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Calculation of energy characteristics of the inductor with reactive power self-compensation

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Abstract

On the basis of inductively bound contours method, specializing of the formula for calculating the efficiency factor for reactive power self-compensation inductor (IS) has been carried out. The mathematical apparatus as the foundation of the software product for the calculation of the inductor efficiency factor in a wide range of influencing factors (electrophysical and geometrical parameters of the inductor and the loading, the level of the inductor winding cooling, electrical parameters of the power source, etc.) has been provided. Examples of graphical dependencies accompanied by some analysis of the obtained results have been supplied.

In the analysis of substitution schemes for electro-technological objects, particularly for induction heating devices, in a number of cases, method of inductively bound contours is used, and this application is largely justified in view of a comparatively applicable analogy between the current contour and the thin coil of the inductor winding, especially under the power source frequency over 50 Hz and small values of the inductor's metal resistivity, including the cryogenic cooling of the winding.

Application of this method allows specializing a widely-known (1) for identifying the efficiency factor for induction heating inductors with regard to inductors of strong capacity connection between the coils (reactive power self-compensation inductors [1-3]).

$$\eta = \frac{R_{\Sigma} - R_1}{R_{\Sigma}}, \tag{1}$$

where R_{Σ} – active resistance of "inductor – loading" system;
R_1 – equivalent input active resistance of the inductor.

Under the second Kirchhoff law, with regard to magnetically bound contours the equations for primary and secondary circuits (of the inductor and the loading) have the form:

$$\dot{I}_1 \cdot \left(R_1 + j\omega L_1 - \frac{1}{j\omega C_1} \right) - \dot{I}_2 \cdot j\omega M_{12} = \dot{U}_1; \tag{2}$$

$$-\dot{I}_1 \cdot j\omega M_{12} + \dot{I}_2 \cdot \left(R_2 + j\omega L_2 \right) = 0, \tag{3}$$

where R_1, L_1, C_1 – active, inductive and capacitive resistance of the self-compensation inductor respectively;
R_2, L_2 – active and inductive resistance of the loading respectively;

M_{12}	–	mutual inductance between the inductor and the loading;
ω	–	angular frequency of the power source ($\omega = 2 \cdot \pi \cdot f$);
$\dot{I}_1$, $\dot{I}_2$	–	current of the inductor with self-compensation and the loading respectively;
$\dot{U}_1$	–	power source voltage.

From (3) the current in the loading will be expressed as

$$\dot{I}_2 = \dot{I}_1 \cdot \frac{j\omega M_{12}}{R_2 + j\omega L_2}. \tag{4}$$

Substituting (4) in (2) allows obtaining

$$\dot{I}_1 \cdot \left(R_1 + j\omega L_1 - \frac{1}{j\omega C_1} \right) + \dot{I}_1 \cdot \frac{\omega^2 M_{12}^2}{(R_2 + j\omega L_2)} \cdot = \dot{U}_1. \tag{5}$$

Having divided the left and the right parts of (5) by $\dot{I}_1$, we get the expression for indentifying the full resistance of the "IS – loading" system

$$Z_\Sigma = \frac{\dot{U}_1}{\dot{I}_1} = \left(R_1 + j\omega L_1 - \frac{1}{j\omega C_1} \right) + \frac{\omega^2 M_{12}^2}{(R_2 + j\omega L_2)}. \tag{6}$$

After simple transformations, we get the active and reactive constituents of "IS – loading" system resistance:

$$R_\Sigma = R_1 + \frac{\omega^2 M_{12}^2}{(R_2^2 + \omega^2 L_2^2)} \cdot R_2; \tag{7}$$

$$X_\Sigma = j \cdot \left(\omega L_1 + \frac{1}{\omega C_1} - \frac{\omega^2 M_{12}^2}{(R_2^2 + \omega^2 L_2^2)} \cdot j\omega L_2 \right). \tag{8}$$

Having substituted the active resistance of "IS – loading" system (7) in (1), we get

$$\eta = \frac{\dfrac{\omega^2 M_{12}^2}{(R_2^2 + \omega^2 L_2^2)} \cdot R_2}{R_1 + \dfrac{\omega^2 M_{12}^2}{(R_2^2 + \omega^2 L_2^2)} \cdot R_2}. \tag{9}$$

After transforming (9), we get the formula for determination of the efficiency factor for the reactive power self-compensation inductor

$$\eta = \frac{1}{1 + R_1/M_{12}^2 \cdot (R_2/\omega^2 + L_2^2/R_2)}. \tag{10}$$

On the basis of the developed methods, the program "KPD" was created in the language Borland DELPHI 7, assigned for the calculation of the efficiency factor for IS, active power liberated in the loading, as well as distribution of currents in each of the branches of the substitution scheme of IS, with the account of the influence of the loading, the inductor input current and the current in the loading.

