Simulation Modeling of Incipient Faults in Power Transformer

Anil Kumar, Ajay Rathore, Ashish Patra

Abstract - This paper presents a method of modeling internal winding faults of three-phase, power transformers to single-phase, distribution transformers. The model which is compatible with the alternative Transients Program, ATP, allows the simulation of turn-to-earth and turn-to-turn faults on either windings of a single-phase, two-winding, distribution transformer. Results of staged internal winding faults of a distribution transformer are compared with the simulation results to validate the model. The experimental results were found to be comparable to those of the simulation.

Index Terms – Internal winding, power transformer, distribution transformer, compatible, alternative transients program (ATP), simulation,

---

1. INTRODUCTION

The transformer is one of the most expensive and important electrical equipment of a power distribution system and hence the loss of such an equipment through catastrophic failure can be very costly.

Deregulation in the USA has caused a drastic change in the electricity market. This change has put utilities under stress since electric energy has become a bulk commodity traded and sold under free market competition resulting in a cost consciousness among utilities. The main driving forces are to reduce maintenance costs, prevent forced outages with the consequential costs, prevent forced outages with the consequentail costs, and work existing equipment harder and longer [1]. utilities are therefore looking for ways to detect developing or incipient faults before they become catastrophic and allow for a change from periodic-to condition-based maintenance. Different techniques have been used in the area of transformer fault detection and diagnosis. The most established diagnostic and monitoring method is the analysis of dissolved gases in the transformer[1]. The method is based on analyzing the types, concentration and production rates of generated gases [2, 3]. The technique is well accepted and has the capability to detect a wide range of failure types. Determination of the degree of polymerization value of cellulose (used in paper insulation) is a standard method for quantifying the degradation of cellulose [4].

Other methods have utilized the measurement of transfer functions of the transformer to detect deformations of the windings [5, 6]. Deformation or changes in geometrical distances of the windings leads to changes in internal capacitance, and thereby a change in the transfer function of the transformer.

A study of the records of modern transformer breakdowns which have occurred over a period of years shows very conclusively that between 70 and 80% of the number of failures are finally traced to short-circuits between turns [7]. These short circuits are a result of degradation or wear of the transformer winding insulation (often called the minor insulation) causing adjacent turns to short (turn-to-turn fault) or turn (s) shorting to any grounded part of the transformer (turn-to-earth faults).

The purpose of the work reported here is aired at developing a technique that utilizes electrical indicators for internal winding fault detection and diagnosis. Towards this, it is attempted to simulate some of the winding faults of single-phase transformers and validate the same with experiments.

A model developed in [8] for three-phase power transformers is adapted to model single-phase distribution transformers to study the effect of internal winding faults at the terminals. Simulation and field test results of staged internal winding faults are presented. A comparison of the two results is made to show the validity of the model.

2. SINGLE-PHASE TRANSFORMER MODEL

Figure (la) shows the winding representation of a single-phase, two-winding transformer in figure (l b).

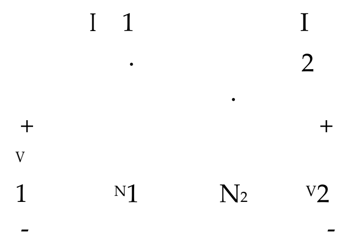

Figure 1a. Two winding transformer

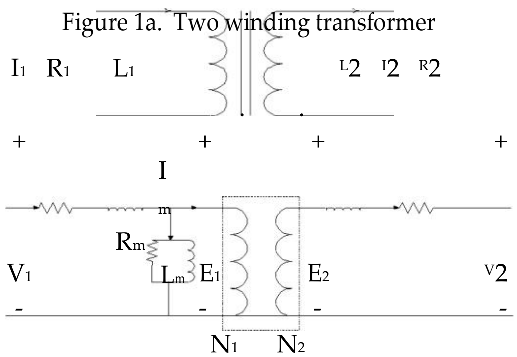

Figure 1b. Equivalent circuit of a two-winding transformer

In figure 1, V_i's are terminal voltages, Ei's the induced voltages, I_i's the winding currents, R_i's the winding resistances, L_i's the winding inductances and N_i's the number of winding. Subscript ' i ' refers to the primary winding, '2' the secondary winding and 'm' the magnetizing branch.

The resistance and inductance of the two-winding transformer are represented in ATP by the 2×2 matrices [R] and [L] as shown in equation (1).

$$\begin{bmatrix} R_1 & 0 \\ 0 & R_2 \end{bmatrix} = \begin{bmatrix} L_1 & M_{12} \\ M_{21} & L_2 \end{bmatrix}$$

Mij is the mutual inductance between windings i and j. BCTRAN, a supporting routine of ATP [9] is used to derive a linear [R] - ω [L] representation for the single-phase, two winding transformers using data of both the open-circuit and short-circuit tests at rated frequency. Stray capacitances are ignored in this representation and hence the model is only valid for up to a few kHz. The derived [R] - ω are of the form shown in (1).

