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Construction and Calculation of a Distributed Levitation Screen of Electromagnetic Transducers to Control the Thickness of the Winding

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Abstract

The requirements for electromagnetic transducers for automatic control of the thickness of the insulation coil of the protecting tube used in the electrical industry have been shown. The design of the transducer with improved characteristics has been presented. Its features have been analyzed that serve to improve the accuracy and reliability of the transducer. The article also discusses the factors, the processes of which must be considered when constructing and designing accurate electromagnetic transducer. It also provides analytical expressions for calculating the distributed field magnetizing coil and the levitation screen, which help taking into account the distributed nature of the magnetic resistance.

Keywords: electromagnetic transducer, field magnetizing coil, residual flux, magnetic resistance, magnet field, levitation, induction, coil flux guide, magnetic system.

INTRODUCTION.

OBasic requirements for devices for measuring the thickness of the insulation of the protecting tubes used in the electrical industry can be formulated as follows. The meter must have high accuracy and speed, be reliable in operation, have linear and stable characteristics with fluctuations in the supply voltage, ambient temperature and humidity, etc. They must ensure continuous transformation of the thickness of the coil into an electrical signal directly during the technological process. In some cases, unevenness (stepping) of the coil is envisaged and this requires automatic movement of the transducer along the measurement object with a single-valued transformation of the coil thickness into an electrical signal. Auxiliary devices are a necessary element of the continuous transmission of the linear parameters of parts to the transducer and introduce their own errors into the overall measurement error.

The above requirements are most fully met by meters that do not require intermediate or additional elements and are made on the basis of a linear induction suspension with a levitation screen. The use of levitation screens simplifies the alignment of the transducers with the measuring object due to the springy property and self-centering of the screen.

In addition, to ensure the measurement accuracy, it is necessary to take into account the distributed nature of the magnetic resistance of the moving part of the transducer and the screen leakage inductance.

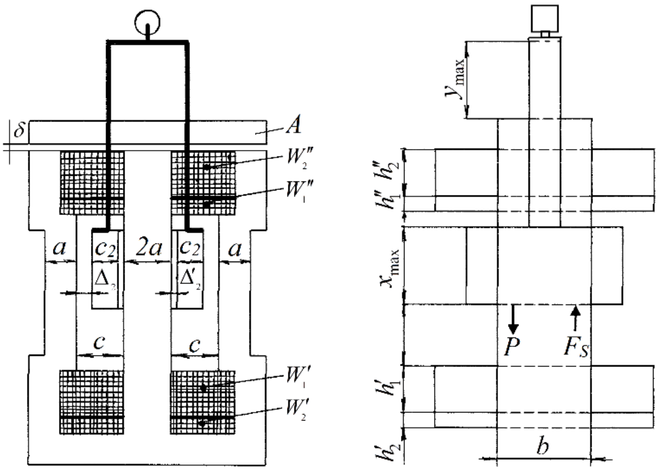
Meters based on a linear induction suspension with a levitation screen can be of various designs [6, 8]. For this purpose, it is rational to use an electromagnetic thickness transducer (ETT) with a levitation screen (LS) of a differential transformer type.

Transducers can be made with the adjustable clearance δ . The clearance is adjusted by changing the position of the armature A. At the same time, the zero position of the force-leading element (FLE) is set, where the residual signal is minimum and the slope of the output characteristic $U_2\left(\delta_m\right)$ is maximum.

1. Constructive solutions for improving the characteristics of ETT with LS.

Picture 1 shows a diagram of the design of an electromagnetic thickness transducer (ETT) with a levitation screen (LS) of a differential transformer type.