The research conducted with the use of this program allowed obtaining a number of graphical dependencies of the IS efficiency factor η on various electrophysical and geometrical parameters of the construction and the supply main.

Here, the following parameters of the IS, loading and supply main were taken: the inductor inside diameter d_{1in} = 0,15 m (changed in the range of 0,05 ÷ 0,15 m); the loading outside diameter d_2 = 0,13 m (changed in the range of 0,03 ÷ 0,13 m); the dielectric thickness δ = 50 micrometer (changed in the range of 50 ÷ 500 micrometer); specific resistance of copper under the temperature 293 K – $1,8 \cdot 10^{-8}$ Ohm·m, under the temperature 77 K – $2,06 \cdot 10^{-9}$ Ohm·m; specific resistance of aluminum under the temperature 293K – $2,8 \cdot 10^{-8}$ Ohm·m, under the temperature 77 K – $3,41 \cdot 10^{-9}$ Ohm·m; specific resistance of steel under the temperature 293 K – $18,9 \cdot 10^{-8}$ Ohm·m, relative permeability of steel – 70; the power source frequency changed in the range of 1 ÷ 10 kHz. It should be noted that each fixed point of the graphical dependencies corresponds to the resonance mode of the inductor.

In fig. 1 ÷ 4 we show as examples the graphical dependencies of the efficiency factor of IS on the number of coils of its winding $\eta = f(W)$, the power source frequency $\eta = f(f)$, the thickness of the insulating dielectric $\eta = f(\delta)$ and the inductor inside diameter $\eta = f(d_{1in})$.

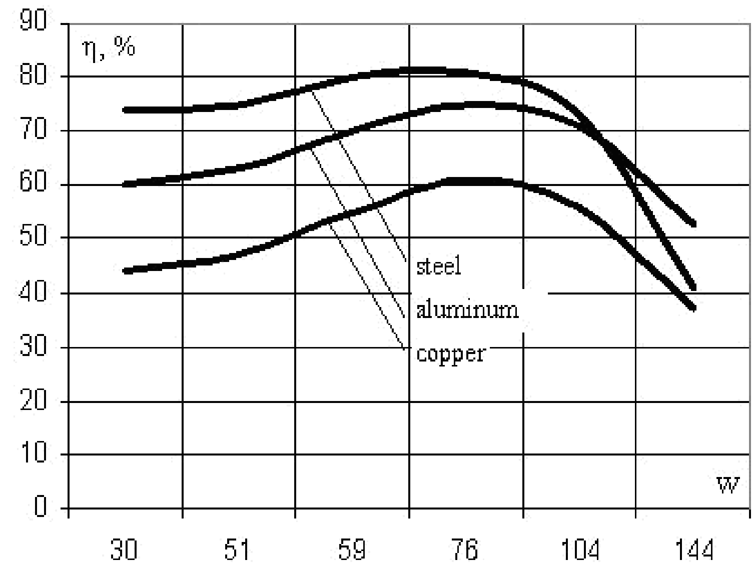

Fig. 1. Dependency of the efficiency factor η of IS on the number of coils of the winding W under T = 293 K, aluminum winding and the loading from different metals

The analysis of dependencies shows that under operation of IS with the winding cooled under the temperature level of 293 K, the copper inductor, having a relatively high η in a thirty-coil range, reduces it in the area of 50 coils, preserving, nevertheless, a relatively high absolute value (on the order of 80 %) in the heating of steel loading. In the range of 70 ÷ 90 coils η changes little and then goes down from 100 coils and further because of the considerable rise of the active resistance of the system "inductor – loading". For the aluminum inductor under the same temperature level of cooling its winding in the range of coils 30 ÷ 76, the rise of η was detected in 20 ÷ 35 %, after which there happens its reduction also connected with the same reason.

