Calculation of Zero Sequence Inductance of a Three-Phase Reactor

Eyup Akpinar[1], Dilara Selici[2]

[1] Dokuz Eylül University, Department of Electrical and Electronics Engineering, İzmir, Turkey
eyup.akpinar@deu.edu.tr
[2] Balıkesir Elektromekanik Sanayi Tesisleri A.Ş., Balıkesir, Turkey
dilara.selici@besttransformer.com

Abstract

Zero sequence impedance is an essential parameter for the analysis of unbalanced faults and protection in the electrical power system. An inductance per phase is used between grid and AC/DC voltage source converter in order to control the real and reactive power flow. The zero sequence value of this inductance is also effective in the current path created by the common mode voltage of the converter. This inductance limits common mode current injected to the network. The currents in passive harmonic filters and shunt reactors are also analyzed by using zero sequence value of their inductance during unbalanced loading. In this paper, the magnetostatic and transient analyses have been carried out on three-legged core by using ANSYS package program to estimate the zero sequence value of the inductance.

Index Terms-- **zero sequence inductance, common mode inductance, shunt reactor.**

1.Introduction

In power systems, the prediction of fault current is essential for the protection of the system components. The zero sequence components (i.e. zero sequence impedance, zero sequence currents and zero sequence voltages) are the variables of the network analyzed under unbalanced operation [1]. When the electrical motors are controlled with the adjustable speed drives, the front end active AC/DC converters are normally connected to the power system through the switching inductance in each phase. This inductance is a control parameter of switching frequency, the real power and reactive power flows between source and converter during steady state and transient operations.

In the applications of three phase converters, a substantial common mode voltage (CMV) between the neutral terminal of machine and earth ground [2] circulates common mode current in the network. The common mode voltage creates unbalance current circulation in three-phase network. Consequently, the zero sequence value of the switching inductance presents an effective role in the prediction of common mode current. Depending on the converter type, modulation frequency and the zero sequence value of switching inductance, the magnitude and frequency spectrum of common mode current vary. The larger common mode current causes EMI problems in the circuit and physically destroys some network components; such as bearings of motor, faulty relay operation, etc [3, 4]. The common mode voltage can be eliminated by selecting a proper switching algorithm in some type of converters like neutral point clamped multilevel converters. But, the CMV appears in any switching strategy on some converters such as two-level three-phase H-bridge voltage source converters [5, 6]. Therefore, the zero sequence value of the switching inductance and passive filter components stay as the main current limiting elements in the motor drive circuit.

The zero and positive sequence reactances for the three-phase transformer are estimated by using the 3D and 2D models in magnetic field solution in [7, 8]. The inductance value can be computed by using stored magnetic energy in the system and applied current to the windings. The results of 3D and 2D are compared and an approximation constant is defined between those results. 2D models and magnetic stored energy for computation of leakage inductance of three-phase shell-type and core-type transformers are also given in [9, 10]. The passive filters and shunt reactors are used together in some industrial applications for harmonic current elimination and reactive power compensation. The zero sequence value of shunt reactor is also needed to predict the current during power system faults.

The zero sequence inductance of a three-leg core basically depends on the selected core structure, material type, dimensions and winding connections. In order to provide a path for zero sequence component of magnetic flux, an extra fourth leg can be added into the core structure. This leg provides a small reluctance for magnetic flux, so it creates a larger value of zero sequence inductance. Consequently, the larger inductance reduces the zero sequence current.

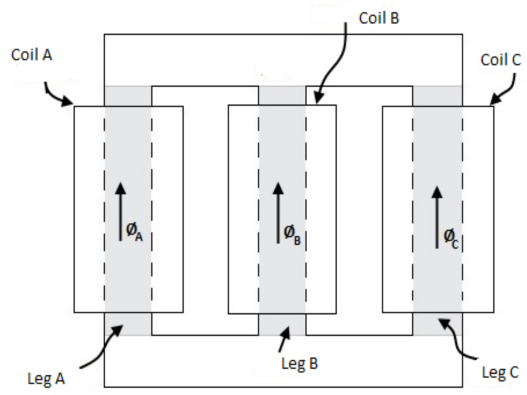


Fig. 1. Three-phase core-type transformer with magnetic flux paths

This work was supported in part by BEST Transformer Co. in Balıkesir, Turkey. E Akpinar is with Dokuz Eylul University, Department of Electrical and Electronics Engineering, Kaynaklar Kampusu, Buca, İzmir, Turkey. e-mail:eyup.akpinar@deu.edu.tr. D. Selici is with BEST Transformer, Organize Sanayi Bölgesi, 7.Cad. No:1, Balıkesir/Turkey.

