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Winding Considerations on the High Frequency Transformers

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Abstract

High frequency transformers, used in switching power supplies, carry high amount of current. High frequency effects like skin, proximity and edge effects are discussed in this paper. Multi stranded or litz wires are used for reducing skin effect, but it will be shown that they are not effective in transformer normal winding. Paralleled interleaved winding is presented for reducing the high frequency effect. Two dimensional simulations based on finite element method are done for investigation of current distribution in high power, high frequency transformers.

Keywords: Eddy Current; Skin; Proximity; Edge; HF Transformer

1. Introduction

Switch mode power supplies (SMPSs) are completely known recently. They are used almost in all of electrical and electronically circuits. With technology development of semiconductor’s construction, transformers cause the limitation of power density of SMPSs, instead. High frequency effects as skin and proximity are main reasons for considerable increasing of transformer winding resistance. Then transformers winding losses cause overheating. The maximum allowable transformer temperature is converting to main limitation of power density in SMPSs. In the other hand transformer leakage inductance causes more overlap of current and voltage at the switches, consequently increasing of switching losses and voltage stresses on the switches [1]. So, High frequency power transformers and high frequency effects are one of interested subjects in power electronic applications [2]-[5].

Skin, proximity and edge are high frequency effects in magnetic components which also investigated by the titles of copper losses, eddy current losses, Ohm losses, conductive losses and AC winding resistance in the various papers. Skin and proximity effects are introduced in [6], [7]. They are scrutinized and modeled for multi-strand wires in high frequency transformers in [8], [9]. It was shown that the total proximity loss increases as the square of the number of strands, so, it is more effective than skin effect.

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The model is developed gradually in [10]-[13]. Generally, two dimensional finite element method (2D FEM) simulations are used for model verification [12], [13]. Edge effect, the other high frequency effect, is introduced in [14] and modeled in [15]. The model is developed gradually in [13], [16]. On the other hand, thermal modeling is an important issue in the transformer design process. Different models are given in [17]-[19]. In all of these papers, the inner side of winding and center arm of core introduced as hot-spots, and current distribution of windings is assumed to be equally distributed in all of coppers. This assumption is also taken in the transformer reliability and life time estimations [20]. But it will be shown that in normal winding although the total current of the windings are equal, the current distribution and continuously copper loss are not equal. Actually, proximity effect makes mid of winding a hot-spot.

For skin effect reduction, it has to be used a thin wire according to skin depth, which depends on operational frequency. Therefore, lots of wires have to be paralleled, for high current rates. They are known as multi strand or litz-wires. But proximity effect is still available in the multi strand wires. The number and diameter of strands to minimize loss in a litz-wire transformer winding is determined in [21]. Anyway, in high power and high frequency transformers optimal case maybe is not practical.

In order to reduce the magneto-motive force (mmf) (and thus the leakage inductance and the proximity effect) interleaved winding is used. Details of interleave winding are discussed in [22], [23]. In this method of winding, each winding is divided into several parts and one layer of the primary and one layer of the secondary are alternately wound around the core. Finally, all parts of each winding are made series. In fact, in the traditional method, winding turn number (N) is reduced and winding current (I) is held constant in order to reduce mmf (mmf=NI). In the case of high current the skin and proximity effects still exists and reduces the performance of the transformer. So in order to improve high power and high frequency transformer’s parameters, in addition to mmf reduction, direct reduction of the skin effect and the proximity effect are also considered. Modified interleaved winding structure is presented in this paper which it decreases current (I) instead turn number (N).

The way of current sharing at paralleled windings, used at high frequency transformer, will scrutinized in this paper and it will be shown that how interleaved winding cause the balance of current sharing in the paralleled windings. Different kinds of transformer windings include normal and modified interleaved, have been simulated with 2D finite element method. Maxwell software is used for FEM simulations.

For complete investigation, the high frequency effects on the winding resistance at different kinds of windings will discussed in section II. After that, current distribution at the paralleled windings used in the transformer will explained in section III, and section IV is the conclusion of the paper.

2. An Overview on High Frequency Effects in Transformers

Generally, if a time variable magnetic field passes through a conductor, causes induction of current on it. Passing undesirable magnetic flux through the windings causes eddy current which this phenomenon at high power or high frequency has been increased so much and it will be one of the most important transformer’s parameters. Skin and, proximity and edge effects are some kinds of eddy current effects. To scrutinize these effects we study a transformer that used in single switch forward SMPS that described in [24]. The transformer’s core is EE50 and for well study 4 paralleled windings has been defined for primary and secondary windings. For simulation simplicity the available conductors in each layer are assumed as a foil conductor and the turn ratio is supposed unity and, the input voltage is 300 Vdc. The output load will are supposed 300 Vdc and 15Ω respectively (assuming 50% duty cycle V_{out} will be 150 Vdc and the output current will be 10Adc).

Fig. 1 shows the current distribution of windings achieved by FEM simulation for a window of the transformer’s bobbin. Fig. 2 demonstrates the curve of current distribution in the middle of layers across the window.
Four paralleled secondary coils are wound close to the core and four primary coils are wound above them which it is defined by normal transformer winding. Each layer consists 50 turn and 2.5A is passing from each coil (or wire), so, 125A is injected to each layer with the apparent direction in the simulations. The area of each layer is \(25.1 \times 10^{-6}\) (w×h=1mm×25.1mm), so, the current density of each layer has to be \(4.98 \times 10^6\) A.

