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# Finite Element Calculation of Winding Type Effect on Leakage Flux in Single Phase Shell Type Transformers

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*Abstract:* - Transformer winding type has a great effect on the flux leakage and flux leakage in it's turn affect considerably voltage drop, magnetic losses and transformer efficiency. Therefore it is necessary to investigate flux linkage and the affected factors on it. In this paper, winding type effect on flux leakage is investigated using 2D finite elements method.
For making a quantified study, two main windings type namely, LHL (helical concentrate) and sandwiches windings are considered and flux leakage is computed for each one. Finite Element computation is made by COSMOS 2.0 software package. To cross check package results, an approximately analytical calculation is performed and the results are compared.

*Key-Words:* - Finite Elements Method, Shell Type Transformer, Leakage Flux, Sandwiches Winding, Concentrate Helical Winding

## 1 Introduction

Nowadays transformer is one of the most important equipments in power energy system. Because of development the distribution network and growth in demand energy in large cities, employing distribution transformer for transfer and providing power to general purpose has been increased overly. Furthermore as transformer remain energized for all the 24 hours of the day, whether they are supplying any load or not, constant losses occurs in it for the whole day and copper losses are different during different period of the day [1]. Therefore both efficiency and the voltage drop in a transformer on load are chiefly affected by its leakage reactance, which must be kept as low as design, and manufacturing techniques would permit. For this purpose it is crucial to be able to calculate leakage reactance.

Although numerical methods for calculating the energy and reactance of transformers and electrical machines have been suggested, there has not been a practical method for determining its accurate value in all cases such as transient or short circuit.

Generally for calculation of leakage reactance and consequently leakage flux three methods have been proposed:

- Image of winding conductor
- Comprehensive modeling of transformer parameters
- Finite element method [2], [3].

Main weaknesses of image method are

- Incapability to calculating the leakage reactance in multilayer secondary winding such as multi-helical or distributed winding or sandwiches winding
- All calculation is based on quadratic core type
- Assume that $\mu = \infty$ in all calculations [4]
- Incapability to calculating reactance with unbalanced windings

Main drawbacks of comprehensive modeling method are

- Difficult obtain all parameters of transformer precisely and very accurate
- Incapability of evaluate inductance in transient and short circuit cases

Besides these methods, FEM with extensive capabilities and advantages recently has been only effective and accuracy method in numerical analysis. Some of these advantages are: [5], [6]

- Applying all operational conditions such as dynamic and static, transient, steady state or in special time
- Considering material characteristic such as B-H curves or other special characteristics that varied with time
- Modeling and analysis can be based on any geometrical figures
- Applying any current, voltage, temperature and etc. input sources

Maybe main drawback of FEM is difficulty to define accurate boundary conditions [7], [8].
In this paper a 150KVA, 6.6/0.4KV single-phase shell type transformer of IRAN-TRANSFO Ltd. with two different winding types (LHL and sandwiches) is analyzed with COSMOS 2.0 software electromagnetic package. The main design parameters of this transformer are shown in table 1.
For this purpose, flux density distribution and leakage flux for each winding is computed. Software obtained results compared with analytical equations in each case.

**Table 1.Design Parameters of the Transformer**

| | | |
|---|---|---|
| Rating | Capacity | 150kVA |
| | Voltage | 6600/440V |
| | Current | 27.73/340.9A |
| | Frequency | 50Hz |
| | Phase | Single-Phase |
| Core | Type | Shell Type |
| | Materials | M5 |
| | Nominal Flux Density | 1.7T |
| Windings | | |
| a) LHL | Current Density (primary) | 1.25A/mm$^2$ |
| | Number of Turns (primary) | 70 turns |
| b) Sandwich | Current Density (primary) | 1.89A/mm$^2$ |
| | Number of Turns (primary) | 70 turns |
| | Number of divisions in each winding | 3 |

## 2 Transformer Windings

Generally there are four windings types that used for conventional low power transformers [9].

