High Frequency Modeling of Power Transformer for Protection under Lightning Over-voltages

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***Abstract*— An advance method for determining the transformer high frequency model parameters for protection of loads from transients, such as surges and lightning over-voltages, is presented in this research. Low voltage side of transformer core is energized by an integrated surge voltage of 450V. Transfer voltage under the influence of integrated voltage signal is calculated to estimate the amount of surges or transients that affect at higher resonance frequency i.e. 7.5 MHz. The highest level of transfer voltage is measured and transformer model parameters are calculated at resonance frequency for load protection. The proposed model for the load protection of transformer is tested and it has been observed that the highest transfer voltage at resonance frequency appears with the efficiency of 99.9%. The similar procedure is also applied to smaller transformer with the capacity and rating of 25kVA and 11kV/440V respectively. The simulation and testing results yield a better performance of the proposed protection model than Piantini,s no load methods of transformer.**

Keywords; Transients; Transformer Protection; Resonance Frequency; Transfer Voltage; Transformer Parameters

I. INTRODUCTION

Transformer is a fundamental part of power systems and used for the transmutation of voltages. If lighting appears or higher current and lower voltage exists, transformer transformation rate will not remain stable and due to lightning these transients transfer to low voltage side of transformer. To conclude the performance of transformer under transients, different models are proposed by the researchers for both loaded and unloaded behavior of transformers. There is an extensive literature to the investigation of high frequency behavior of transformer for parameter calculation using different techniques.

II. PREVIOUS STUDIES

In transformer transients occur due to switching or lightning. Switching transients have low frequencies as compared to lightning surges [1]. Medium voltage Lines (MW) and Low voltages lines (LV) can be disrupted by lightening in numerous ways. Lightning surges can be ease with the use of high insulation grounding shielding wires and installing surge arrestor [2]. A core type distribution transformer is designed for the electromagnetic surges applications and attribute of impulse from all terminals of transformer is measured in [3]-[4]. In aforesaid models RLC parameters are investigated using impedance analyzer. In [5] an advanced model for calculation of induced lightning over-voltages is investigated which is the modified model of Morched et al. high frequencies model. In [6] reflection co-efficient technique with scattering matrix is used to investigate the linear and non-linear behavior of high frequency transformer under lightning stock. Leakage winding inductance, magnetic losses, and capacitance are calculated by parametric extraction. In [7]-[8] an improved technique for transformer life evaluation using frequency response analysis (FRA) is presented.

Transformer parameters determination can be divided into two categories. In first category internal structure of transformer, geometry and material properties like self and mutual inductances, windings resistance and capacitances are required. But the required data are barely ever provided by manufacturer. A core problem in distribution system is the atmospheric discharges due to lightning over-voltages that originate problem for transformer and other feeder components. These high overvoltage discharges affecting the home adornments. To conquer these challenges, it is obligatory to attain the protected transformer models clarified in [9]-[14]. In aforesaid models oscillation occur due to impulse voltage injected to transformer windings are investigated. The impedance constants are directly calculated by transformer winding parameters. In [15] a transformer model based on hybrid lumped parameters is presented. The quasi-stationary electromagnetic very fast transients using steep and chopped impulse is investigated. Model parameters are reduced by originate a two coil model in hybrid model.

In second category internal structure of transformer is not required and transformer is consider as black box which can be driven either by voltage or current source. Newly developed high frequency transformer model is presented in [16]-[23]. In foresaid high frequency models affect of transferred surges and simulation results are carried out by using transient software program called EMTP/ATP. The relation between magnetic and electric magnitude of the transformers have been investigated through a model of transformer undergo to high frequencies. In [17] scale technique is used to analyze and investigate the model parameter of high frequency transformer. In [24] M Heindl analyzes black box, white box and gray box model. White box model has high complexity and its bandwidth is low as compared to gray and black box. But it allows deeper system view. While gray box lies between white and black box model. Furthermore, techniques utilizing FEM for determining the transformer's parameters presented in [25]-[26] are complex and case dependent.

