

Modeling and Simulation of Three-Phase Power Transformer

V. D. Dhote¹, P. G. Asutkar², Subroto Dutt³

¹ Department of Electrical Engineering, Ballarpur Institute of Engineering, Ballarpur, Dist. Chandrapur, India

^{2&3} Department of Electrical Engineering, Rajiv Gandhi College of Engineering and Research Technology, Chandrapur, India

Abstract

Power transformers are among the most important and expensive equipments in the electric power systems. Consequently the transformer protection is an essential part of the system protection. This paper presents a new method for locating transformer winding faults such as turn-to-turn, turn-to-core, turn to transformer body, turn-to-earth, and high voltage winding to low voltage winding. In this study the current and voltage signals of input and output terminals of the transformer are measured by Fourier transform signals measure in matlab/simulation.

Keywords- turn-to-turn faults, short circuit, Fourier transformation, matlab/simulation.

I. INTRODUCTION

THE electrical faults of transformers are classified in two types: external and internal faults. External faults are those that occur outside of the transformer: overloads, overvoltage, over-fluxing, under frequency, and external system short circuits. Internal faults are those that occur inside of the transformer: winding phase-to-phase, phase-to-ground, winding inter-turn, over-fluxing, and etc [1]. A very large number of transformers are used in the electric power systems. These costly and critical devices provide the necessary voltage conversions to transfer power through the system. Internal faults in transformers can cause huge damages in a very short time, and in some cases the damages are repairable [2], and also about 70%-80% of transformer failures are caused by internal faults [3]. So fault locating is a necessary work for repairing the faulted transformers, which can be repaired and turned back in service again.

Internal faults especially turn-to-turn faults are common in transformer failures. There are many different techniques available for detecting and/or locating these kinds of faults such as: high frequency analysis [3], Frequency Response Analysis (FRA) [4,], Artificial Neural Networks (ANNs) and winding transfer functions [6], finite element analysis [7], online diagnostics of transformer winding insulation failures by Park's vector approach [8], combination of discrete wavelet transforms and back-propagation neural networks [9] experimental studies [10], [11],

double Fourier series [12], numerical technique based on symmetrical components [13], Genetic Algorithm (GA) [14], and etc. Also transformer model's equivalent circuit is different in each method. In this paper, the physical model of a 440V/440V transformer is simulated in MATLAB/Simulink.

This transformer model's equivalent circuit considers each of the winding turns separately [4], so simulating and testing the faults in each one of the winding turns or sections is possible. In this equivalent circuit just three turns of each of the primary and secondary windings are modeled, which is a simplified model of windings with n turns, and this simplification decreases the process time. Some of the equivalent circuit's elements values are measured from [4] and others are experimental values. All of the mentioned faults are applied in this model one by one in different step times and analyzed. The first step after applying faults on the model is calculating the Fourier transform of the signals. In further analyzes the harmonics and frequency components of all of the faults are extracted from the Fourier transform's plots and are saved as indexes. And the last step is pattern recognition which the fault signals of a real transformer can compared with the saved indexes in the database and the type and location of the fault can be measured.

II. PROPOSED WORK

The physical model of a transformer is simulated in MATLAB/Simulink. This transformer model's equivalent circuit considers each of the winding turns separately [4], so simulating and testing the faults in each one of the winding turns or sections is possible.



Fig.1 - The three phase transformer with tapping.

In this equivalent circuit just three turns of each of the primary and secondary windings are modeled, which is a simplified model of windings with n turns, and this simplification decreases the process time. Some of the equivalent circuit's elements values are measured from [3] and others are experimental values. All of the mentioned faults are applied in this model one by one in different step times and analyzed.

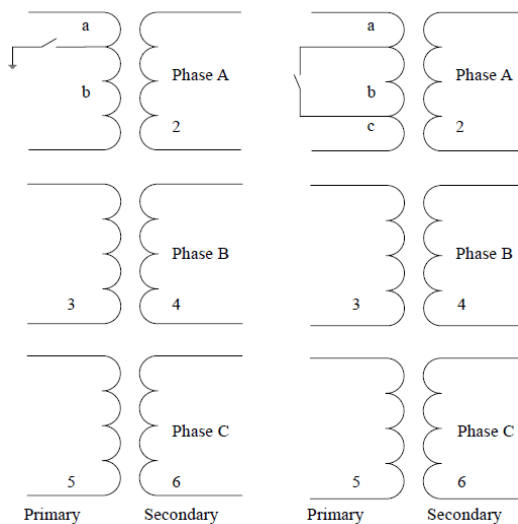


Fig.2 - The three phase transformer equivalent ckt.