In order to increase the accuracy of thickness control, increase the linearity of the characteristics and reliability of the operation of the transducers in the developed design, the dimensions of the LS (h_2 и c_2) and the operating clearance (c) have been optimized, the power and output characteristics have been improved, and effective designs of the FLE have been created. The developed transducers have the following features:



Pic. 1. Scheme of construction of a differential-transformer ETT with LS

1. In order to create a uniform magnetic field in the operating air clearance and limit excessive increase in the height of the magnetic circuit, the end sections of the W-shaped magnetic circuit can be made stepped (Pic. 1). In such EMF, in these areas, there are sections of the field magnetizing coil (FMC) W_1', W_1'' and of the test coil (TC) W_2', W_2''.

Sections of the FMC $W_1' - W_1''$ and of the TC $W_2' - W_2''$ are turned on in series-opposite. By doing so, the conditions $W_1' >> W_1''$ are satisfied, since in this case the resulting lifting force $F_S = F_S' - F_S''$, compensating for the gravity force of the FLE P lifts it to its initial (upper) position, as shown in Pic. 1. In this position, i.e. in the initial state $(\delta_m = x = 0)$, the resulting voltage at the output of the test coil U_2 should be equal to zero. With this purpose the condition $W_2'' >> W_2'$ has been taken. As a result, the general condition $W_1' W_2' = W_1'' W_2''$ has been obtained and satisfied.

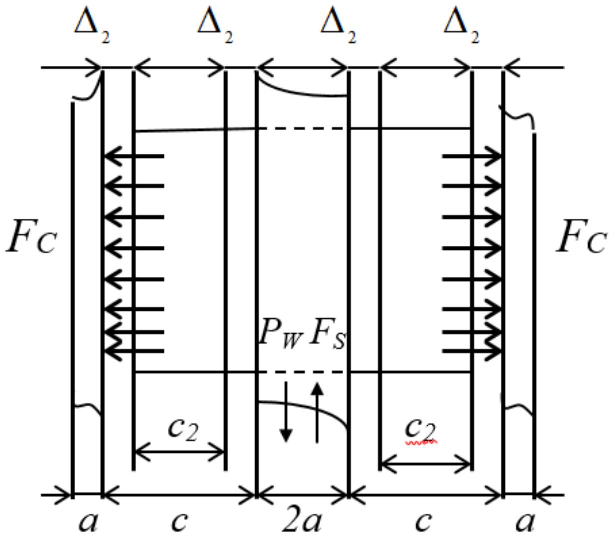
To improve the electromagnetic connection between the sections of the coils, the measuring sections $W_2' - W_2''$ can be located either closer to the end sections of the magnetic circuit (Fig. 1), or outside concentrically to the sections of the FMC. In the second version, the total height of the coils is less, so the height of the magnetic circuit will also be less.

2. In order to reduce friction between the movable and stationary parts of the transducer, as well as to increase the stability of the movable part, the FLE is fork-shaped and the contact with the measurement object is obtained through a fluoroplastic roller. Fluoroplast has high mechanical strength and lubricity. The dimension of the FLE $y_{мак}$ is decreased to the value of the maximum LS stroke $x_{мак}$, i.e. $y_{мак} = x_{мак} = \delta_{m\,мак}$ (pic. 1).

The design of LS and FLE provide longitudinal (vertical), transverse and thermal stability of the moving part of the transducer [1].

To ensure longitudinal stability in the initial position FLE ($\delta_m = x = 0$) the lifting force F_S, acting from below on LS, must fully compensate for the gravity forces LS P_W and FLE P_f (pic. 2) [2]:

$$F_S = P = P_W + P_f$$



Pic.2. Distribution of forces acting on LS

For a tight contact of the roller with the aforementioned items $F_S > P$ is necessary. Lateral stability is achieved by increasing centering forces F_C (pic.2). For this purpose, the clearances between the walls LS and the rods of the magnetic circuit Δ_2 are reduced to a minimum value ($\Delta_2 = 0{,}1 - 0{,}5\ mm$), and the ratio $n_{e2} = \frac{h_2}{c_2}$ is selected within $(2-6)$. The maximum value of the thickness LS c_2 in this case can be equal to the depth of penetration of an electromagnetic wave Δ_D into an aluminum LS.

