Моделювання теплового зосередженого параметру тороїдального трансформатора

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Тороїдальні трансформатори мають деякі переваги, у тому числі менший розмір, у порівнянні з трансформаторами такої самої потужності з серцевиною ЕІ. Рис.1 представляє структуру тороїдального трансформатора.

Довговічність трансформатора залежить від довговічності ізолятора, а довговічність ізолятора залежить від найгарячішої місцевої температури. Так, визначення температурного профілю це важливе завдання в розробці трансформатора й оцінці його довговічності.

Дана стаття вперше представляє три методи передачі тепла, тобто провідність, конвекцію і радіацію. Провідність це теплопередача в серцевині, ізоляційних матеріалах й ізольованому повітрі в обмотці. Конвекція передає тепло з поверхні вторинної обмотки у довкілля. У статті описується основна схема теплового еквіваленту. Розрахунок теплової стійкості представлено в рівняннях 2 і 3.

Серцевина моделі теплового зосередженого параметру трансформатора складається з джерела тепла і двох симетричних опірних елементів ізоляційного матеріалу серцевини, якщо втрати в серцевині централізовані. Для ізоляційних матеріалів, немає ніякого джерела тепла, тому модель зосередженого параметру ізоляції складається тільки з теплової стійкості. Модель теплового зосередженого параметру для первинної і вторинної обмотки складається з джерела тепла та теплової стійкості, а температура довкілля може розглядатися як джерело напруги постійного струму.

Розгляд кожного звою (Рис. 6) – це складне завдання для термального моделювання, тому більш доцільно централізувати мідь (Рис. 7), шляхом розподілу мідної і повітряної зон як концентричних кругів для спрощення моделі.

На Рис. 9 пропонується нова модель теплового зосередженого параметру для трансформатора. Її дія перевіряється експериментально. У статті також виведено температурний профіль, заснований на представленому моделі та визначено температуру найгарячішого місця.

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Thermal Lumped Parameter Modeling of a Toroidal Transformer

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Toroidal transformers have *some* ***advantages, including smaller size in comparison with the same rating EI core transformers. This paper presents a simple but accurate thermal lumped parameter model for toroidal transformers to calculate different point temperatures. The model is also verified experimentally.***

Keywords – Toroidal transformer, thermal modeling, lumped parameter.

I. Introduction

Toroidal transformers are widely used in low power applications, for instance, up to 5 KVA, because of some advantages, including higher efficiency, smaller size, lower weight, lower leakage flux, and lower off-load losses in comparing with EI core transformers. Suitable voltage regulation, low noise and low interference arise from the low leakage flux.

Fig. 1 shows the structure of a toroidal transformer. The cross-section of the ring is usually square or rectangular, but more expensive cores with circular cross-sections are also available.

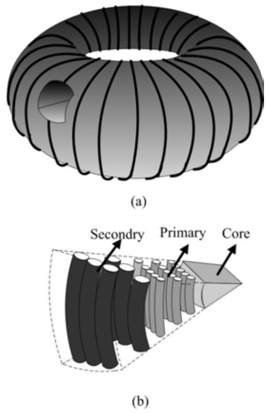

Fig. 1. Toroidal transformer

The transformer life depends on the insulator life, and the insulator life depends on the hottest spot temperature. So, determination of the temperature profile is an important task in transformer design and life estimation.

Since the transformer has been used recently, some investigations are not sufficiently performed including the thermal behavior.

This paper first introduces three heat transfer methods. Then, basic theory of the thermal equivalent circuit is described. A new thermal lumped parameter model for the transformer is proposed, and the results are verified experimentally. Furthermore, based on the presented model, the temperature profile for the studied case is extracted and the place and the temperature of the hottest spot are obtained.

II. Heat Transfer

There are three well known forms of heat transfer, which are described in this section [1], [2].

A.Conduction

The conduction heat transfer is defined as the transfer of heat between objects that are in physical contact.

B.Convention

The convection heat transfer is defined as the transfer of heat between an object and its environment, due to circular fluid motion. Convection can be divided into natural and force convection. In force convection, heat transfer is facilitated using cooling fans.

C.Radiation

The radiation heat transfer is defined as the transfer of heat to or from a body by means of the emission or absorption of electromagnetic radiation. This form of heat transfer can be neglected in power transformers.

