

## Finite Element Analysis of Leakage Inductance of 3-Phase Shell-Type and Core Type Transformers

<sup>1</sup>Mehdi Zare, <sup>2</sup>Seyyed Mohammad Pedram Razi, <sup>2</sup>Hassan Feshki Farahani and  
<sup>1</sup>Alireza Khodakarami

<sup>1</sup>Department of Electronic, Shahr-e-Qods Branch, Islamic Azad University, Shahr-e-Qods, Iran

<sup>2</sup>Department of Electrical Engineering, Ashtian Branch, Islamic Azad University, Ashtian, Iran

**Abstract:** Leakage inductance in the transformers specially power transformer is important and has considerable effects on transformer operation which should be limited in acceptable range. The leakage inductance is created due to flux leakage that is inevitable. By considering the transformer type, the leakage inductance can be different. In this study, the leakage inductance for two type transformer Shell Type Transformers (STT) and Core Type Transformer (CTT) are studied. In STT, much magnetic fields created by windings are entered to core that leads to significant reduction of magnetic fluxes. However in CTT, core is located in only one part of windings and as a result leakage flux is more in these areas. In this type of transformer, leakage flux and inductance are different because magnetic fields in two close legs differ from each other. In this paper, to obtain leakage inductance, two samples of these transformers of STT and CTT are modeled by ANSYS and then they are simulated by FEM. Leakage inductance value for each transformer is obtained and compared.

**Key words:** Finite element analysis leakage flux, leakage inductance, shell-type and core-type transformers

### INTRODUCTION

Leakage inductances are one of undesirable parameters of transformers which have many disadvantages such as waveform distortion, voltage drop, rising time increasing and so on. Therefore, their values should be minimized. For this purpose, several methods have been presented ( Lord, 1971; (Lord, 1971; Erickson, 1997; Redondo *et al.*, 2002; Kim *et al.*, 2004; Redondo *et al.*, 2007; Babaie and Farahani, 2010; Khodakarami *et al.*, 2010; Farahani, 2011; Farahani and Khalili, 2011). One of the methods to reduce leakage inductance is to use two auxiliary windings between primary and secondary windings of transformer. This can cause to reduce leakage flux and consequently leakage inductance reduction (Redondo *et al.*, 2002; Khodakarami *et al.*, 2010).

Because pulse rising time have direct relation with inductance, so, rising time will also decreased due to inductance reduction. Other effective parameters on leakage inductance are locations of different layers of primary and secondary windings and also how they are wound. In Erickson, (1997), Kim *et al.*, (2004) and Farahani (2011), for three different cases, location of primary and secondary windings are analyzed using finite element method and the optimal order is obtained.

Core type impact on leakage inductance value has been studied in Kim *et al.*, (2004) ; Farahani and Khalili (2011). For this purpose, three different core types with the same nominal power and window area are modeled in ANSYS and simulated by FEM and they have been compared after that.

In this study, leakage inductance values for two shell-type and core-type transformers have been obtained and then compared with each other. To do so, these two transformers have been modeled and then is simulated using ANSYS. Besides, leakage inductances have been obtained by energy and current equations of transformers. Finally, obtained values have been compared and analyzed.

### FINITE ELEMENT ANALYSIS OF TRANSFORMER

To compare and investigate leakage inductance of two types of shell-type and core-type transformers, they have been simulated. In continue, obtained results have been studied.

ANSYS software which uses FEM for calculation is a suitable tool to analyze electrical and magnetic fields. Moreover, these fields existence in transformer and also the necessity to study these fields in order to suitable design, powerful finite element software ANSYS has been used which is able to calculate electromagnetic fields in

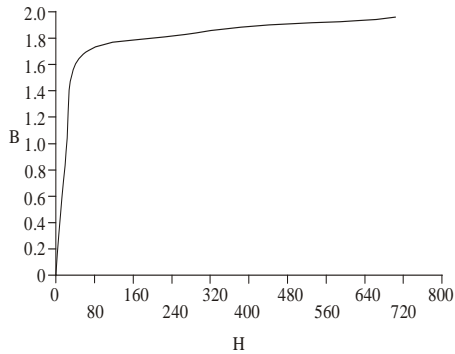


Fig. 1: B-H curve applied to ferrite core in software

transformer. In these analyses, core is modeled in B-H characteristic curve and point method of B and H which is applied in table form. B-H curve is shown in Fig. 1.