Moreover, from the ratios $c_2 \le \Delta_D$; $F_2 = I_2 W_2 = I_2 = j_2 h_2 c_2 = j_2 n_{e2} c_2^2$ it is easy to establish the values n_{e2} and c_2, since the ampere turns F_2 and the current density j_2 of the LS are known. With an increase in the ratio n_{e2}, the LS overheating decreases and its thermal stability increases, since there is almost no "thermal drift". Here, an important role is also played by the satisfaction of the condition $F_S > P$ (when $x=0$). In order to increase the stability of the FLE, the dimension $y_{мак}$ is decreased to $x_{мак}$.

2. Factors that should be taken into account when calculating ETT with LS

It is necessary to take into account the following factors in the calculation and design of ETT.

1. An analysis of the ETT designs shows that the levitation screen is often made in the form of a single-turn coil, the height

of which in many cases is comparable to the height of the field magnetizing coil. Therefore, when calculating the magnetic and electrical circuits of such devices, it is necessary to represent the LS as a distributed short-circuited coil having a magnetic resistance $\dot{Z}_{M2}$ of a distributed nature. In works, as a rule, the LS is represented as a concentrated single-turn coil, the magnetic resistance of which is determined from the expression:

$$\dot{Z}_{M2} = \frac{j\omega W_2^2}{r_2 + jx_{2S}} . \qquad (1)$$

In the calculations, the leakage inductance of the moving coil is often unreasonably neglected and it is believed that $r_2 >> x_{2S}$, whilst the leakage inductance is defined as:

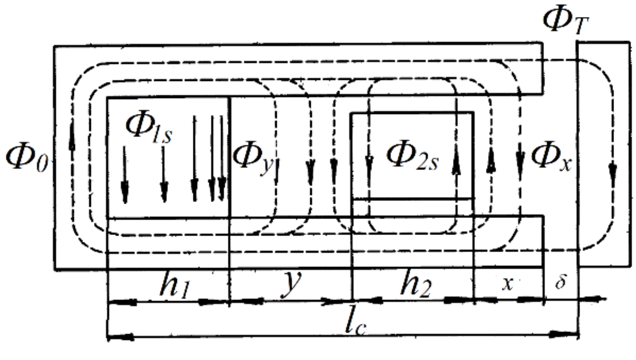
$$x_{2S} = \omega L_{2S} = \omega W_2^2 \Lambda_{2S} .$$

In this case, expression (1) takes the form:

$$\dot{Z}_{M2} \approx \frac{j\omega W_2^2}{r_2} . \qquad (2)$$

In the calculations for distributed short-circuited windings, expression (2) in can cause significant errors. Therefore, it is necessary to determine the magnetic resistance of the LS regarding x_{2S}.

2. Analytical expressions obtained for the diagram of fluxes and inductances of multi-turn coils are unsuitable for calculating the resulting magnetic fluxes created with a single-turn (solid) coil. Π The diagram of the distribution of fluxes in the magnetic circuit shown in Figure 3 corresponds to the pattern of the distribution of magnetic fluxes with the release of leakage fluxes Φ_{1S} and Φ_{2S}. To determine the resulting magnetic fluxes, it is necessary to represent the LS in the equivalent circuit of the magnetic circuit as a complex magnetic resistance $\dot{Z}_{M2}$, as described in [1].



Pic. 3 Diagram of the distribution of magnetic fluxes of the magnetic circuit of the ETT with LS

Magnetic conductances are complex and take into account the finite dimensions of the coils and sections of the magnetic circuit:

$$\dot{\Lambda}_{1S} = \frac{h_1}{3}\lambda \dot{m}_{1S} = \frac{h_1}{3}\lambda(m_{1Sa} - m_{1Sp}) \ ;$$

$$\dot{\Lambda}_y = \lambda y \dot{m}_y = \lambda y (m_{ya} - jm_{yp}) \ ;$$

$$\dot{\Lambda}_x = \lambda x \dot{m}_x = \lambda x (m_{xa} - jm_{xp}) \ ,$$

Here, the coefficients *m* take into account the dimension of the coil h_1, the lengths of the sections *y* and *x* , and core losses [1].

