Transformer Internal Faults Simulation

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***Abstract*—this paper presents a novel method of modeling internal faults in a power transformer. The method leads to a model which is compatible with commercial phasor-based software packages. Consequently; it enables calculation of fault currents in any branch of the network due to a winding fault of a power transformer. These currents can be used for evaluation of protective relays' performance and can lead to better setting of protective functions.**

***Index Terms*—Transformers, transformer windings, modeling, short circuit currents, internal fault**

I. INTRODUCTION

Here is an ongoing need to develop analyses and systems for better protection of power systems. Transformers are widely used in the power system and are among the most important and the most expensive equipments. Failure of a power transformer may lead to loss of power in parts of a system, which can be costly and inconvenient for customers. Therefore; the protection of power transformers is of high importance.

The internal short circuit currents for a transformer may be larger than its terminal short circuit currents. Accordingly, high current stage protection is used in transformer differential protection in order to protect transformers against such large internal short circuit currents immediately.

Therefore, for adequate power transformer protection, an accurate method of calculation of internal faults should be available.

There are several researches in the area of simulation of internal faults in a power transformer [1]-[4]. Nevertheless; all of these methods consider that the transformer is separated from the network. However; transformers are always used inside an actual power system. Therefore; the contribution of the network in an internal fault in a transformer should be regarded. Moreover; none of the previous methods is capable of considering the transformer internal faults in short circuit analysis, and none has been addressed in the practical fault analysis standards (such as IEC, IEEE, etc.).

Calculation of fault currents due to a winding fault of a power transformer, not only at the terminals of the power transformer but also in any branch of the network, was the motivation for doing this study.

This paper presents a method of modeling internal faults of power transformers in phasor-based fault analysis. The model is fully compatible with software packages which are using phasor-based fault analysis. Moreover; it considers the contribution of the network surrounding the transformer, and can calculate the fault currents in any branch of the network.

The winding fault can be single phase to ground or two phase to ground or three phase to ground. Although internal two phase to ground fault and three phase to ground fault rarely happen in a power transformer, the model enables calculation of fault currents in these situations too.

II. TRANSFORMER MODEL

A. Basic Transformer Model

The basic transformer model used is the one presented in [5]. In this model, the excitation and short circuit tests in positive and zero sequences are used to compute two matrices [R] and [L] modeling for a healthy transformer. In the case of a three phase transformer, with two windings for each phase, these matrices are of order 6 as shown in (1)-(2).

$$R = \begin{bmatrix} R_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & R_2 & 0 & 0 & 0 & 0 \\ 0 & 0 & R_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & R_4 & 0 & 0 \\ 0 & 0 & 0 & 0 & R_5 & 0 \\ 0 & 0 & 0 & 0 & 0 & R_6 \end{bmatrix} \quad (1)$$

$$L = \begin{bmatrix} L_{11} & M_{12} & M_{13} & M_{14} & M_{15} & M_{16} \\ M_{21} & L_{22} & M_{23} & M_{24} & M_{25} & M_{26} \\ M_{31} & M_{32} & L_{33} & M_{34} & M_{35} & M_{36} \\ M_{41} & M_{42} & M_{43} & L_{44} & M_{45} & M_{46} \\ M_{51} & M_{52} & M_{53} & M_{54} & L_{55} & M_{56} \\ M_{61} & M_{62} & M_{63} & M_{64} & M_{65} & L_{66} \end{bmatrix} \quad (2)$$

Where R_i and L_i are the resistance and self-inductance of coil i, and M_{ij} is the mutual inductance between coils i and j, see Figure 1. This model is based on the physical concept of representing windings as mutually coupled coils. The method of calculating the two matrices' elements is summarized below. However; all theoretical details relating to this model are explained in [5].

If the winding resistances are known, the [R] matrix is known. If they are not known, they could be calculated from load losses. For two-winding transformers, one could assume that per unit values of primary and secondary resistances are equal [5].

