CALCULATION OF ADDITIONAL POWER LOSSES IN MULTILAYER WINDING CYLINDRICAL INDUCTOR

A.O. Berezyuk, post grad. *
I.P. Kondratenko, Doctor of Science

On the basis of the numerical finite element method the method of calculation of additional power losses in the windings of the multilayer inductors with the uneven distribution of components of the electromagnetic field along the winding inductor has been developed.

Cylindrical inductor, additional power losses, multilayer winding.

The efficiency of the induction heating devices is mainly determined by its coefficient of performance (COP). Efficiency of the induction heating devices is determined by physical properties and geometrical dimensions and load inductor, namely length of winding, number of layers, the number of turns in the layer, a gap between the coils, inducing wire configuration. Efficiency is calculated as the ratio of power that transferred to the load (utility power) to full capacity, which consists of net power and power losses in the windings.

Other applies only to electric efficiency. Full efficiency of the induction heating devices must also include the losses associated with heat transfer heat from the heated boot on coil construction elements and the environment. It will be considered only electrical efficiency, but the authors are well aware that the full efficiency of inducing device remains priority value and the choice of geometric dimensions inductor is also an optimization problem concerning the choice of the thickness of insulation layer.

---

* Scientific Advisor - Doctor of Science I.P. Kondratenko

However, the experience of induction heating devices, especially those that involve heating to a temperature at which the radiant heat transfer component is not determinative shows that efficiency primarily determined by the losses in the inductor winding.

Thus, reducing electrical losses in the winding of the inductor is the most appropriate way to improve the efficiency of the induction heating devices.

The aim of research - development of numerical methods of calculating additional power losses in multilayer inductor windings based on the uneven distribution of the electromagnetic field along the winding inductor.

Materials and methods of research. It is known that in multilayer windings of induction units are separate layers of different size electromagnetic field, resulting in increased power loss in the inner layers of windings (due to the emergence of these eddy currents) [4]. Therefore, to determine the additional power losses, as in some turns in the coil and in general, it is necessary to approach allowing for the distribution of the electromagnetic fields in the environment and, of course, the design features of the inductor. It is clear that these features are related to the mutual spatial orientation vectors intensity alternating magnetic field and the characteristic size of the inductor winding conductors.

Below we consider the use of numerical finite element method to calculate the additional power losses in the coil, which takes into account the spatial distribution of the electromagnetic field long enough multilayer inductor.

Consider a multilayer cylindrical coil (Fig. 1), whose length is three times its diameter. Under these conditions, the field inside the inductor equal split [1], which allows for uniform heating load. Loading inductor is ferromagnetic pipe.

Perform simulation of electromagnetic fields such electromagnetic system while maintaining uniform distribution of the electromagnetic field inside the inductor. Thus, the modeling conducted for the inductor with geometrical dimensions: length inductor (current region) $a = 0{,}6\,m$; the height of each layer winding (coil) $\mathrm{h} = 0{,}0035\,m$; the number of winding layers $\mathrm{n} = 3$; the inner diameter of the coil $\mathrm{d} = 0{,}165\,m$; the outer diameter of the pipe $\mathrm{d} = 0{,}155\,m$, the inner diameter of the pipe $\mathrm{d} = 0{,}143\,m$. Electrical parameters of downloads: electrical conductivity $\sigma = 9{,}15 \cdot 10^6\ {}^{S}\!/\!_{m}$, magnetic permeability of ferromagnetic downloads described dependence:

$$\mu = \frac{830}{1 + 0{,}025 B_z^{\ 9}}\,. \tag{1}$$

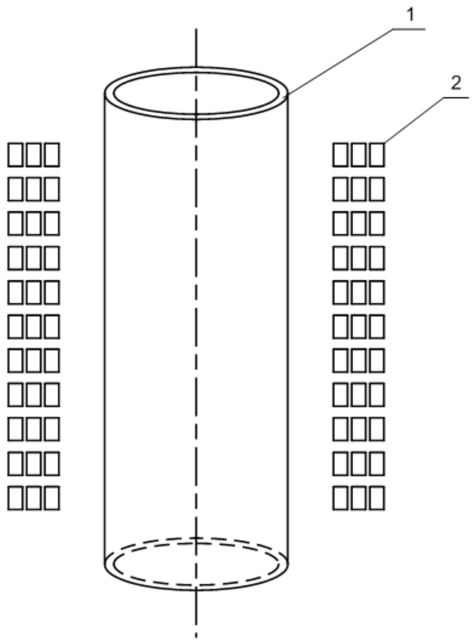


Fig. 1. The scheme investigated the induction system:
1 - download the inductor;
2 - multi-winding