3. When determining the active resistance of the screen r_2 , ignorance of the depth of penetration of an electromagnetic wave into the screen causes an additional error in calculating the magnetic resistance of the screen $\dot{Z}_{M2}$ and of magnetic fluxes.

4. The overheating temperature of the continuous screen τ_2 during operation of the ETT can reach 80-120^0 C. At this temperature, its ohmic resistance r_{20} increases greatly. This also leads to a decrease in the magnetic resistance of the screen $\dot{Z}_{M2}$, because the penetration depth of the electromagnetic wave strongly affects this resistance.

5. The active resistance of a continuous screen r_2 is inversely proportional to its height h_2, and the leakage inductive resistance x_{2S} increases with increasing height h_2. The overheating temperature τ_2 decreases with the increase of the screen height h_2. Consequently, there is an optimal height value h_2 at which the electrical resistance of the screen Z_2 is minimum, and its magnetic resistance $\dot{Z}_{M2}$ is maximum. An increase in the magnetic resistance of the screen $\dot{Z}_{M2}$ enhances the screening effect on the magnetic flux and causes an increase in the sensitivity of the ETT.

3. Calculation of inductances of distributed field magnetizing coils and levitation screen

Based on the classical method for determining the leakage inductances of inductively coupled coils [4], one can write:

$$L_{1S} = L_{11} - \frac{W_1}{W_2} M \ ; \quad L_{2S} = L_{22} - \frac{W_2}{W_1} M \ . \qquad (3)$$

Then the equivalent magnetic conductivity on the paths of leakage fluxes and mutual inductances will be determined as:

$$\Lambda_{1S} = \frac{L_{11}}{W_1^2} - \frac{M}{W_1W_2} \quad ;$$

$$\Lambda_{2S} = \frac{L_{22}}{W_2^2} - \frac{M}{W_1W_2} \quad ; \ \Lambda_{12} = \frac{M}{W_1W_2} \quad . \qquad (4)$$

Applying the values L_{11}, L_{22} and M in (4), after simple transformations we obtain:

$$\dot{\Lambda}_{1S} = \frac{\dot{k}_{1S} + \dot{k}_{11}\dot{k}_{12}}{2Z_\mu h_1} \ ; \ \dot{\Lambda}_{2S} = \frac{\dot{k}_{2S} + \dot{k}_{22}\dot{k}_{21}}{2Z_\mu h_2},$$

where k - coefficients calculated according to the method [7] and take into account the dimension of the coils and core losses.

Thus, after mathematical transformations, the leakage inductance of the distributed stationary field coil is determined as:

$$\tilde{L}_{1S} = W_1^2 \frac{\dot{k}_{1S} + \dot{k}_{11}\dot{k}_{12}}{2\dot{Z}_\mu h_1},$$

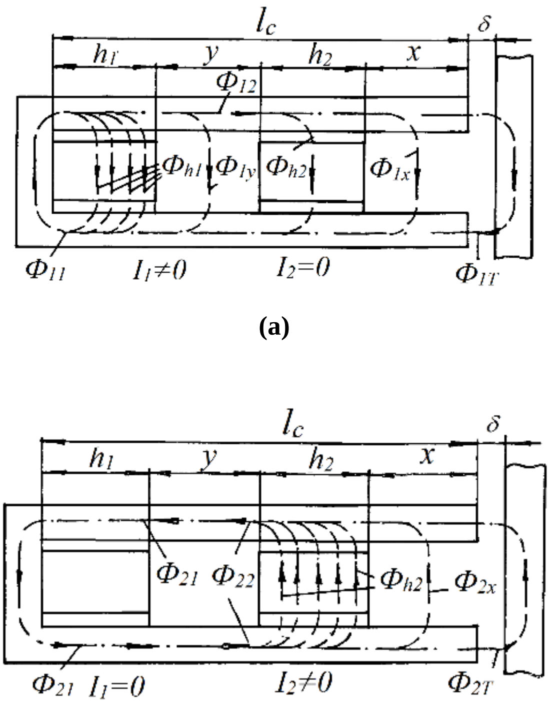
whilst the leakage inductance of the distributed levitation short-circuited coil:

$$\tilde{L}_{2S} = W_2^2 \frac{\dot{k}_{2S} + \dot{k}_{22}\dot{k}_{21}}{2\dot{Z}_\mu h_2};$$

Coefficients k can be calculated for special cases $\dot{Z}_0 = \dot{Z}_T = 0$ and

$$\dot{Z}_0 = 0 \ ; \ \dot{Z}_T = \frac{1}{\Lambda_T}.$$

The total magnetic resistance of the base of the magnetic circuit Z_{MC} is usually much less than the magnetic resistance of the end section and therefore provided the condition $Z_{MC} << \frac{1}{\Lambda_\delta}$ и $Z_{MC} << \frac{1}{\Lambda_T}$ the inductances can be calculated without taking into account the magnetic resistance of the steel sections, since the errors in calculating the electromagnetic parameters will be insignificant. Diagrams of magnetic flux distribution for distributed field magnetizing coils W_1 and the screen W_2 are shown in pic. 4, which is the basis for calculating the magnetic conductivity of air sections and flows.



(a)

(b)

Pic.4. Magnetic flux distribution schemes for distributed field magnetizing coils and screen: *a*- in the absence of current in the LS; *b*- in the absence of current in the FMC.

The magnetic flux created by the field magnetizing coil consists of several components (pic. 4,*a*) [2,5]:

$$\Phi_{11} = \Phi_{1T} + \Phi_{1x} + \Phi_{h2} + \Phi_y + \Phi_{1h} \ . \qquad (5)$$

Since

$$\Phi_{1T} = I_1W_1\Lambda_T \ ; \ \Phi_{1x} = I_1W_1\lambda x ; \ \Phi_{h2} = I_1W_1\lambda h_2 \ ;$$

$$\Phi_y = I_1W_1\lambda y \ ; \Phi_{1h} = \Phi_{1S} = \frac{1}{2} I_1W_1\lambda h_1 ,$$

then the expression (5) can be written as:

$$\Phi_{11} = I_1W_1\left[\lambda\frac{h_1}{2} + \lambda(l_c - h_1) + \Lambda_T\right],$$

The elementary leakage flux and the distribution law of the leakage fluxes of the field magnetizing coil are determined as follows:

$$d\Phi_{1S} = \frac{I_1W_1}{h_1} x\lambda dx \ ; \qquad (6)$$

$$\Phi_{1hx} = \int_0^x d\Phi_{1S} = \int_0^x \frac{I_1W_1}{h_1} x\lambda dx = \frac{I_1W_1}{2h_1}\lambda x^2 \ . \qquad (7)$$

Then the flux linkage with the field magnetizing coil:

$$\Psi_{11} = \Psi_{1S} + \Psi_T + \Psi_{l_c - h_1} = I_1 W_1^2 \left\lfloor \Lambda_T + \lambda(l_c - h_1) + \frac{1}{3} h_1 \lambda \right\rfloor,$$

where according to (6), (7) total flux linkage of leakage and end flux will be equal:

$$\Psi_{1S} = \int_0^{h_1} \frac{W_1}{h_1} x d\Phi_{1hx} = \frac{I_1 W_1^2}{h_1^2} \lambda \int_0^{h_1} x^2 dx = \frac{1}{3} I_1 W_1^2 \lambda h_1 ;$$

$$\Psi_T = I_1 W_1^2 \Lambda_T ; \Psi_{l_c - h_1} = I_1 W_1^2 \lambda (l_c - h_1) .$$