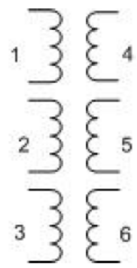

Figure 1. Three phase transformer windings.

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For calculation of the [L] matrix, at first, it is assumed that it is of order 2, as shown in (3).

$$L = \begin{bmatrix} L_{aa} & L_{ab} \\ L_{ba} & L_{bb} \end{bmatrix} \quad (3)$$

Where a, b are the primary and secondary windings of the three-phase power transformer. Each of the elements of (3) is replaced by a 3×3 sub matrix so that [L] will be of order 6 as in (2). The 3×3 sub matrices are as shown in (4).

$$\begin{bmatrix} L_s & L_m & L_m \\ L_m & L_s & L_m \\ L_m & L_m & L_s \end{bmatrix} \quad (4)$$

Where L_s is the self inductance of a phase or leg and L_m is the mutual inductance among the three phases or legs. These self and mutual inductances are related to the positive and zero sequence values L_1 and L_0 by

$$L_s = (L_0 + 2L_1)/3 \quad (5)$$

$$L_m = (L_0 - L_1)/3 \quad (6)$$

Positive and zero sequence inductances of the winding "a" are calculated from the exciting current of the positive and zero sequence excitation tests, if "a" is the excited winding.

$$L_{0-aa} = 1/I_{exc-0} \quad (7)$$

$$L_{1-aa} = 1/I_{exc-1} \quad (8)$$

Equations (7), (8) are valid in per unit values. For the other windings, it is reasonable to assume that the per unit inductances are practically the same as in (7), (8). With the diagonal element pairs known, The off-diagonal element pair values (L_{s-ab}, L_{m-ab}) are calculated from the short circuit input inductance with (9).

$$L_{ab} = L_{ba} = \sqrt{((L_{aa} - L_{ab}^{short})L_{bb})} \quad (9)$$

L_{ab}, L_{ba} are calculated separately for positive and zero sequences, and then the values will be converted to the L_s, L_m from (5), (6).

B. Faulty Transformer Model

In order to model a transformer with a fault between a coil and earth, the faulty coil is divided into two parts [1]. See Figure 2. therefore; [R] and [L] matrices of a transformer with one faulty winding are of order 7.

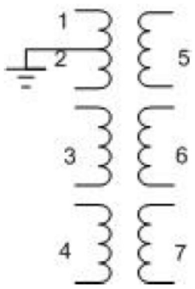

Figure 2. Three phase transformer with a turn to earth fault.

The 7×7 diagonal matrix [R] will be determined with the help of following relations:

$$R_1 = \frac{n_1}{n} \times R_a \quad (10)$$

$$R_2 = \frac{n_2}{n} \times R_a \quad (11)$$

Where n_1, n_2 are the number of turns of coils 1,2. n is the number of turns of whole phase, and R_a is the total resistance of the healthy phase (R_1 in (1)).

For determining the 7×7 matrix [L], the elements related to faulty sub-coils 1 and 2 must be calculated. The other elements are known from the basic transformer model, which is described in the previous section. The method used for calculation of elements associated with faulty sub-coils is like [1], which is verified by experimental results. The difference between model used in this paper and the model presented in [1] is that the model in [1] is a transient model, but the model here is its steady state version.

III. MODELING THE SURROUNDING NETWORK

In order to model the power system surrounding the transformer, two-port thevenin equivalent circuit concept is used [6]. Consider the transformer shown in Figure 3. It is located between busbars p and q in a power system. In order to model the surrounding network by mathematical equations, the transformer is separated from the power system first. Then the thevenin equivalent circuit is calculated:

$$\begin{bmatrix} V_{p1} \\ V_{q1} \end{bmatrix} = \begin{bmatrix} Z_{pp\_1} & Z_{pq\_1} \\ Z_{qp\_1} & Z_{qq\_1} \end{bmatrix} \begin{bmatrix} -I_{p1} \\ I_{q1} \end{bmatrix} + \begin{bmatrix} V_p^0 \\ V_q^0 \end{bmatrix} \quad (12)$$

Where Z_{pp-1}, Z_{pq-1}, Z_{qp-1}, Z_{qq-1} are positive sequence elements of the ZBUS matrix. V_p^0, V_q^0 are pre-fault voltages. The same relation exists for negative and zero sequence networks. However; pre-fault voltages of these networks will be zero.

