Resonant Mode of Inductors with Reactive Power Self-compensation

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Abstract

The design procedure of resonant mode inductors with self-compensation of reactive power is resulted. Results of theoretical researches of resonant mode inductors of the given type in a wide range of influencing factors are submitted.

Dependences of number of coils in the winding of inductors from factors influencing it are received, character of change of inductive and capacitor resistance of inductor winding is determined.

Essential increase of power parameters of induction heating installation, in particular reduction in reactive power and natural increase *cos φ*, is possible at using in it the inductor with self-compensation (IS) [1,2].

Structurally IS differs from the inductors of traditional performance (fig. 1). The inductor winding is executed as a two-layer one. It consists of two conducting tapes 1 and 2, shared by an isolated dielectric 3. The beginning of the first conductor and the end of the second are connected to the power supply of the alternating current of required frequency; and accordingly the end of the first conductor and the beginning of the second conductor are disconnected. Similar connection is necessary that currents in tape conductors have an identical direction, and the magnetic fields created by these currents be developed. The current in tape conductors exists as a current of conductivity and becomes isolated through the dielectric as a current of displacement. Intensity of a total magnetic field depends on the number of coils and inductor current and is chosen out from the active power required for heating loading 4.

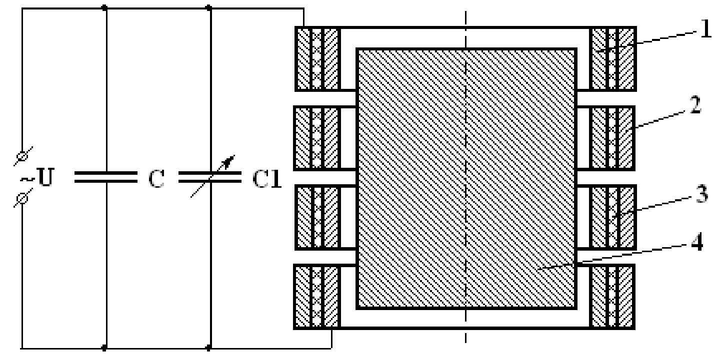

Fig. 1. The sketch of "inductor with self-compensation – loading" system

Thus, the inductor design of the given type allows to create in it significant own electric capacity which compensates own and mutual to inductance of the inductor, and also mutual inductance of the inductor and heated loading. As against indemnification by means of the concentrated capacities we have process of continuous indemnification during all length of the inductor winding.

As a result, in case of partial indemnification required capacity of the condenser battery serving for increase natural *cos* φ, of the induction heater (capacity *C*, fig. 1) is considerably reduced. In case of full indemnification necessity for use of means of artificial indemnification disappears.

Operating mode of the inductor is the resonant mode achievable by equality inductive X_L and capacitor X_C of resistance of the inductor winding. It depends in particular on electro physical parameters of elements and its components and can be maintained by their corresponding choice.

At calculation of inductance of winding L_1 it is necessary to take into account, that currents in heteronym conductors of the winding have a concordant direction, and the density of the current at axial direction decreases from the place of its inputting mutual to periphery, i.e. $j_a = f(x)$. Thus, inductance of cylindrical section with spiral winding by a tape conductor at the account of inductance coefficients pays off under the formula

$$L_1 = \frac{\mu_0}{h} \cdot \left[n^2 \cdot S_0 + (n-1)^2 \cdot S_1 + (n-2)^2 \cdot S_2 + \ldots + S_{n-1}\right], \tag{1}$$

where S_0 – the area of cross-section section of the first coil of the winding (a ring formed by an end face of an conductor of the first coil), m^2;

$S_1, S_2, \ldots, S_{n-1}$ – difference between the areas of cross-section section of the second and first coils, the third and the second, *n* and *(n-1)* coils of the winding, m^2.

At entering loading into working area of the inductora its influence affects in increase in active resistance of system at size of brought active resistance R_{br} that is connected to consumption of active inductor power from the network and its transfer to loading. At the same time, reactive resistance of the system decreases for the size of reactive brought resistance X_{br} that could be explained by the bucking action of loading on inductor current [3].

Thus, total reactive resistance of system X_Σ will be equal to

$$X_\Sigma = X_{L1} - X_{C1} - k_{com}^2 \cdot X_{L2}, \tag{2}$$

where X_{L1}, X_{C1} – inductive and capacitor resistance of the inductor accordingly, Ω;

X_{L2} – inductive resistance of loading, Ω;

K_{com} – coefficient of communication.