To model internal faults, the [R], ω [L] matrices are revised where some of their elements are computed by BCTRAN for a transformer without faults in the winding, and the other elements computed from mathematical equations modeling faults in the winding.

2.1 Turn-to-earth fault

A turn-to-earth fault on the primary winding divides the primary winding into sub-coils as shown in fig. 2.

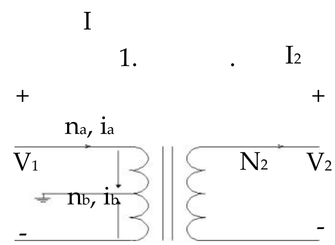

Fig. 2. Single-phase transformer with a turn-to-earth fault on primary

$$[R] = \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_2 \end{bmatrix} \; | \, \omega[L] = \omega \, |$$

$$\begin{bmatrix} L_a & M_{ab} & M_{a2} \\ M_{ba} & L_b & M_{b2} \\ M_{2a} & M_{2b} & L_2 \end{bmatrix} \qquad ...(2)$$

[R] is determined using the relations :

$$R_a = \frac{n_a}{N_1} \times R_1 ; R_b = \frac{n_b}{N_1} \times R_1 \qquad ...(3)$$

L_2 is determined from BCTRAN and the remaining elements in the matrix, ω [L], are computed from mathematical relations of the faulted coil. Determination of L_a, L_b, and $M_{ab} = M_{ba}$ is based on the rules of consistency, leakage and proportionality. Derivation and use of equations based on these rules can be found in [8]. Using the rules of proportionality and leakage, we have

$$L_a = \frac{L_1}{\frac{1}{k^2} + \frac{2}{k} + 1} ; L_b = \frac{L_1}{k^2 + 2k + 1} ;$$

$$M_{ab} = \frac{L_1}{k + \frac{1}{k} + 2} \qquad ...(4)$$

Where k = $\frac{n_a}{n_b}$. The principle of consistency leads to:

$$M_{12} = M_{a2} + M_{b2} \qquad ...(5)$$

Since we are using a shell-type single-phase transformer all coils are wound on the same leg. If $n_a > n_b$ then

$$M_{a2} = M_{12}\sqrt{\frac{L_a}{L_1}} \qquad ...(6)$$

M_{12}, L_1, L_2 are obtained from the 2×2 matrix computed by the BCTRAN routine and L_a is computed by (4). This gives

$$M_{b2} = M_{12} - M_{a2} \qquad ....(7)$$

2.2 Turn-to-turn fault

A turn-to-turn fault on the primary divides the winding of the primary into three sub-coils as shown if figure (3).

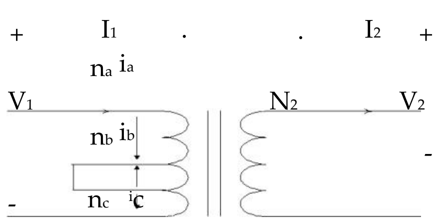

Figure 3. Single-phase transformer with a turn-to-turn fault on primary.

The transformer in this case is represented by the 4×4 matrices [R] and ω [L] in (8).

$$[R] = \begin{bmatrix} R_1 & 0 & 0 & 0 \\ 0 & R_b & 0 & 0 \\ 0 & 0 & R_c & 0 \\ 0 & 0 & 0 & R_2 \end{bmatrix}$$

$$\omega[L] = \omega \begin{bmatrix} M_{ba} & L_b & M_{ba} & M_{b2} \\ M_{ca} & M_{cb} & L_c & M_{c2} \\ M_{2a} & M_{2b} & M_{2c} & L_2 \end{bmatrix} \quad ....(8)$$

[R] is determined using the relations :

$$R_a = \frac{n_a}{N_1} \times R_1;\ R_b = \frac{n_b}{N_1} \times R_1;$$

$$R_c = \frac{n_c}{N_1} \times R_1 \qquad ...(9)$$

L_a, L_b, L_c, M_{ab}, M_{ac} and M_{bc} are determined numerically using the rules of consistency, leakage and proportionality. M_{a2}, M_{b2} and M_{c2} are determined using the consistency principle which results in (10).

$$M_{a2} + M_{b2} + M_{ca} = M_{12} \qquad ..(10)$$

$$M_{a2} = M_{12}\sqrt{\frac{L_a}{L_1}};\ M_{b2} = \sqrt{\frac{L_b}{L_1}} \qquad .(11)$$

M_{ac} is then computed using (10) and (11). In (11), the leakage between the primary and the secondary coil is assumed to be close to the leakage between the faulted coil on the primary and the secondary coil.