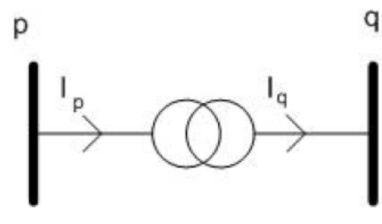

Figure 3. A transformer between busbars p, q in a power system.

These three sets of equations (of three sequences) can be rewritten as the following equations:

$$\begin{bmatrix} V_{p1} \\ V_{p2} \\ V_{p0} \end{bmatrix} = \begin{bmatrix} Z_{pp\_1} & 0 & 0 \\ 0 & Z_{pp\_2} & 0 \\ 0 & 0 & Z_{pp\_0} \end{bmatrix} \begin{bmatrix} -I_{p1} \\ -I_{p2} \\ -I_{p0} \end{bmatrix} + \begin{bmatrix} Z_{pq\_1} & 0 & 0 \\ 0 & Z_{pq\_2} & 0 \\ 0 & 0 & Z_{pq\_0} \end{bmatrix} \begin{bmatrix} I_{q1} \\ I_{q2} \\ I_{q0} \end{bmatrix} + \begin{bmatrix} V_p^0 \\ 0 \\ 0 \end{bmatrix} \quad (13)$$

$$\begin{bmatrix} V_{q1} \\ V_{q2} \\ V_{q0} \end{bmatrix} = \begin{bmatrix} Z_{qp\_1} & 0 & 0 \\ 0 & Z_{qp\_2} & 0 \\ 0 & 0 & Z_{qp\_0} \end{bmatrix} \begin{bmatrix} -I_{p1} \\ -I_{p2} \\ -I_{p0} \end{bmatrix} + \begin{bmatrix} Z_{qq\_1} & 0 & 0 \\ 0 & Z_{qq\_2} & 0 \\ 0 & 0 & Z_{qq\_0} \end{bmatrix} \begin{bmatrix} I_{q1} \\ I_{q2} \\ I_{q0} \end{bmatrix} + \begin{bmatrix} V_q^0 \\ 0 \\ 0 \end{bmatrix} \tag{14}$$

By using the Fortescue transformation, the above equations may be transformed into phase quantities:

$$\begin{bmatrix} V_{pa} \\ V_{pb} \\ V_{pc} \\ V_{qa} \\ V_{qb} \\ V_{qc} \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} & Z_{14} & Z_{15} & Z_{16} \\ Z_{21} & Z_{22} & Z_{23} & Z_{24} & Z_{25} & Z_{26} \\ Z_{31} & Z_{32} & Z_{33} & Z_{34} & Z_{35} & Z_{36} \\ Z_{41} & Z_{42} & Z_{43} & Z_{44} & Z_{45} & Z_{46} \\ Z_{51} & Z_{52} & Z_{53} & Z_{54} & Z_{55} & Z_{56} \\ Z_{61} & Z_{62} & Z_{63} & Z_{64} & Z_{65} & Z_{66} \end{bmatrix} \begin{bmatrix} -I_{pa} \\ -I_{pb} \\ -I_{pc} \\ I_{qa} \\ I_{qb} \\ I_{qc} \end{bmatrix} + \begin{bmatrix} V_{pa}^0 \\ V_{pb}^0 \\ V_{pc}^0 \\ V_{qa}^0 \\ V_{qb}^0 \\ V_{qc}^0 \end{bmatrix} \tag{15}$$

Where V_{pa}, V_{pb}, V_{pc} are phase voltages of the busbar "p". V_{qa}, V_{qb}, V_{qc} are phase voltages of the busbar "q". I_{pa}, I_{pb}, I_{pc}, I_{qa}, I_{qb}, I_{qc} are phase currents of I_p and I_q which are shown in Figure 3.