III. Thermal Equivalent Circuit

To compute the temperature of different locations in the transformer, heat transfer should be modeled. To facilitate the analysis, a thermal equivalent circuit can be proposed. The equivalent thermal and electrical parameters are well known as [3]:

Table 1

Equivalent thermal and electrical parameters

Thermal	***Electrical***
Power loss (W)	Current source (A)
Thermal resistance (°K/W)	Resistance (Ω)
Temperature (°K)	Voltage (V)
Thermal capacity (J/°K)	Capacitance (F)

In this paper, the thermal capacitances are ignored, since they do not affect the steady state temperatures.

In a simple system, the source of loss, transfers heat to ambient (Fig. 2), so the thermal equivalent circuit can be considered as Fig. 3 [3].

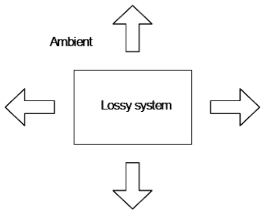

Fig. 2. Heat transfer system

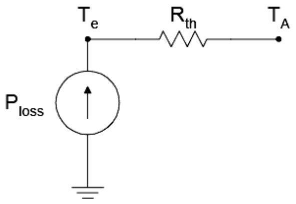

Fig. 3 Thermal equivalent circuit

The following equation can be used to find the temperature of the material.

$$T_e - T_A = P_{loss} . R_{th} \tag{1}$$

where P_{loss} is the system loss, and R_{th} is the equivalent thermal resistance.

Thermal resistance for conduction heat transfer can be calculated as follows [4-6]:

$$R_{conduction} = \frac{l}{l A_c} \tag{2}$$

where l is the thickness of the material, λ is the material conductivity, and A_c is the side area of the material.

The convection thermal resistance can be also calculated as follows:

$$R_{convection} = \frac{1}{12(1+\sqrt{V})A} \tag{3}$$

where A is the contact area to the ambient, and V is the wind speed of the ambient. Since usually the transformer is used in indoor areas, V is considered for the speed of the air force cooling system. So using fans can effectively reduce the convection thermal resistance and facilitates heat transfer.

IV. Lumped Parameter Modeling of the Toroidal Transformer

To obtain a lumped parameter model for heat transfer in toroidal transformers, the available paths for heat transfer should be identified. To do so, the transformer should be divided into sections and the heat source and thermal resistances should be determined in each section.

D. Core

The transformer core lumped parameter model consists of a heat source and two symmetrical thermal resistances to the insulation of the core, if the core loss is centralized.

The core losses consist of eddy current and hysteresis losses, which depend on the flux density. Fig. 4 shows the flux distribution of the transformer core, provided by finite element method. As illustrated, the core flux and as a result the core losses is not uniform. The core loss in the interior surface of the core is higher. So, to make an accurate model, it is proposed to divide the core into some sections. For each section, the losses and the thermal resistances to the adjacent sections should be calculated. The core loss for each part can be calculated using the average value of the flux density and the value of the W/kg core loss reported in the core datasheet. For this case four sections are considered. P_1, P_2, P_3, and P_4 are calculated as the section's losses.

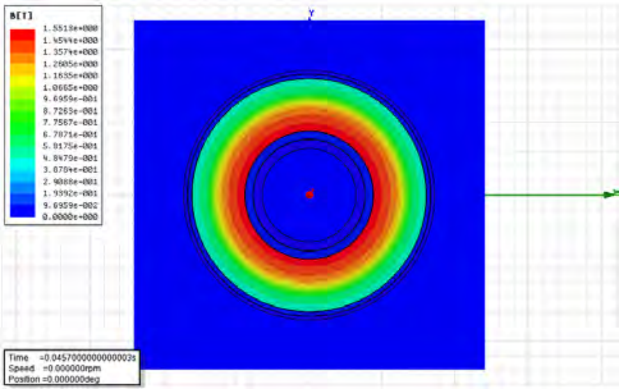

Fig. 4. Flux distribution of the iron core

The heat transfer in the core is conduction. So, Eq. 2 can be used to calculate the lumped parameter resistance.

Finally, the core lumped parameter model can be considered as Fig. 5.