3. COMPUTER SIMULATION

Figures 4a and 4b show the implementation of turn-to-earth and turn-to-turn faults in ATP respectively.

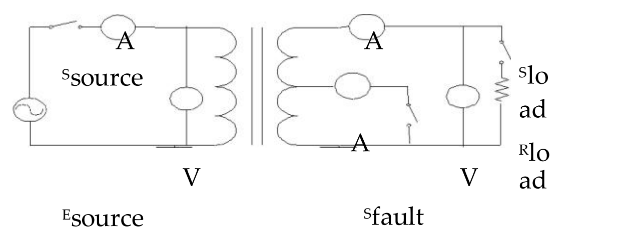

Figure 4a. Simulation setup for turn-to-earth fault on the secondary

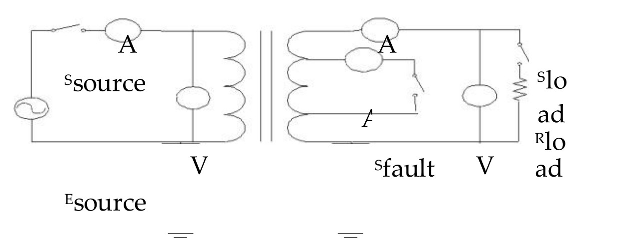

Figure 4b. Simulation setup for turn-to-turn fault on the secondary

A single-phase, 50Hz, two-winding, 25kVA, 7200V / 240V transformer is used for the simulations. In both cases

ISSN 2229-5518

the primary of the transformer is connected to an ideal sinusoidal source, E_{source}, through switch, S_{source}, closed at time, $t = 0.$ The secondary is connected to a purely resistive load, $R_{load} = 2.34\,\Omega$ through swith,

S_{load}, closed at time, $t = 0$, Turn-to-earth and turn-to-turn faults are staged on both winding of the transformer. The currents and voltages on both the primary and the secondary sides are monitored in addition to the current circulating through the shorted windings.

4. EXPERIMENTAL SETUP

Figure 5 shows the experimental setup used to study the terminal behavior of a transformer under various internal winding fault conditions. The transformer and load have the same ratings as used in the simulations.

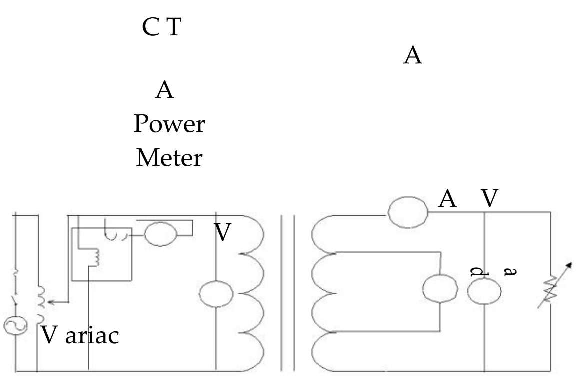

Figure 5. Experimental setup with turn-to-turn fault on secondary.

The primary of the transformer had 780 turns total in 12 layer: 112 turns in the first 6 layers and 108 turns in the last layer. The windings are made of copper. The secondary has two sets of windings of 13 layers each made of aluminum sheets. The secondary could be connected for either 120 V (the two sets connected in parallel) or 240V (the two sets connected in series) output. For the work reported in this paper, the secondary was connected for a 240V output and faults were staged on the primary winding of the transformer.

The primary side of the transformer was connected to a variac capable of supplying up to 240V, 22A maximum. Due to high circulating current in the shorted winding, a voltage far less than the rated was supplied through the variac. For this experiment, the supply voltage was maintained at 100 Vrms for all cases. The secondary side is connected to a variable, pure, resistive load. The load used here was a 2.304 ohms. Meters to measure the voltages and currents on both sides and also the circulating current in the shorted winding were connected as shown in figure 5 above.

5. RESULTS

Validation of the proposed method was waveforms in two steps:

1. Prior to faults initiation, the waveforms of terminal voltages and currents of both the primary and secondary winding modeled using methods in section II are compared to terminal voltages and currents of primary and secondary windings modeled using the BCTRAN routine of ATP. It was found that the proposed model generated waveforms similar to those generated using the BCTRAN routine of ATP. This validates the models for normal operating conditions of the transformer.
2. Under fault conditions, actual field experiments are conducted as explained in section IV. Figure 6a shows the primary current waveform obtained during simulation of a turn-to-earth fault on the 280th turn of primary and figure 6b shows the primary current waveform for a turn-to-turn fault between turns 337 and 364 of the primary. The fault initiated at t=0.04 seconds.