IV. COMBINING TWO MODLES

Transformer and network models are described in the previous sections. The two models must be combined so that the currents in both sides of the transformer can be calculated. The transformer equations with one faulty phase are:

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \\ V_7 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} & Z_{14} & Z_{15} & Z_{16} & Z_{17} \\ Z_{21} & Z_{22} & Z_{23} & Z_{24} & Z_{25} & Z_{26} & Z_{27} \\ Z_{31} & Z_{32} & Z_{33} & Z_{34} & Z_{35} & Z_{36} & Z_{37} \\ Z_{41} & Z_{42} & Z_{43} & Z_{44} & Z_{45} & Z_{46} & Z_{47} \\ Z_{51} & Z_{52} & Z_{53} & Z_{54} & Z_{55} & Z_{56} & Z_{57} \\ Z_{61} & Z_{62} & Z_{63} & Z_{64} & Z_{65} & Z_{66} & Z_{67} \\ Z_{71} & Z_{72} & Z_{73} & Z_{74} & Z_{75} & Z_{76} & Z_{77} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \\ I_7 \end{bmatrix} \tag{16}$$

And the network equations are as shown in (15). In order to combine two sets of equations, network equations must be transformed into a suitable form. Accordingly, the two relations below are used:

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \\ V_7 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} & A_{15} & A_{16} \\ A_{21} & A_{22} & A_{23} & A_{24} & A_{25} & A_{26} \\ A_{31} & A_{32} & A_{33} & A_{34} & A_{35} & A_{36} \\ A_{41} & A_{42} & A_{43} & A_{44} & A_{45} & A_{46} \\ A_{51} & A_{52} & A_{53} & A_{54} & A_{55} & A_{56} \\ A_{61} & A_{62} & A_{63} & A_{64} & A_{65} & A_{66} \\ A_{71} & A_{72} & A_{73} & A_{74} & A_{75} & A_{76} \end{bmatrix} \begin{bmatrix} V_{pa} \\ V_{pb} \\ V_{pc} \\ V_{qa} \\ V_{qb} \\ V_{qc} \end{bmatrix} \tag{17}$$

$$\begin{bmatrix} -I_{pa} \\ -I_{pb} \\ -I_{pc} \\ I_{qa} \\ I_{qb} \\ I_{qc} \end{bmatrix} = \begin{bmatrix} B_{11} & B_{12} & B_{13} & B_{14} & B_{15} & B_{16} & B_{17} \\ B_{21} & B_{22} & B_{23} & B_{24} & B_{25} & B_{26} & B_{27} \\ B_{31} & B_{32} & B_{33} & B_{34} & B_{35} & B_{36} & B_{37} \\ B_{41} & B_{42} & B_{43} & B_{44} & B_{45} & B_{46} & B_{47} \\ B_{51} & B_{52} & B_{53} & B_{54} & B_{55} & B_{56} & B_{57} \\ B_{61} & B_{62} & B_{63} & B_{64} & B_{65} & B_{66} & B_{67} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \\ I_7 \end{bmatrix} \tag{18}$$

Where V_1, V_2, etc. and I_1, I_2, etc. are voltages and currents of transformer windings. V_{pa}, V_{pb}, etc. and I_{pa}, I_{pb}, etc. are defined in the previous section.

The elements of the [A], [B] matrices are dependent upon the transformer's winding connection.

