

EFFECT OF CORE SATURATION DUE TO GEOMAGNETICALLY INDUCED CURRENT IN SINGLE PHASE, DISTRIBUTION TRANSFORMER WITH TURN-TO-EARTH FAULT

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ABSTRACT

In this era of deregulation, loading transformers to their optimum capacity is becoming normal practice, which in turn applies high stresses on the insulation of the transformers and increases the probability of occurrence of turn-to-turn or turn-to-earth faults, and hence cause the system to collapse. Researches have being employed for exploring ways of detecting these faults in transformers in the incipient stage. This paper focused on the observation of the effect of core saturation on the transformer, due to geomagnetically induced current. A dynamic model of three winding single phase transformer, suffering from short-circuit fault in either of its windings was developed from existing two winding transformer model, and consistency and proportionality theories were used in determining the three windings parameters. MATLAB SIMULINK software was used in the simulation of the model. Effect of core saturation due to geomagnetically induced current was observed in the primary inrush current. This is due to the geomagnetic disturbances which gave rise to geomagnetic surface potentials on the surface of the earth.

KEYWORDS: *Healthy Transformer Model, Faulty Transformer Model, Short circuit fault, Core Saturation, Geomagnetically induced current, dc Components.*

INTRODUCTION

Transformer is widely used in power system, and is the most important equipment with the regulation, diagnosis and maintenance of power equipment, especially power transformers, become increasingly important to keep power systems in reliable operation. The fault of a distribution transformer may leave thousands of homes without light. Devices of such kind are very expensive and therefore monitoring systems will be valuable for preventing damage to the transformers. Generally, monitoring is the observation of transformer conditions. It can either be online (when the transformer is operating), or offline (i.e. when the transformer is switched off in order to measure data). Therefore, the needed corrective maintenance should be taken in to account to stop outages and reduce down time. Many researches have been proposed to investigate abnormal electrical phenomena associated with transformers. Experiment have shown that circuit breaker restriking could be a major cause of transformer successive failures (Xuzhu Dong, 2002). According to Nuclear energy institute (2006), the major causes of Transformer failure are Manufacture fault, short circuit faults, abnormal transient fault, premature insulation fault, and aging of the insulation materials. External faults include overloads, over-current, over-voltage, reduced system frequency, and external short circuit such as a short circuit created on the secondary windings (Palmer-Buckle and

Anderson, 1999). Recent record suggests that about 70% to 80% of transformer failures are due to internal winding faults (Ciulavu and Helerea, 2008), therefore, internal faults are the focus of this research.

Failure of distribution transformer in power system leads to loss of power and finally inconveniencing the customers. To estimate such faults there is need for determining the parameters that are usually affected by these faults, but some of the parameters are unmeasurable because they are internally generated and only affect the terminal paramers when they are to certain magnitude. A means of determining these parameters prior to failure occurrence, in power system equipment, particularly transformer is very important. In this work, terminal parameters (primary and secondary voltages and currents) are used to determine the effect of geomagnetically induced current in distribution Transformer with short circuit in one of its windings.

DEVELOPED TWO WINDING TRANSFORMER MODEL

Chee Mun Ong (1998), in his book titled "Dynamic simulation of electric machinery" presented a two windings transformer model in which the flux linkages are the state variables, the terminal voltages are the inputs and the winding currents are the out puts. The developed two windings model is given as;

$$\varphi_1 = \int \left(\omega_b V_1 - \omega_b r_1 \frac{\varphi_2 - \varphi_m}{x_{12}} \right) dt \quad (1)$$

$$\varphi'_2 = \int \left(\omega_b V'_2 - \omega_b r'_2 \frac{\varphi'_2 - \varphi_m}{X'_{l2}} \right) dt \quad (2)$$

Where φ_1 is the flux leakage component of winding 1, φ'_2 is the flux leakage of winding 2 referred to winding 1, V_1 is primary terminal voltage, V'_2 is the secondary terminal voltage referred to primary, r_1 is the primary winding resistance, r'_2 is the secondary winding resistance referred to primary, X'_{l1} is the primary winding reactance, X'_{l2} is the secondary winding

reactance referred to the primary, φ_m is the mutual flux linking both the windings and ω_b is the base frequency.

