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By F. F. Mende

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I. Introduction

To the laws of self-induction should be carried those laws, which describe the reaction of such elements of radio-technical chains as capacity, inductance and resistance with the galvanic connection to them of the sources of current or voltage. These laws are the basis of the theory of electrical chains. The motion of charges in any chain, which force them to change their position, is connected with the energy consumption from the power sources. The processes of interaction of the power sources with such structures are regulated by the laws of self-induction.

To the self-induction let us carry also that case, when its parameters can change with the presence of the connected power source or the energy accumulated in the system. This self-induction we will call parametric. Subsequently we will use these concepts: as current generator and the voltage generator. By ideal voltage generator we will understand such source, which ensures on any load the lumped voltage, internal resistance in this generator equal to zero. By ideal current generator we will understand such source, which ensures in any load the assigned current, internal resistance in this generator equally to infinity. The ideal current generators and voltage in nature there does not exist, since both the current generators and the voltage generators have their internal resistance, which limits their possibilities.

If we to one or the other network element connect the current generator or voltage, then opposition to a change in its initial state is the response reaction of this element and this opposition is always equal to the applied action, which corresponds to third Newton's law.

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II. Current Self-Induction and Potential Well on the Superconductive Rings

Let us introduce the concept of the flow of the current self-induction

$$\Phi_{L,I} = LI.$$

If inductance is shortened outed, and made from the material, which does not have effective resistance, for example from the superconductor, then

$$\Phi_{L,I} = L_1 I_1 = const,$$

where L_1 and I_1 - initial values of these parameters, which are located at the moment of the short circuit of inductance with the presence in it of current. Let us name this regime the law of the frozen flow for the short-circuited superconductive outlines [1-5]. In this case we have:

$$I = I_1 L_1 / L, \qquad (2.1)$$

where I and L - the instantaneous values of the corresponding parameters.

In flow regime examined of current induction remains constant, however, in connection with the fact that current in the inductance it can change with its change, this process falls under for the determination of parametric self-induction. The energy, accumulated in the inductance, in this case is equal

$$W_L = \frac{1}{2}\frac{(L_1 I_1)^2}{L} = \frac{1}{2}\frac{(const)^2}{L}.$$

Stress on the inductance is equal to the derivative of the flow of current induction on the time:

$$U = \frac{d\Phi_{L,I}}{dt} = L\frac{\partial I}{\partial t} + I\frac{\partial L}{\partial t}.$$

Let us examine the case, when the inductance L_1 is constant.

$$U = L_1 \frac{\partial I}{\partial t}. \qquad (2.2)$$

Designating $\Phi_I = L_1 I$, we obtain $U = \frac{d\Phi_I}{dt}$.

Let us integrate over (2.2) the time:

$$I = Ut/L_1. \qquad (2.3)$$

Thus, the capacity, connected to the source of direct current, presents for it the effective resistance

$$R = L_1/t, \qquad (2.4)$$

which decreases inversely proportional to time.

The power expended by source linearly depends on the time:

$$P(t) = U^2 t/L_1. \qquad (2.5)$$

Integral of (2.5) on the time is the accumulated in the inductance energy:

$$W_L = U^2 t^2/(2L_1). \qquad (2.6)$$

After substituting into expression (2.6) the value of stress from relationship (2.3), we obtain:

$$W_L = L_1 I^2/2.$$

This energy can be returned from the inductance into the external circuit, if we open inductance from the power source and to connect effective resistance to it.

Now let us examine the case, when the current I_1, which flows through the inductance, is constant, and inductance itself can change. Then we have:

$$U = I_1 \frac{\partial L}{\partial t}. \qquad (2.7)$$

Consequently, the value

$$R(t) = \partial L/\partial t, \qquad (2.8)$$

plays the role of the effective resistance [1-5]. As in the case of the electric flux, effective resistance can be (depending on the sign of derivative), and positive, and negative, i.e., inductance can how derive energy from without, so also return it into the external circuits.

Introducing the designation $\Phi_L = LI_1$ and, taking into account (2.7), we obtain:

$$U = \Phi d_L dt/. \qquad (2.9)$$

The relationship (2.1), (2.6) and (2.9) we will call the rules of current self-induction, or the flow rules of current self-induction. From relationships (2.6) and (2.9) it is evident that, as in the case with the electric flux, the method of changing the flow does not influence eventual result, and its time derivative is always equal to the applied potential difference. Relationship (2.6) determines the current self-induction, during which there are no changes in the inductance, and therefore it can be named simply current self-induction. Relationships (2.7-2.8) assume the presence of changes in the inductance; therefore we will call such processes current parametric self-induction.

The law of the frozen current (2.1) leads to not the known earlier phenomenon of magnetic potential pit on the superconductive rings.