Using (17), (18), the two sets of equations can be solved together. In the case of star winding and not grounded star point, both sets of equations and [A], [B] matrices are changed slightly since a new variable appears in this case (neutral point voltage). The relations (17), (18) will become:

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \\ V_7 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} & A_{15} & A_{16} & A_{17} \\ A_{21} & A_{22} & A_{23} & A_{24} & A_{25} & A_{26} & A_{27} \\ A_{31} & A_{32} & A_{33} & A_{34} & A_{35} & A_{36} & A_{37} \\ A_{41} & A_{42} & A_{43} & A_{44} & A_{45} & A_{46} & A_{47} \\ A_{51} & A_{52} & A_{53} & A_{54} & A_{55} & A_{56} & A_{57} \\ A_{61} & A_{62} & A_{63} & A_{64} & A_{65} & A_{66} & A_{67} \\ A_{71} & A_{72} & A_{73} & A_{74} & A_{75} & A_{76} & A_{77} \end{bmatrix} \begin{bmatrix} V_{pa} \\ V_{pb} \\ V_{pc} \\ V_{qa} \\ V_{qb} \\ V_{qc} \\ V_n \end{bmatrix} \tag{19}$$

$$\begin{bmatrix} -I_{pa} \\ -I_{pb} \\ -I_{pc} \\ I_{qa} \\ I_{qb} \\ I_{qc} \\ V_n \end{bmatrix} = \begin{bmatrix} B_{11} & B_{12} & B_{13} & B_{14} & B_{15} & B_{16} & B_{17} & 0 \\ B_{21} & B_{22} & B_{23} & B_{24} & B_{25} & B_{26} & B_{27} & 0 \\ B_{31} & B_{32} & B_{33} & B_{34} & B_{35} & B_{36} & B_{37} & 0 \\ B_{41} & B_{42} & B_{43} & B_{44} & B_{45} & B_{46} & B_{47} & 0 \\ B_{51} & B_{52} & B_{53} & B_{54} & B_{55} & B_{56} & B_{57} & 0 \\ B_{61} & B_{62} & B_{63} & B_{64} & B_{65} & B_{66} & B_{67} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \\ I_7 \\ V_n \end{bmatrix} \tag{20}$$

In this case, by combining the transformer and the network equations there will be 7 equations and 8 variables.

Therefore; an additional equation is needed, for the system will be deterministic as written in (19), (20):

$$I_{pa} + I_{pb} + I_{pc} = 0 \tag{21}$$

$$I_{qa} + I_{qb} + I_{qc} = 0 \tag{22}$$

The method used for analysis of two or three phase to ground faults is similar to the method which is already presented.

In order to calculate fault currents in other parts of the power system, two sets of currents in primary and secondary sides are transformed into the sequence components. Then, these sequence currents will be injected into the appropriate sequence ZBUS matrices. Therefore; voltages and currents in other parts of power system will be calculated. It should be noted that the corresponding ZBUS matrices of the power system is calculated without considering transformer, i.e. the transformer is separated from the power system.

V. SIMULATION RESULTS

For demonstration of performance of proposed method two simulations has been carried out.

A. Comparison between two faulty transformer models

A comparison is made between transient [1] and steady state models of faulty power transformer, and Figure 4 shows the system model used for this comparison. The transformer is 230kv/109.8kv with YgYg winding connection.

Transformer parameters are as follows:

Z_{s11}=0.2054666+i0.41432E+05

Z_{m11}=-i*0.5416527496E-01

Z_{s12}=Z_{s21}=i*0.1977101943E+05

Z_{m12}=Z_{m21}=i*0.9553782211

Z_{s22}=0.742333E-01+i*0.9437875034E+0.4

Z_{m22}=i*0.736830605

Where windings 1, 2 are a, b in (3), and Z_{s11}=R_1+i*L_{s11}. (R_1 and L_{s11} are defined in (10), (5) respectively). Load and terminal impedances are as follows:

Z_{LO}=32.55+i*15.76, Z_{TL}=3+i*3

Fault has occurred in 50% percent of phase "a" of primary side winding, and fault time is 0.2 seconds. Figs. 5-11 show the winding's currents. Table I show the result of this comparison. The closeness of currents calculated by two models validates use of the steady state model.