DERIVATION OF THREE WINDING TRANSFORMER MODEL

Consider a single phase transformer with the turn-to-earth fault in one of its windings. The affected winding will be divided into two, resulting in three winding transformer. Thus;

$$\therefore \varphi_1 = \varphi_{l1} + \varphi_m \quad (3)$$

$$\varphi_2 = \varphi_{l2} + \varphi_m \quad (4)$$

$$\varphi_3 = \varphi_{l3} + \varphi_m \quad (5)$$

Where φ_i is the flux leakage component of winding i , and φ_m is the mutual flux between the three windings. Let N_1 be the number of turns of winding one, then, the effective flux linkage of winding one is

$$\lambda_1 = N_1 \varphi_1 = N_1 (\varphi_{l1} + \varphi_m) \quad (6)$$

The above equation can be expressed in terms of leakage permeance (p) of each winding, mutual permeance (p_m) of the whole circuit and magnetomotive forces (mmfs) of the windings, as shown below;

$$\begin{aligned} \lambda_1 &= N_1 [N_1 I_1 P_{l1} + (N_1 I_1 + N_2 I_2 + N_3 I_3) P_m] \\ &= (N_1^2 P_{l1} + N_1^2 P_m) i_1 + N_1 N_2 P_m i_2 + N_1 N_3 P_m i_3 \end{aligned} \quad (7)$$

Similarly, the flux linkages of windings two and three become

$$\lambda_2 = (N_2^2 P_{l2} + N_2^2 P_m) i_2 + N_1 N_2 P_m i_1 + N_2 N_3 P_m i_3 \quad (8)$$

$$\lambda_3 = (N_3^2 P_{l3} + N_3^2 P_m) i_3 + N_3 N_1 P_m i_1 + N_2 N_3 P_m i_2 \quad (9)$$

Equations (7) to (9) can be expressed in terms of self inductances of the individual windings and mutual inductance between the three windings.

$$\therefore \lambda_1 = L_{11} i_1 + L_{12} i_2 + L_{13} i_3 \quad (10)$$

$$\lambda_2 = L_{21} i_1 + L_{22} i_2 + L_{23} i_3 \quad (11)$$

$$\lambda_3 = L_{31} i_1 + L_{32} i_2 + L_{33} i_3 \quad (12)$$

Where L_{ii} is the self inductance of winding i and L_{ij} is the mutual inductance between windings i and j .

The self inductance of winding one may be considered as the sum of its leakage, L_{l1} and magnetising, L_m inductances when its own current i_1 is acting along. Thus, for winding one $i_2 = i_3 = 0$;

$$\therefore L_{11} = \frac{\lambda_1, i_2=i_3=0}{i_1} = N_1^2 P_{l1} + N_1^2 P_m = L_{l1} + L_m \quad (13)$$

Also for windings two and three

$$L_{22} = \frac{\lambda_2, i_1=i_3=0}{i_2} = N_2^2 P_{l2} + N_2^2 P_m = L_{l2} + L_m \quad (14)$$

$$L_{33} = \frac{\lambda_3, i_1=i_2=0}{i_3} = N_3^2 P_{l3} + N_3^2 P_m = L_{l3} + L_m \quad (15)$$

THE INDUCED AND TERMINAL VOLTAGES EQUATIONS

The induced voltage of each winding is equal to the rate of change of its flux linkage. Therefore from equation (10)

$$e_1 = \frac{d\lambda_1}{dt} = L_{11} \frac{di_1}{dt} + L_{12} \frac{di_2}{dt} + L_{13} \frac{di_3}{dt}$$

Replacing $L_{11}i_1$ by $(L_{11} + L_{m1})$, $L_{12}i_2$ by $\frac{N_2 L_{m1} i_2}{N_1}$ and $L_{13}i_3$ by $\frac{N_3 L_{m1} i_3}{N_1}$ the voltage induced in winding one can be expressed as

$$e_1 = L_{11} \frac{di_1}{dt} + L_{m1} \frac{d(i_2 + \frac{N_2}{N_1} i_2 + \frac{N_3}{N_1} i_3)}{dt}$$

$$\therefore e_1 = L_{11} \frac{di_1}{dt} + L_{m1} \frac{d(i_1 + i'_2 + i'_3)}{dt} \quad (16)$$

also,

$$e_2 = L_{12} \frac{di_2}{dt} + L_{m1} \frac{d(i_2 + \frac{N_2}{N_1} i_1 + \frac{N_3}{N_1} i_3)}{dt}$$

