. Introduction

In a power system, at light loads only one transformer would be employed, and as the load increased additional transformers would be connected in parallel as required [1]. Nowadays operation of power transformers in parallel is common and it is usually because of one of the following reasons [2]:

1. Increased Load: If the power of a feeded load need to be increased, one of the economical and easy solutions is to add a second transformer in parallel operation.
2. Flexible Operation: transformers can operate in parallel in several ways ensuring reliability, safety, critical load selection and ease of maintenance operation without outage of service.
3. High Power: Sometimes it is the only way to operate in high power applications due to size and weight restrictions.

On the other hand paralleled operation of power transformers has some disadvantages: increasing short-circuit currents, circulating currents that causes in increasing of copper losses, overloading one of the paralleled transformers, and reducing the permissible load kVA. When paralleling two transformers some conditions should be met, they are mentioned here for single-phase transformers operating in parallel that we use them for our analysing and calculations and simulations [3]:

1. Equal voltage ratings.
2. Equal ratio of transformation.
3. Equivalent impedances which are inversely proportional to their current rating.
4. Ratios of equivalent resistance to equivalent reactance which are equal.

For paralleling two transformers especially in transmission and distribution systems there exist some methods in literatures. Depiction of the fundamental presumption of operation for the most operated different paralleling methods is as fallow [4]:

A. Master/Follower Paralleling Method

The main assumption of master/follower paralleling method is that, in the all configurations of operation of system, the requested operation objectives are met by keeping the same physical tap position on all paralleled transformers. The operation is composed of one active control commanding additional transformers tap changers to follow. A tap operation feedback system is needed to confirm to the master unit that the following unit has operated.

B. Negative Reactance Paralleling Method

The negative reactance paralleling method is regularly used as a short-term emergency solution to paralleling transformers. It composes of using the line drop compensation setting at a negative reactance value.

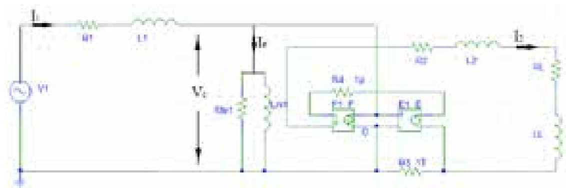

Fig. 1. Circuit diagram of a normal transformer in PSpice environment

C. Power Factor Paralleling Method

The power factor paralleling method is based on the operation of paralleled transformers under condition of same power factor for each transformer. Relative power factors can be determined by comparing the relative angle of the transformer currents. This method usually does not bias the controls to operate. Further, it is difficult to apply power factor methods in substations with more than two paralleled transformers without a daisy chain arrangement. In applications where there is a difference in impedance, the power factor method will result in the transformer with the highest KW loading (lowest impedance) also having the highest VAr loading.

D. Circulating Current Paralleling Method

The main idea of circulating current paralleling method is that a continuous circulating current path is maintained for all system operating configurations, and also an undesirable change in the relative tap positions of the paralleled transformers causes changes in the circulating current magnitude.

E. VAr Balancing (ΔVAR) Paralleling Method

The VAr balancing (ΔVAR) paralleling method's theoretical basis is that paralleled transformers are meant to share the VAr load (as well as the KW load) of the load bus. Since the KW sharing of the paralleled transformers is determined by the relative transformer and system impedances and not the tap position, KW flow should not be able to affect tap position choice. Further, that the best choice of loading parallel transformers is to maintain the VAr sharing regardless of KW loading.

There are so many researches in the field of parallel operation of transformers. One of the most attractive fields is the investigation of circulating current [5]-[6]. The safe operation of the paralleled transformers is one the most important issues [7]. In this paper the equivalent circuit diagram of a normal transformer with its appropriate active and reactive power equations is presented. By direct measurement of voltages and currents of two paralleled transformers, the impedances have been calculated and then the calculated values has been used in the simulated circuit and all the results have been validated for describing the VAr balancing (ΔVAR) paralleling method.