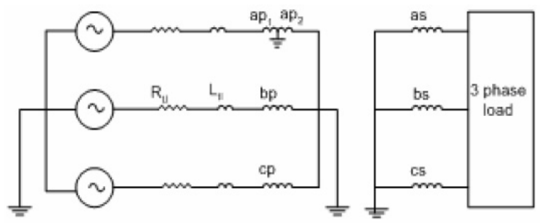

Figure 4. System model for an internal fault in winding ap.

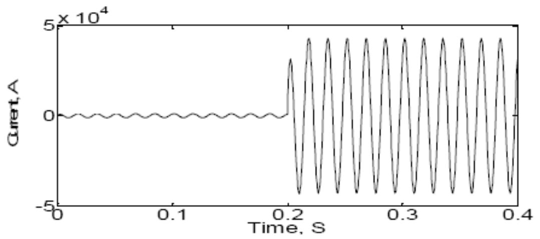

Figure 5. Winding ap1 current for an internal single phase to ground fault.

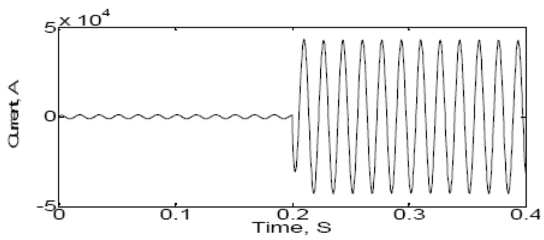

Figure 6. Winding ap2 current for an internal single phase to ground fault.

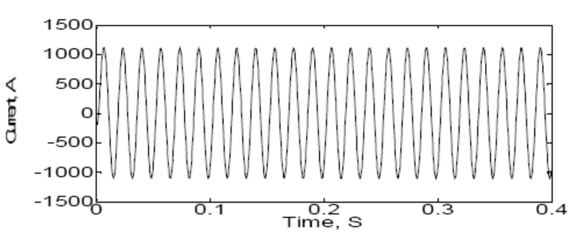

Figure 7. Winding bp current for an internal single phase to ground fault.

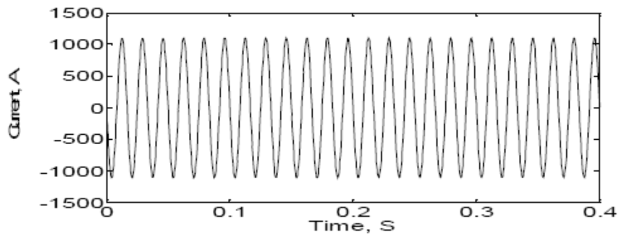

Figure 8. Winding cp current for an internal single phase to ground fault.

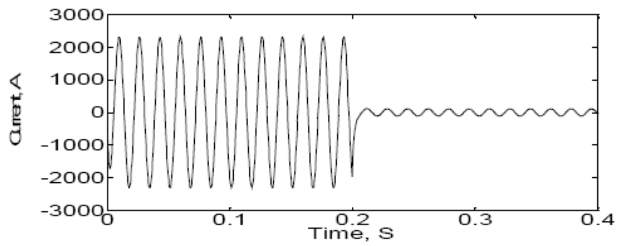

Figure 9. Winding as current for an internal single phase to ground fault.

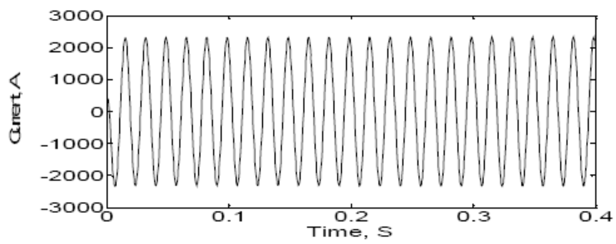

Figure 10. Winding bs current for an internal single phase to ground fault.

