VOL. 11, NO. 10, MAY 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

MODELING DISTRIBUTION TRANSFORMERS FOR INRUSH TRANSIENTS STUDY

H. Abdull Halim[1,2], Thinh Dao[1], and B. T. Phung[1]
[1]School of School of Electrical Engineering and Telecommunications, University of New South Wales, Sydney, Australia
[2] School of Electrical Systems Engineering, Universiti Malaysia Perlis, Perlis, Malaysia
E-Mail: hanahalim@unimap.edu.my

ABSTRACT

In a transformer energization study, transformer modeling is one of the major challenges. The representation of windings, the modeling of the magnetic iron core and the ability to specify flux are the main focuses. Other than that, the interfacing network, iron saturation, losses, transformer data and the connection should also be taken into account. This paper presents a transformer model for slow-front transients caused by 50 Hz line energization. Three single-phase 16 kVA, 11 kV/ 250 V distribution transformer models are used. This classic transformer model (include the leakage reactance and magnetising branch) are adopted from PSCAD/EMTDC master library and further modeled by combination of analytical analysis and measurements. Core saturation is modeled using an ideal current source across the specified winding; the saturation curve is constructed using curve-fitting method, generated by MATLAB Optimization. The circuit breaker is modeled using Maximum Closing Time Span (MCTS). For modeling validation, a transformer of same rating was employed as the test object. Since the PSCAD simulation and experimental measurements give similar results, it demonstrates the capability of the model to accurately represent the energization transient of a distribution transformer.

Keywords: transformer modeling, power system transients, inrush current, energization transient, PSCAD/ EMTDC.

INTRODUCTION

Power system transients including inrush currents, over voltages, and lightning impulse stresses can be harmful to the power and distribution transformers. Even though this sudden change in the system cannot be eliminated in total, it can possibly be reduced to a safe state. Malfunctioning of the system due to the high inrush current can occur in many ways such as voltage dips, sympathetic inrush, harmonic resonance over-voltages and also excessive mechanical and electrical stresses. All these can further result in protection malfunctioning, system equipment damage and power quality problems.

In order to reduce the transient, a number of electricity providers have installed synchronised breakers [1]. It is aimed to minimise the high inrush but this industry practice then results in higher over voltages and increasing resonance risk.

A detailed study of transformer model is carried out to facilitate development of methods to minimise the inrush. Transformer is a complex structure and to model the transformer itself is a challenge. The estimation of some parameters can be difficult. As mentioned in [1], the error can occur both during the measurement stage and post processing. In transformer energization, the inrush current occurred is considered as one of the most demanding low-frequency transient to be modeled. Thus, if the transformer model can correctly predict inrush current transients, it can also be utilised to predict other switching transients.

In this paper, the modeling of transformer where inrush current occurs during energization is proposed, in line with what is available in PSCAD/ EMTDC – a popular simulation tool for analyzing power systems transients. In order to model a three-phase saturable transformer, three single-phase two-winding transformers are constructed and modeled in the simulation. This transformer modeling takes into consideration the core modelling, its saturation and its estimation. Next, circuit breaker modeling is presented and then the simulation results with detailed discussion. Finally, measurements from laboratory experiments are presented to compare and validate the model.

TRANSFORMER MODELING

Detail modeling of transformer representation is complex due to the variations in core and coil design and their complex behaviors during transient phenomena. In transformer energization study, the focus should be on the windings and core estimation. According to the CIGRÉ report WG 33-02 in [2], transient frequency ranges can be classified into four groups. Table-1 shows the modeling recommendation from them.

Table-1. Transformer modeling recommendation. [2].

Parameter	Low Frequency Transients	Slow Front Transients	Fast-Front Transients
Short- circuit impedance	Very important	Very important	Important
Saturation	Very important	Very important [1]	Negligible
Iron losses	Important [2]	Important	Negligible
Eddy currents	Very important	Important	Negligible
Capacitive coupling	Negligible	Important	Very important

Note: 1) Only for transformer energization, otherwise important
2) Only for resonance phenomena

To develop a model for a three-phase transformer, transformer physical design information and characteristic data are needed. Often, the only information available is what is on the nameplate, or maybe the basic factory test results [3]. There is no information on the transformer core type, core material, etc. It should be noted that the "RMS exciting current" taken from factory tests is actually the average of the three measured true RMS phase currents [3].

