Practical approaches for reducing eddy current losses in transformer windings

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The paper is focused on comparison of approaches for eddy current losses reduction in transformer windings. The study covers round wires and Litz wire designs. Design considerations are derived based on the advantages and disadvantages of five compared approaches: parallel wires designs, windings in parallel, Litz wire designs, interleaved windings design and half layer designs. Possible number of paralleled windings is analyzed depending on core type. Applications of Litz wire are investigated based on loss reduction as well as much lower filling factor, lower heat dissipation ability and lower temperature grade compared to round wire designs. Interleaved windings advantage is derived to a factor limited to √2 because of deteriorated heat transfer. Half layer designs provide 4 times loss reduction, but a non-careful winding causes transverse fields that increase the losses considerably. The proposed by the author comparison and guidelines are useful for the optimization of transformers windings designs to reduction of copper losses.

Практически подходи за намаляване на загубите от вихрови токове в намотки на трансформатори (Венцислав Вълчев). *Статията е насочена към сравняване на подходите за намаляване на загубите от вихрови токове в намотките на трансформатори за силовата електроника. Проучването обхваща решения със кръгли проводници и многожилни проводници (лицендрат). Изведените съображения и насоки се основават на предимствата и недостатъците на петте сравнени подхода: използване на паралелни проводници, използване на намотки в паралел, конструкции с многожилни проводници, дизайн на намотки с т.н. 'половин слоеве'. Възможният брой намотки в паралел е анализиран в зависимост от вида на използваната сърцевина. Приложенията на многожилни проводници са изследвани въз основа на намаляването на загубите при тях, както и на недостатъците им свързани с ниския коефициент на запълване, по-ниската способност за разсейване на топлината и по-ниска допустима температура в сравнение с дизайните с кръгли проводници. Преимуществото на секционираните намотки се ограничава от влошения топлообмен и достига до √2. Конструкциите с т.н. 'половин слой' осигуряват до 4 пъти намаляване на загубите. Изведените резултати от сравненията и предложените насоки улесняват оптимизацията на проектирането с оглед намаляване на загубите в намотките.*

I. Introduction

Nowadays power electronics components are designed to provide increasing the operating frequency in order to obtain low volume and weigh of the equipment. But in the same time higher frequencies cause higher losses in magnetic cores and in windings of the magnetic components. Main part of the winding losses dependent on frequency are so called eddy current losses.

Contemporary model of losses in windings as well current distribution in Litz wire strands are presented in [1]. A high level of accuracy is achieved in [2] combining newly-developed approaches into a novel loss calculation framework. The introduced loss models are verified by FEM simulations and experimental measurements. A fast approach to choosing number and diameter of strands of Litz wire is presented in [3] suitable for power electronics components.

Useful overview of the most known analytical models used to calculate the medium frequency resistance for several winding technologies in presented in [4]. The models are compared by 3D finite element methods (3DFEM) simulations.

Strategies to reduce copper losses in critical connections by either interleaving parallel copper plates or interchanging plates are shown in [5]. The presented results are obtained by 2D FEM simulations and experiments. High frequency loss analysis based on Preisach modeling is presented in [6]. An analytical optimization for round wire windings losses is analyzed in [7], for cases under sine currents based on well-known Dowell's equation [8].

The conclusion of the above study is there analytical and FEM approaches improving the accuracy in eddy current losses calculation. Anyhow, the designer needs guidelines and considerations how to proceed when it is necessary to reduce these losses. The paper is focused on round wires and Litz wire design comparison. Foil and planar designs are next research targets.

II. Practical approaches for reducing eddy current losses in transformer windings

The following five approaches will be considered in the paper:

- Paralleling Wires;
- Paralleling Windings Using Symmetry in the Magnetic Path;
- Using Litz Wire;
- Interleaved Windings;
- Half layer design.

Paralleling wires

A general approach to reduce eddy currents in windings is to use wires with a smaller diameter that are connected in parallel. Thinner wires are subjected to reduced losses, according to the equation for penetration depth δ given as:

(1) $$\delta = \sqrt{\frac{2\rho_c}{\omega\mu}},$$

where $\omega=2\cdot\pi\cdot f$ is the frequency of the applied magnetic field, μ - the permeability of the material, μ_0 - the permeability of vacuum, $\mu_0=1.25664\text{x}10^{-6}$, for copper $\mu \approx \mu_0$ and ρ_c - the electrical resistivity of the conducting material (copper), the typical values: $\rho_c=23\text{x}10^{-9}\Omega$ at 100°C, $\rho_c=17.3\text{x}10^{-9}\Omega$ at 25°C.