In this paper, the zero sequence inductance has been calculated for three-legged core given in Fig. 1 by using the FEA analysis. This structure is commonly used by the transformer manufacturers since it is a cost effective design in assembling process. The phase winding on center leg shows the inductance value which is different than those of the other two phases, if the legs have same cross-sectional area. Therefore, the core design has been changed to the geometries providing equal reluctances for all three phases, like a circular or triangular structure which provides equal reluctance to all three phases. The approach given in this paper is applicable to calculate the zero sequence value of inductance for three phase reactors.

2. Symmetrical Components

The unbalanced circuit variables, like a set of three-phase voltage or current can be resolved into three balanced components. The corresponding electrical networks to these voltage and current components are called as the sequence networks [11]. In order to identify the voltage applied to the phase winding during the FEM analysis of zero sequence value of inductance, the symmetrical components of the voltages are calculated first. The phase voltages V_A, V_B, V_C can be resolved into its positive, negative and zero sequence components as follows:

$$V_A = V_{A1} + V_{A2} + V_{Ao} \tag{1}$$

$$V_B = V_{B1} + V_{B2} + V_{Bo} \tag{2}$$

$$V_C = V_{C1} + V_{C2} + V_{Co} \tag{3}$$

Here, V_{A1}, V_{B1}, V_{C1} are positive sequence, V_{A2}, V_{B2}, V_{C2} are negative sequence and V_{A0}, V_{B0}, V_{C0} are zero sequence voltages.

The following relation is given in matrix form between the symmetrical components and unsymmetrical three-phase voltages,

$$\begin{bmatrix} V_{A1} \\ V_{A2} \\ V_{A0} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \tag{4}$$

where, a is a complex number and it is defined below;

$$a = e^{j\frac{2\pi}{3}}$$

If the same voltage is applied to all three windings of the reactor ($V_A = V_B = V_C = V$), then the zero, positive and negative sequence components can be calculated by using (4). The zero sequence component is equal to the applied voltage magnitude while the positive and negative sequence components are zero as being in (5).

$$V_{Ao} = V, \quad V_{A1} = 0, \quad V_{A2} = 0 \tag{5}$$

When the three windings in Fig. 2 are excited by the currents with same magnitudes and frequency without any phase differences (unbalanced case), only the zero sequence current component flows through the network. Therefore, the zero sequence equivalent circuit can be used to analyze the reactor in this particular case, when the neutral point is grounded in shunt reactor or passive filters. The zero sequence network will have a closed path from the ground of windings to the ground of power source.

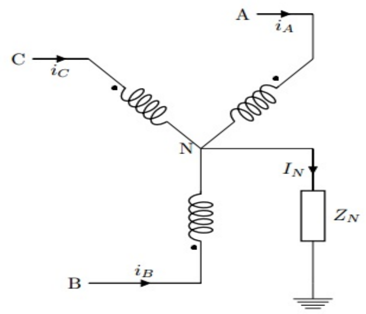


Fig. 2. Three-phase grounded reactor

The zero sequence equivalent circuit of the grounded reactor can be modeled as being shown in Fig. 3 [11].

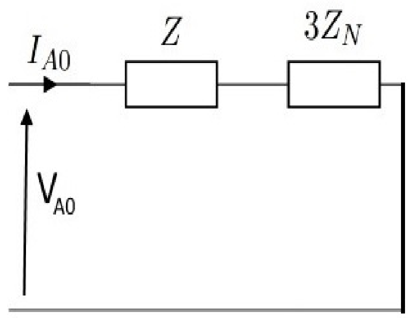


Fig. 3. Zero sequence equivalent circuit for grounded reactor

The circuit consists of the zero sequence impedance of reactor (Z) and the impedance between the neutral point and ground Z_N for current limiting and/or protection purpose. The zero sequence equivalent impedance is computed from the voltage and current components as given below;

$$Z_0 = \frac{V_{A0}}{I_{A0}} \tag{6}$$

where,

$$Z_0 = Z + 3Z_N \tag{7}$$

When the neutral point is solid grounded, $Z_N = 0$, then

$$Z_0 = Z \tag{8}$$

The above analysis shows that the same amount of current can be applied to the windings in magnetostatic analysis, while the same voltage can be used in transient analysis of the finite element method. Therefore, the following section will cover the estimation of zero sequence impedance based on the finite element analysis.