In this paper approximation of impedance parametric values in RLC expression form of transformer's modeling for high frequency is proposed using a simple method. Moreover, obtained results in transient states are compared with those obtained after integration of protection circuit in the transformer.

III. PARAMETERS ESTIMATION

In order to determine Transformer's parameters under influence of transients, the lightening signal is modeled and applied aforesaid lightning signal into transformer primary side, the purpose of applying this signal is to magnetize the transformer core with additional transient signals. The integrated voltage applied at primary side along with impulsive lightening signal shown in figure 1(a), (b) and transformer block circuit is described in figure 2.

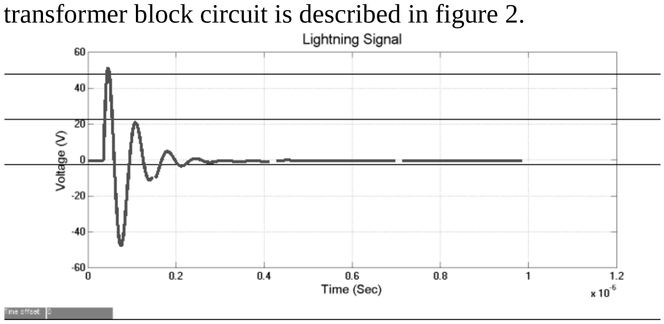


Fig. 1. (a) Simulated Integrated Voltage signal.

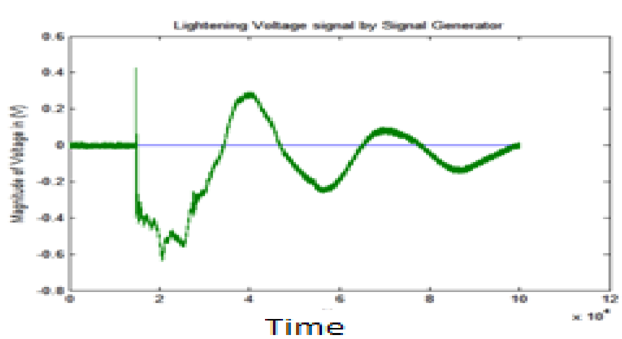


Fig. 1(b). Actual Integrated Voltage signal.

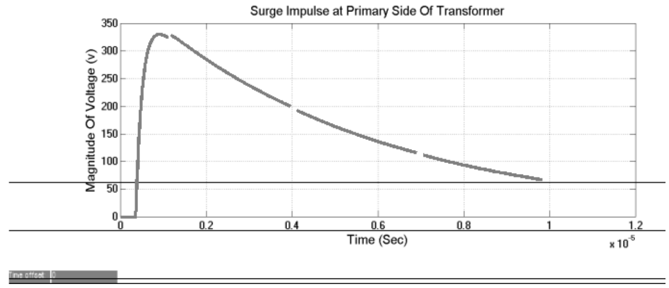


Fig. 1(c). Simulated lightning Impulse Signal.

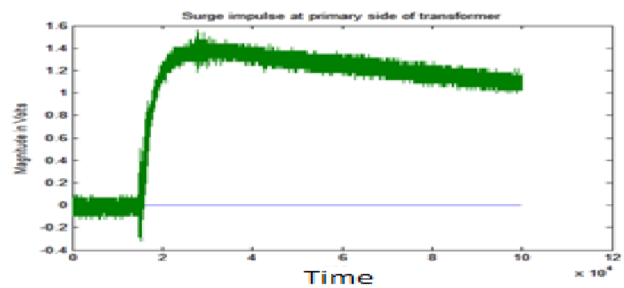


Fig. 1(d). Experimental lightning Impulse signal.

The Model of lightening voltage and surge generator for impulse voltage is shown in appendix A. The integrated signal consisting of lightening and Impulse voltages are applied at primary side of the transformer in order to magnetize transformer coils with the load of 100 kHz resonance frequency at secondary side exhibited by fig. 2(a). After applying the impulse and integrated signal on primary side, noted the values of voltages and current from the secondary side of transformer and obtained the digitalized data of currents and voltages waveforms. The experimental setup for investigating the time based response after applying the impulse is shown in figure 2(b).