### SIMULATION OF SHELL TYPE TRANSFORMER

In this part, only the right leg of a three-phase transformer with shell type core is investigated. In this model, this leg includes primary and secondary windings and transformer core. The core is M5 which has nonlinear characteristic.

- Secondary and primary windings have 32 turns (2 layers) and 1524 turns respectively.

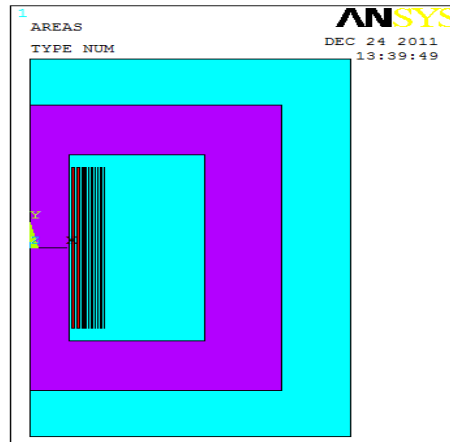


Fig. 2: One phase of 3-phase shell-type transformer

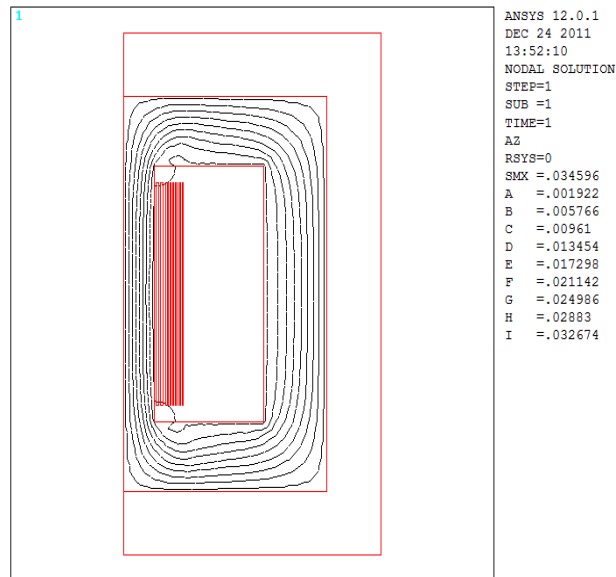


Fig. 3: Flux lines in shell type transformer

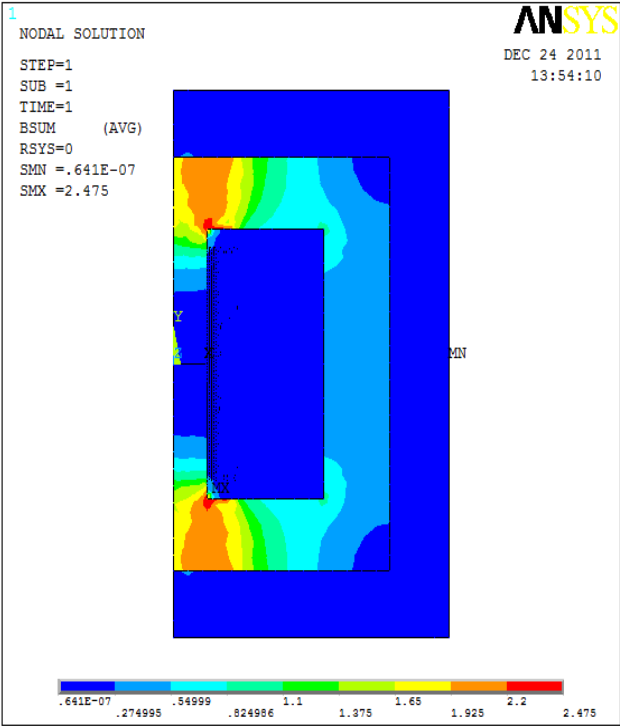


Fig. 4: Magnetic flux density in shell-type transformer

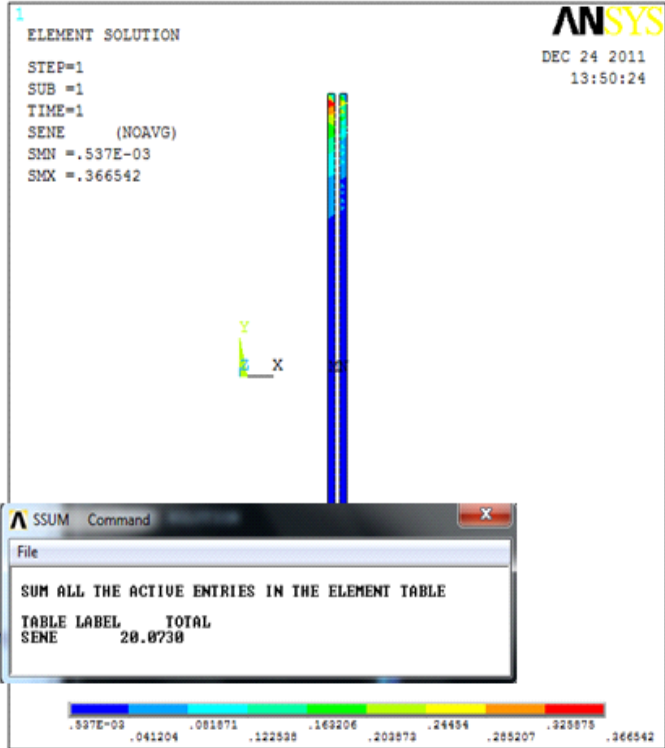


Fig. 5: Stored energy contour in secondary of shell-type transformer

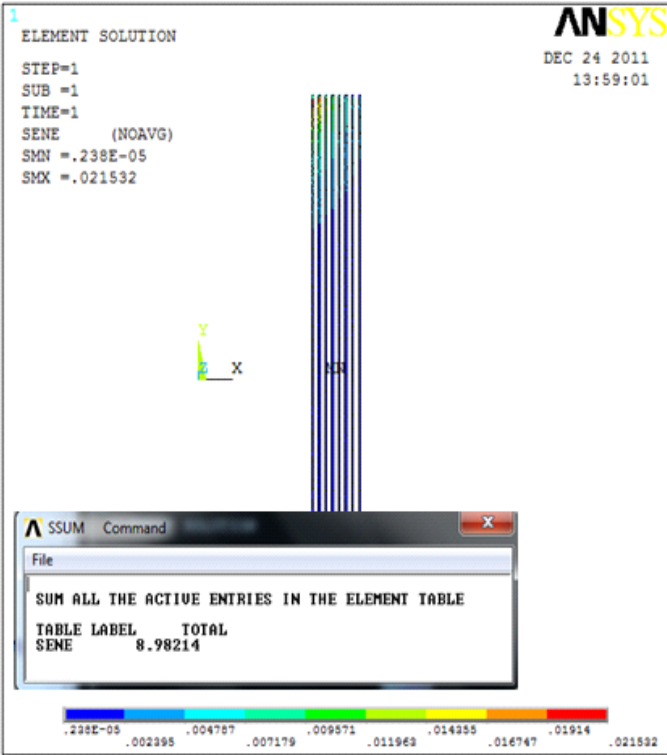


Fig. 6: Stored energy contour in primary of shell-type transformer

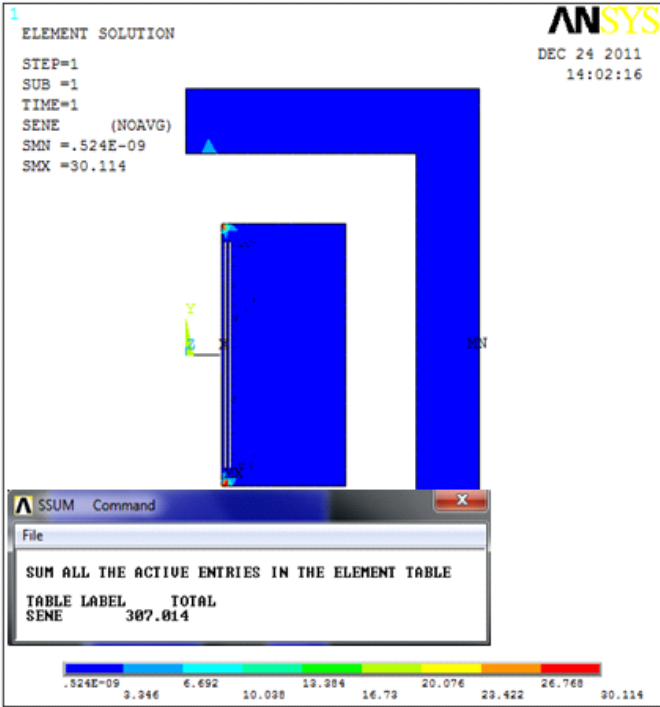


Fig. 7: Stored energy in air space of shell-type transformer