The first step after applying faults on the model is calculating the Fourier transform of the signals. In further analyzes the harmonics and frequency components of all of the faults are extracted from the Fourier transform's plots and are saved as indexes.

III. EXPERIMENT SETUP

The three phase laboratory core-type transformer in open geometry design; there is a possibility to connect both primary and secondary windings either in star (wye) or in delta connection. The investigated transformer is with wye-wye connections; the rated data for this case are: Burden Total 900VA; Per Phase 300VA; Current 1.18Amps. The equal limb $2\frac{1}{2}$ " stack, 440/440V, 3 coils – 254Volts each with tapings are 50%, 86.6% and 100%. The physical model of a transformer is simulated in MATLAB/Simulink. This transformer model's equivalent circuit considers each of the winding turns separately [4], so simulating and testing the faults in each one of the winding turns or sections is possible.

The used transformer model as mentioned before has only three turns in each of the windings. So simulating all of the possible short circuit faults in each of the turns and all of the possible turn-to-turn faults are achievable. Primary winding to secondary winding faults are simulated several times too, because each time different primary winding turns

are short circuited into different secondary winding turns. Different cases of inter turn short circuit are staged, considering the effect of number of turns shorted on primary and secondary and load condition. Experimental set up is as shown in Fig.3



Fig.3: Experiment setup of 0.9 KVA, three phase transformer.

IV. LINEAR MODEL VALIDATION

For the model validation a three-phase, three-leg transformer, of 0.9 kVA, 440/440 V, was used. The transformer has three-windings per phase on the primary and on the secondary side, having, one of each, been modified by addition of a number of tapping's connected to the coils, for each of the three phases, allowing for the introduction of different percentages of shorted turns at several locations in the winding, for subsequent studies of inter-turn short-circuits occurrence.

The direct and homopolar short-circuit and excitation tests were performed with the transformer having a star-star winding connection, without neutral wire, in order to obtain the matrices elements. The transformer digital model, with Y/Y connections, was initially tested under no-load conditions. With the secondary side open-circuited, a symmetrical three-phase voltage system, with transformer nominal values, was applied to the primary side. The primary side energized by a symmetrical three-phase voltage system, with transformer nominal values.

In this simulation all of the data is generated by the current and voltage signals of input and output terminals of the transformer model's equivalent circuit, one time in no load mode and another time in with-load mode. No-load mode's scopes obtain three parameters: input voltage, input current, and output voltage. With-load mode's scopes obtain four parameters: input voltage, input current, output voltage, and output current. Each of these scopes' time domain data is saved in a separate table. Both of the no-load and with-load tests are applied once without fault and several times with different types of short circuit faults that mentioned earlier. When a fault happens, a ripple is generated in the scope's output. These ripples have a very lower frequency band than the waveform, and a variable domain, and it happens in a very short time. After the ripples, the

sinusoidal waveform continues, but the waveform's domain is changed: usually voltage domains are decreased and current domains are increased, depends on the number of short circuited turns and location of faults. And also the measured terminal: output or input.

All of the faults are applied in several step times so the fault can occur in different locations of the scopes sinusoidal output waveform. This is so important to have the faults' data in different step times because the ripples' domains vary in each point of the waveform. And the worst situations are those that the fault happens in $y=0$ or when it happens in each of the peaks of waveform. In these situations the ripple's domain has the biggest size and usually the ripple's domain is several times bigger than the waveform's domain itself. And the more it is bigger; the more it is dangerous for the transformer. In the firstly simulations (no-load and with-load without applying any of the faults), two step times for each signal is measured (in $y=0$ and in the peak) to apply the faults in these times.

There is also important to apply the fault in the simulation after several sinusoidal cycles when the transformer is stable, not running it with a fault at first, because having the ripples values is important for our next analysis. After simulating all of the faults in both no-load and with load mode, and running each of the faulted circuit models in MATLAB/Simulink one by one in several step times, each of the waveform output values is saved in a separate table, then there are ready for the next process; The Fourier transform. Fast Fourier Transform (FFT) of each of the voltage and current waveforms is calculated. Then by plotting the absolute value of each of the waveforms' FFT result, faults are diagnosable in the plotted figures.