Multiply through by $\frac{N_2}{N_1}$ yields

$$\frac{N_2}{N_1} e_2 = \frac{N_2}{N_1} L_{12} \frac{di_2}{dt} + \frac{N_2}{N_1} \left\{ L_{m1} \frac{d(i_2 + \frac{N_2}{N_1} i_1 + \frac{N_3}{N_1} i_3)}{dt} \right\}$$

$$\therefore e'_2 = L'_{12} \frac{di_2}{dt} + L_{m1} \frac{d(i_2 + i'_2 + i'_3)}{dt} \quad (17)$$

Similarly,

$$e'_3 = L'_{13} \frac{di_3}{dt} + L_{m1} \frac{d(i_3 + i'_2 + i'_3)}{dt} \quad (18)$$

Where e'_2 and e'_3 are induced voltages of winding two and three respectively, referred to winding one. And L'_{12} and L'_{13} are the leakage inductances referred to winding one.

Adding the resistive voltage drops to equation (16) to (18), the resultant voltage at the terminal of each of the windings can be written as:

$$V_1 = i_1 r_1 + L_{11} \frac{di_1}{dt} + L_{m1} \frac{d(i_1 + i'_2 + i'_3)}{dt} \quad (19)$$

$$V_2 = i'_2 r'_2 + L'_{12} \frac{di_2}{dt} + L_{m1} \frac{d(i_2 + i'_2 + i'_3)}{dt} \quad (20)$$

$$V_3 = i'_3 r'_3 + L'_{13} \frac{di_3}{dt} + L_{m1} \frac{d(i_3 + i'_2 + i'_3)}{dt} \quad (21)$$

THE THREE WINDING TRANSFORMER MODEL

The total flux linkages of the three windings are chosen as the state variables. In term of these variables, equation (19) to (21) can be written as :

$$V_1 = i_1 r_1 + \frac{1}{\omega_b} \frac{d\varphi_1}{dt} \quad (22)$$

$$V_2 = i'_2 r'_2 + \frac{1}{\omega_b} \frac{d\varphi'_2}{dt} \quad (23)$$

$$V_3 = i'_3 r'_3 + \frac{1}{\omega_b} \frac{d\varphi'_3}{dt} \quad (24)$$

Where $\varphi_1 = \omega_b \lambda_1$, $\varphi'_2 = \omega_b \lambda'_2$, $\varphi'_3 = \omega_b \lambda'_3$ and ω_b is the base frequency at which the resistances are computed and is given by $\omega_b = 2\pi f$, f is the supply frequency in Hz. The flux linkage per second of the windings can be expressed as:

$$\varphi_1 = \omega_b \lambda_1 = X_{11} i_1 + \varphi_m \quad (25)$$

$$\varphi'_2 = \omega_b \lambda'_2 = X'_{12} i'_2 + \varphi_m \quad (26)$$

$$\varphi'_3 = \omega_b \lambda'_3 = X'_{13} i'_3 + \varphi_m \quad (27)$$

Where

$$\varphi_m = \omega_b L_{m1} (i_1 + i'_2 + i'_3) \quad (28)$$

Using equations (25) to (27), the current through each winding can be expressed interms of their respective fluxes and the mutual flux between them,

$$\therefore i_1 = \frac{\varphi_1 - \varphi_m}{X_{11}} \quad (29)$$

$$i'_2 = \frac{\varphi'_2 - \varphi_m}{X'_{12}} \quad (30)$$

$$i'_3 = \frac{\varphi'_3 - \varphi_m}{X'_{13}} \quad (31)$$

Substituting the values expressions of currents in to equation (28) yields:

$$\frac{\varphi_m}{X_{m1}} = \frac{\varphi_1 - \varphi_m}{X_{11}} + \frac{\varphi'_2 - \varphi_m}{X'_{12}} + \frac{\varphi'_3 - \varphi_m}{X'_{13}} \quad (32)$$

Where $X_{m1} = \omega_b L_{m1}$

Collecting like terms yields:

$$\varphi_m \left[\frac{1}{X_{m1}} + \frac{1}{X_{11}} + \frac{1}{X'_{12}} + \frac{1}{X'_{13}} \right] = \frac{\varphi_1}{X_{11}} + \frac{\varphi'_2}{X'_{12}} + \frac{\varphi'_3}{X'_{13}} \quad (33)$$

Letting

$$\frac{1}{X_M} = \left[\frac{1}{X_{m1}} + \frac{1}{X_{11}} + \frac{1}{X'_{12}} + \frac{1}{X'_{13}} \right] \quad (34)$$