In this work, transformer modeling for slow-front transients is considered. This is suitable for simulation of power system transients such as excitation inrush currents and switching overvoltage, originated from line energization.

The saturable transformer model can be represented in several configurations. The model includes the leakage reactance and a magnetising branch. The core saturation is modeled using an ideal current source across the specified winding.

Another standard model available in PSCAD is UMEC, the acronym for Unified Magnetic Equivalent Circuit model. However, it requires the transformer dimensional data, which is, in this case, not available. Thus, the classic saturable three-phase transformer model is used instead of the UMEC model.

Saturable transformer modeling

Known as the non-linear version of the classic Steinmetz model [4], saturable transformer component (STC) model is a two and/or three winding single phase transformer model. Mathematically, a single-phase N-winding transformer can be described by:

$$\left[\frac{di}{dt}\right] = \left[L\right]^{-1}[v] - [L]^{-1}[R][i] \quad (1)$$

Thus, the magnetising current depends on the applied winding voltage integration:

$$i(t) = \frac{1}{L}\int v_1(t) \quad (2)$$

and the flux density equation is:

$$B(t) = \frac{1}{n_1 A_c}\int v_1(t)dt \quad (3)$$

When flux density is high, it will result in the core saturated. It happens when volt-seconds λ_1 are too large, where:

$$\lambda_1 = \int_{i_1}^{i_2} v_1(t)dt \quad (4)$$

and voltage in saturation is represented in:

$$v = \frac{d}{dt}\lambda \quad (5)$$

It can be used to model a three-phase transformer, constructed using three single-phase two-winding units. The input data needed are the values of resistance and inductance of each star branch, the turn ratios, and the data for defining the magnetising branch [4]. Figure-1 and Figure-2 show the star-circuit representation of single-phase and three-phase transformers.

The model discussed the three phase 16 kVA, 11 kV/ 250 V transformer. In this PSCAD simulation, the primary branch is treated as an uncoupled *R- L* branch, and both of the windings being handled as two-winding transformer. The circuit representing the core is connected across the terminals of the LV winding. Other required data are the positive sequence leakage resistance, no load losses and copper losses values. Saturation data are needed to be input.

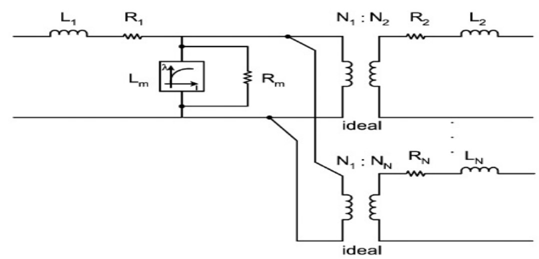


Figure-1. Star-circuit representation of single-phase N-winding transformers [5].

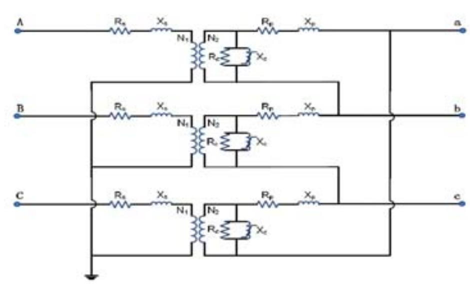


Figure-2. Constructing three- phase transformer from three two-winding STCs. [6].

Modeling multi-limb transformer

The importance of modeling the multi-limb transformers was discussed in many researches. Norton transformer representation has been proposed and improved. Nowadays, it uses a combination of duality and leakage inductance representation [7]. This Norton equivalent transformer can directly be derived from the magnetic equivalent circuit analysis. This formulation allows detailed magnetic equivalent circuits to be easily implemented in electromagnetic transient programs. In PSCAD/ EMTDC, this generalised model of a Norton equivalent for modeling the multi-limb transformer is easily implemented.

Core type and modeling

Core type (including the coupling between phases, zero sequence impedance and non-uniform saturation in different parts of the core) will influence the behavior of the transformer during transient events [8].

Core construction will determine the mutual coupling between windings. Since the classic transformer model is used for this study, the classical core modeling is chosen. The current source represents the magnetic core saturation, as shown by a block diagram format in Figure-3. [9].