1) spiral type
2) crossover type
3) helical type
4) continues disc type

Spiral coils are only suitable for windings that carrying a high current, and used for l.v. In general, they are not normally used for currents of less than 100A. Crossover type of winding is suitable for currents up to 20A and very largely used for h.v. windings of distribution transformers. The helical coil, in effect, covers the intermediate range of current and total windings turns between the heavy current spiral coils and the multiple disc coils. Moreover with adjusting tap, it could be used for high voltage transformers. Because of these advantages and easiest for operator to wound it in core type transformers, this type used largely in distribution transformers. Continues disc type is suitable for h.v. windings for high voltage transformers and because of increasing total cost, often not used in distribution transformers.
Moreover windings that considered above, for especially applications there are some other arrangement of coils such as sandwiches windings, foil windings, distributed helical or distributed continuous winding and etc for pulse transformers, high current transformer (current injector) and overall cases for reducing leakage reactance or reducing thermal effect and so on.
Main advantages of sandwiches windings rather than conventionally helical type are better robustness in large electromagnetic force, lower leakage flux with increasing the division number of each winding and economical rather than continue disc type or distributed type. This winding has some drawbacks as compared to concentric winding:

- Required more labour in its manufacture.
- More difficult to insulate from each other and the yoke.

In our simulation general characteristics of transformer's geometry with LHL winding are:

- Width of Duct is 0.6 cm.
- Winding mean radial of l.v. ($r_{L1}$) is 9.3 cm and ($r_{L2}$) is 17.26 and ($r_H$) for h.v. winding is 13.06 cm.
- Height of both l.v. and h.v. winding is 29 cm.
- $r_{OUT}$-$r_C$=10.26 cm and $a_L$=2.3 cm and $a_H$=4.6 cm.

And for sandwiches winding

- Winding duct's width is 0.6 cm and number of division fir l.v. and h.v. is 3.
- Winding mean radial of l.v. and h.v. ($r_H$ and $r_L$) winding is 12.6 cm.

All parameters and geometrical figures of both winding are shown in Fig. 1 and Fig. 2 for LHL and sandwiches winding respectively.
Pre-analyzed of these characteristics for sandwiches winding shown in Fig. 3. Because of axisymmetric topology of transformer, all simulation is based on axisymmetric simulation. Note that to have very low leakage flux, the amp-turn of two l.v. coils that situated near the yoke and lower end of winding is half rather than other l.v. coils.

## 3 Finite Element Analysis

The fundamental assumptions for this analysis are:

- The magnetic field is treated as 2D.
- The amp-turns of primary and secondary

windings are equal and uniformly distributed along the windings and opposite during short circuit.

- Saturation and eddy currents within the conductor and tanks are neglected.
- $\mu_{air} = 1$ and constant.
- All analysis is based on magneto-static.