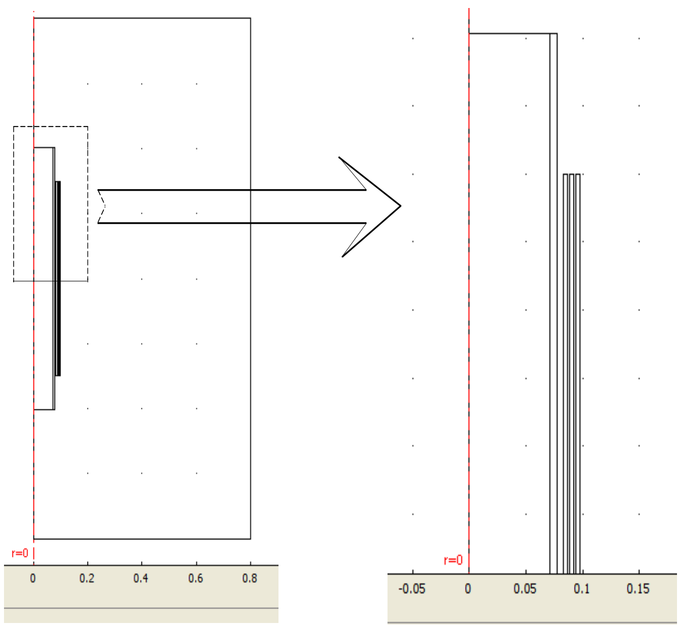


Fig. 2. The estimated model is a multi-layer cylindrical coil of downloading as a ferromagnetic pipe

Current density in the windings is determined by its recommended for electrical machines largest current in the conductors. Let the current density in the conductor will be $2 \cdot 10^6\ A/m^2$.

Multi-layer (three-layer) winding inductor in the software environment Comsol was asked some current areas of zero conductivity. Current density in each region is the same as the region separated from one another electrical insulating layers. The estimated model of the inductor is shown in Fig. 2.

For the correct solution of electromagnetic problems on the borders of the distribution area asked the following conditions:

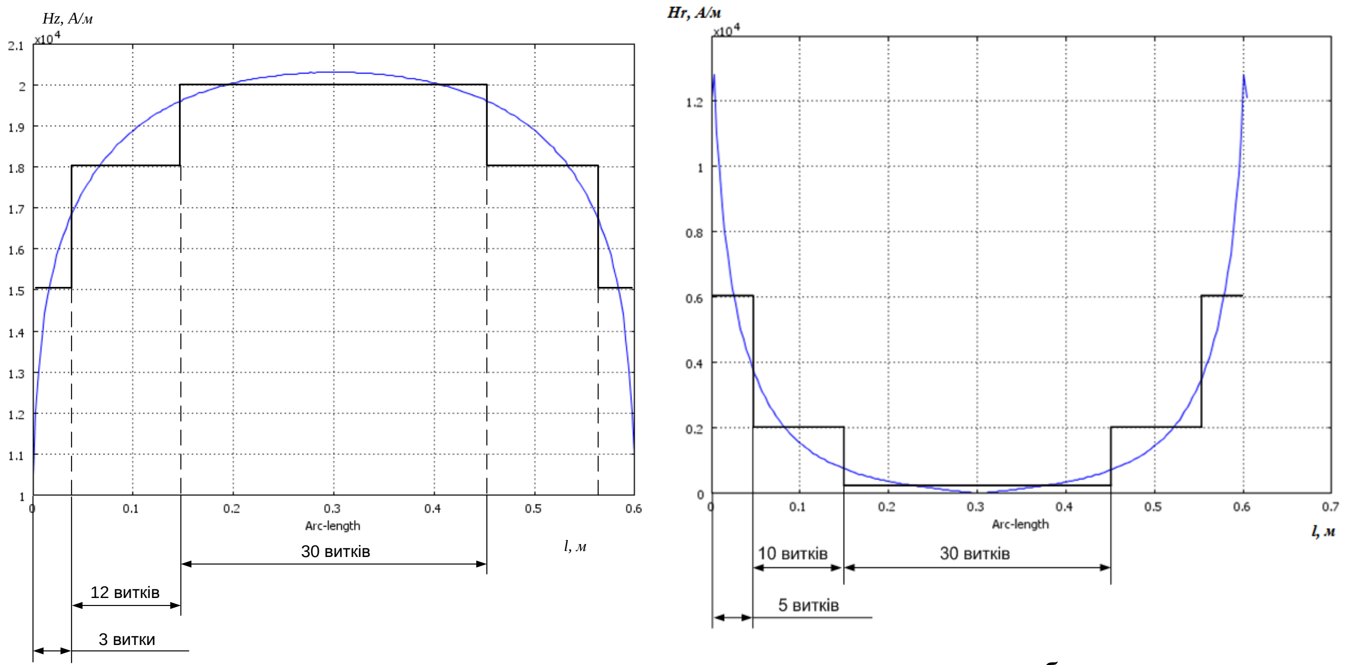
- the condition of axial symmetric symmetry about an axis, $r = 0$;