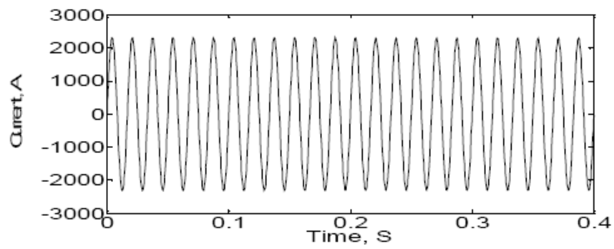

Figure 11. Winding cs current for an internal single phase to ground fault.

TABLE I. COMPARISON BETWEEN THE RESULTS OF TRANSIENT AND STEADY STATE TRANSFORMER MODELS FOR AN INTERNAL SINGLE PHASE TO GROUND FAULT.

	TRANSIENT MODEL	STEADY STATE MODEL
i_{ap1}(A)	3.020E4	3.024E4
i_{ap2}(A)	3.017E4	3.018E4
i_{bp}(A)	787.009	783.154
i_{cp}(A)	776.403	777.580
i_{as}(A)	80.5395	80.4138
i_{bs}(A)	1639.1	1637.9
i_{cs}(A)	1628.5	1626.2

B. Simulation of the proposed method

A sample network is shown in Figure 13. The faulty transformer is located between sub1 and sub2 busbars, to which primary side winding and secondary side winding of transformer are connected respectively. A single phase to ground fault is located in the primary side winding as shown in Figure 12. The transformer's winding connection is DYg1.

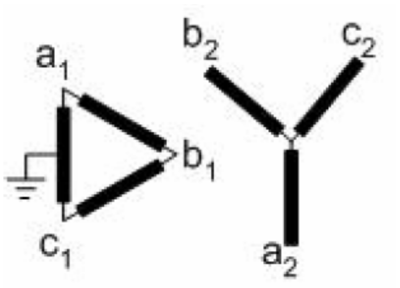

Figure 12. A DYg1 transformer with a turn to earth fault.

The transformer and network data are listed in tables II, III.

TABLE II. TRANSFORMER DATA

Short circuit data	Positive sequence impedance (p.u.)	0.01+i*0.1
	Zero sequence impedance (p.u.)	0.01+i*0.1
Excitation data	Positive sequence current (p.u.)	0.004
	Zero sequence current (p.u.)	0.004

TABLE III. NETWORK DATA

Positive sequence impedance (p.u.)	Z_{pp}[1]	0.0261+i*0.0502
	Z_{qq}	0.0281+i*0.1294
	Z_{pq}	0.000882+i*0.00173
Negative sequence impedance (p.u.)	Z_{pp}	0.0281+i*0.0507
	Z_{qq}	0.0058+i*0.083
	Z_{pq}	0.000241+i*0.001
Zero sequence impedance (p.u.)	Z_{pp}	0.0401+i*0.0706
	Z_{qq}	0.0058+i*0.4978
	Z_{pq}	0

The [A], [B] matrices for this transformer are as follows:

$$A = \begin{bmatrix} \frac{1}{\sqrt{3}} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{-1}{\sqrt{3}} & 0 & 0 & 0 \\ \frac{-1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & 0 & 0 & 0 & 0 \\ 0 & \frac{-1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (23)$$

$$B = \begin{bmatrix} \frac{-1}{\sqrt{3}} & 0 & \frac{1}{\sqrt{3}} & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{-1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & 0 & 0 & 0 \\ 0 & \frac{1}{\sqrt{3}} & 0 & \frac{-1}{\sqrt{3}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 \end{bmatrix} \quad (24)$$