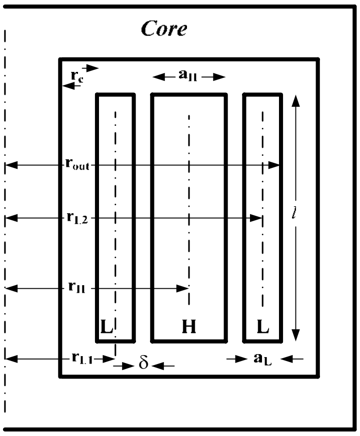


**Fig.1. configuration of LHL winding**

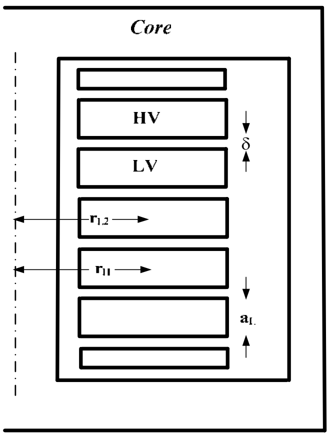


**Fig.2. configuration of sandwiches winding**

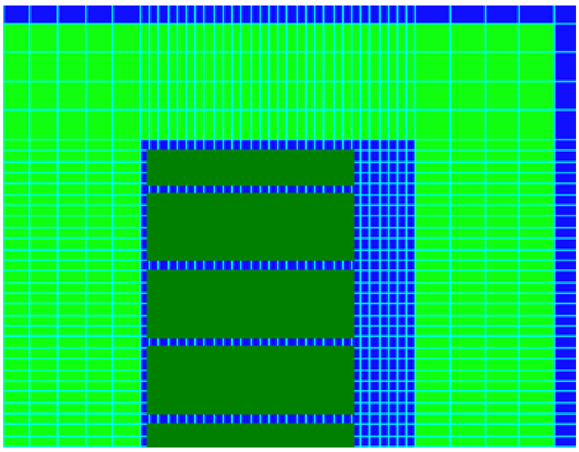

**Fig.3. Pre-analyzed transformer using Quadratic meshes in Cosmos software. Olive green mesh indicate sandwiches winding**

Generally calculation of mutual and self-inductance in most of the FEM software is based on calculating total energy. The total energy of magnetic field in a volume V is

$$W = \frac{1}{2\mu_0}\int_V B^2 dV \qquad (1)$$

The boundary conditions are defined by (2) and (3); the magnetic field outside the blue box in figure 3 is zero in the model. Equation (2) describes the behavior of the tangential components and (3) states that the normal component is continuous

$$\hat{n}\times(A_2 - A_1) = 0 \qquad (2)$$

$$\hat{n}\bullet(A_2 - A_1) = 0 \qquad (3)$$

Thus saying that the tangential and normal components of $A$ are continuous and we have chosen $A_2 = A_1 = 0$ at the boundary.

This boundary condition is a Dirichlet condition and is used as definition of infinity and axis-symmetry in Ace [10], [11], [12]. The total stored magnetic energy for the transformer is given by (4)

$$W_{total} = \frac{1}{2}L_p I_p^2 + \frac{1}{2}L_s I_s^2 + M I_p I_s \qquad (4)$$

Where $M$ is mutual inductance and $L_p$ and $L_s$ are the self-inductance of primary and secondary windings respectively. The primary inductance $L_p$ is calculated with a current flowing in the primary conductor while the secondary circuit is open, and vice-versa for the secondary inductance $L_s$. The mutual inductance is calculated using equation (5) where the index $_p$ means primary and $_s$ secondary winding energy. When the difference between $W_{total}$ with $W_p$ and $W_s$ is calculated, the first two terms in 4 calculated and the mutual inductance can be solved. It is then straightforward to calculate the coupling factor and mutual inductance.

$$|M| = \frac{W_{total} - W_s - W_p}{2 I_s I_p} \qquad (5)$$

Fig. 4 and Fig. 5 show the magnetic flux distribution in windings and core with LHL and sandwiches winding respectively. Note that maximum value of flux be in four corner of core and mean value of flux that seen in major part of core is approximately 1.5T. For have a better observation about leakage flux, Fig. 6 shown a flux density into vector plot.

For comparison these results with analytical method we have:

$$R\varphi = LI \Rightarrow R * AB = LI$$

$$RAB = \frac{N^2}{R} * I \Rightarrow B = 1.7059\ T$$

Note that this value is a mean average of magnetic flux density and saturation is neglected. Because of reducing FEM error that causing when overlap between nodes and between meshes created, we don't use auto-mesh to meshing the core and windings. Because of that the shape of core and winding in 2D simulation is rectangular; we proposed quadrilateral first order mesh for meshing.

Equations (6) and (7) give the leakage inductance in sandwiches and LHL winding respectively [1], [12]. Note that these equations give the mean of leakage reactance between turns of winding, not all leakage that dissipated in oil and yoke of transformer.

$$L_{leakage} = \frac{\mu_0}{2}\frac{L_{mt}}{a_L}\frac{N_P{}^2}{n}\left(\delta + \frac{r_H + r_L}{6}\right) \quad (6)$$

$$L_{leakage} = \frac{\mu_0 N_p^2}{L + 0.16(r_{out} - r_c)} * [\frac{a_L}{3}(r_{L1} + r_{L2}) + \delta(r_{\delta 1} - r_{\delta 2}) + \frac{a_H}{4} r_H] \quad (7)$$

All considered parameters in above equations shown in Fig. 1 and Fig. 2.