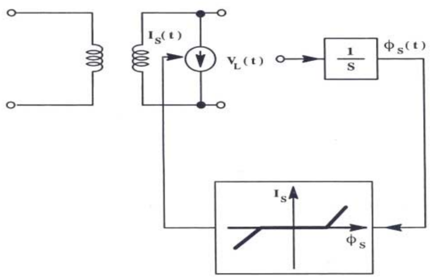


Figure-3. Modeling the transformer saturation in PSCAD/ EMTDC.

In Figure-4, the voltage across the first winding is represented by E_1 and the voltage across the second winding is represented by E_2. L_{11} denotes the self-inductance of the first winding and L_{22} denotes the self-inductance of the second winding.

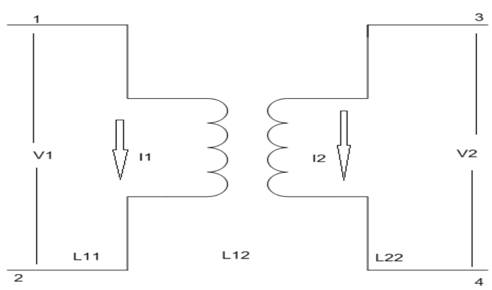


Figure-4. Two mutually coupled windings.

Thus, the relationship between voltage and current in the circuit is:

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} L_{11} & L_{12} \\ L_{12} & L_{22} \end{bmatrix} . \frac{d}{dt} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \quad (6)$$

For multi-limb construction, the mathematical equation in matrix form can be expressed as:

$$\begin{bmatrix} V_{a1} \\ V_{b1} \\ V_{c1} \\ V_{a2} \\ V_{b2} \\ V_{c2} \end{bmatrix} = \begin{bmatrix} r & 0 & 0 & 0 & 0 & 0 \\ 0 & r & 0 & 0 & 0 & 0 \\ 0 & 0 & r & 0 & 0 & 0 \\ 0 & 0 & 0 & R & 0 & 0 \\ 0 & 0 & 0 & 0 & R & 0 \\ 0 & 0 & 0 & 0 & 0 & R \end{bmatrix} . \begin{bmatrix} i_{a1} \\ i_{b1} \\ i_{c1} \\ i_{a2} \\ i_{b2} \\ i_{c2} \end{bmatrix} + \quad (7)$$

$$\begin{bmatrix} L_1 & M_1 & M_2 & M_3 & M_4 & M_5 \\ M_1 & L_2 & M_6 & M_7 & M_8 & M_9 \\ M_2 & M_6 & L_3 & M_{10} & M_{11} & M_{12} \\ M_3 & M_7 & M_{10} & L_4 & M_{13} & M_{14} \\ M_4 & M_8 & M_{11} & M_{13} & L_5 & M_{15} \\ M_5 & M_9 & M_{12} & M_{14} & M_{15} & L_6 \end{bmatrix} . \frac{d}{dt} \begin{bmatrix} i_{a1} \\ i_{b1} \\ i_{c1} \\ i_{a2} \\ i_{b2} \\ i_{c2} \end{bmatrix}$$

where for a unit with n-windings, this equation will be in n-th order. Matrix Equation. (7) can also be expressed as:

$$V_{n.1} = R_{n.n}.i_{n.1} + L_{n.n}.\frac{d}{dt}i_{n.1} \quad (8)$$

By applying the rule of integration:

$$i(t) = i_{inj} + G.v(t) \quad (9)$$

where i_{inj} represents current injection, G represent admittances connected between transformer terminals.

It can be concluded that in PSCAD/ EMTDC software, all models used this Trapezoidal Rule. In mathematical modeling, it is noted that the trapezoidal rule of integration has faster convergence and very accurate. For periodic function, it is very stable at all-time step selections too.

Estimation of core saturation curve

In many cases, the transformer open circuit test is the only data source for approximating the saturation curve. However, when modeling for the equivalent circuit of transformer, another issue is the lack of reliable data from which to obtain the parameters of the equivalent circuit, i.e. leakage inductance, nonlinear magnetising inductance for core saturation and nonlinear resistance for core loss. Thus, some nonlinear optimisation strategy must be implemented in this case.