The dependence of penetration depth δ of copper (Cu) conductors as a function of the operating frequency f for temperatures 25°C and 100°C is shown in Fig.1. In general, it is beneficial to use parallel wires or windings, if they carry the same EMF (flux). But if the EMF is different and there is leakage inductance between the paralleled windings (or wires), then high circulating currents flow. These currents are unwanted, as they cause high losses. The first approach is using several (p) wires together wound side by side. This approach is good when each wire is placed in the same distance to the other layer (or to an air gap).

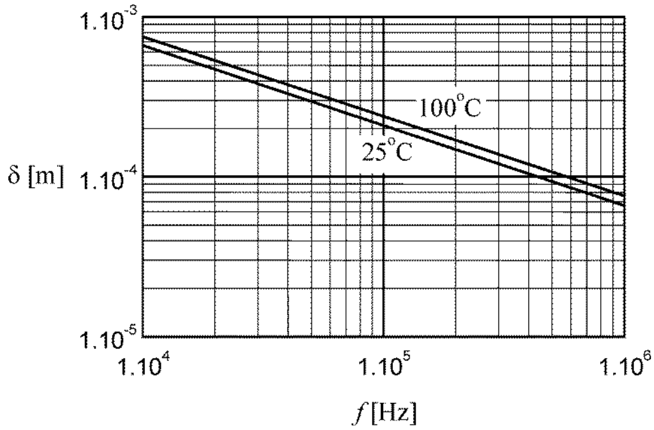

Fig.1. Penetration depth δ for copper wires as a function of operating frequency for temperatures T=25°C and T=100°C.

Practically, winding two or three wires in parallel is feasible, but more than four wires is already not advisable.

The analysis of the losses in this case can be split in two cases: low frequency (LF) and high frequency (HF) cases depending on the ratio d/δ (wire diameter/penetration depth according to eq.1).

Low frequency case: d<1.6δ

The LF case is advisable (typical) in designs with several layers. While maintaining the total cross section, using p wires in parallel the designer can expect to reduce the eddy current losses by a factor p while maintaining the same wire cross-section. The eddy current losses $P_{cu,eddy,par}$ are found as [9]:

(2) $$P_{cu,eddy,par} = P_{cu,eddy,orig}\, p\left(\frac{d_{par}}{d_{orig}}\right)^4 = \frac{l_w \pi \frac{d_{par}^4}{4} N^2}{p\, 48\, \rho_c}\left(\frac{2\pi f I_{ac} \mu_0}{w}\right)^2,$$

where d_{par} is the diameter of the wires in parallel, l_w - the conductor length of the winding ($l_w=N\cdot p\cdot l_T$), l_T - the mean length of one turn, w - the width of the winding and I_{ac} is the AC current RMS value.

<u>Conclusion:</u> The eddy current losses $P_{cu,eddy,par}$ are inverse proportional to the number p of wires in parallel:

(3) $$P_{cu,eddy,par} = \frac{P_{cu,eddy,orig}}{p},$$

High frequency case: d<2.7δ

The high frequency case is possible in single layer designs. The use of parallel wires with the same total cross section may even increase the eddy current losses. In the case of a single layer transformer, it is usually not beneficial using parallel wires. A better approach is using the highest diameter, which fills the layer completely.

The calculation of losses can be done by the approach of the proposed wide frequency method in [9]. The eddy current losses are given by the following equation:

(4) $$P_{eddy} = \left(R_0\, I_{ac}^2\right) m_E^2\ k_{tf}\,,$$

where R_0 is the ohmic resistance of the winding, m_E - the equivalent number of layers and k_{tf} can be found by using Fig.2.

The geometric parameters used to describe k_{tf} are:

- copper fill factor in the direction of the layer η can be defined as $\eta=n\cdot d/w$, where d is the wire diameter, n is the number of turns in a layer, w is the winding width;
- copper fill factor in the direction perpendicular to the layer λ can be defined as $\lambda= m_E\cdot d/h$, where h is the window height.