Brought active resistance R_{br} is equal to active resistance of loading R_2 and is defined under the formula

$$R_{br} = 4 \cdot \rho_2 \cdot h / \pi \cdot D_2^2, \tag{3}$$

where D_2 – diameter of loading, m.

Brought reactive resistance X_{br} is equal to reactive resistance of loading X_2. Inductance of loading L_2, H, determined under the formula for the ring with current of the cross-section equal to depth of penetration of an electromagnetic wave in a material of loading Δ_e, м.

$$L_2 = \mu_0 \cdot \frac{D_2 - \Delta_e}{2} \cdot \left(\ln \frac{4 \cdot (D_2 - \Delta_e)}{h + \Delta_e} - 0{,}5\right), \tag{4}$$

$$\Delta_e = 503 \cdot \sqrt{\rho_k / \mu_k \cdot f}. \tag{5}$$

The index k in (5) corresponds 1 at calculation Δ_e for the inductor and 2 at calculation Δ_e for loading.

The coefficient of communication between the inductor and loading is determined under the formula

$$k_{com} = \frac{2 \cdot \pi \cdot f \cdot M_{12}}{\sqrt{R_{br}^2 + X_{br}^2}}, \tag{6}$$

where M_{12} – mutual inductance between the inductor and loading, H.

Mutual inductance M_{12} is determined for two cylindrical coaxial asymmetric coils (inductor 1 and loading 3) with backlash 2 between them. Thus loading is equivalent to the coil with number of coils $W = 1$. Conditionally it is accepted that the backlash is filled with coils with the same step of winding, as at the inductor winding. The number of coils of the fictitious coil 2 is determined as

$$W_2 = (D_1 - D_2) / 4 \cdot (b + \delta), \tag{7}$$

where D_1 – inner diameter of the inductor, m.

Mutual inductance M_{12} between the inductor and loading is determined under the formula

$$M_{12} = (L_{123} + L_2 - L_{12} - L_{23}) / 2, \tag{8}$$

where L_{123}, L_{12}, L_{23} – inductance of the coils made of coils 1,2 and 3; 1 and 2; 2 and 3 accordingly, H;

L_{12} – inductance of the fictitious coil 2, H.

Inductance of coils L_{123}, L_{12}, L_{23} is calculated according to (1).

The electric capacity C of the inductor is calculated as for cylindrical section with spiral winding by the tape conductor under the formula

$$C = 5{,}65 \cdot 10^{-7} \cdot W \cdot h \cdot \varepsilon \cdot D_{av} / \delta, \tag{9}$$

where W – the number of winding coils in the inductor;

ε – relative dielectric permeability of the isolated material;

D_{av} – average diameter of the winding, m.

$$D_{av} = D_1 + 2 \cdot (b + \delta) \cdot W. \tag{10}$$

The submitted design procedure is realized as software product «REZONANS 1», created in Borland DELPHI environment for functioning in WINDOWS shell by means of which theoretical researches of the inductor with self-compensation of reactive power in a wide range of influencing factors (frequencies of the power supply f, a temperature level of inductor cooling, relative dielectric permeability ε of the isolated material, the material itself and magnetic properties of loading, the geometrical sizes of loading and the inductor, etc.) are carried out. Results of researches as graphic dependences are submitted in figures 2 ÷ 5.

Researches have shown that the most essential influence on number of coils W of the inductor winding is rendered with the following parameters: frequency of the power supply f; thickness of the dielectric δ; relative dielectric permeability ε. The analysis of dependence W

and the charge of nonferrous metal G from ε of the isolated dielectric at different frequencies f the power supply, levels of cooling, materials of a current carrying conductor have shown their similar character.

At change of frequency from 50 Hz up to 10 kHz the number of coils decreases in a range from 15 up to 30 times at a nitric level of cooling and from 30 up to 60 times at a neon level of cooling (at increase ε from 5 up to 10^4). And at transition of the material of the inductor winding from copper on aluminum the number of coils of the winding is reduced on 1,5 ÷ 2,0 % (fig. 2).