3. Finite Element Analysis

A three-phase shunt reactor has the rated values of 25 kVAR, 380 V and 50 Hz. The number of turns per phase is 65. The phase windings are excited with the rated value of 38 A. It should be noted that the dc currents at that value $(I_A = I_B = I_C = 38A)$ are applied to the windings during the magnetostatic analysis with the FEA. The FEA has been performed by using ANSYS-Maxwell package program [12]. The core dimensions in Fig. 4 are given below:

$l_y = 510mm$, $l_x = 475mm$,

$l_{tx} = 80mm$, $l_{dz} = 75mm$

l_{tx}: width of each leg in x-axis. Top and bottom core yokes have the same width in y-axis. l_{dz} : length (depth) of core in z-axis.

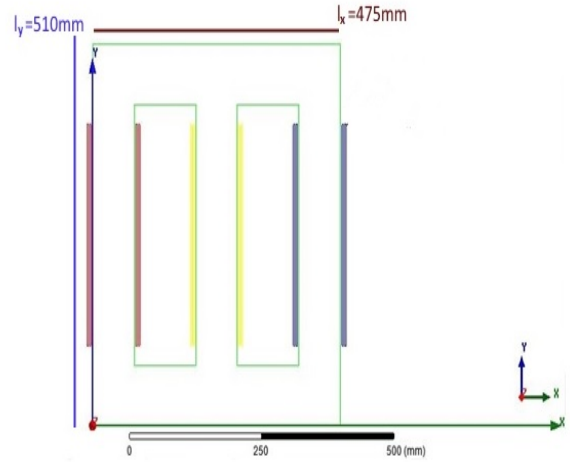


Fig. 4. Core dimensions and windings

The core is made of the sheet steel material (steel1010 in package program) with the B-H curve given in Fig. 5. The mesh structure that is automatically created by the package program [12] has been given in Fig. 6.

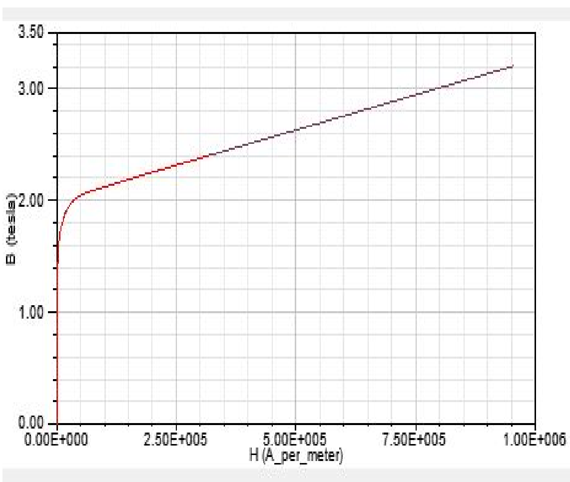


Fig. 5. B-H curve of the core material

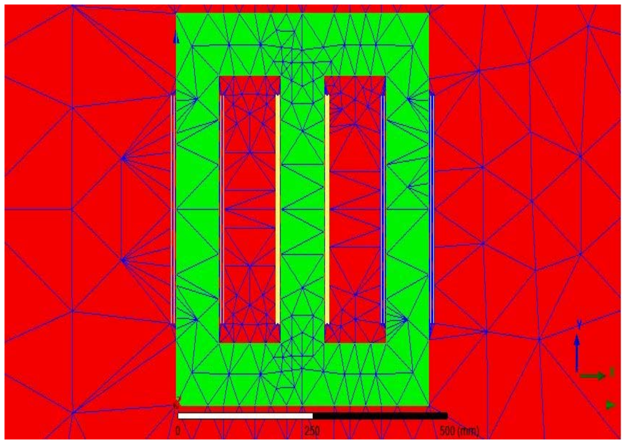


Fig. 6. Mesh plot of the simulation

When the reactor's coils are excited with the currents of $I_A = I_B = I_C = 38A$, the leakage flux lines circulating around their coils (not linking the other coils) are clearly observed in Fig. 7. These flux linkages create the leakage inductance. There is no mutual flux circulating between coils on three legs. The ratio between total flux linkage on each coil and its exciting current will give the value of zero sequence inductance. In this calculation, the inductance is not affected from the level of current, since the flux lines are circulating through air. The excitation current is selected at the rated value of windings as an input and the flux linkage is estimated as output by the package program.