To use the provided graphs (Fig.2) for any frequency f_{op} and wire diameter, the equivalent frequency of the considered design should be first found:

(5) $$f_{eq} = f_{op}\left(\frac{d}{0.5}\right)^2,$$

where d is the wire diameter of the considered design, [mm].

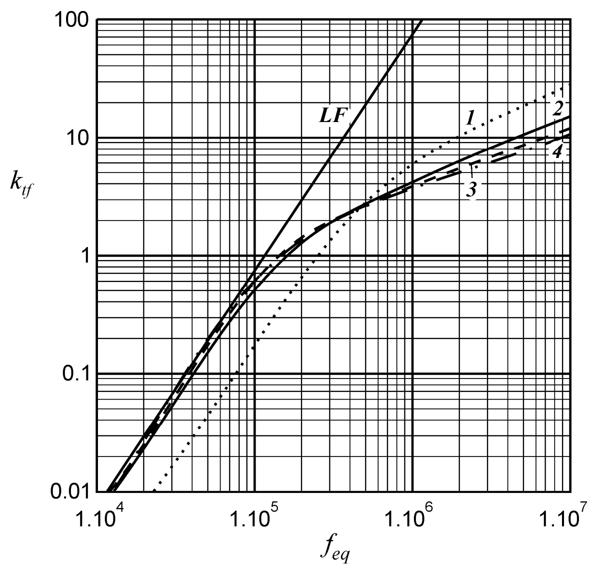

Fig.2. Transformer cases, typical transformer factor k_{tf} for d=0.5mm, η=0.9, ρ=23x10^{-9} and λ=0.5, 1) dotted line: half layer, m_E=0.5; 2) solid line: single layer, m_E=1; 3) dashed: two layers, m_E=2; 4) dash-dot: three or more layers, m_E>2. LF – low frequency approximation [9].

Paralleling windings using symmetry in the magnetic path

Another approach to reduce eddy current losses is to use windings in parallel, thus decreasing the conductor thickness while keeping the total turn cross-section the same. This approach is applicable when there is natural symmetry of the core shape to wind different coils with the same number of turns. The requirement is that all the windings (coils) carry the same current! This fact is obligatory to avoid circulating currents, causing high losses.

Some possible arrangements meeting this requirement are listed below and shown in Fig.4. Possible number of paralleled windings for different cores:

- EE and EI types, see Fig.3,a: 2 windings in parallel;
- UU types, see Fig.3,b: 4 windings in parallel;
- Multiple air gaps designs, if well-arranged then 2 times more windings than the number of gaps;
- Ring cores, in principle infinite number of windings.

Using Litz wire

Another approach to reduce eddy current losses in using many parallel wires combined in Litz wire, also called bunched conductors. Each Litz wire contains a number of strands that are individually insulated and all the strands use their positions in the section equally. Thus, in the widely spread transverse field, each strand carries the same flux.

The advantage of Litz wire is that usually much lower eddy currents losses are generated, as the diameter of the individual strands is low.

Anyhow, there are also disadvantages of Litz wire designs:

- much lower filling factor almost 2 times compared to full wire designs;
- lower heat dissipation ability;
- lower temperature grade.

The other fact is that the total DC resistance is usually 5% higher as the wire length increases due to twisting of the strands.

Calculating eddy current losses in Litz wire is the same as in the case with p parallel wires. We consider a Litz wire containing p strands. In low frequency approximation, the final effect of reducing is by a factor p.

To demonstrate the approach we analyze a practical design case, in which low frequency approximation is valid ($d<1.6\delta$).