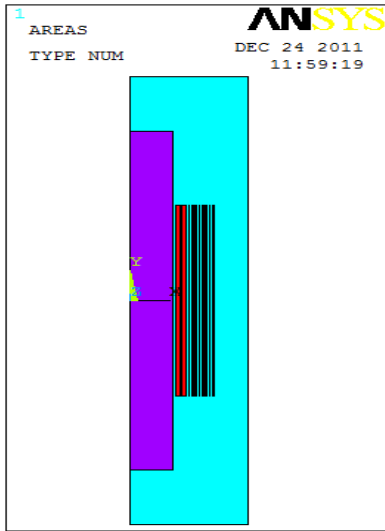


Fig. 8: One phase of 3-phase core-type transformer

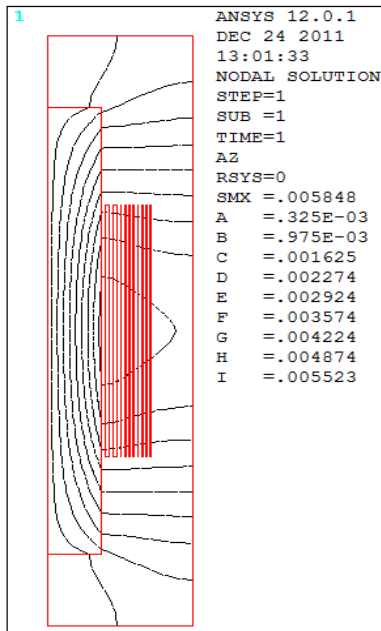


Fig. 9: Flux lines in core-type transformer

Cross section area of primary winding is rectangular and for secondary winding is round (circular). To decrease calculation mass and also to increase convergence speed, cross sectional area is considered rectangular.

The objective of this simulation is to calculate primary and secondary inductances, magnetic energy stored in window area and around windings. A sample 3-phase shell-type transformer is modeled and simulated in continue and obtained results are presented as well.

The model of shell-type transformer is shown in Fig. 2. This model includes primary and secondary windings, core, and air space. Primary and secondary inductances can be determined using this model and applying current density to windings. Energy method can be used to obtain inductance.

Flux lines are shown in Fig. 3 which flux value is less in corners. Magnetic flux density in core is plotted in Fig. 4. This figure can also prove that flux is less in core corners.

- **Calculation of secondary leakage inductance:** By applying current flux of 3 A/mm<sup>2</sup> to secondary winding area, transformer can be simulated and magnetic analysis can be done as well. In this simulation, different parameters can be calculated which among them stored energy in air space and in secondary winding can be mentioned. The contour of stored energy in secondary winding is shown in Fig. 5. Secondary winding leakage inductance can be determined by:

$$w = \frac{1}{2} Li^2 \Rightarrow L = \frac{2W}{i^2} \quad (1)$$

According to Fig. 5, total energy stored in secondary winding is equal to 20.07 J. By replacing this value in energy equation; secondary inductance per phase of shell-type transformer is obtained which is equal to 85.04 mH. It should be mentioned that in this calculation, current of secondary part of transformer is 687 A.