The leakage inductance of the reactor can also be calculated by using the stored magnetic energy and exciting current as well. The total stored magnetic energy is estimated by the package program. The flux density and energy density distributions on the core are given in Fig. 8 and Fig. 9, respectively. The core structure used here creates unequal reluctance values for three phase flux paths. The center leg has different reluctance and flux density distribution than the others. This drawback of the core creates unbalance in the flux linkages under the excitation of balanced three-phase voltage source, too.

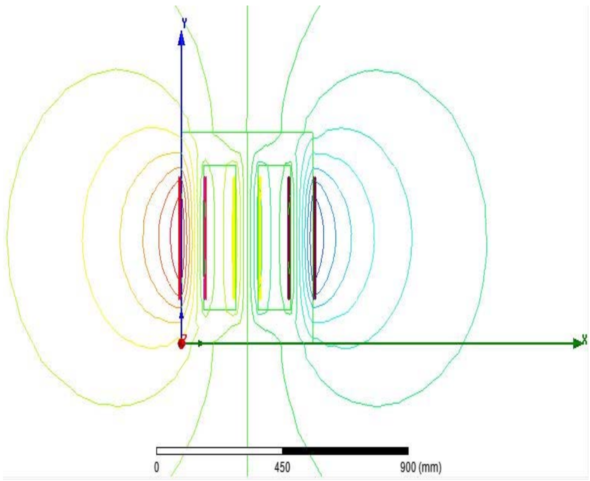


Fig. 7. Leakage flux lines in core

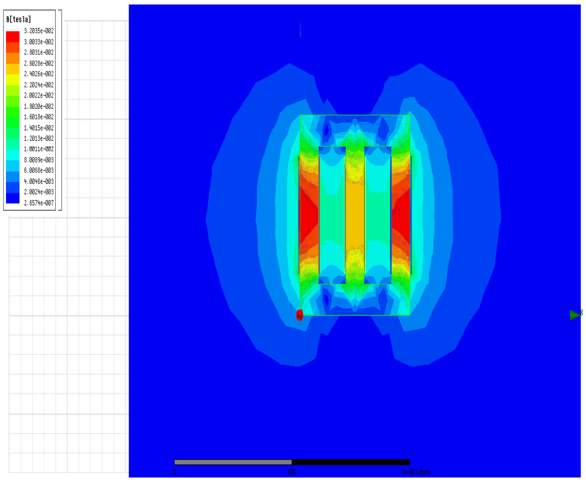


Fig. 8. Magnetic flux density distribution

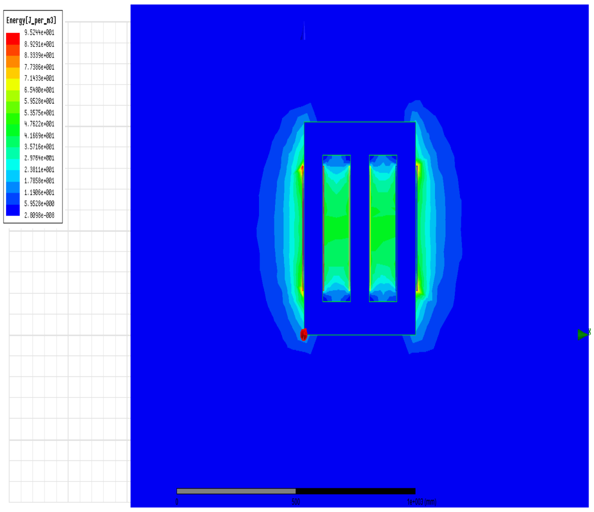


Fig. 9. Total magnetic energy distribution

In order to obtain balanced flux linkages and currents in the operation, the magnetic core can be designed in a circular or triangular structure that creates equal reluctance and inductance values for each phase.

Fig. 10 shows the output of the program consisting of flux linkage and total energy estimated in the core. It should be noted that those values are calculated at unit length in z-direction. The value of total energy density corresponding to minimum delta energy (%) is taken into consideration during calculation. The total energy and flux linkage are computed by multiplying the data generated by the program with the depth of the core. The flux linkage computed on the coil in center leg is %16.2 less than that value of outer leg. This difference could be minimized by changing the cross sectional area of center leg, but it has been left as it is in this work in order to highlight the reason of unequal values of inductances. During the design stage of a three-phase transformer or three-phase reactor with the pre-specified core shape, the dimensions of the magnetic core can be properly estimated in order to obtain optimum solution for dimensions.