Equation (33) can be written more compactly as:

$$\varphi_m = X_M \left[\frac{\varphi_1}{X_{11}} + \frac{\varphi'_2}{X'_{12}} + \frac{\varphi'_3}{X'_{13}} \right] \quad (35)$$

Substituting the currents of equations (29) to (31) in to equation (22) to (24) yields:

$$V_1 = \frac{\varphi_1 - \varphi_m}{X_{11}} r_1 + \frac{1}{\omega_b} \frac{d\varphi_1}{dt} \quad (36)$$

$$V'_2 = \frac{\varphi'_2 - \varphi_m}{X'_{12}} r'_2 + \frac{1}{\omega_b} \frac{d\varphi'_2}{dt} \quad (37)$$

$$V'_3 = \frac{\varphi'_3 - \varphi_m}{X'_{13}} r'_3 + \frac{1}{\omega_b} \frac{d\varphi'_3}{dt} \quad (38)$$

Rearranging the above equation yields:

$$\varphi_1 = \int \left(\omega_b V_1 - \omega_b r_1 \frac{\varphi_1 - \varphi_m}{X_{11}} \right) dt \quad (39)$$

$$\varphi'_2 = \int \left(\omega_b V'_2 - \omega_b r'_2 \frac{\varphi'_2 - \varphi_m}{X'_{12}} \right) dt \quad (40)$$

$$\varphi'_3 = \int \left(\omega_b V'_3 - \omega_b r'_3 \frac{\varphi'_3 - \varphi_m}{X'_{13}} \right) dt \quad (42)$$

Equations (29) to (31) and (39) to (41) form the basic dynamic model of a single-phase transformer suffering from internal fault. Flux linkages are the state variables, the terminal voltages are the inputs and the winding currents are the outputs.

DETERMINATION OF THREE WINDING TRANSFORMER PARAMETERS

Short circuit fault occurs between the windings at a particular position, it is therefore necessary to determine the position of the short circuit and parameters, such as resistances and inductances for the proper performance of the model.

Generally, the matrix representation of single-phase, N-Winding transformer as presented by Brabdwajn, Dommel and Dommel, (1982) is shown below;

$$\begin{bmatrix} V_1 \\ \vdots \\ V_N \end{bmatrix} = \begin{bmatrix} r_{11} & \dots & r_{1N} \\ \vdots & \ddots & \vdots \\ r_{N1} & \dots & r_{NN} \end{bmatrix} \begin{bmatrix} i_1 \\ \vdots \\ i_N \end{bmatrix} + \begin{bmatrix} L_{11} & \dots & M_{1N} \\ \vdots & \ddots & \vdots \\ M_{N1} & \dots & L_{NN} \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_1 \\ \vdots \\ i_N \end{bmatrix} \quad (43)$$

Therefore, a single-phase, 2-winding transformer can be represented by;

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} \\ r_{21} & r_{22} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} + \begin{bmatrix} L_{11} & M_{12} \\ M_{21} & L_{22} \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} \quad (44)$$

Where V_i is the voltage of winding i , r_{ii} is the self resistance of winding i , r_{ij} is the mutual resistance between winding i and j , L_{ii} is the self inductance of winding i , M_{ij} is the mutual inductance between winding i and j , and i_i is the current of winding i .

Note that, there is no mutual resistance between winding one and two, therefore

$$r_{12} = r_{21} = 0,$$

Now let

$$M_{12} = M_{21}, r_{11} = r_1, r_{22} = r_2, L_{11} = L_1 \text{ and } L_{22} = L_2.$$

So equation (44) becomes;

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} r_1 & 0 \\ 0 & r_2 \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} + \begin{bmatrix} L_1 & M_{12} \\ M_{12} & L_2 \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} \quad (45)$$

A short circuit fault in one of the winding will split the particular winding in to two. By considering a short circuit in the secondary winding, the winding is splited in to two sub coils and hence the number of turns, the resistance and the inductance. Therefore

$$N_2 = n_a + n_b \quad (46)$$

Where n_a is the number of turns of sub coil 'a' of winding two and n_b is the number of turns of sub coil 'b' of winding two.