A. Harmonics and Frequency Components

Power system harmonics are sinusoidal components of Periodic waveforms that have frequencies that are multiples of the fundamental frequency of the waveform [15]. For example if the system frequency (fundamental frequency) is 50 Hz, typical harmonics are odd harmonics such as the third harmonic (150 Hz), the fifth harmonic (250 Hz), the seventh harmonic (350 Hz), and so on. And also the third harmonic is one of the most important harmonics in harmonic analysis of a power system. The power system's sine form generated voltage and current are defined mathematically as:

$$v(t) = V_m \sin(\omega t) \quad \dots\dots\dots (1)$$

$$i(t) = I_m \sin(\omega t) \quad \dots\dots\dots (2)$$

Where V_m , I_m are the amplitudes of voltage and current Waveforms and ω is the angular frequency of the signal ($\omega = 2\pi f = 2\pi (50 \text{ Hz}) = 314$

rad/s for the frequency of 50 Hz). All of the noticed equations are related to Linear Time-Invariant (LTI) systems. For dealing better with non-linear electrical systems, engineers use the Fourier theory which says that any periodic waveform can be described as the summation of the series of sine curves with different frequencies and amplitudes [15]. Thus by using the Fourier theory, the periodic pulses of (1) can be modeled as:

$$V(t) = V_0 + V_1 \sin(\omega t) + V_2 \sin(2\omega t) + \dots\dots\dots + V_n \sin(n\omega t) \quad \dots\dots\dots (3)$$

Which V_0 is the DC value of the waveform, and $V_1, V_2, V_3 \dots$ are the peak values of the series. The fundamental harmonic (the first harmonic) has the f frequency, the second harmonic's frequency is $2f$, and the n th harmonic's frequency is nf .

In this simulation the frequency components are extracted from the circuit models (the healthy model and all of the faulted models) all in both no-load and with-load mode. Then the harmonics of each signal is extracted from the calculated signal FFTs that mentioned before. And all of the harmonic values are saved in separate tables as indexes for referring to them in cases of real fault for comparison.

B. Fourier Transform Equations

In Fourier analysis the Fourier series are used for processing periodic signals and the Fourier transform is used for processing a periodic signals. Since the periodic signals of transformer become a periodic during the fault, we need Fourier transforms for analyzing and processing the signals. For the periodic time-continuous signal of $f(t)$ the Fourier transform $g(j\omega)$ is defined as:

$$g(j\omega) = \int_{-\infty}^{+\infty} f(t)e^{j\omega t} dt$$

V. METHODOLOGY

- a. Detailed literature survey of different Frequency Component analysis techniques and Harmonic analysis techniques.
- b. In MATLAB/simulink, all of the data is generated by the current and voltage signals of input and output terminals of the transformer model's equivalent circuit, one time in no-load mode and another time in with-load mode.
- c. When a fault happens, a ripple is generated in the scope's output. These ripples have a very lower frequency band than the waveform, and a variable domain, and it happens in a very short time.
- d. After the ripples, the sinusoidal waveform continues, but the waveform's domain is changed: usually voltage domains are decreased and current domains are increased, depends on the number of short circuited turns and location of faults. And also the measured terminal: output or input.

e. In the firstly simulations (no-load and with-load without applying any of the faults), two step times for each signal is measured (in $y=0$ and in the peak) to apply the faults in these times. There is also important to apply the fault in the simulation after several sinusoidal cycles when the transformer is stable, not running it with a fault at first, because having the ripples values is important for our next analysis.

f. After simulating all of the faults in both no-load and with load mode, and running each of the faulted circuit models in MATLAB/Simulink one by one in several step times, each of the waveform output values is saved in a separate table, then there are ready for the next process.

g. The Fourier transforms of each of the voltage and current waveforms are calculated.

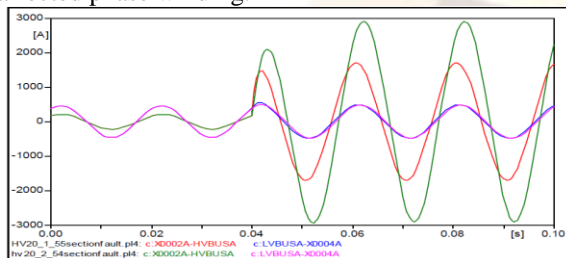
h. Comparison and analysis of results to get a sensitive technique for the fault detection and identification in the power transformer.

VI. SIMULATION RESULTS

The used transformer model as mentioned before has only three turns in each of the windings. So simulating all of the possible short circuit faults in each of the turns and all of the possible turn-to-turn faults are achievable. Each of the single turn short circuit faults is simulated and all of the possible turn-to-turn faults are simulated too. Other kinds of faults such as turn-to-core, turn-to-transformer body, turn-to-earth, and primary winding to secondary winding are simulated. Primary winding to secondary winding faults are simulated several times too, because each time different primary winding turns are short circuited into different secondary winding turns. Some of the plotted figures of voltage and current signals' FFTs are represented as samples in below, and list of the simulated faults are showed.