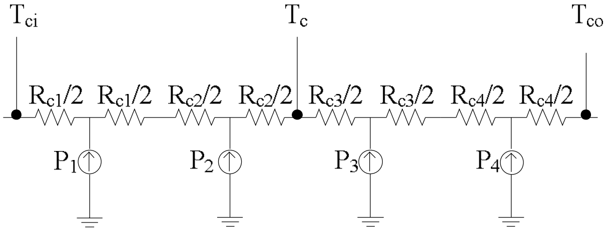

Fig. 5. Core lumped parameter model

The core thermal resistances are low since the conductivity of the iron is high. As a result, the interior and the exterior surface of the core have approximately the same temperature, i.e. $T_{ci} \approx T_{co}$.

E. Insulations

The insulations of the machine are between the core and the primary winding, the primary winding and the secondary winding, and the secondary winding and the ambient. There is no heat source in this part of the transformer, so the lumped parameter model of the insulations only consists of a thermal resistance. The heat transfer form in the insulations is conduction and the thermal resistance can be calculated using Eq. 2. The conductivity of the insulation is low. However, since the thickness of the insulations is very low, the insulation thermal resistance is low.

F. Primary and Secondary Windings

The thermal lumped parameter model for Primary and secondary windings consists of heat source and thermal resistances. The heat source arises from the copper loss. Considering each turn (Fig. 6) is a complex task for thermal modeling. So it is more appropriate to centralize the copper (Fig. 7), dividing the copper and air area as the concentric circles in order to simplify the model.

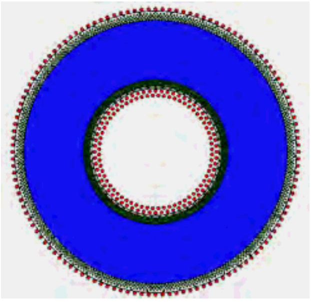

Fig. 6. Detailed toroidal transformer windings

A percentage of the winding's area is air, which should be considered in heat transfer analysis. The air area between the turns can be calculated using the final dimension of the transformer, the number of turn of the windings, and each wire cross section area. The air area can be divided in two sections and centralized around the centralized area of the copper. The winding's losses should be also divided in two sections since the thermal modeling is bilateral in interior and exterior parts. So the lumped parameter model of the winding can be considered as follows.

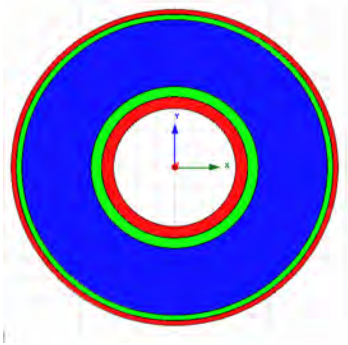

Fig. 7. Simplified windings

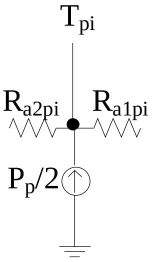

Fig. 8. Thermal lumped parameter model of windings

The heat transfer in the air area is conduction. Since the air is confined and cannot move, there is no convection in this part. Since the conductivity of the air is low and the confined air volume is considerable, the thermal resistances in the lumped parameter model have high value, which determines the temperature difference between different points.

G. Ambient

The ambient temperature can be considered as a dc voltage source. The heat transfer from the exterior of the secondary winding to the ambient is convection. The wind speed should be considered zero, since there is no air force cooling device.

Fig. 9 shows the complete thermal lumped parameter model for the toroidal transformer. The temperature of different points of the transformer can be calculated simply. Since the transformer temperature distribution is not symmetrical for interior and exterior part, the model is bilateral. Fig. 10 shows the temperature profile of the transformer with different load conditions. As expected, the hottest spot of the transformer in low load condition is on the iron core, since the core loss is higher than the copper loss. However, increasing the load the hottest spot moves on the primary winding in the interior part of the transformer.