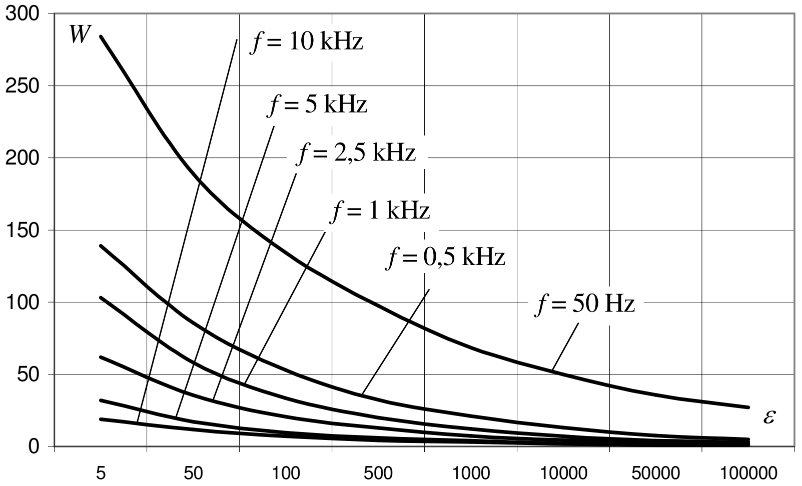

Fig. 2. Dependence of number of coils of the inductor W from dielectric permeability ε at $H = 0{,}1$ m, $\rho = 194 \cdot 10^{-11}$ Ω·m, $\delta = 50$ μm, $D_1 = 0{,}15$ m

Absolute increase of dielectric from 5 up to 10^5 leads to decrease in number of coils of the inductor winding from 10 times at low frequencies (50 Hz) up to 34 times ($f = 1000$ Hz). The further increase of frequency does not conduct to substantial increase of their growth, and in the field of frequencies 5 ÷ 10 kHz its decrease is marked.

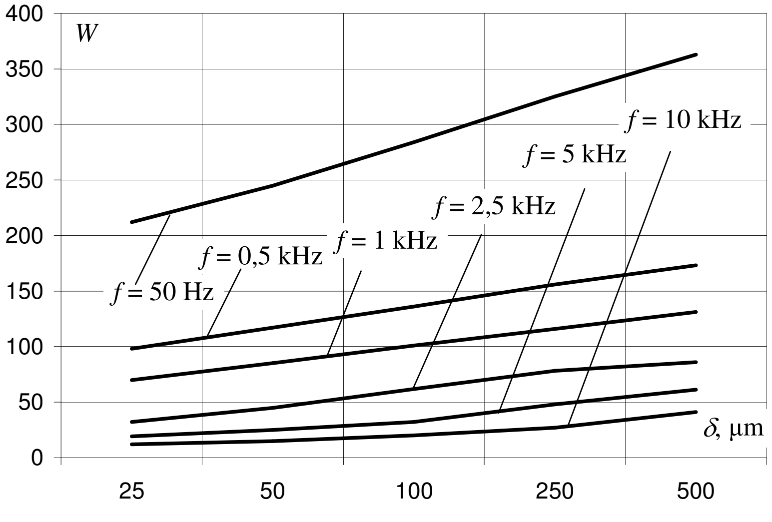

Fig. 3. Dependence of number of inductor coils W from thickness δ dielectric at $H = 0{,}1$ m, $\rho = 194 \cdot 10^{-11}$ Ω · m, $\varepsilon = 10$, $D_1 = 0{,}15$ m

Thickness of the δ dielectric is necessary to recognize as good means of regulation of number of coils of the winding change, it is placed between heteronym conductors of the inductor (fig. 3). So, at increase of δ from 25 μm up to 500 μm, W increases in a range from 1,7 up to 3,4 times at a nitric level of cooling irrespective of the material of current carrying conductors of the winding. At a neon level of cooling the range of change of number of coils is wider – from 1,5 up to 3,8 times for aluminum windings and from 1,3 up to 3,8 times for copper windings.

Use for the purposes of heating as loading metal of a various assortment leads to necessity of change of settlement internal diameter of the inductor D_1. So, heating the hire of the cylindrical form for the subsequent plastic deformation predetermines range D_1 in limits from 0,05 m up to 0,25 m. Increase D_1 from 0,05 m up to 0,25 m at change of frequency of the power supply from 50 Hz up to 10 kHz leads to increase in number of coils from 1,13 times up to 3,3 times on the dependence close to linear at a nitric level of cooling, both for copper inductor, and for aluminum one (fig. 4).