There are two approaches to improve the non-linear characteristic: linear extrapolation and curve fitting [1]. For linear extrapolation method, it assumes a constant slope of the saturation curve after the last point of the non-linear curve. The accuracy of this method can be questionable when the two last points of the piecewise nonlinear curve lie in the 100% to 110% excitation level range [6] which means the complete saturation is not being reached throughout the open circuit test. A linear addition of the curve will result in a simple under-estimation of current for any level beyond the last identified point. On the other hand, curve fitting is a method of constructing a curve, by allowing the additional artificial points of the saturation characteristic. It is performed to add the new segments of data in the non-linear curve, possibly due to constraints.

From Equation. (8), L and R elements are derived from the short circuit test and open circuit test for the transformer. In this work, all three results of the open-circuit test from equivalent transformers (T1 and T2) are measured. From the open circuit test, the graph is plotted in Microsoft Excel. However, the voltage and current data did not provide sufficient data to accurately model the saturation curve of the transformer. For improving the non-linear data from the open-circuit, the curve fitting method is preferred. The curve fitting point can be generated easily by Microsoft Excel, using the logarithmic trend line options. Besides Excel, MATLAB Optimization toolbox can be used to generate the saturation curve. From this, the curve fitting equation is obtained as indicated in Figure-5.

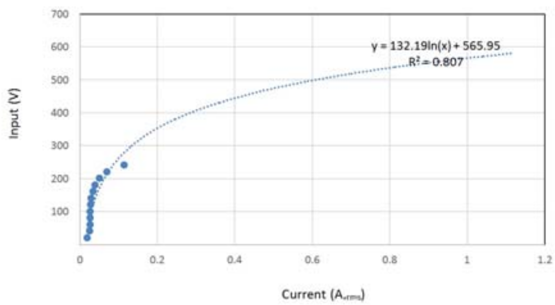


Figure-5. Saturation curve after curve fitting.

Modeling transformer parameters

From the open circuit test, short circuit test and DC test for all the transformers, the values for the electrical parameters are calculated and shown in Table-2.

Table-2. Parameters for Transformer 1 and 2.

Parameters (symbol)	T1	T2
Apparent Power (kVA)	16	16
Frequency (Hz)	50	50
HV level (V)	11,000	11,000
LV level (V)	250	250
HV current (A)	1.45	1.45
LV current (A)	32-64	32-64
R_{dc}(HV) (Ω)	49.292	47.158
R_{dc}(LV-a_1a_2) (Ω)	0.044	0.045
R_c(Ω)	4166.67	3289.47
X_m(Ω)	1959.29	1298.41
R_{eq}(Ω)	120.08	124.36
X_{eq}(Ω)	231.87	243.21

COMPONENT MODELING

Circuit breaker modeling

There is a guideline for circuit breaker modeling. From [9], they categorised the importance each of operation in closing and opening the circuit breaker by their frequency ranges. In this particular case (slow front transients), closing operation is very important to take note, whilst opening the breaker is applicable for other situations.

In breaker modeling of this work, each pole in a three-phase circuit breaker was modelled as an ideal time controlled switch. It opens at the first current zero crossing after the ordered tripping instant and closes at any part of the power cycle. The closing time span modelled of this breaker consists of common order time, t_{order} and random offset time for each pole ($t_{offset,A}$, $t_{offsetB}$ *and* $_{toffset.C}$). Thus, the closing time for each pole was determined by:

$$T_{Aclose} = t_{order} \pm t_{offset,A}$$

$$T_{Bclose} = t_{order} \pm t_{offset,B}$$

$$T_{Cclose} = t_{order} \pm t_{offset,C}$$

It can be seen that in both modeling approaches, the Maximum Closing Time Span (MCTS) determines the offset closing time. However, MCTS is an uncertain value [6]. According to [10], it is suggested that the typical MCTS is between 3 and 5 ms. In this work, MCTS is set at 5 ms.