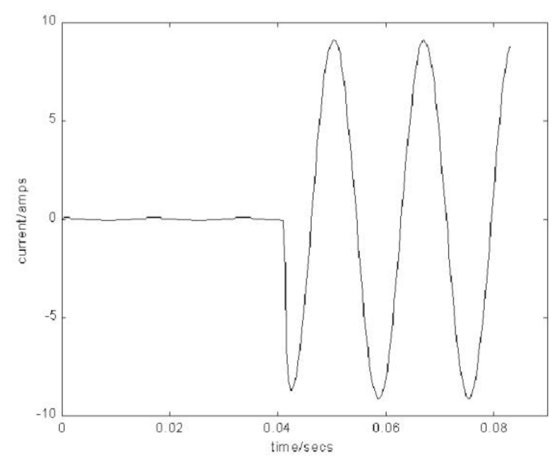

Figure 6a. Primary current for turn-to-earth fault on the 280th turn of primary.

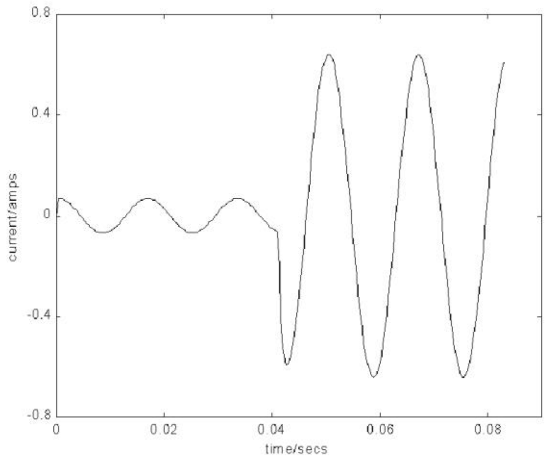

Figure 6b. Primary current for turn-to-earth fault between turns 337 and 364 of primary

For faults on the primary side, the primary current showed a visible change. The other terminal values remained approximately constant before and after the fault.

Table 1 gives a comparison of the results between simulation and experimental test. Case P280_F is a turn-to-earth fault between the 280th turn on the primary and the ground. Case P4_5F is a turn-to-turn fault between turns 337 and 364 on the primary. The $\boldsymbol{V_i}$'s are voltages in volts and the $\boldsymbol{I_i}$'s are currents in amps. All values are rms. The subscript 'I' stands for the primary and '2' for the secondary.

Table 1. Comparison of simulation and experimental results

Case	Parameter	Simulation	Experiment
P280_F	V_1	99.98	100.50
	V_2	3.84	3.02
	I_1	4.96	6.46
	I_2	1.32	1.66
P4_5F	V_1	99.98	100.20
	V_2	3.83	3.32
	I_1	0.45	0.51
	I_2	1.66	1.46

The results in table 1 show the simulation and experimental results are quite close within the limits of experimental errors. The validates the model.

6. CONCLUSION

A method has been presented to model and simulate internal winding faults of a two-winding, single-phase, distribution transformer. Simulation results indicate that the proposed method yields correct results. Further, from table 1, the results of the field experiments are in close agreement with the simulation results, thus validating the proposed method.

7. ACKNOWLEDGEMENT

The authors thanks to MITS department Gwalior and Director Mr. Sajaeev Jain MITS Gwalior to contonous encouragement to this work.

8. REFERENCES

1. Bengtsson, C., "Status and trends in transformer Monitoring", IEEE 1995 Powertech Conference, Stockhlom, Sweden, pp. 1379 – 1384.
2. "IEEE Guide for the Interpretation of Gases Generated in Oil Immersed Transformer", IEEE St andard C57.104-1991, New York IEEE Press, 1992
3. Stebbins, D. Rand., et al., "Dissolved Gas Analysis of Transformers Oil", Panel Session, 1997 Winter Meeting. PES/ IEEE, February 1997, NY.
4. Allan. D. M., "Practical Life-Assessment Techniques for Aged Transformer Insulation", IEEE Proceedings A, Vol. 140, No. 5 September, 1993, pp. 404-408.
5. Bak-Jensen, J., et al, "Detection of Faults and Aging Phenomena in Transformer by Transfer Functions", IEEE Transactions on Power Delivery, Vol. 10, No. 1, January 1995, pp. 308-314.
6. Swanevelder, P, Hancke, G.P. "Utilizing the Transfer Function in Transformers Testing", IMTC' 94, May 10-12.
7. Stigant, S.A. Franklin S. A. "The J & P Transformer Book", 10th Ed., John Wiley & Son, NY-Toronto.
8. Bastard. P. et al, "A Transformer Model for Winding Fault Studies", IEEE Transactions on Power Delivery, Vol. 9, No. 2 April 1994, pp. 690-699.
9. Alternative Transients Program (ATP) Rule Book, Canadian/American EMTP Users Group, 1987-1995.