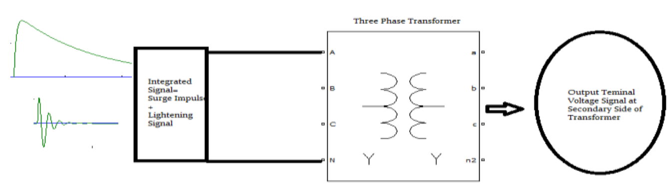
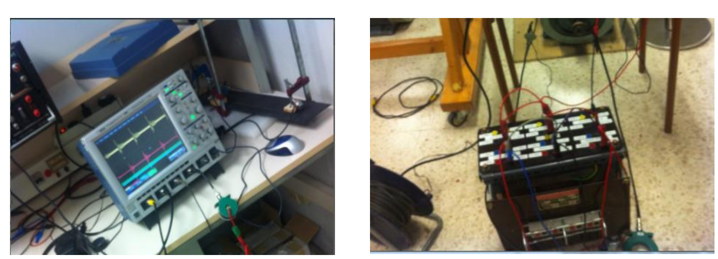


Fig. 2(a). Transformer block diagram.



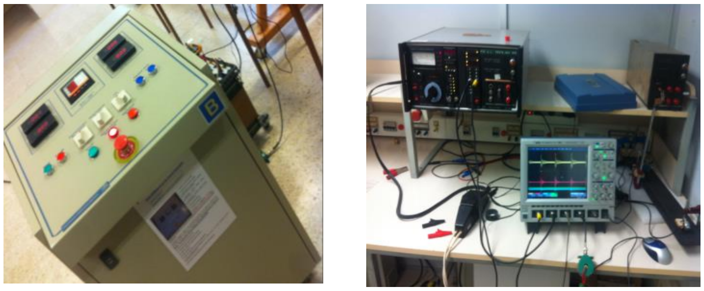


Fig. 2 (b). Experimental setup of Transformer testing and parameter estimation.

IV. FFT ANALYSIS OF TRANSFORMER VOLTAGE UNDER INTEGRATED IMPULSE AND INTEGRATED SIGNAL

Transfer voltage is measured by taking HV side as input and LV side as output. Highest magnitude of transfer voltage is measured at 7.5_MHz resonance frequency by transfer function method. The magnitude and phase angle of transfer voltage is $6.945e\text{-}4\angle -145.5°$. The Module input called as integrated voltage at transformer's primary side is exhibited by fig. 3(a), the Module output called the voltage measured at transformer's secondary side is exhibited by fig. 3(b), and module transfer function is called FFT analysis of transfer voltage w.r.t integrated voltage at 100_k Hz resonance frequency load, shown in figure 3(c).

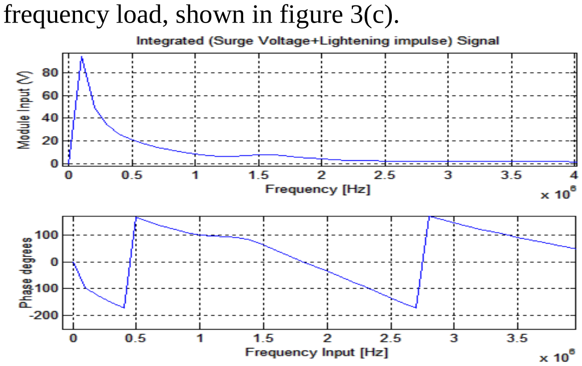


Fig. 3(a). Module and Phase angle of Input Voltage.

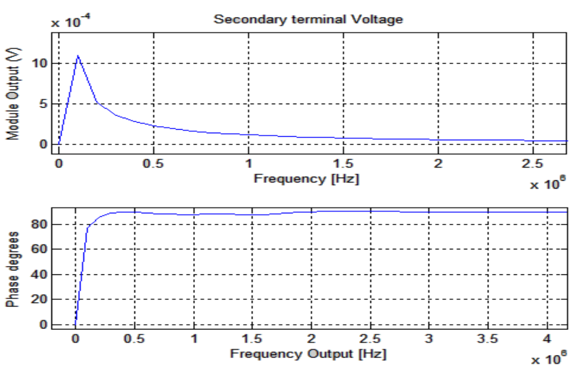


Fig. 3(b). Module and phase angle of Output Voltage.