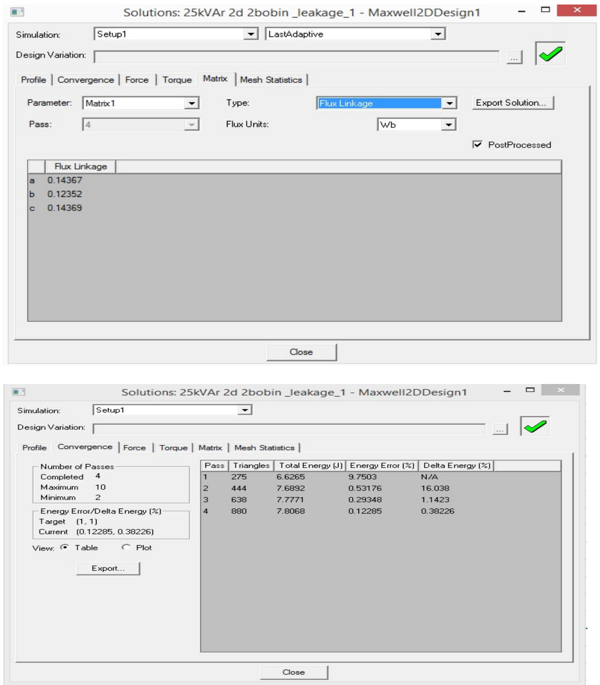


Fig. 10. The flux linkages around the coils and the total magnetic energy density

The values of flux linkages per length for three coils are given below,

$$\lambda_a = 0.14367 \text{ Wb}, \ \lambda_b = 0.12352 \text{ Wb}, \ \lambda_c = 0.14369 \text{ Wb}$$

The leakage inductance of each phase can be computed by using flux linkage and exciting current,

$$L_A = \frac{\lambda_A}{I_A} = \frac{0.14367}{38}(0.075) = 0.283mH$$

$$L_B = \frac{\lambda_B}{I_B} = \frac{0.12352}{38}(0.075) = 0.243mH$$

$$L_C = \frac{\lambda_C}{I_C} = \frac{0.14369}{38}(0.075) = 0.283mH$$

Therefore, the zero sequence impedance and its per unit value Z_{pu} are

$$Z = j(2\pi 50)0.283x10^{-3} = j89x10^{-3} \text{ Ohms}$$

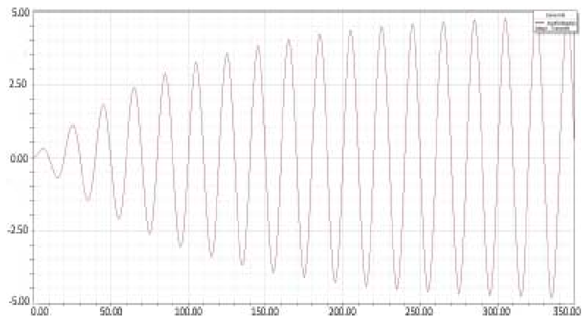
$$Z_{pu} = \frac{89x10^{-3}}{(220/38)}x100 = 1.5\,pu$$

The total magnetic energy should be equal to the sum of three phases. Therefore, leakage inductance per phase can also be calculated by using stored energy and exciting current;

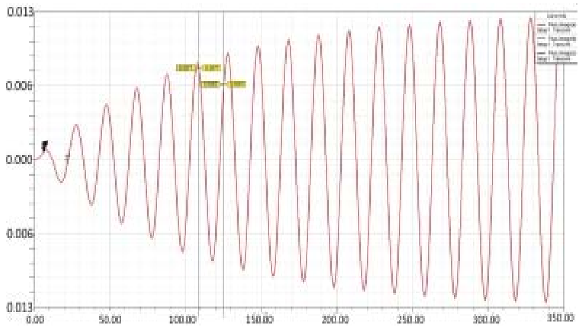
$$L = \frac{2W}{3I^2}(0.075)$$

$$L = \frac{2x7.8068}{3x38^2}(0.075) = 0.27mH$$

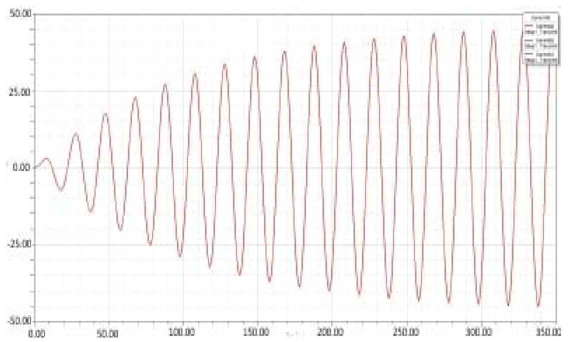
Consequently, both methods based on flux linkage and energy gives almost the same values.