Therefore equation (45) becomes;

$$\begin{bmatrix} V_1 \\ V_a \\ V_b \end{bmatrix} = \begin{bmatrix} r_1 & 0 & 0 \\ 0 & r_a & 0 \\ 0 & 0 & r_b \end{bmatrix} \begin{bmatrix} i_1 \\ i_a \\ i_b \end{bmatrix} + \begin{bmatrix} L_1 & M_{1a} & M_{1b} \\ M_{a1} & L_a & M_{ab} \\ M_{b1} & M_{ba} & L_b \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_1 \\ i_a \\ i_b \end{bmatrix} \quad (47)$$

Equation (47) can be expressed as

$$V = RI + L \frac{di}{dt} \quad (48)$$

Where

$$V = \begin{bmatrix} V_1 \\ V_a \\ V_b \end{bmatrix}, R = \begin{bmatrix} r_1 & 0 & 0 \\ 0 & r_a & 0 \\ 0 & 0 & r_b \end{bmatrix}, I = \begin{bmatrix} i_1 \\ i_a \\ i_b \end{bmatrix} \text{ and } L = \begin{bmatrix} L_1 & M_{1a} & M_{1b} \\ M_{a1} & L_a & M_{ab} \\ M_{b1} & M_{ba} & L_b \end{bmatrix}$$

Elements of R and L can be computed according to the rule of consistency, leakage and proportionality as illustrated by Bastart et al (1993), using the following expressions;

$$r_a = \frac{n_a}{N_1} r_2; r_b = \frac{n_b}{N_1} r_2 \quad (49)$$

Also,

$$\left. \begin{aligned} X_{i1} = \omega L_1 &\Rightarrow L_1 = \frac{X_{i1}}{\omega} \\ &\Rightarrow L_2 = \frac{X_{i2}}{\omega} \end{aligned} \right\} \quad (50)$$

Where $\omega = 2\pi f$, that is the base frequency in rad/sec. f is the supply frequency in Hz and r_1, r_2, X_{i1} , and X_{i2} are the transformer resistances and inductances respectively.

Also,

$$L_a = \frac{L_2}{\frac{1}{k^2} + \frac{1}{k} + 1} \quad (51)$$

$$L_b = \frac{L_2}{k^2 + 2k + 1} \quad (52)$$

$$M_{ab} = M_{ba} = \frac{L_2}{k + \frac{1}{k} + 2} \quad (53)$$

Where,

$$k = \frac{n_a}{n_b} \quad (54)$$

where K is the transformer turns ratio.

METHODOLOGY

A single-phase, 120/240V, 1.5kVA, 60Hz, pole-type transformer with the following parameters was used to test the developed model:

$$r_1 = 0.25\Omega, r'_2 = 0.134\Omega, x_{i1} = 0.056\Omega, x_{i2} = 0.056\Omega \text{ and } x_{m1} = 708.8\Omega.$$

To run the faulty transformer model two fault scenarios were adopted.

CASE 1: FAULT AT THE PRIMARY WINDING

In this case the primary winding is considered to split in to two, in which 90% of the winding is healthy and 10% is faulty and shorted. Parameters for each sub coil of the winding are computed. These are r'_a and r'_b, L'_a and L'_b . From equation (49)

$$r'_a = \frac{n_a}{N_1} r_1 \text{ and } r'_b = \frac{n_b}{N_1} r_1$$

As a result of the fault

$$n_a = \frac{90}{100} N_1 \text{ and } n_b = \frac{10}{100} N_1$$

Now $r_1 = 0.25\Omega$, therefore

$$r'_a = 0.225\Omega, \text{ and } r'_b = 0.025\Omega$$

The reactances are computed using equation (50) to (54) following the computation of the inductances.

Therefore $x'_{lb} = 2\pi fL'_b = 5.6 \times 10^{-4}\Omega$ and $x_{la} = 2\pi fL_a = 0.0453\Omega$.

And $r_2 = 0.134\Omega$ and $x_{l2} = 0.056\Omega$ (unchanged)

NOTE that for the faulty condition, the subcoils parameters of the primary winding are r_a , r'_b , x_{la} and x'_{lb} .