The character of the change of η for inductors with the winding cooled under the temperature level of 293 K is preserved regardless of the kind of metal of the inductor and the heated loading. The absolute figures of η, however, are a bit higher with the copper inductor, especially under the heating of the steel loading. In the whole, the most effective level of the power source frequency is 5 kHz for non-magnetic loading and the range of 2,5 ÷ 10 kHz for ferromagnetic loading. Here, while it is preferable to use for the heating of the non-magnetic loading the dielectric of 50 micrometer thickness, for the heating of the ferromagnetic loading the best results are shown by the IS winding with the dielectric of 100 micrometer thickness in the whole frequency range, with the exception of 1 kHz frequency, where the dielectrics of 50 micrometer and 100 micrometer are approximately equivalent. Under the heating of the steel loading in the frequency range 2,5 kHz, there is some dip in the dependency of $\eta = f(\mathrm{f})$, especially noticeable with a IS with aluminum winding.

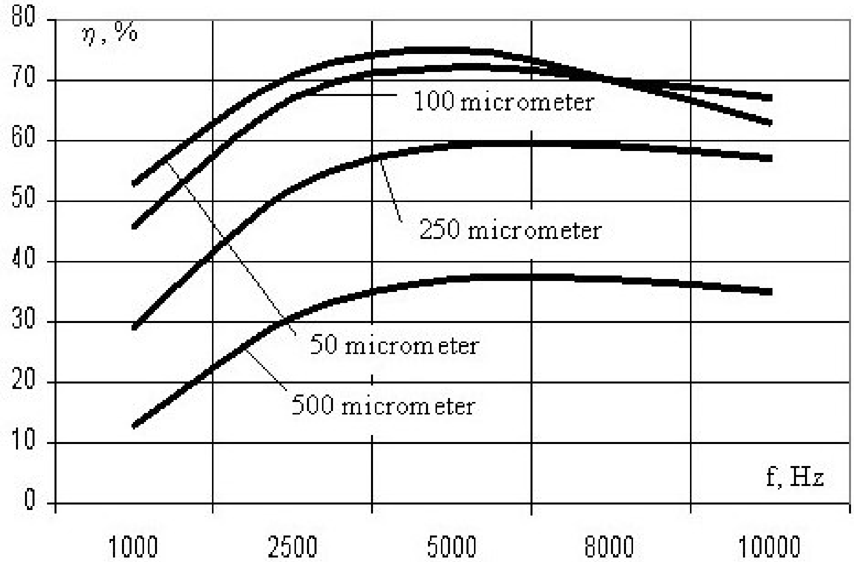

Fig. 2. Dependency of IS efficiency factor η on the power source frequency f for the aluminum inductor under the temperature T = 293 K, different thickness of the dielectric δ and the aluminum loading

In whole, it is necessary to say about the tendency to the reduction of IS η with the growth of the thickness of the dielectric δ which is detected in the majority of cases, though, with different rate of progress. The biggest progress was detected for IS with the winding cooled at the temperature level of 293 K and the loading from a non-magnetic material. Under the rise of δ from 50 до 500 micrometer, η lowers with aluminum IS by 2 ÷ 2,5 times for the whole range of operation frequency with the exception of the frequency of 1 kHz, where the reduction is more than 4 times. In this case the absolute figures of η for IS are not large either, making 35-53 % under the minimal δ.

Most considerably the rise of δ accompanies the reduction of η with IS from copper under the heating of aluminum work material. The change dynamics has a character resembling a linear one with the slope angle near to 45°. Here η from relatively large values (70 ÷ 85 %) in the whole analyzed frequency range under the minimal thickness of the dielectric reduces approximately by 4 times under δ = 500 micrometer. For the frequency of 1 kHz this reduction makes more than 6 times.