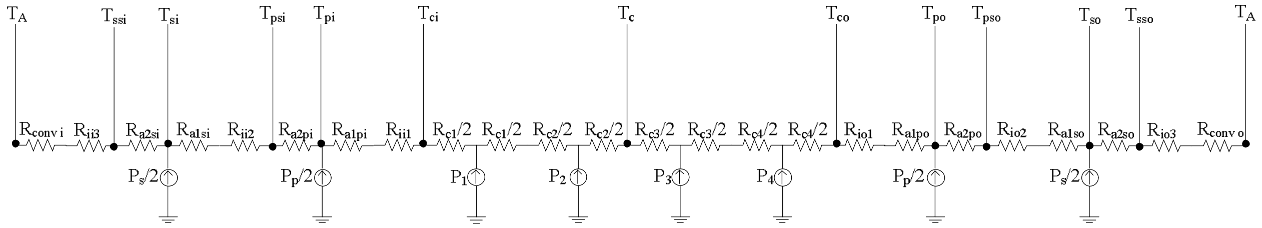

Fig. 9. Thermal lumped parameter modeling

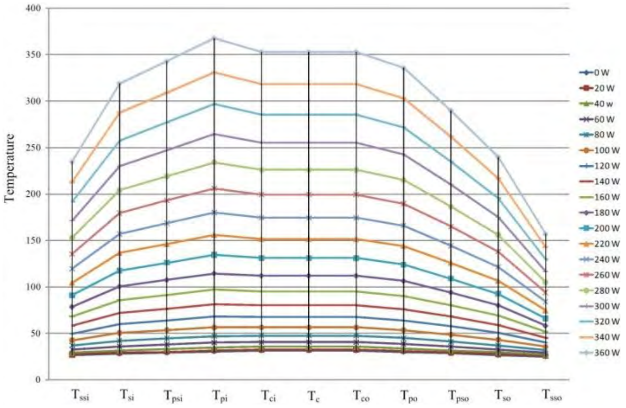

Fig. 10. Temperature distribution

V. Experimental Verification

To verify the proposed model, an experimental set has been studied, and three temperature sensors are embedded in order to measure the temperature in different points. Figs. 11, 12, and 13 show the temperature comparison of the experimental and the lumped parameter model on the core, between primary and secondary windings, and on the secondary winding, respectively. It is shown there is a good agreement between them.

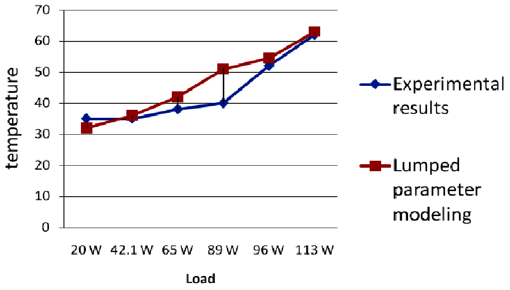

Fig. 11. Temperature on the core

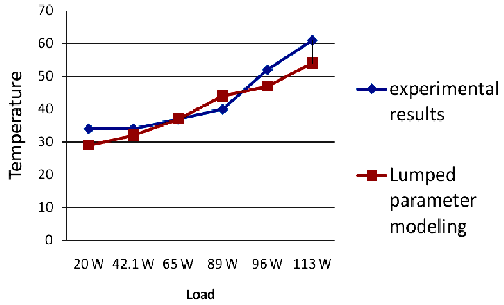

Fig. 12. Temperature between primary and secondary windings

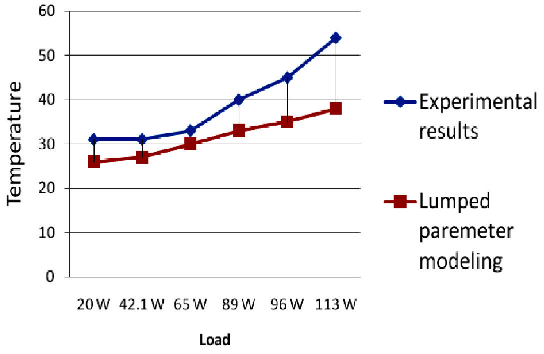

Fig. 13. Temperature on the secondary winding

There are unavoidable differences between the thermal lumped parameter modeling and the experimental results, which arise from the approximate nature of the lumped parameter model.

Conclusion

This paper presented a new, very simple but accurate thermal model for toroidal transformers. It is shown the hottest spot of the machine varies with the load. In low loads, the hottest spot of the machine is on the interior part of the core. However, for higher loads the hottest spot place has been changed to the primary winding. Finally, the model is verified with experimental results.

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