A. Turn-to-turn Fault on primary side

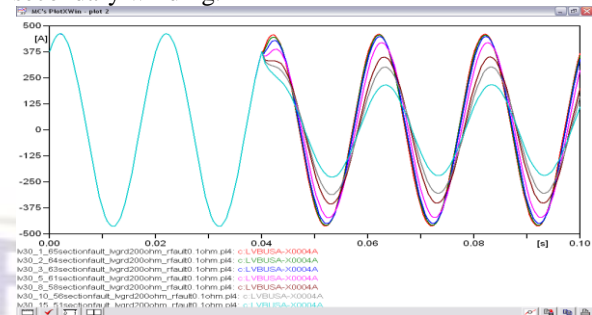
If the faults take place in the primary winding, the faulty turns will act as an three phase transformer load on the winding, and the reactance is that between the faulty turns and the whole of the affected phase winding.



B. Turn-to-turn Fault on secondary side

A short circuit of a few turns of the winding will give rise to a heavy fault current in the short-circuited loop, but the terminal currents will be very

small, because of the high ratio of transformation between the whole winding and the short-circuited turns. The simulation of turn-to-turn fault is started by short-circuited one section (three turns) of the secondary winding.



VII. CONCLUSION

In this paper a simplified model of a power transformer simulated and different kinds of faults applied on it. The frequency components and the harmonics of the FFT signals of all of the simulated faults are extracted and saved as special indexes. The indexes are saved in the database and could be compared with any kind of similar transformer for finding the short circuit fault's location. This method can also be used for other kinds of internal winding faults too.

REFERENCES

- [1] IEEE Std C37.91-2000, "IEEE Guide for Protective Relay Applications to Power Transformers."
- [2] J. Webster (ed.), "Wiley Encyclopedia of Electrical and Electronics Engineering," Transformer Protection, (c) 1999, John Wiley & Sons, Inc.
- [3] M. R. Barzegaran and M. Mirzaie, "Detecting the position of winding short circuit faults in transformer using high frequency analysis," European Journal of Scientific Research, vol. 23, 2008, pp. 644-658.
- [4] A. Shintemirov, W. J. Tang, W. H. Tang, and Q.H. Wu, "Improved modeling of power transformer winding using bacterial swarming algorithm and frequency response analysis," Electric Power Systems Research, vol. 80, 2010, pp. 1111-1120.
- [5] M. A. Abdul Rahman, H. Hashim, and P. S. Ghosh, "Frequency response analysis of a power transformer," Electrical Engineering Department, College of Engineering, Universiti Tenaga Nasional.
- [6] M. Faridi, M. Kharezi, E. Rahimpour, H.R. Mirzaei, and A. Akbari, "Localization of turn-to-turn fault in transformers using artificial neural networks and winding transfer function," International Conference

- on Solid Dielectrics, Potsdam, Germany, July 4-9, 2010.
- [7] H. Wang and K.L. Butler, "Finite element analysis of internal winding faults in distribution transformers," IEEE Transactions on Power Delivery, vol. 16, July 2001.
- [8] L. M. R. Oliveira and A.J. Marques Cardoso, "On-line diagnostics of transformer winding insulation failures by Park's vector approach," Proceedings of the 9th International Electrical Insulation Conference, pp. 16-21, Berlin, Germany, June 18-20, 2002.
- [9] A. Ngaopitakkul and A. Kunakorn, "Internal fault classification in transformer windings using combination of discrete wavelet transforms and back-propagation neural networks," International Journal of Control, Automation, and Systems, vol. 4, no. 3, pp. 365-371, June 2006.
- [10] L. Satish and Subrat K. Sahoo, "Locating faults in a transformer winding: an experimental study," Electric Power Systems Research, vol. 79, pp. 89-97, 2009.
- [11] P. Palmer-Buckle, K. L. Butler, and N. D. R. Sarma, "Characteristics of transformer parameters during internal winding faults based on experimental measurements," IEEE Transmission and Distribution Conference, 1999.
- [12] A. S. Reddy and M. Vijaykumar, "Neural network modeling of distribution transformer with internal winding faults using double Fourier series," International Journal of Computer Science and Applications, vol. 1, December 2008.
- [13] T.S. Sidhu, H.S. Gill, and M.S. Sachdev, "A numerical technique based on symmetrical components for protecting three-winding transformers," Electric Power Systems Research, vol. 54, pp. 19-28, 2000.
- [14] V. Rashtchi, E. Rahimpour and E. M. Rezapour, "Using a genetic algorithm for parameter identification of transformer R-L-C-M model," Electrical Engineering, vol. 88, pp.417-422, 2006.