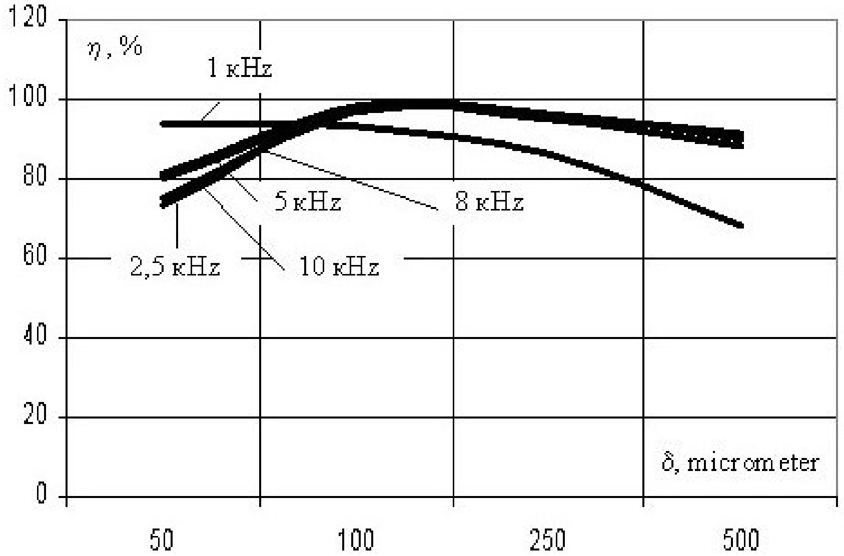

Fig. 3. Dependency of IS efficiency factor η on the thickness of the dielectric δ for the inductor from aluminum under T = 293 K, different power source frequency f and steel loading

For IS with the loading from ferromagnetic material, the maximum values of η are observed not under the minimal thickness of the dielectric δ (50 micrometer), as in the case with the heating of non-magnetic loading, but in the range of thickness 100 ÷ 200 micrometer, practically in the whole range of the analyzed frequencies with the exception of 1 kHz frequency, which later reduces even more than the rest ones.

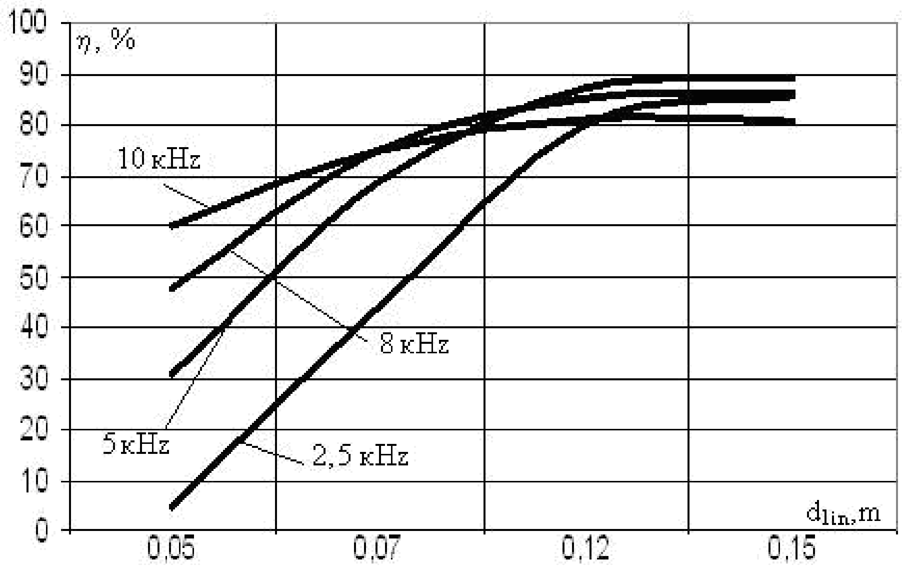

Fig. 4. Dependency of IS efficiency factor η on the inside diameter of the inductor d_{1in} for the inductor from copper under T = 293 K, different power source frequency f and steel loading

The analysis of the dependencies $\eta = f(d_{1in})$ showed that for IS with the winding cooled at the temperature level 293 K and non-magnetic loading, irrespective of the kind of metal of the inductor, the most effective is the heating of work material with the diameter 50 mm ± 10 mm in the whole analyzed range of the power source frequency. In whole, rather effective is the IS made from copper for heating the work material with the diameter from 50 to 130 mm under the frequency of the power source from 5 до 10 kHz and the IS from aluminum for heating aluminum work material of the same diameter under the frequency of the power source from 5 to 10 kHz. In the cited cases η of the inductor makes 75 ÷ 95 %.

In the heating of ferromagnetic loading the best values of IS η correspond to the maximum analyzed inside diameters of the inductor and loading irrespective of the kind of metal of the inductor. The most effective range is the range of inside diameters of the inductor 0,12 ÷ 0,15 m for the whole frequency range of the power source (fig. 4.).

Generally, it should be noted that in view of the peculiarities of the IS resonance mode, which is the operating mode of the inductor, the dependency of IS efficiency factor requires further study and analysis.

References

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