- the condition of magnetic insulation on the external borders, $A_\varphi = 0$;

- for all other boundaries are automatically assigned a continuity condition (on the borders of the winding and rod), $\mathbf{n}(\mathbf{H}_1 - \mathbf{H}_2) = 0$,

where **H** - magnetic field, A/m; **n** - vector of the outer normal.

Thus, for each of the layers of windings in the axial zone was defined distribution ρ- and z-components of the magnetic field H. As a result of the distribution of the components of the magnetic field, overcurrent area of each layer winding was divided into zones in which the magnitude of the magnetic field adopted constant (Fig. 3). Therefore, further solution of the problem is reduced to finding the power losses in a single development solution and subsequent spread to other areas of the respective coils.



а б

Fig. 3. Separation of current area into zones with constant tension magnetic field in the inner layer: a) z-component; b) ρ-component

Thus, in each zone highlighted single coil (Fig. 4) with the appropriate physical properties (electrical conductivity $\sigma = 5 \cdot 10^7 \, {}^{S}\!/_{m}$) under a predetermined value ρ- and z-components of the magnetic field in each zone (Fig. 3), by means of integration radius for axial symmetric formulation (embedded in the package Comsol), power loss can be found in it.

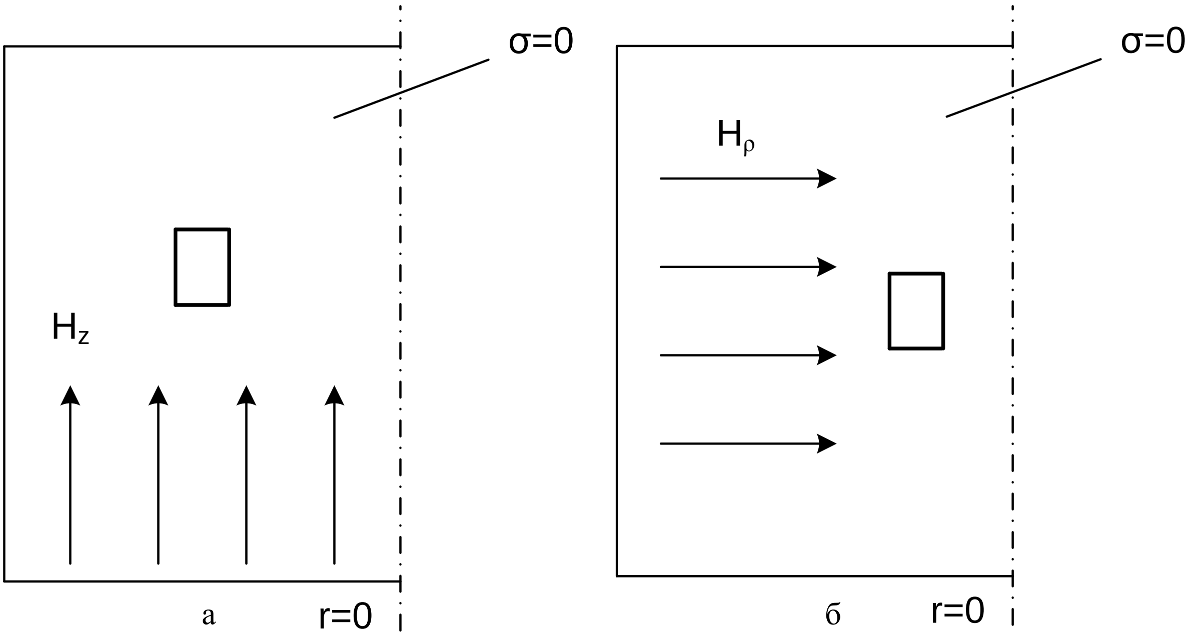


Fig. 4. Bold single coil inductor in an outside magnetic field: a) the action of the coil ρ-component of the magnetic field; b) the action of the coil z-component of the magnetic field