2. Analysis

For a normal transformer, excitation current (Ie), core current (Ife), magnetization current (Im) and core voltage (Vc) is obtained by using primary and secondary winding parameters. Primary and secondary winding resistances R1, R2 and leakage reactances X1, X2 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 R1, X1, R2, X2 are assumed to be known or can be determined for fundamental frequency [8]. 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 [10]-[11]:

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

In this way we can say that:

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

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:

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

That results in:

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

Combining the equations of active and reactive power gives,

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

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

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

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

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. 2, schematic circuit diagram of two paralleled transformer in PSpice environment. The simulation results are shown in fig. 3. As it can be seen, the calculated values are approximately equal to the simulated results. For the first transformer of two paralleled transformer configuration,

The input and output voltages and currents are as:

$V_{11} = 219.91 \angle 0$ v,

$I_{11} = 2.889 \angle -9.9$ A,

$V_{21} = 104.69 \angle -1.27$ v

$I_{21} = 5.509 \angle -3.8$ A.

For the second one the measurements were as:

$V_{12} = 219.91 \angle 0$ v,

$I_{12} = 2.791 \angle -9.3$ A,

$V_{22} = 104.69 \angle -1.27$ v

$I_{22} = 5.285 \angle -1.92$ A.

the obtained values of resistances and reactances of transformers calculated by the mentioned method were:

$R_{fes1} = 199.826\ \Omega$,

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X_{ms1} = 619.99 Ω,

R_{fes2} =180.424 Ω,

X_{ms2} = 533.248 Ω.

The calculation of active and reactive power of each part of transformers result in:

P_{fe1} = 21.647 W,

Q_{m1} = 67.164 VAr,

P_{fe2} = 26.245 W,

Q_{m2} = 77.507 VAr.

The excitation currents of each transformer calculated as:

Ie1=329 mA

Ie2=329 mA.

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

Ifep1=100 mA,

Imp1=331 mA,

Ifep2=122.19 mA,

Imp2=361 mA.

As it can be seen the results of the calculated power and simulated power are the same. The power distribution in two paralleled transformer is proportional to the values of core and winding impedance and reactance.

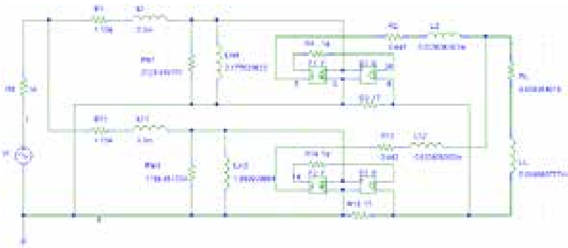

Fig. 2. Parallel connection of two normal transformer

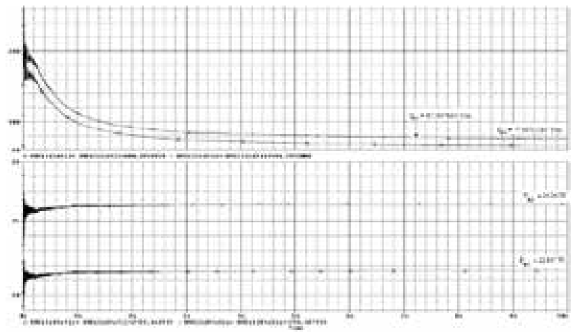

Fig.3. Simulated active power P_{fe1} and P_{fe2}, and reactive power Q_{m1} and Q_{m2} of paralleled transformer

Conclusion

In this paper the equivalent circuit diagram of a normal transformer with its appropriate active and reactive power equations was presented. By direct measurement of voltages and currents of two paralleled transformers, the impedances and reactances of transformers and also the active and reactive power have been calculated and then the calculated values has been used in the simulated circuit and all the results have been validated for describing the VAr balancing (ΔVAR) paralleling method. As it was shown the power sharing in the transformer was on the inverse base of transformers impedances portion.

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