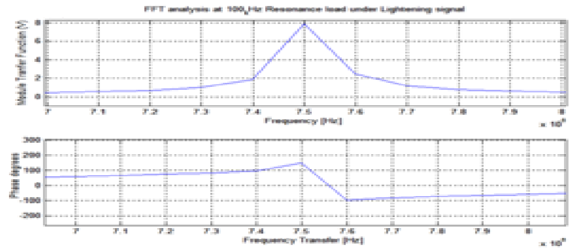


Fig. 3(c). Module and Phase Angle of primary Transfer Voltage.

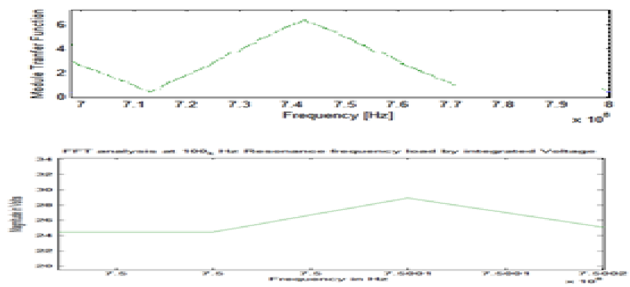


Fig. 3(d). Module and Phase Angle of secondary Transfer Voltage.

V. FFT ANALYSIS OF TRANSFORMER IMPEDANCES:

After estimating the magnitude of highest transient voltage and its resonance frequency, the next step is to estimate the impedances of primary, secondary and magnetizing side of transformer. FFT analysis approach is used to determine the impedance parameters of transformer.

$$Vp = Ip * Z11 + Is * Z12 \qquad (1)$$
$$Vs = Ip * Z21 + Is * Z22 \qquad (2)$$
$$Z_{11} = V_p/I_p \;|\; I_s = 0, \qquad (3)$$
$$Z_{21} = V_s/I_p \;|\; I_s = 0 \qquad (4)$$

Equations (1) to (4) represent the idea of two port network analysis. The black box analysis technique is used to determine the parameters of transformer that are capable to withstand during surges. The novelty of this research is to estimate the behavior of transformer with a specific resonance frequency load and its protections using a very simple method. Transformer T-ie model is constructed and the measured parameters are shown in figure 4.

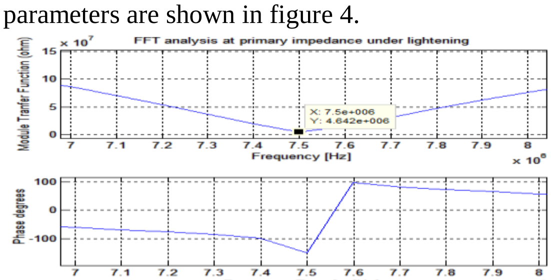


Fig. 4(a). FFT analyses of transfer primary impedance.

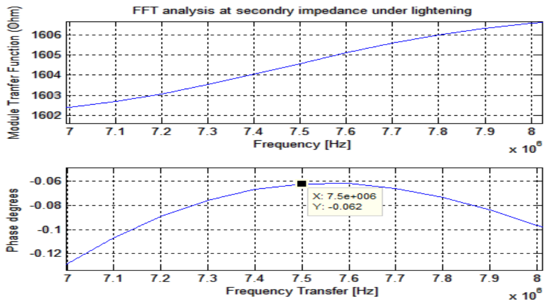


Fig. 4(b). FFT analysis of transformer secondary impedance

The magnetizing impedances are obtained by FFT analysis of transformer connected in parallel with transformer's magnetizing side (Z_{11}-Z_m and Z_{22}-Z_m), shown in figure 5