CASE 2: FAULT IN THE SECONDARY WINDING

Here also, the secondary winding is assumed to be divided in to two, 90% of the winding is healthy and left open and the remaining 10% is faulty due to short circuit. The following parameters are computed. In this situation, number of winding of the two sub coils of the winding are given by

$$n_a = \frac{90}{100}N_2 \text{ and } n_b = \frac{10}{100}N_2, \text{ therefore}$$

$$K = \frac{\frac{9}{10}N_2}{\frac{1}{10}N_2} = 9$$

$$\Rightarrow r'_a = 0.1206\Omega \text{ and } r'_b = 0.0134\Omega$$

The reactances are computed using equation (50) to (54) as shown below

$$L_a = \frac{L_2}{K^2 + K + 1} \text{ and } L_b = \frac{L_2}{K^2 + 2K + 1}, \text{ therefore}$$

$$x'_{la} = 0.0453\Omega \text{ and } x'_{lb} = 2\pi fL'_b = 5.6 \times 10^{-4}\Omega$$

$r_1 = 0.25\Omega$ and $x_{l1} = 0.056\Omega$ (unchanged)

RESULTS AND DISCUSSION

SIMULATION RESULTS

On running the healthy transformer model the following wave forms in figure 1 to figure 3 were obtained.

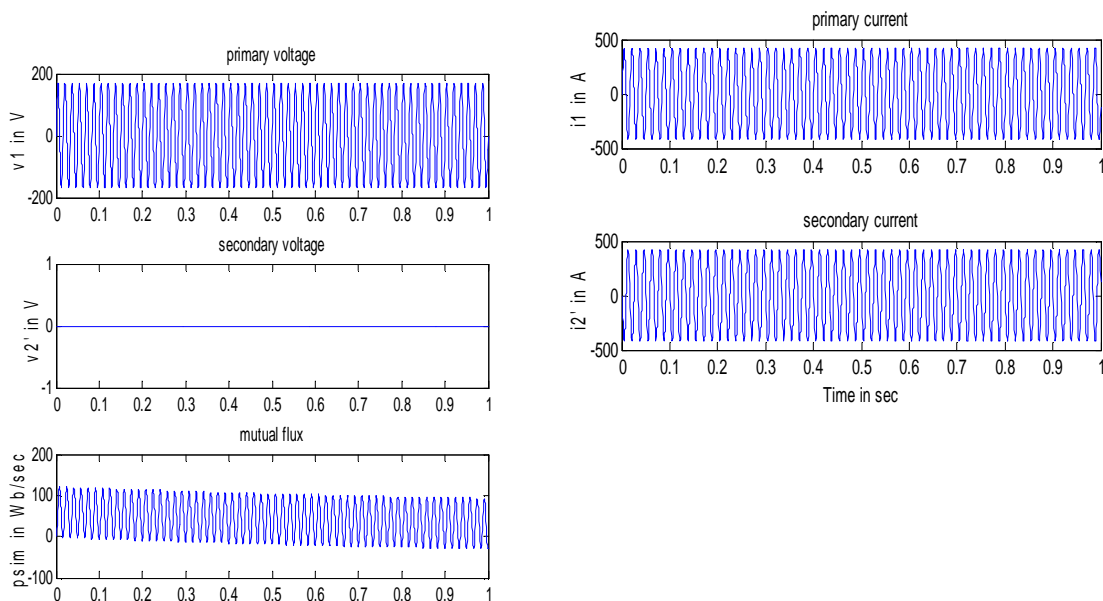


Fig 1: Plot of v_1 , v_2 and ϕ_m for Healthy Transformer

Fig 2: Plot of i_1 and i_2 of Healthy Transformer

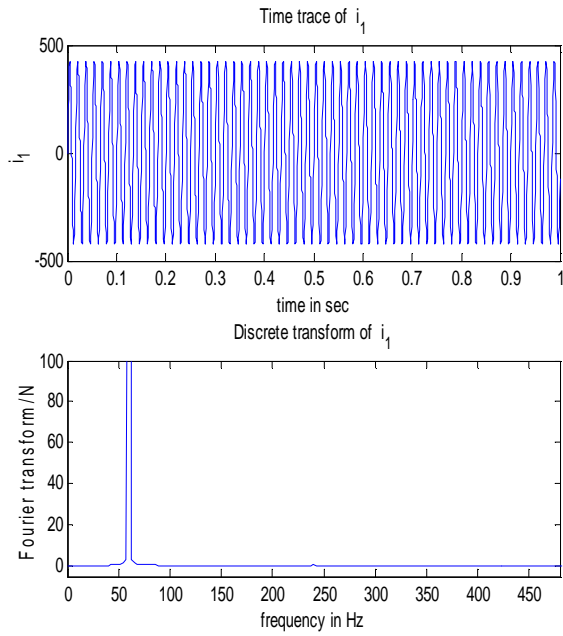


Fig 3: FFT Plot of the Primary Inrush Current for Healthy Transform

Running the model with the parameters in CASE 1, the waveforms obtained are shown in figure 4 to figure 6.