Then the self-inductance of the distributed field magnetizing coil:

$$L_{11} = \frac{\Psi_{11}}{I_1} = W_1^2 \left\lfloor \Lambda_T + \lambda(l_c - h_1) + \frac{1}{3} h_1 \lambda \right\rfloor .$$

Mutual inductance between coils W_1 and W_2 is:

$$M_{12} = \frac{\Psi_{12}}{I_1} = \frac{\Psi_T + \Psi_{1x} + \Psi_{h2}}{I_1} = W_1 W_2 (\Lambda_T + \lambda x + \frac{1}{2} \lambda h_2),$$

where

$$\Psi_{h2} = \int_0^{h_2} \frac{W_2}{h_2} x d\Phi_{h2} = \int_0^{h_2} \frac{W_2}{h_2} x I_1 W_1 \lambda dx = \frac{1}{2} I_1 W_1 W_2 \lambda h_2 ;$$

$$\Psi_{1x} = I_1 W_1 W_2 \lambda x ; \ \Psi_{1T} = I_1 W_1 W_2 \Lambda_T .$$

The fluxes and inductances of the distributed screen are defined similarly. (pic. 4,*b*):

$$\Phi_{22} = \Phi_{2T} + \Phi_{2x} + \Phi_{2h} ; \Phi_{2T} = I_2 W_2 \Lambda_T ;$$

$$\Phi_{2x} = I_2 W_2 \lambda x ; \quad \Phi_{2S} = \Phi_{2h} = \frac{1}{2} I_2 W_2 \lambda h_2 ;$$

$$\Psi_{2S} = \int_0^{h_2} \frac{W_2}{h_2} x d\Phi_{2hx}$$
$$= \frac{I_2 W_2^2}{h_2^2} \lambda \int_0^{h_2} x^2 dx = \frac{1}{3} I_2 W_2^2 \lambda h_2 ;$$

$$\Psi_{22} = I_2 W_2^2 \left\lfloor \Lambda_T + \frac{1}{3} \lambda h_2 + \lambda x \right\rfloor ;$$

$$L_{22} = W_2^2 \left[\Lambda_T + \frac{h_2}{3} \lambda + \lambda x \right] ;$$

$$M_{21} = \frac{\Psi_{21}}{I_2} = \frac{\Psi_{2h} + \Psi_{2x} + \Psi_{2T}}{I_2}$$
$$= W_1 W_2 (\Lambda_T + \lambda x + \frac{1}{2} \lambda h_2) .$$

Here:

$$\Psi_{h2} = \frac{1}{2} I_2 W_2 W_1 \lambda h_2 ; \Psi_{2x} = I_2 W_2 W_1 \lambda x ;$$

$$\Psi_{2T} = I_2 W_2 W_1 \Lambda_T .$$

The leakage inductances of the coils according to (3) are determined:

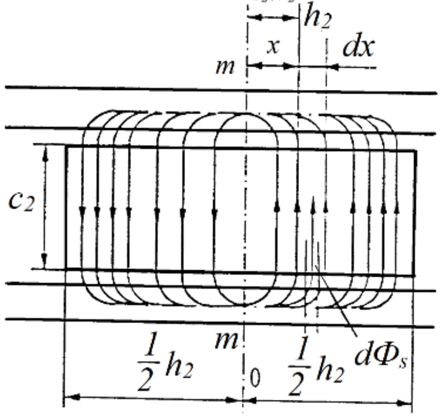
$$L_{1S} = L_{11} - \frac{W_1}{W_2} M = W_1^2 \lambda (l_c - \frac{4h_1 + 3h_2}{6} - x) ; \quad (8)$$

$$L_{2S} = L_{22} - \frac{W_2}{W_1} M = -\frac{1}{6} W_2^2 \lambda h_2 . \quad (9)$$