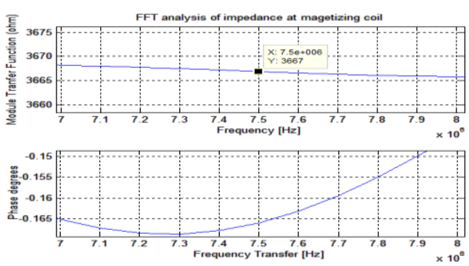


Fig. 4(c). FFT analyses of transfer magnetizing Impedance

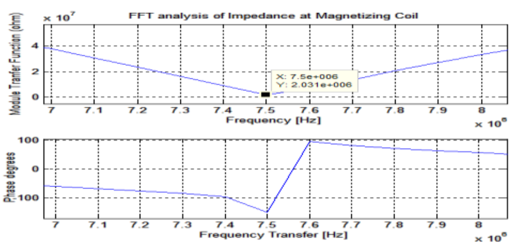


Fig. 4(d) FFT analysis of transformer magnetizing Impedance

VI. Tie Parameter of Transformer Model

$$Z11 - Zm = -4004279.406 - j2341303.73 \tag{5}$$

$$Z22 - Zm = 1998.244 + j711.764 \tag{6}$$

$$Z12 = Z21 = Zm = 3672.715\angle -168.798^\circ \tag{7}$$

Equation (5) described the primary impedance of proposed model. Negative imaginary part of primary impedance equations shows the capacitive effect of high voltage (HV) side. Equation (6) shows the secondary impedance which has inductive effect and positive imaginary part verifies it. While (7) shows the magnetizing impedance.

1. Transformer Protection Model By Surges

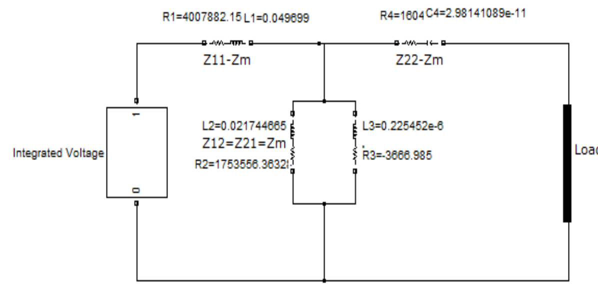


Fig. 5.Transformer High frequencies modeling for transient's protection.

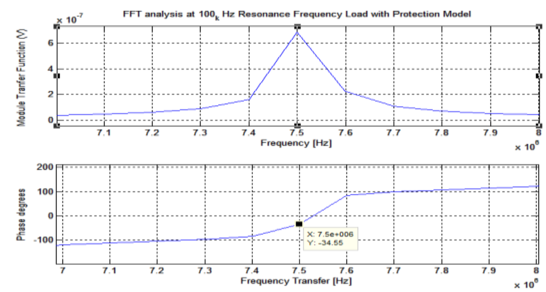


Fig. 6(a).FFT analysis of transfer voltage with protection model of transformer.

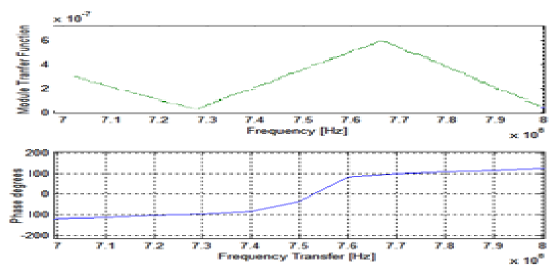


Fig. 6(b).FFT analysis of transfer voltage with protection model of transformer.

TABLE[I] RLC ELEMENTS OF TRANSFORMER MODEL FOR SURGE PROTECTION AT 7.5-MHZ FREQUENCY

S.No	Impedance	R	L	C
1	Z11-Zm	4007882.15 (Ω)	0.049699 (H)	0 (F)
2	Z22-Zm	1604 (Ω)	0 (H)	2.98141089e-11 (F)
3	Z12=Z21	3602.744 (Ω)	0.015140905e-3 (H)	0 (F)

TABLE[II] TRANSFER VOLTAGE ANALYSIS

S.No	Transformer appearance	Transfer Voltage
1	With Nominal Voltage	$0.4844\angle 0^\circ$
2	With Integrated Voltage	$7.554\angle 145.5^\circ$
3	With Protection Model	$6.819e-7\angle -34.55^\circ$

$$\text{Efficiency of proposed model} = \left(\frac{\text{transfer voltage by protection}}{\text{transfer voltage by lightning} - 100} \right) * 100 = 99.9\%$$

Equation (8) shows that proposed model has efficiency 99.9% for the protection of load from lightning surges.