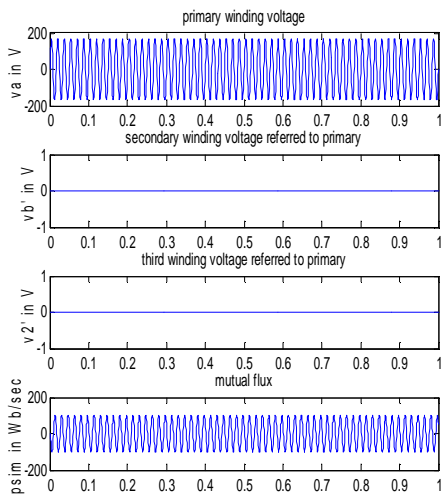


Fig 4: Plot of v_a , v'_b , v'_2 and ϕ_m of Faulty Transformer

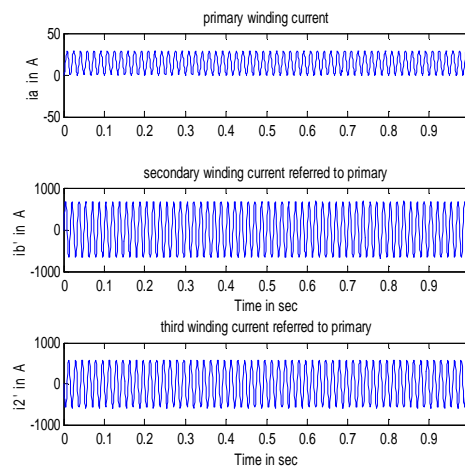


Fig 5: Plot of i_a , i'_b and i'_2 of Faulty Transformer

And the FFT plot of the primary inrush current is given below;

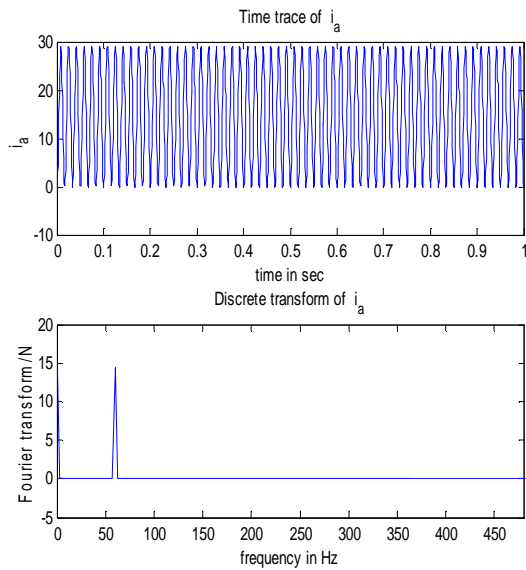


Fig 6: FFT Plot of the Primary Inrush Current for Faulty Transformer

Running the model with the parameters in CASE 2, the results in figure 7 to 9 were obtained.

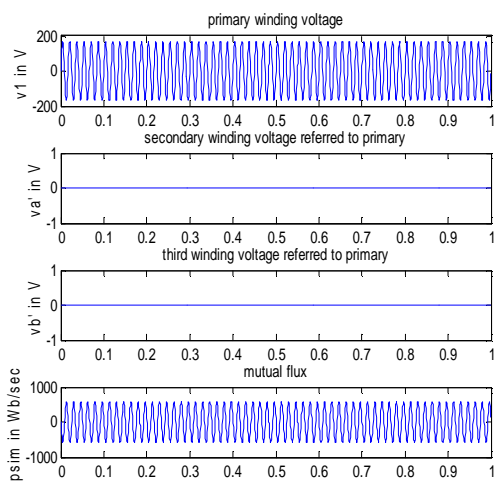


Fig 7: Plot of v_1 , v'_a , v'_b , and ϕ_m of Faulty Transformer.