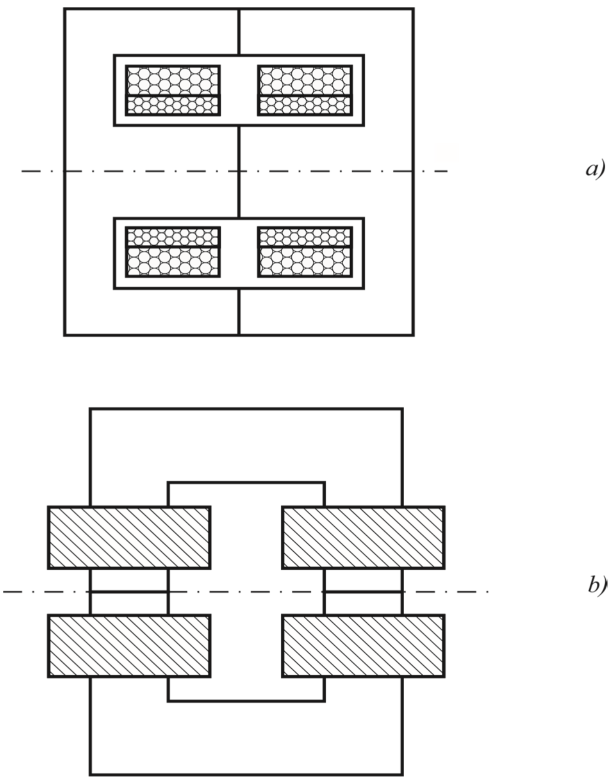

Fig.3. Possible number of paralleled windings for different cores, a) EE core set: two windings in parallel, b) UU core set: four windings in parallel.

The target is increasing the winding current in an already made transformer design with a factor α, trying to maintain the same ohmic and eddy current loss within the same core size. To have the same ohmic losses we would have to increase the diameter with a factor α, as the current is increased and the DC losses depend of the second power of the current. However, this would increase the eddy current loss by a factor α^4 due to the diameter increase (see eq.2), and additionally by a factor α^2 due to the transverse field increase, (square dependence on current)! Totally, to maintain the original eddy current loss, a reduction in factor of α^6 (in losses) has to be provided. The required Litz wire diameter is α^{-2} times the original wire. For example, if we want to double the current, α=2, and the required number of strands will be 64 and the required Litz wire diameter should be 4 times lower than the original diameter. Then the design will have the same eddy current losses.

Interleaved Windings Design

This approach is only applicable to transformers, see Fig.4.

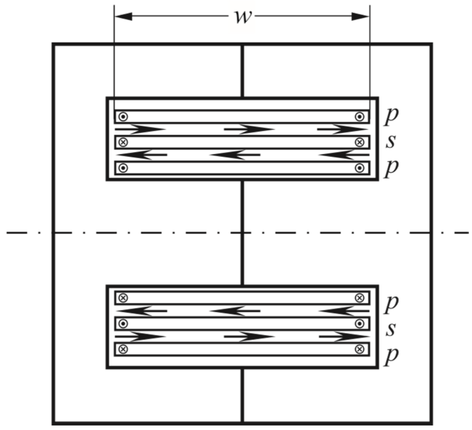

Fig.4. Interleaved windings design of a transformer.

If the design is changed from Primary/Secondary (P/S) to P1, S1, S2, P2 or P1, S1, P2, S2 with the same type of wires, both the ohmic losses and the eddy current losses will be reduced by a factor of 2. The disadvantage of such a design is the feasibility and the deteriorated heat transfer. In practice, taking in mind the reduced thermal capability of the component, the current handling capability could be considered increased to ½ in that case.

Half layer transformer design

A half layer design is a specific case in the above mentioned approach of interleaving windings. It takes place when the secondary winding is between two primary windings (secondary winding is "sandwiched" between two primary windings), Fig.5. In a half-layer transformer design the equivalent number of layers and using eq.4, a considerable reduction to 25% of the eddy current losses is found. This value is much lower compared to the typical round wire design. The explanation is that in the half layer design, the transverse field is zero and only local fields are present. In practical realizations, the half layer designs indeed perform well, but a non-careful winding (e.g. non-equal winding width of the layers) generates parasitic transverse fields that increase the losses considerably.

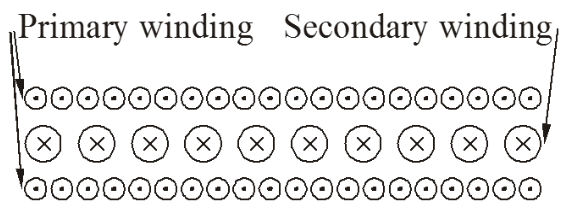

Fig.5. Half layer design as transformer winding arrangement, the secondary winding is "sandwiched" between two primary windings.