Skin depth is calculated from equation 1 [12].

\[
\delta = \frac{1}{\sqrt{\pi \sigma \mu_0 f}}
\]

where \(\sigma\), \(\mu_0\) and \(f\) are copper conductivity, vacuum permeability and working frequency respectively. It is \(0.422\)mm for frequency of 25kHz.

According to figs 1 and 2, the peak of current density at the first layer is \(10.8 \times 10^6\)A which it is 2.17 times more than its average. The peak of current density is 23, 35 and \(46 \times 10^6\)A in the second, third and fourth layers respectively according to proximity effect. It means that the peak of current distribution is 18.4 times more than its average and the copper dissipation is 338 times more than its DC value \((P=RI^2)\). This causes the fourth layer, or middle of transformer winding, an extremely hot-spot and critical point for the insulation breakdown failures.
Fig. 3 shows the current distribution curve in the length, Y axis, of the first layer. The edge effect is clear in this figure which is described in [14], [16]. Although the current density in the edge of layers is more than its middle, its peak is not critical.

This means that ordinary paralleling of some thin conductors instead of one thick one doesn’t modify the AC resistance of winding and treat as a thick conductor.

3. The effect of Paralleled Interleaved Winding on the Current Density Distribution

In order to reduce the mmf (and continuously, the leakage inductance and proximity effect) interleaved winding is used which its details are discussed in [1, 18]. In this method of winding, each winding is divided into several parts and one layer of the primary and one layer of the secondary are alternately wound around the core. Finally, all parts of each winding are made series. In fact, in this method, N is reduced and I is held constant in order to reduce mmf=NI. In the case of high current the skin effect, and to some extent, the proximity still exists and reduces the performance of the transformer. So in order to improve high power and high frequency transformer’s parameters, in addition to mmf reduction, direct reduction of the skin effect and the proximity effect are also considered. For this purpose thin conductor should be used instead of thick conductors, but the proximity effect issue is not resolved by paralleling the conductors and some other contrivances such as displacement of the conductors’ positions has to be implemented.

Modified interleaved winding minimizes the mmf, the skin effect and the proximity effect. In this approach, the base of conductor selection is the penetration depth. Interleaving winding is done based on the reduction of current (instead of the reduction of the number of turns) (mmf=NI, I is reduced and N is held constant). The design stages are as follows:

Considering the switching frequency, the conductor’s radius is taken equal to the penetration depth.

The number of conductors is determined based on the effective current trough the winding:

\[ N = \frac{\text{the effective current through winding}}{\text{effective allowable current trough the chosen conductor}} \]

To do the transformer winding, initially, one or two layers of the primary winding are fully wound. Then one or two layers of the secondary are wound and go on. It may seem that in this method, since the length of the wire on the first layer or the layers close to the core is less than conductors, the conductor’s resistance on the outer layers is larger and more current is carried by the inner conductor. But, actually because of total elimination of the skin and proximity effects, the winding resistances in different layers are almost the same and the difference can be ignored. On the other hand, the layers have a good coupling because of interleaved winding, so they have almost equal self-inductance which is very big in comparison with the coil resistance.

Fig. 4 is shown a sample transformer belong to a SMPS. There are three layers for primary and two layers for secondary winding. The magneto-motive force (MMF) is reduced to one third with utilizing this kind of winding.

Fig. 5 shows the current distribution of windings for a window of the transformer’s bobbin. Fig. 6 demonstrates the curve of current distribution in the middle of layers across the window for the paralleled interleaved winding and the previous conditions.

Each paralleled wire carries one fourth of the total current in the interleaved winding. There are four paralleled layers, so, the maximum mmf decreases to one fourth which it is a great modification in the current distribution. According to figs 5 and 6, the peak of current density at all layers is \(11.5 \times 10^6\) amperes (one fourth of figs 1 and 2). So, the copper dissipation is distributed equally in the windings and the inner side of windings will be the hot-spots. In the other point of view, the failure rate of transformer is reduced and its reliability is increased by this manner of winding.
It is noticeable that the achieved results can be applied to the low frequency but high power transformers.

**Fig. 4.** A sample transformer with paraleled interleave winding

**Fig. 5.** Current distribution of windings for a window of the transformer’s bobbin in interleave winding

**Fig. 6.** The curve of current distribution in the middle of layers across the window for interleave winding

**4. Conclusion**

High frequency effects, as skin, proximity and edge are investigated in this paper. Investigation was based on FEM simulations results. It is shown that in ordinary paralleling windings, which are used for decreasing skin effect, the paralleled windings treat as a unit winding. For improving transformer performance and decreasing its copper loss, interleaved winding should be used. It is shown that the maximum of current density in normally paralleled winding is almost four time of in paralleled interleaved. So, the maximum copper loss dependent hot-spot in the normally winded transformer is 16 times of interleaved transformer, which it reduces the efficiency and reliability considerably.

**References**