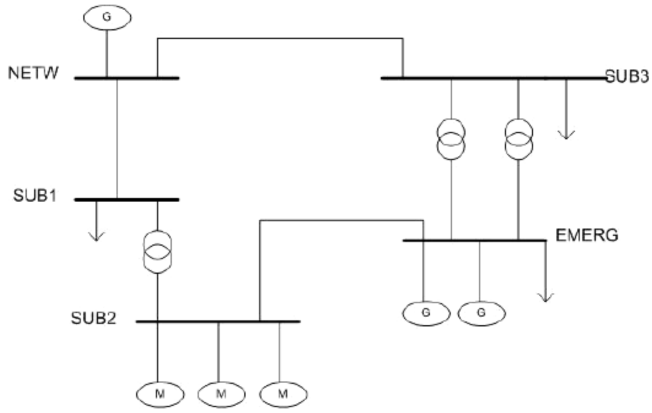

Figure 13. A sample network.

A single phase to ground fault is set at the primary side terminal of the transformer (phase a), and fault currents are compared with the results of a commercial phasor-based software2. The two sets of currents are shown in table IV.

Magnitude and angle of the currents are shown. The closeness of the two sets of currents shows that modeling of the network surrounding the transformer and its combination with faulty transformer model is done accurately.

TABLE IV. COMPARISON OF TERMINAL FAULT CURRENTS

	Proposed model	Phasor-based software
I_{pa}	15.01<-60.71	15.02<-60.77
I_{pb}	1.2439<-92.49	1.2325<-90.54
I_{pc}	1.351< -69.4	1.3717<-71.74
I_{qa}	2.207< 103.2303	2.25<102.72
I_{qb}	2.1566< -84.4441	2.1718<-83.92
I_{qc}	0.2964<-7.3479	0.2697<-8.55

Then, the fault point is moved from terminal of phase a to the terminal of phase c. Magnitude of the fault currents are shown in Figs. 14, 15. If fault point is in the middle of the faulty phase, fault currents of the phases a, c of the primary side are expected to be equal as in Fig.14. Fault currents in phases b, c of the secondary side are also equal, which shows that the model is correctly performed.

VI. CONCLUSION

A new modeling approach has been developed which enables calculation of the transformer internal faults in short circuit analysis. The model is validated and is compatible with phasor-based software packages. Therefore; it can be widely used for the purpose of protection of power transformers and power systems.

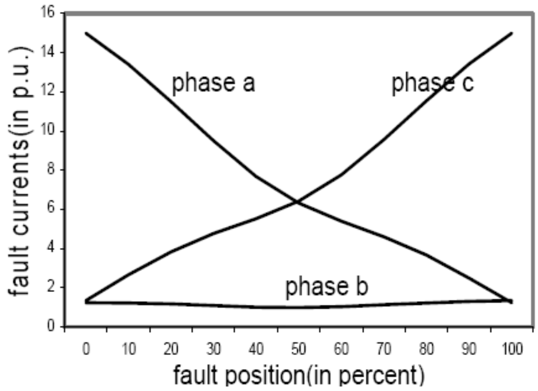

Figure 14. Fault currents as a function of fault position (percentage of coil from the terminal of phase a) in the primary side.

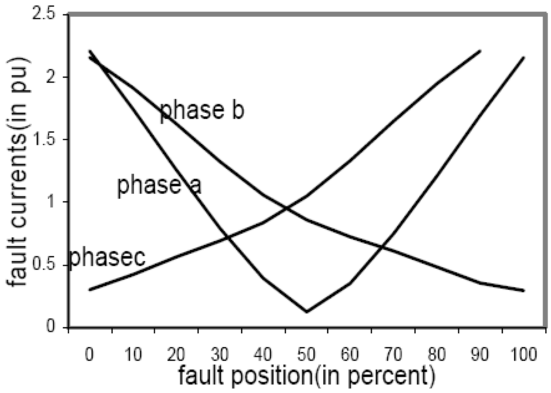

Figure 15. fault currents as a function of fault position (percentage of coil from the terminal of phase a) in the secondary side.

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