SIMULATION RESULT

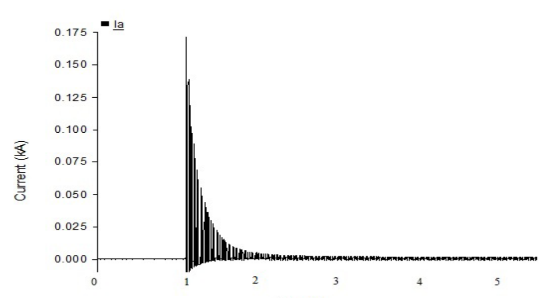
Saturation modeling

The transformer modeling is simulated using PSCAD/ EMTDC. All the design parameters including the calculated positive sequence leakage reactance, no load losses and copper losses are used in the transformer design. As the same rated transformer is available in the laboratory, the normal inrush at the same switching angle with the lab work is carried out. Here, the single phase 16 kVA transformer is energised, and the decay of the inrush is observed. It is known that it depends on the *L/R* ratio of the circuit. Figure-6 shows the decay of the inrush transients and flux for the transformer. The current peak is at 175 A at 60° phase angle.

Inrush transient study in parallel transformers

The PSCAD model is developed similar from STC model. The STC models were performed by magnetising transformer T1 while transformer T2 is energised with or without the load. Figure-7 shows the current of transformer T1 when T2 is energised but unloaded. It can be seen that the most severe current occurred in L1 phase, which is a consequence of applying V1 to T1 at zero-crossing. In phase L2, the current spike occurred during the energization and then decays to zero while in phase L3 the inrush transient current is relatively small. It is noted that the current is more, about -0.35 kA in phase L1 and 0.85 kA in phase L2. Figure-8 shows the current of transformer T2 at the same condition. It can be seen that the current decays gradually into saturation.

After that, magnetisation of transformer T1 is performed while T2 is loaded. Figure-9 shows the current in T1 for each phase L1, L2 and L3. When T2 is loaded, it is clearly seen that the inrush T1 will have greater impact on the amplitude. Comparing with Figure-7, the peak current at -0.35 kA is increased to -0.43 kA for L1 phase and 0.85 kA is increased to 1.22 kA for L2 phase.



ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

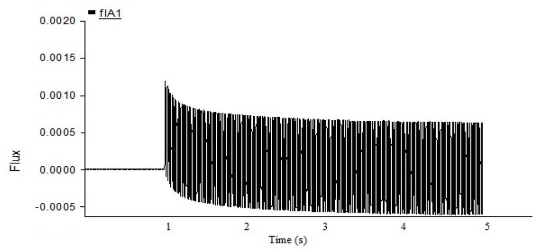


Figure-6. Decaying inrush and flux for the transformer.

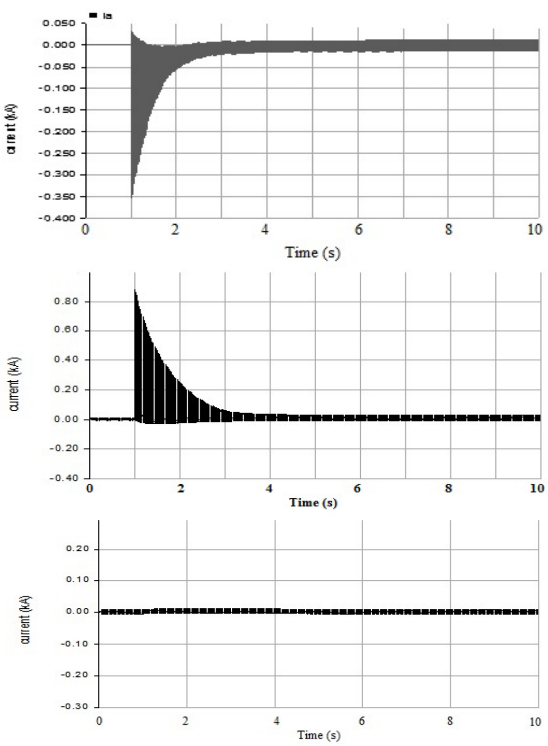
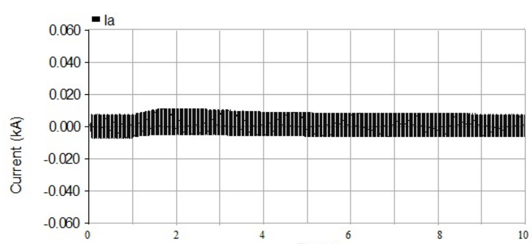


Figure-7. Phase current waveform of T1 (L1, L2 and L3 respectively).