- **Calculation of primary leakage inductance:** Primary leakage inductance can be also obtained by applying 3 A/mm<sup>2</sup> current flux to primary winding area and measuring stored energy in primary winding and air space (using finite element method). Besides, primary inductance value can be calculated by energy stored in air space and primary winding values by replacing in equation  $W=Li^2/2$ . Contour of stored energy in primary winding is shown in Fig. 6. As it is clear in this figure, total stored energy in whole primary winding is 8.98 J. By using this value and winding current (15 A), primary inductance per phase of shell-type transformer can be obtained which is equal to 80 mH.
- **Calculation of stored energy in air space:** Stored energy in air space depends on core and windings locations. Proximity of core and winding affects on the stored energy in air space and leakage fluxes. Hence, in this structure, stored energy in air space and winding are regarded in output of simulation. Stored energy in free space is plotted in Fig. 7. This stored energy in free space is equal to 307.014 J.

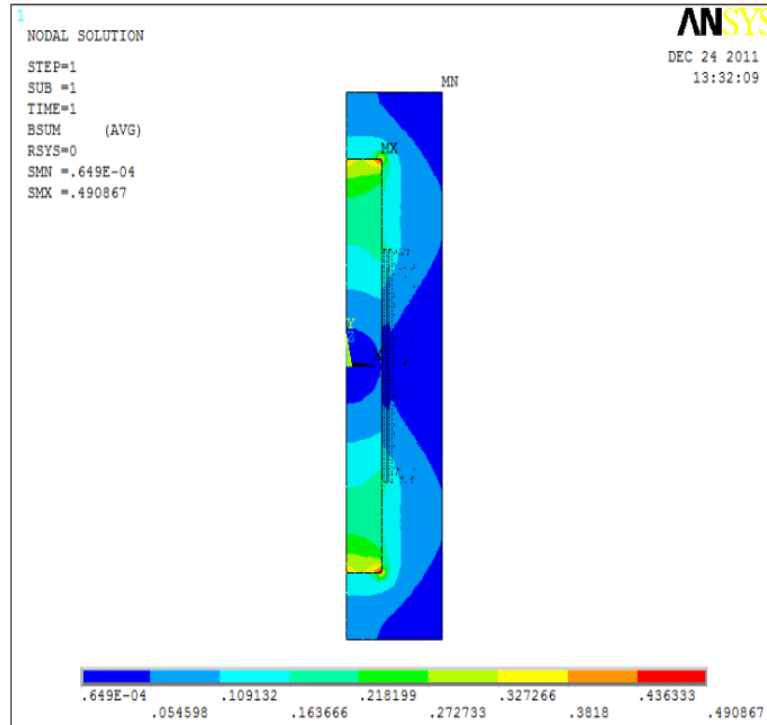


Fig. 10: Magnetic flux density distribution in core-type transformer

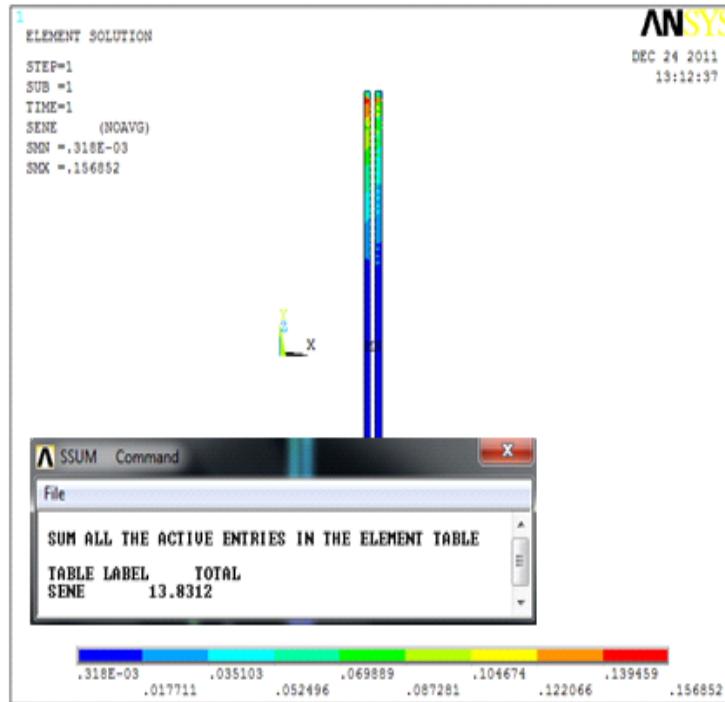


Fig. 11: Stored energy contour in secondary winding of core-type transformer

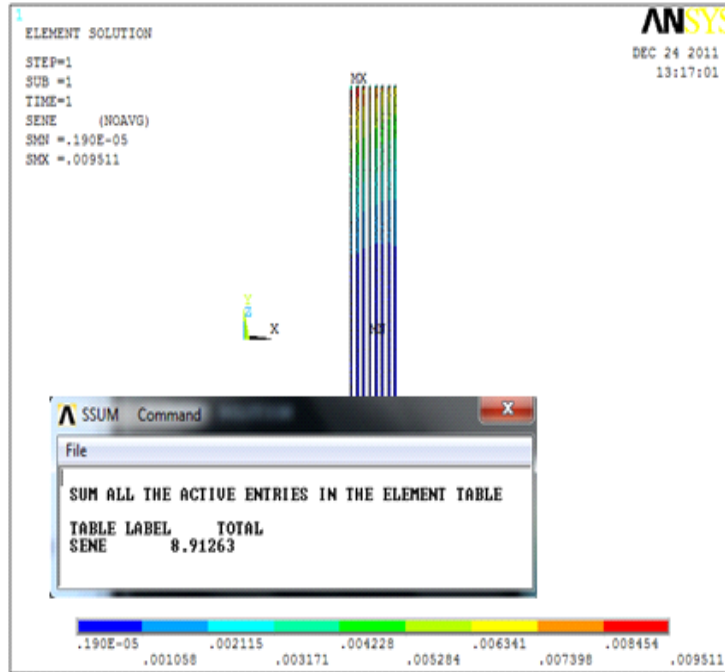


Fig. 12: Stored energy contour in primary winding of core-type transformer

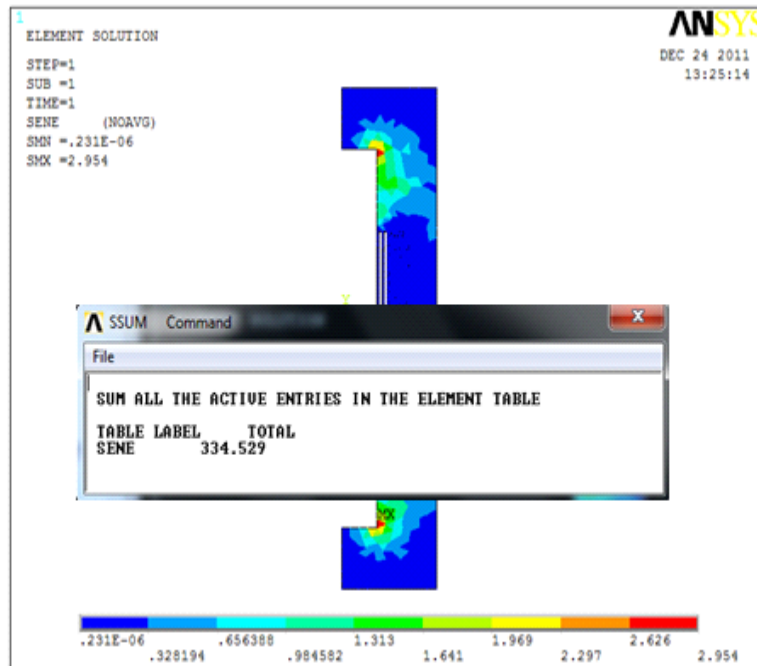


Fig. 13: Stored energy in free space of shell-type transformer

**Calculation of leakage inductance for core-type transformer:** Similar to shell-type transformer, for three-phase core-type transformer, according to Fig. 8, only

right leg of transformer (including primary and secondary windings and their core) is modeled and simulated by finite element analysis.