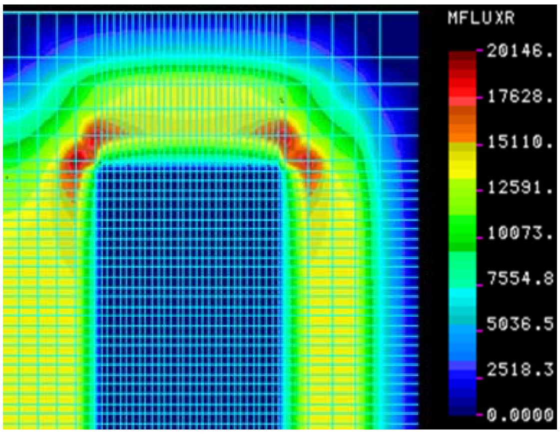


**Fig. 4. Magnetic flux distribution with using LHL winding in CGS**

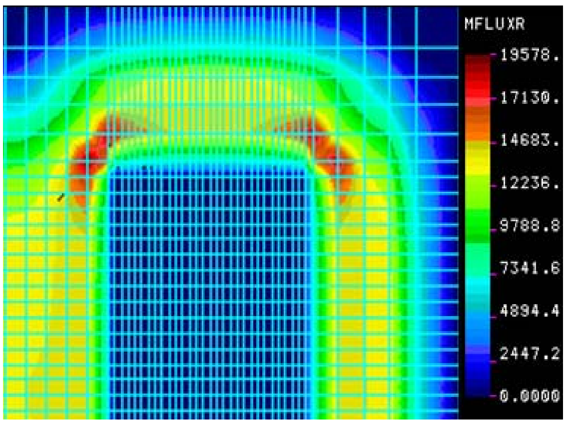


**Fig. 5. Magnetic flux distribution with using sandwiches winding in CGS**

In equation 6, n is number of each winding divisions in sandwiches winding. From above equations we consider that decreasing δ or $r_L$ we could have very low leakage reactance, but thermal limitations that occurs in these cases is very effective and maybe can deform and damage all insulations and conductors. Using equations (6) and (7) and get n=3 we calculate leakage inductance 3.57mH for sandwiches winding and 7.11mH for LHL windings.

Table 2 gives the leakage inductance using LHL and sandwiches winding that obtained analytical and finite element methods.

**Table 2.Comparison of Obtained Results with Two Winding Type**

| Winding Type | LHL | | Sandwiches | |
|---|---|---|---|---|
| Calculation Method | analytical | Fem | analytical | Fem |
| Leakage Inductance (μH) | 7.11 | 9.42 | 3.57 | 5.46 |

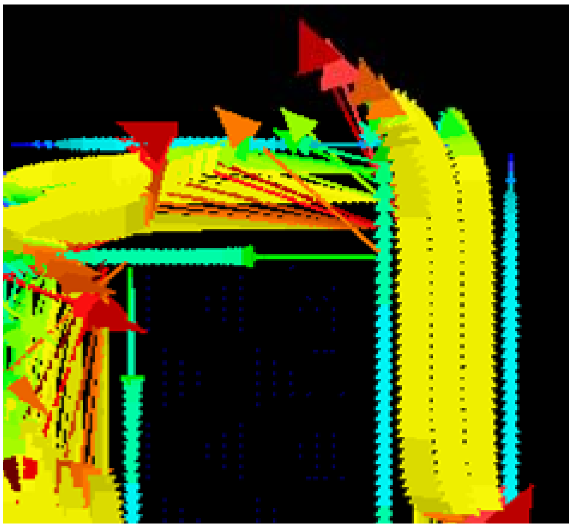

**Fig. 6. Vector plot of magnetic flux, green vector representative the leakage flux**

## 4 Conclusion

The effect of winding type on transformer leakage inductance is investigated about typically distribution shell type transformer. For this purpose two winding type compared and evaluated: sandwiches winding and concentrate helical winding.

Obtained results from COSMOS 2.0 and finite element method compared with analytical method. Results show that using sandwiches winding we can reduce leakage inductance nearly 42% comparing LHL windings.

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