If we take a look at the simulation results of transformer T2 currents (Figure-10, separately for each phase L1, L2 and L3), the transition into the saturation phase is faster, but does not satisfy the sympathetic inrush theory. Thus, it can be concluded that the model satisfies the sympathetic inrush current transient issue as long as T2 is in no-load condition.



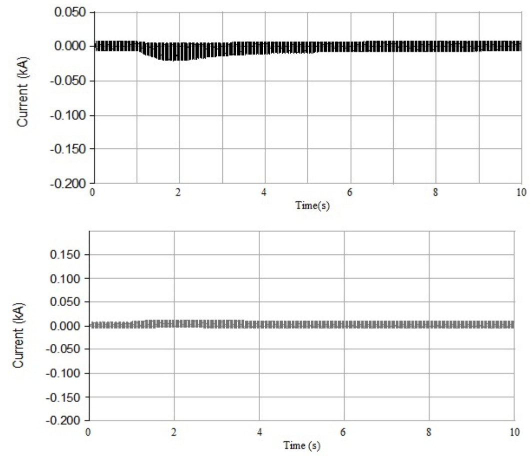


Figure-8. Phase current waveform of T2 (L1, L2 and L3 respectively).

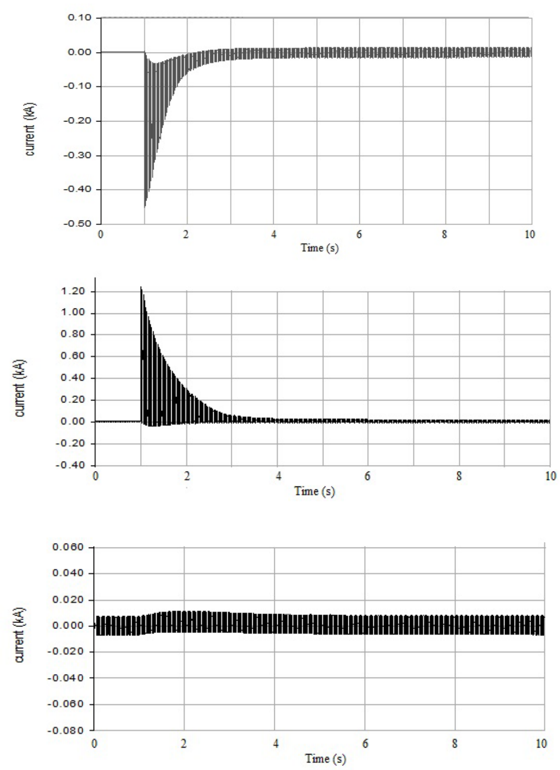
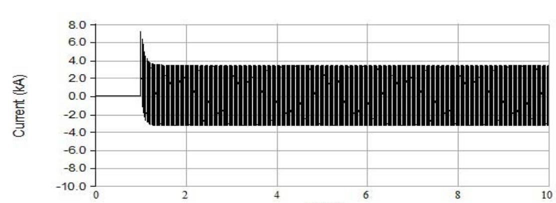


Figure-9. Phase current waveform of T1 (L1, L2 and L3 respectively) when T2 is loaded.



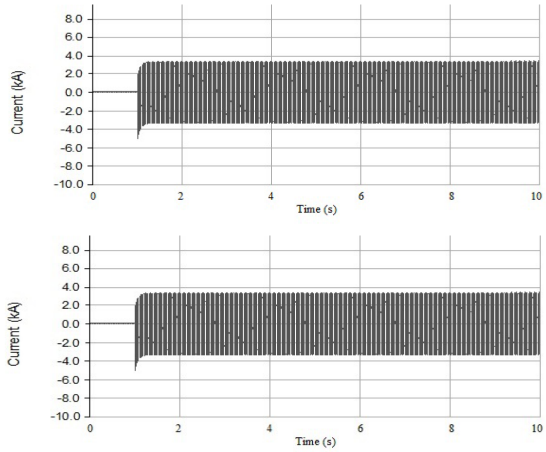


Figure-10. Phase current waveform of T2 (L1, L2 and L3 respectively) when T2 is loaded.

VALIDATION ANALYSIS

For validation of the transformer inrush modeling, experiment was set up in the laboratory to measure the transients and compare the results to that of simulation. A single-phase distribution transformer was employed as the test object. The specification of the transformer in the experimental work was same as specification in the modeling, as shown in Table-2.