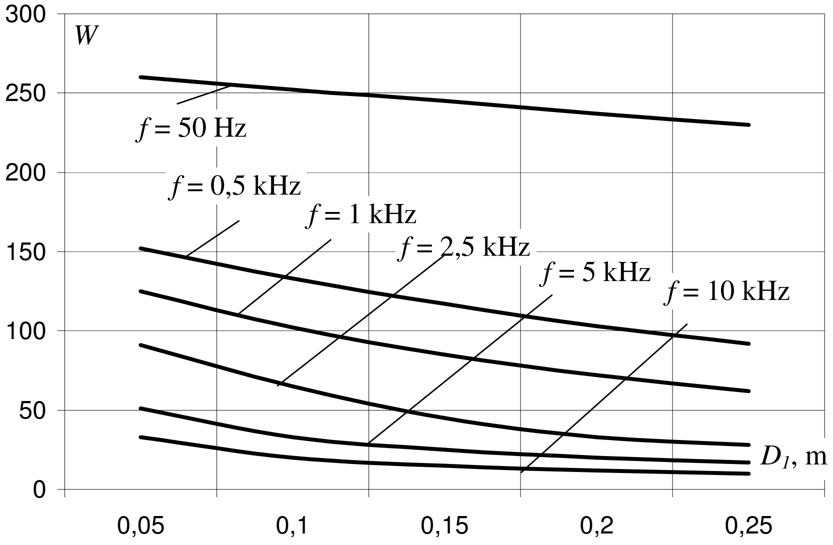

Fig. 4. Dependence of number of inductor coils W from internal inductor diameter D_1 at $H = 0{,}1$ m, $\rho = 194 \cdot 10^{-11}\ \Omega \cdot$ m, $\varepsilon = 10$, $\delta = 50$ μm

Character of change of capacitance X_C depending on number of coils of the inductor winding as calculations show, and it is close to hyperbolic (fig. 5).

Thus, X_C in inverse proportion to the number of coils and average diameter of the winding. All other sizes influencing X_C, do not vary with increase or reduction of number of coils of the winding at the set parameters (frequency of the power supply f, relative dielectric permeability ε, thickness of the dielectric δ, a level of cooling and metal of the inductor winding).

The analysis shows that the ratio of capacitances of two coils, with number of the coils distinguished on one, is determined by expression

$$\frac{X_{C\,i}}{X_{C\,i+1}} = \frac{(W+1) \cdot D_{av\,w+1}}{W \cdot D_{av\,w}}. \tag{11}$$

It explains sharp reduction X_C at small number of coils of the winding and more linear character of change X_C at large values W.

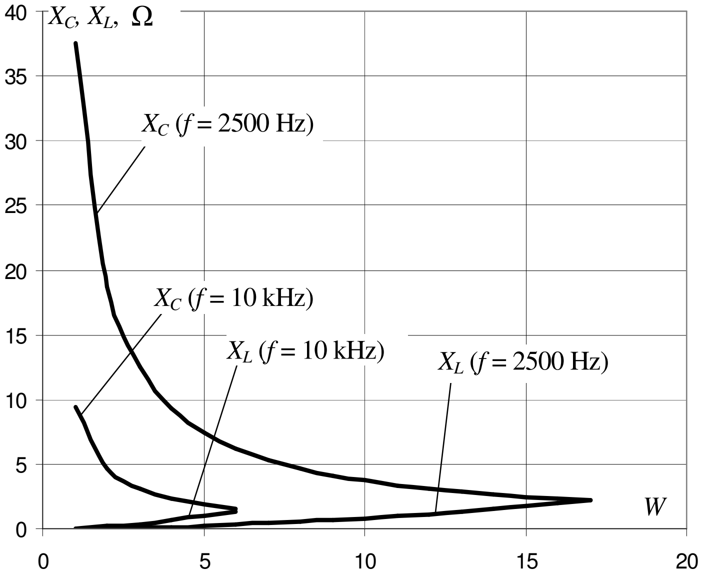

Fig. 5. Change capacitor X_C and inductive X_L resistance of the inductor winding on its length at $\delta = 50$ µm и $T = 20$ K

Inductive resistance of the winding X_L in direct ratio to a square of number of coils W_2, average diameter of winding D_{av} and size ψ dependent in turn from external diameter of the winding ($\psi = f(D_{ext})$).

$$L = 5 \cdot 10^{-8} \cdot W^2 \cdot D_{av} \cdot \psi. \tag{12}$$

The mathematical analysis shows that inductive resistance of the winding X_L in the greater degree depends on a square of number of coils of the winding. At increase in number of coils of the winding its inductive resistance changes on the right branch of the parabola which is described by the equation $Y = A \cdot X^2$, where $X = W$, $A = 5 \cdot 10^{-8} \cdot D_{av} \cdot \psi$. And $A < 1$, therefore branches of the parabola are depressed to axis X, i.e. increase X_L from coil to coil occurs gradually that approaches character of change X_L to linear one.

References

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