Design considerations for half layer transformer cases:

- The outer windings will have higher turn length;
- Usually the leakage inductance decreases inverse proportional to the number of interleaving windings in parallel;
- The parasitic capacitance of the windings is almost proportional to the number of interleaved windings;
- Any half layer design is to be realized carefully to avoid non-equality in winding width.

III. Conclusion

Based on the carried out analyze in this paper the following design considerations are derived concerning reduction of eddy current losses in transformer windings:

1. Parallel wires design is useful, if the wires carry the same EMF. Caution is to be taken because if EMF is different and there is the leakage inductance between the paralleled windings (or wires), then high circulating currents flow. Practically, winding two or three wires in parallel is feasible, but more than four wires design is already not advisable. The eddy current losses are inverse proportional to the number p of wires in parallel.

2. Windings in parallel designs provide the same eddy current losses reduction as in paralleling wires approach. This approach is applicable when there is natural symmetry of core shape to wind different coils with the same number of turns. Possible number of paralleled windings depends on the type of core: EE and EI - 2 windings in parallel; UU types - 4 windings in parallel; ring cores - a few windings in parallel.

3. Litz wire advantage is that usually much lower eddy currents losses are generated, as the diameter of the individual strands is low. Disadvantages of Litz wire are much lower filling factor, lower heat dissipation ability and lower temperature grade compared to round wire designs, also some increase of leakage inductance.

4. Interleaved windings design for instance P1, S1, S2, P2 or P1, S1, P2, S2, realized with the same type of wires as a conventional one, provides reduction by a factor of 2 in both ohmic and eddy current losses. The disadvantage of such a design is the feasibility and the deteriorated heat transfer, so as a result the benefit is limited to ½ in that case.

5. Half layer designs perform well in loss reduction (4 times), but a non-careful winding (e.g. non-equal winding width of the layers) generates parasitic transverse fields that increase the losses considerably.

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REFERENCES

[1] Leibl, M., G. Ortiz, J. W. Kolar. Design and experimental analysis of a medium-frequency transformer for solid-state transformer applications. IEEE Journal of emerging and selected topics in power electronics, Vol. 5, No. 1, March 2017, pp. 110-123.

[2] Mühlethaler, J., J. W. Kolar, A. Ecklebe. Loss modeling of inductive components employed in power electronic systems. Proc. 8th IEEE Int. Conf. Power Electron., ICPE ECCE Asia, May/Jun. 2011, pp. 945–952.

[3] Sullivan, C. R., R. Y. Zhang. Simplified design method for litz wire. IEEE Appl. Power Electron. Conference, APEC, Mar. 2014, pp. 2667–2674.

[4] Pereira, A., B. Lefebvre, F. Sixdenier, M. A. Raulet, N. Burais. Comparison between numerical and analytical methods of AC resistance evaluation for medium frequency transformers: Validation on a prototype. Proc. IEEE Elect. Power Energy Conference, EPEC, Oct. 2015, pp. 125–130.

[5] Cougo, B., J. W. Kolar, G. Ortiz. Strategies to reduce copper losses in connections of medium-frequency high-current converters. Annual Conf. IEEE IECON, Melbourne, VIC, Australia, Nov. 2011, pp. 1602–1607.

[6] Cheng, K. W. E., W. S. Lee, C. Y. Tang, L. C. Chan. Dynamic modelling of magnetic materials for high frequency applications. ELSEVIER Journal of Materials Technology, 2003, 139, pp. 578-584.

[7] Wojda, R. P., M. Kazimierczuk. Analytical optimization of solid–round-wire windings, IEEE Trans. on Ind. Electr., Volume: 60, Issue: 3, March 2013. pp. 1033 – 1041.

[8] Dowell, P. Effects of eddy currents in transformer windings, Proc. of the Institution of Electrical Engineers, 1966, Vol.113, No.8, pp.1387–1394.

[9] Van Den Bossche, A., V. C. Valchev, S. T. Barudov. Practical wide frequency approach for calculating eddy current losses in transformer windings, IEEE International Symposium on Industrial Electronics, Montreal, Canada, 9-13 July, 2006, pp. 1070-1074.

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