For this problem on distribution within these regions wondered boundary conditions:

- the condition of axial symmetric symmetry about an axis, $r = 0$;

- the condition of magnetic insulation on the sides of the borders, $\mathbf{A}_{\varphi} = 0$;

- the external borders of the settlement area was asked condition $\mathbf{H}_{\varphi} = \mathbf{H}$,

where **H** - magnetic field the zone;

- the boundaries of the conductor is automatically assigned continuity condition $\mathbf{n}(\mathbf{H}_1 - \mathbf{H}_2) = 0$.

Therefore, knowing the number of turns in each area, you can find additional power loss in each layer and in the coil as a whole.

The results of research. Thus, a combined problem solving, we can calculate additional power losses in the windings of a cylindrical coil with regard to heterogeneity distribution ρ-and z-components of the magnetic field along the winding inductor.

Also, studies for other geometrical parameters downloads (changing pipe diameter and pipe wall thickness) at a constant value of current density in the windings. Found that losses in the windings of the inductor multilayer (in our case, the three-layer) does not depend on the geometry of the boot.

When comparing the results of numerical simulations with known expressions calculation of additional power losses in the windings eg transformers [3] or electric motors [2], which are characterized by relatively large value of magnetic permeability (due to ferromagnetic core), the coefficient of additional losses in the winding inductor multilayer calculated numerical methods differed significantly. Thus, the calculation of losses in the winding numerical method proposed additional loss coefficient was 1.028, and the coefficient of additional losses calculated by the transformer expression:

$$k_D = 1 + g\beta^2 \left(\frac{\mathrm{f}}{\rho \cdot 10^4}\right)^2 a^4 (n^2 - 0{,}2), \qquad (2)$$

was 1,0045. In the formula (2) $g = 1{,}73$ - empirical coefficient; a - the size of the conductor is perpendicular to the direction of lines of magnetic induction field scattering, cm; n - number of conductors in the winding direction perpendicular to the direction of lines of magnetic induction field dissipation; ρ - specific density of the wire material, kg/m^3.

This discrepancy between the results may be explained by a nonuniform distribution of the magnetic field along the winding inductor compared to the transformer, which is characterized by the presence of ferromagnetic core.

For multilayer cylindrical inductor geometric parameters of which are given above, using the gauge RLC-meter BR2876 series of experimental studies were conducted to determine the electrical resistance of the winding at a frequency of 50 Hz.

Found that the experimental value of resistance winding inductor is defined at 50 Hz, is 0,102 Ohm, which coincides with the value calculated by the technique of definition of additional losses.

Conclusions

1. The method of calculating the additional power losses in the windings of cylindrical multilayer inductors, which is based on numerical simulation of induction heating in the volume of the entire installation and determine the distribution of electromagnetic field components along the winding multilayer inductor to determine the electrical conditions in which the coils are winding;
2. The proposed approach allows us to identify additional power losses in separate groups of conductors and multilayer coil as a whole, and thus to improve the accuracy of calculating the energy performance of cylindrical inductors.

References

1. Кондратенко І.П. Дослідження розподілу температури в завантаженні циліндричного індуктора / І.П. Кондратенко, В.П. Лисенко, Д.С. Комарчук // Науковий вісник НУБіП України. Серія: «Техніка та енергетика АПК» – К., 2012. – Вип. 184, Ч.1. – С.74 – 82.
2. Постников И.М. Проектирование элекрических машин / И.М. Постников. – К.: Госэнергоиздат, 1960. – 910 с.
3. Тихомиров П.М. Расчет трансформаторов: [учеб. пособие для вузов.] / П.М. Тихомиров.[4-е изд., перераб. и доп.] –М.: Энергия, 1976. –544 с.
4. Установки индукционного нагрева: [учеб. пособие для вузов; под ред. А.Е.Слухоцкого] / А.Е. Слухоцкий, В.С. Немков, Н.А. Павлов, А.Б. Бамунэр . – Л.: Энергоиздат, 1981. – 328 с.