(a) Input voltage applied to the primary windings (Y-axis: Volts, X-axis: Time)



(b) Waveforms of flux linkages (Y-axis: Webers-Turn, X-axis: Time)



© Waveforms of exciting currents (Y-axis: Ampers, X-axis: Time)

Fig. 11. Result of transient analysis

The transient analysis of the program is also used to verify the estimation of inductance from magnetostatic approach. The flux linkages and current values are estimated as function of time. Fig. 11a shows the applied voltage in time while the flux linkage and current waveforms in Fig. 11b and Fig. 11c respectively are estimated from the solution of the FEA. At any points selected on time axis, the corresponding current and flux linkage values can be obtained. Those values can be used to estimate zero sequence inductance per length.
The leakage inductance estimated here has the same value with result of the magnetostatic solution.

4. Conclusion

The calculation of zero sequence inductance is carried out by using the transient and magnetostatic methods. When the coils have been excited with the dc currents at the rated value, the leakage flux lines are created but the mutual effect does not appear between the coils. Hence, it can be clearly stated that this zero sequence inductance is same as the leakage inductance. The inductance is computed based on energy and flux leakage methods in magnetostatic solution. The result is also verified from transient analysis by using flux leakage method. The leakage flux distribution has shown that the flux lines which leave the ferromagnetic core can circulate through the tank, if it exists. The tank and magnetic core can create a low reluctance path for leakage flux lines, but this is not taken into consideration.

5. References

[1] A. Garin, Zero-phase-sequence characteristics of transformers. Part II, *Gen.Electr. Rev.* 43 pp. 174–179, April 1940.

[2] Alexander L. Julian, Giovanna Oriti, Thomas A. Lipo, “Elimination of Common-Mode Voltage in Three-Phase Sinusoidal Power Converters”, *IEEE Transactions on Power Electronics*, vol. 14, no:5, pp. 982-989, 1999.

[3] A. Binder and A. Muetze, "Scaling Effects of Inverter-induced Bearing Currents in AC Machines," *IEEE Transactions on Industry Applications,* vol. 44, no. 3, pp. 769-776, May/Jun., 2008.

[4] H. Tischmacher, S. Gattermann “Investigations on Bearing Currents in Converter-fed Electrical Motors”, *20. International Conference on Electrical Machines (ICEM)*, pp 1764-1770, 2012.

[5] Y. S. Lai and F. S. Shyu, "Optimal Common-mode Voltage Reduction PWM Technique for Inverter Control with Consideration of the Dead-time Effects-Part I: Basic Development," *IEEE Transactions on Industry Applications,* Vol. 40, No. 6, pp. 1605-1612, 2004.

[6] A. R. Sanjeevan, R. S. Kaarthik, K. Gopakumar, P.P. Rajeevan, J. leon, L.G. Franquelo, “Reduced Common-mode Voltage Operation of a new Seven-level Hybrid Multilevel Inverter Topology with a single DC voltage source”, *17. European Conference on Power Electronics and Applications*, pp. 1-10, 2015.

[7] E. Sorrentino, J. C. Burgos, “About the Difference Between Zero-sequence Magnetizing Impedances of a 3-phase Core-type Transformer”, *Electric Power Systems Research*, 116, pp 439–443, 2014.

[8] Jialong Wang ; Lascu,R. “ Zero sequence circuit of three-legged core type transformers”, *IEEE 62. Annual Conference for Protective Relay Engineers*, pp 188-212, 2009.

[9] E. Sorrentino, J. C. Burgos, “Application of 2D linear Models for Computing Zero-sequence Magnetizing Impedances of 3-phase Core-type Transformers”, *Electric Power Systems Research*, 117, pp 123–133, 2014.

[10] M. Zare, S. M. Razi, H. F. Farahani and A. Khodakarami, “Finite Element Analysis of Leakage Inductance of 3-Phase Shell-Type and Core Type Transformers”, *Engineering and Technology* 4(12), June 15, 2012.

[11] Arthur R. Bergen, Vijay Vittal, Power Systems Analysis, Second Edition, Prentice Hall.

[12] Ansys Maxwell V.16 Training Manuel, Lecture I: Introduction to Ansys Maxwell, Ansys Inc., May 21, 2013.