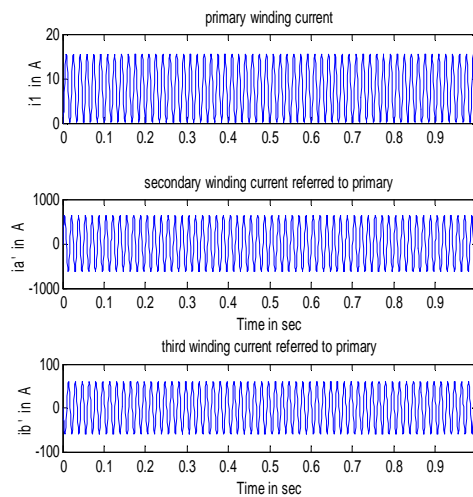


Fig 8: Plot of i_1 , i'_a and i'_b of Faulty Transformer.

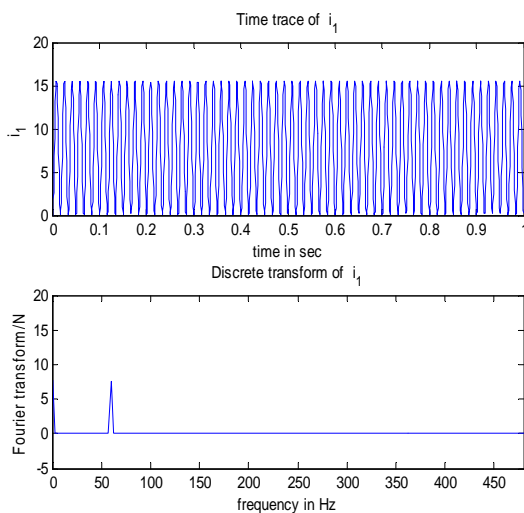


Fig 9: FFT Plot of the Primary Inrush Current for Faulty Transformer

DISCUSSION

From the above wave forms, it can be observed that there is no dc component in the primary inrush current of the healthy transformer model, and there is in the faulty transformer model, when switching the transformer with the secondary shorted (i.e $V_2=0$). This is due to saturation effects as a result of geomagnetically induced current.

When transformer developed short circuit between the phase and neutral, geomagnetically induced currents (GICs) can flow through the short circuit in to the transformer. GEOMAGNETIC disturbances can give rise to geomagnetic surface potentials on the surface of the earth, causing geomagnetically induced currents (GICs) to be established. These currents flow in the transmission lines and windings of transformers by entering and leaving the directly earthed neutrals of the windings. Since the frequency of GIC is very low (typically 0.01 to 0.001 Hz), its effect on the operation of a transformer designed for 50 or 60Hz is akin to continuous dc or quasi dc (Philip, 2002).

Also, it can be observed that there are dc components as shown in the FFTs of the primary inrush currents, as shown in the two cases. When transformer is subjected to a dc injected current, besides its normal operating current, the transformer core will be driven in to saturation and hence harmonic currents will be generated (Al-Haj and El-Amin, 2000).

Core saturation affects can also occur as a result of the increase of the supply voltage. This effect is referred to as "Symmetrical saturation". Each transformer is designed to operate within a fixed range of flux density. If transformer supply voltage increases to certain percentage the flux density will also rise to a range above normal (Al-Haj and El-Amin, 2000). Because of the nonlinearity of

the transformer core saturation, the magnetizing inrush possibly occurs when a transformer is energized. Transformers are designed to operate below the knee of the saturation curve. However, when transformer is switched-on on no-load, flux builds upto a high value, thereby falls in the saturation region and this causes the current to increase. When a transformer is switched-off, the excitation current follows the hysteresis curve to zero. The flux density value will change to a non-zero value, depending on the material of the core. If the transformer is switched on again at the zero crossing instant of voltage, the flux should be at its negative peak as flux lags behind applied voltage by $\pi/2$. Referring to the constant flux linkage theorem, the flux instead of starting from negative maximum value starts from certain value, called residual flux (Φ_r). Flux eventually reaches the positive peak value of $2\Phi_m + \Phi_r$ in the half cycle. This drives the core into saturation thereby resulting in high currents (Xu et al, 2005). Also, saturation can increase the REACTIVE POWER absorption of the transformer, leading to voltage-control problem, generating significant harmonic currents, and cause heating of the internal components of the transformer itself, leading to gas relay alarm/operation as well as possible damage (Philip, 2002).

CONCLUSION

Three winding transformer state space model is developed. Parameters of the developed model are computed using proportionality and consistency theories. And MATLAB\$SIMULINK® software is used in developing the model. It is observed that geomagnetically induced current results to saturation effect on the faulty transformer. This is because of the presence of dc components in the primary inrush current as shown in the wave forms.

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