VII. CONCLUSION

The proposed model for transformer load protection from lightening surges of specific resonance frequency is tested at 100_k Hz resonance frequency load. Same integrated voltage is applied without protection model forload, and tested the transfer voltage at highest resonance frequency that was 7.5_MHz with voltage magnitude of V=7.945∟145.50 ° whereas when the protection model is applied at the transformer the transfer voltage measured is V= 6.819e-7∟-34° at the same resonance frequency. Therefore, it can be very easily realized that the transformer model for protection of load from transients or lightening signal is very efficient and having the protection efficiency about 99.9%.

VIII. APPENDIX A

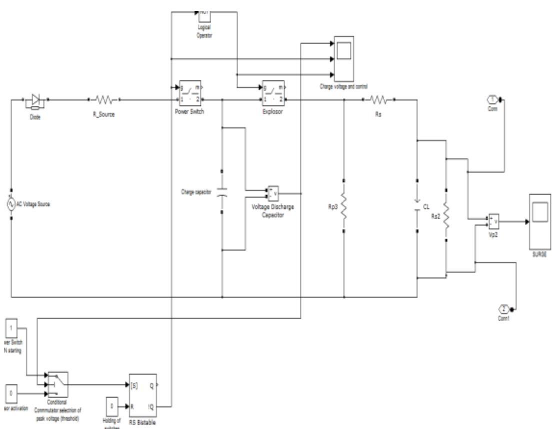


Fig. 7. Surge generator model.

REFERENCES

[1] A. De, D. Debnath and A. Chakrabarti, "A Study on the Impact of Low-Amplitude Oscillatory Switching Transients on Grid Connected EHV Transformer Windings in a Longitudinal Power Supply System," in *IEEE Transactions on Power Delivery*, vol. 24, no. 2, pp. 679-686, April 2009.

[2] P. F. Obase, A. Piantini, and A. G. Kanashiro “Overvoltages transferred to low voltage networks due to direct strokes on the primary” *Proceedings of the VIII International Symposium on Lightning Protection*, pp. 489-494, SãoPaulo, Nov. 2005

[3] T. Noda, H. Nakamoto, and S. Yokoyama, “Accurate modeling of core-type distribution transformers for electromagnetic transient studies,” IEEE Trans. Power Del., vol. 17, no. 4, pp. 969–976, Oct. 2002

[4] T. Noda, M. Sakae, and S. Yokoyama, “Simulation of lightning surge propagation from distribution line to consumer entrance via pole-mounted transformer,” IEEE Trans. Power Del., vol. 19, no. 1, pp. 442–444, Jan. 2004.

[5] A. Borghetti, A. Morched, F. Napolitano, C. A. Nucci, andM. Paolone, “Lightning-induced overvoltages transferred through distribution power transformers”, *IEEETransactions on Power Delivery*, vol. 24, n. 1, pp. 360-372, Jan. 2009.

[6] J. Biernacki and D. Czarkowski, "High frequency transformer modeling," *ISCAS 2001. The 2001 IEEE International Symposium on Circuits and Systems (Cat. No.01CH37196)*, Sydney, NSW, 2001, pp. 676-679 vol. 2. doi: 10.1109/ISCAS.2001.921401.

[7] J. Pleite, E. Olias, A. Lazaro, and J. Vazquez, “Modeling the transformer frequency response to develop advanced maintenance techniques,” presented at the 14th PSCC, Sevilla, Spain, Jun. 24–28, 2002

[8] Kanashiro, A. G., A. Piantini, and G. F. Burani. "A methodology for transformer modelling concerning high frequency surge." *Proceedings of the International Symposium on Lightning Protection (VI SIPDA)*. 2001.