Primary and secondary winding numbers are 32 T (2 layers) and 1524 T (8 layers), respectively. Similar to shell-type, primary winding cross sectional area is rectangular and that of secondary winding is circular. Generally for better comparison, all characteristics of both shell-type and core-types transformers are considered the same.

Moreover, in these simulations, magnetic energy stored in free area and windings are required in order to calculate primary and secondary leakage inductance values. Flux lines for core-type transformer are shown in Fig. 9. This figure shows that some lines close their paths outside the core. Magnetic flux density in core is plotted in Fig. 10. According to this figure, the maximum flux density is in output core corners and its value is equal to 490 mT.

**Calculation of secondary inductance leakage:** By applying current flux of 3 A/mm<sup>2</sup> to secondary winding, transformer is simulated and magnetically analyzed. Required values for this simulation are stored energy in air space and secondary winding as well. Figure 11 indicates stored energy contour in winding. According to this figure, total stored energy in secondary winding is equal to 13.83 J. By replacing this value in (1), secondary inductance per phase of core-type transformer is obtained equal to 58.6 mH. Current of secondary winding is considered as 687 A.

**Calculation of primary leakage inductance:** Primary leakage inductance can be obtained by applying current density to primary winding and carrying out finite element method similar to previous part. Stored energy contour in primary winding is plotted in Fig. 12.

Total energy stored in the whole primary winding is 8.91 J. Primary inductance per phase of core-type transformer is obtained equal to 79.2 mH using (1).

**Calculation of stored energy in air space:** The energy stored in air space depends on core and winding locations. Stored energy in free space is plotted in Fig. 13. This stored energy in free space is equal to 334.529 J.

## CONCLUSION

In this study, primary and secondary inductance values have been compared for two different shell-type and core-type transformers.

For this purpose, two transformers with the same characteristics have been modeled and simulated using

ANSYS. Leakage inductance values of different windings have been determined using obtained results and calculating energy values of various parts. Obtained results have shown that primary and secondary leakage inductance of shell-type transformer is more than those of core-type transformer due to proximity of windings to core. Leakage inductance values have been obtained equal to 85.04 and 80 mH respectively. Also, these values for core-type transformer were calculated equal to 58.6 and 79.2 mH respectively. Furthermore, stored energy in free spaces of shell-type and core-type were calculated 307 J and 334 J, respectively. These results have proved that core-type transformer has rather more leakage flux in comparison with shell-type transformer.

## REFERENCES

- Babaie, H. and H.F. Farahani, 2010. Analysis of thermal behavior of high frequency transformers using finite element method. *J. Electromagnetic Anal. Applicat.*, 2: 627-632.
- Erickson, R.W., 1997. *Fundamentals of Power Electronics*. Chapman and Hall, United States.
- Farahani, H.F., 2011. Finite element analysis to find the optimal windings arrangements for reduction of leakage inductance in high frequency transformers. *Aust. J. Basic Appl. Sci.*, 5(11): 219-227.
- Farahani, H.F. and M. Khalili, 2011. Investigation the effect of core type on the leakage inductance in the high frequency transformers. *Adv. Mater. Res.*, 443-440: 3890-3894.
- Khodakarami, A., S.M. Pedramrazi and H.F. Farahani, 2010. Analysis of auxiliary winding effect on the leakage inductance reduction in the pulse transformer using ANSYS. *J. Electromagnetic Anal. Applicat.*, 2(9): 513-518.
- Kim, S.C. and S.H. Nam and D.H. Kim, 2004. Development of high-power density 4-kV pulse transformers for TWTA. *IEEE Trans. Plasma Sci.*, 32(5): 1873-1878.
- Lord, H.W., 1971. Pulse transformers. *IEEE Transact. Magnetic MAG*, 7(1): 17-28.
- Redondo, L.M. and E. Margato and J.F. Silva, 2002. Rise time reduction in high-voltage pulse transformers using auxiliary windings. *IEEE Transact. Power Elect.* 17(2): 196-206.
- Redondo, L.M. and J.F. Silva and E. Margato, 2007. Pulse shape improvement in core-type high-voltage pulse transformers with auxiliary windings. *IEEE Transact. Magnet.*, 43(5): 1973-1982.