In order to analyze the expression for the leakage magnetic conductivity in the path of the screen leakage fluxes Φ_{2S} we represent (9) in the form:

$$\Lambda_{2S} = \frac{1}{2} (\frac{1}{3} \lambda h_2) . \quad (10)$$

It corresponds to the series connection of two identical conductivities ($\frac{1}{3} \lambda h_2$). And the physical meaning of the given equivalent circuit corresponds to the distribution pattern of magnetic leakage fluxes shown in Pic. 5, which suggests that the leakage fluxes are closed only within the screen height. In this case, the magnetic neutral $m - m$ divides the screen in half, the fluxes of which are the same in magnitude, but directed oppositely relative to this line.



Pic. 5. Diagram of the distribution of the leakage fluxes of the LS to the determination of the screen leakage inductance

The magnetomotive force per unit height of the screen h_2 is I_2W_2/h_2. The difference in magnetic potentials between the fluxes located at a distance *x* from the magnetic neutral lines $m-m$, are $U_{Mx}=I_2W_2x/h_2$. Then the elementary leakage flux $d\Phi_{Sx}$ from the site dx, located at a distance x from the line $m-m$, can be found on the basis of Kirchhoff's law for the magnetic circuit:

$$\sum_{j=1}^{n}\Phi_j\frac{1}{\Lambda_j}=\sum_{j=1}^{n}F_j\ .$$

Elementary leakage flux:

$$d\Phi_{Sx}=\frac{I_2W_2}{h_2}x\lambda dx\,.$$

From here on

$$\Phi_{Sx}=\int\frac{I_2W_2}{h_2}x\lambda dx=\frac{I_2W_2}{h_2}\lambda\frac{x^2}{2}\,.$$

The leakage flux passing through the section of the rod at a distance *x* from the neutral line is (pic. 5):

$$\Phi_x=\Phi_{Sh}-\Phi_{Sx}=\frac{I_2W_2}{2h_2}\lambda(h_2^2-x^2)\,.$$

The leakage flux in the place of the magnetic neutral is obtained by taking $x=0$:

$$\Phi_S=\frac{1}{2}I_2W_2\lambda h_2\,.$$

The corresponding flux linkage is:

$$\Psi_S=\int_0^{h_2}\frac{W_2}{h_2}xd\Phi_{Sx}=\int_0^{h_2}\frac{I_2W_2^2}{h_2^2}\lambda x^2dx=\frac{1}{3}I_2W_2^2\lambda h_2\,.$$

Then the inductance and leakage conductance for one of the halves of the distributed screen will be:

$$L'_{2S}=\frac{\Psi_S}{I_2}=\frac{1}{3}W_2^2\lambda h_2\ ;\ \Lambda'_{2S}=\frac{1}{3}\lambda h_2\,.$$

The total leakage conductivity of the screen is determined by the formula (10).

CONCLUSIONS

1. In the majority of works devoted to the calculation of the parameters of an electromagnetic screen made in the form of a solid frame and a short-circuited coil, the leakage inductive resistance is not taken into account, since $x_{2s} << r_2$ are accepted unreasonably. This assumption gives large inaccuracies in the calculations of the magnetic resistance Z_{M2} and screen current I_2, magnetic fluxes and inductions. Here, calculations have proved that the resistances x_{2S} and r_2 are comparable parameters.
2. A real diagram of magnetic fluxes can be obtained only if the electromagnetic screen is represented in the equivalent circuit in the form of a complex magnetic resistance, which is determined through the distributed parameters of the screen.
3. In this work, the screen is presented as a source of a distributed magnetomotive force, and its leakage inductive resistance is found based on the distribution of fluxes along the screen height.
4. Leakage fluxes of the electromagnetic screen within its height form a magnetic neutral, which significantly changes the approach to calculating the equivalent magnetic conductivity and inductive resistance of the screen leakage. This approach allows to more accurately determine the parameters of the screen and ETT in general.

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