Prior to experiment, the open-circuit and short circuit tests were performed. The supply voltage was generated by AMETEK CSW555; the voltage magnitude was controlled via embedded software in a personal computer. Also required is a point-on-wave switching device which was designed and constructed using Msp430g2553 microcontroller.

Using the same switching angle as simulation, the transformer energization is performed. Here, it is energised at 60°. The result is shown in Figure-11. Comparing with the simulation in Figure-6., the peak of magnetising inrush is 174 A which matches the result from simulation. Therefore, it validates the transient and the winding model.

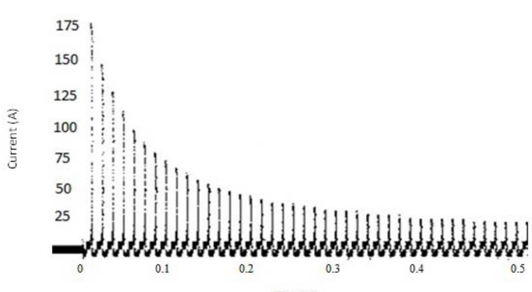


Figure-11. Magnetising inrush.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the assistance by Zhenyu Liu with the experimental work, the student sponsorship by the Malaysian Government together with Universiti Malaysia Perlis, and the financial support by the Australian Research Council (LP120100704).

CONCLUSIONS

In this paper, a single-phase distribution transformer model is developed and presented based on transformer topology with the concern for its inrush currents. The modeling is suitable with what available in PSCAD/EMTDC software, which is to combine 3 single phase classic saturation transformers. The suggested modeling combines the theories and the measurements (including all the parameters and core losses calculations), and then tested by simulation. Then, the core saturation modelling has been carried out using the curve fitting method, generated both by Microsoft Excel logarithmic trend line option and MATLAB Optimization toolbox. For validation, experimentation in the laboratory has been carried out.

The results show that the inrush transients in transformer are satisfied for both conditions: normal inrush current and also sympathetic inrush current (where transformers are in parallel connection), provided that transformer T2 is in no-load condition. These results satisfy the three-phase transformer representation and its topology. In conclusion, the model is adequate for electromagnetic transient study where core saturation is a concern. The proposed model is verified, and it is good for use in investigating the transformer energization issues and other power system transients.

Work is currently in progress to extend the modeling for realistic power system networks which include other components such as transmission lines/cables and loads. Furthermore, the following works are in progress:

(i) To model and compare the core saturation curve using Frohlich Equation.
(ii) The model is also expected to be improved on the hysteresis characterisation.

REFERENCES

[1] N. Chiesa. 2010. Power Transformer Modeling for Inrush Current Calculation. PhD Thesis, Department of Electric Power Engineering, Norwegian University of Science and Technology.

[2] The Council on Large Electric Systems. 1990. Guidelines for Representation of Network Elements when Calculating Transients.

[3] S. D. Cho. 2002. Parameter Estimation for Transformer Modelling. Doctor of Philosophy Electrical Engineering, Michigan Technological University.

[4] WG C4.307. February 2014. Transformer Energization in Power Systems: A Study Guide. CIGRÉ Technical Brochure 568.

ARPN Journal of Engineering and Applied Sciences

[5] J. A. Martinez and B. A. Mork. 2005. Transformer modeling for low- and mid-frequency transients - a review. IEEE Transactions on Power Delivery. 20: 1625-1632.

[6] P. Jinsheng. 2013. Assessment of Transformer Energization Transients and Their Impacts on Power Systems. Doctor of Philosophy, Faculty of Engineering and Physical Sciences, The University of Manchester.

[7] W. Enright. 1996. Transformer models for electromagnetic transient studies with particular reference to HV dc transmission. Doctor of Philosophy in Electrical and Electronic Engineering, University of Canterbury, Christchurch, New Zealand.

[8] D. Muthumuni. Transformer Models for Transient Simulations. ed: Manitoba HVDC Research Centre Inc, Canada.

[9] R. A. Turner and K. S. Smith. 2010. Transformer Inrush Currents. IEEE Industry Applications Magazine. 16: 14-19.

[10] H. M. Ryan. 2001. High voltage engineering and testing. United Kingdom: The Institution of Electrical Engineers.