[9] De Carvalho, T. O., et al. "Analysis of lightning-caused distribution transformer failures." *Lightning Protection (XI SIPDA), 2011 International Symposium on*. IEEE, 2011.

[10] Guevara Cortés, B., J. López Bonilla, and S. Vidal Beltrán. "Simulación del blindaje a una línea de distribución contra descargas atmosféricas." *Nova scientia* 6.11 (2014): 93-112.

[11] Okabe, Shigemitsu, et al. "A high-frequency model of an oil-immersed transformer, and its use in lightning surge analysis." *Electrical Engineering in Japan* 134.1 (2001): 28-35.

[12] Y. Shibuya and S. Fujita, “High frequency model and transient response of transformer windings,” in Proc. IEEE Power Eng. Soc. Transmission and Distribution Conf. Exhibit., Asia Pacific, Oct. 6–10, 2002, vol. 3, pp. 1839–1844.

[13] Y. Shibuya and S. Fujita, “High frequency model of transformer winding,” Electr. Eng. Jpn, vol. 146, no. 3, 2004.

[14] Popov, M., et al. "Modelling, simulation and measurement of fast transients in transformer windings with consideration of frequency-dependent losses." *IET Electric Power Applications* 1.1 (2007): 29-35.

[15] Y. Wang, W. Chen, C. Wang, L. Du, and J. Hu, “A hybrid model of transformer windings for very fast transient analysis based on quasi-stationary electromagnetic fields,” Elect. Power Components Syst., vol. 36, pp. 540–554, 2008.

[16] Wang, Xuegong, et al. "Transient recovery voltage investigation in the application of 15kV circuit breaker failure." *IPST 2005, Montereal, Canada* (2005).

[17] A. Piantini, J. M. Janiszewski, and C. P. Braz, “Utilization of reduced models for the analysis of lightning induced over voltages on over head lines,” in *Proc. 2010 Int. Conf. on High Voltage Engineering and Application*(ICHVE), pp. 160–163, 2010.

[18] P.G. Blanken, “A lumped winding model for use in transformer models for circuit simulation,” IEEE Trans. Power Electron., vol.16, no.3, pp. 445–460, May 2001.

[19] A.Piantini and J. M. Janiszewski, “Scale models and their application to the study of lightning transients in power systems," Vernon Cooray. (Org.). Lightning Electromagnetic. 1ed. London, pp. 719-764, 2012

[20] A. Piantini and J. M. Janiszewski, "The use of shield wires for reducing induced voltages from lightning electromagnetic fields," Electric Power Systems Research, vol. 94, pp. 46-53, Jan. 2013.

[21] K. Ragavan and L. Satish, “An efficient method to compute transfer function of a transformer from its equivalent circuit,” IEEE Trans. Power Del., vol. 20, no. 2, pt. 1, pp. 780–788, Apr. 2005.

[22] A.N.deSouza,M. G. Zago, O. R. Saavedra, C. C. ObaRamos,and K. Ferraz, “A computational tool to assist the analysis of the transformer behavior related to lightning,” Int. J. Elect. Power Energy Syst., vol. 33, no. 3, pp. 556–561, Mar. 2011.

[23] P. Mitra, A. De, and A. Chakrabarti, “Resonant behavior of EHV transformer windings under system originated oscillatory transient over voltages,” Int. J. Elect. Power Energy Syst., vol. 33, no. 10, pp. 1760–1766, Dec. 2011.

[24] Heindl, M., S. Tenbohlen, and R. Wimmer. "Transformer modeling based on standard frequency response measurements." *International Symposium on High Voltage Engineering, Hannover, Germany*. 2011.

[25] E. Bjerkan, “High frequency modeling of power transformers—stresses and diagnostics,” Ph.D. dissertation, Dept. Elect. Power Eng., Norwegian Univ. Sci. Technol., Trondheim, Norway, 2005.

[26] N. Y. Abed and O. A. Mohammed, "Physics-Based High-Frequency Transformer Modeling by Finite Elements," in *IEEE Transactions on Magnetics*, vol. 46, no. 8, pp. 3249-3252, Aug. 2010.

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