Assume that in two coaxially located superconductive rings the currents are frozen; moreover current in the lower ring is considerably more than in the upper. In accordance with Savart law the magnetic induction of lower ring on the axis in the plane of upper ring takes the form:

$$B = \frac{\mu_0 I_1 R_1^2}{2\left(R_1^2 + z_0{}^2\right)^{3/2}},$$

where μ_0 - the magnetic constant, z_0 - the distance between the rings, R_1 - the diameter of lower ring, I_1 - the current, frozen in the lower ring.

If a radius of upper ring composes R_2, its diameter considerably smaller than a radius of lower ring, then the magnetic flux, created by lower ring and which penetrates upper ring, will comprise

$$\Phi_2 \cong \frac{\mu_0 I_1 R_1^2 R_2^2}{2\left(R_1^2 + z_0{}^2\right)^{3/2}}.$$

We will consider that the distance between the rings is considerably more than the diameter of lower ring, then

$$\Phi_2 \cong \mu_0 I_1 R_1^2 R_2^2/\left(2z_0{}^3\right).$$

If in the upper ring current is frozen I_2, that the flow is connected with it

$$\Phi_2 = L_2 I_2,$$

where L_2 - the inductance of upper ring.

Let us assume that in the initial position of rings direction of flow in them coincides, and rings are attracted. During lowering of lower ring the currents of induction will compensate currents in the upper ring, and current in it will reach the zero value, when the equality will be carried out

$$\Phi_2 \cong \frac{\mu_0 I_1 R_1^2 R_2^2}{2{z_0}^3}.$$

In this case the distance between the rings will comprise

$$z_0 = \left(\frac{\mu_0 I_1 R_1^2 R_2^2}{2\Phi_2}\right)^{1/3} = \left(\frac{\mu_0 I_1 R_1^2 R_2^2}{2L_2 I_2}\right)^{1/3}.$$

With obtaining of this relationship the mutual inductance of rings is not taken into account, since the distance between the rings is great, and it was also considered that the current I_1 practically does not change with the approximation of upper ring to lower.

At point z_0 the currents of induction completely compensate the current, frozen in the upper ring; therefore, this ring will no longer interact with the lower ring. With further rapprochement of rings the current of induction in the upper ring changes its initial direction and it will be opposite in the direction of flow in the lower ring, and, therefore, it will begin from it to be repulsed. But if rings will be moved away from each other, then in the upper ring they will arise current, the coinciding in the direction with the currents in the lower ring, and rings will be attracted. Thus, the position of upper ring at point z_0 is potential well. Such properties of the superconductive suspensions in the literary sources are not described.

This analysis of the possibility in principle of obtaining potential well on the superconductive rings with the frozen currents does not consider the mutual inductance $M(z)$ of rings, which for two circular outlines of a radius R_1 and R_2 with the common axis and by the distance z between them is expressed as the complete elliptic integrals of the 1st $K(k)$ and 2nd $E(k)$ kind [6, 7]:

$$M(z) = \mu_0 f\left(k(z)\right)\sqrt{R_1 R_2},$$

$$f(k) = \left(\frac{2}{k} - k\right)K(k) - \frac{2}{k}E(k) = \frac{2}{k}\left[\left(1 - \frac{k^2}{2}\right)K(k) - E(k)\right], \quad k^2 = \frac{4R_1R_2}{z^2 + \left(R_1 + R_2\right)^2},$$

$$K(k) = \int_0^{\frac{\pi}{2}} \frac{d\theta}{\sqrt{1 - k^2\sin^2\theta}}, \quad E(k) = \int_0^{\frac{\pi}{2}} \sqrt{1 - k^2\sin^2\theta}\, d\theta.$$

Subsequently for the calculations their own inductances of rings with radii of the section of wires will be used also r_1 and r_2:

$$L_{10} = \mu_0 R_1\left(\ln\frac{8R_1}{r_1} - 1.75\right), \quad L_{20} = \mu_0 R_2\left(\ln\frac{8R_2}{r_2} - 1.75\right).$$

Let us freeze currents I_{10}, I_{20} in two secluded superconductive rings with its own inductances L_{10}, L_{20}. It will arrange these rings coaxially at a great distance so that the directions of flow in them again would coincide and let us begin to draw together them. Then we have relationships, which express the law of conservation of the frozen flows in the superconductive rings:

$$L_{10}I_1(z) + M(z)I_2(z) = L_{10}I_{10}; \quad L_{20}I_2(z) + M(z)I_1(z) = L_{20}I_{10}. \tag{2.10}$$

From them we will obtain relationships for the currents:

$$I_1(z) = \frac{I_{10}L_{10}L_{20} - I_{20}L_{20}M(z)}{L_{10}L_{20} - M^2(z)}; \quad I_2(z) = \frac{I_{20}L_{10}L_{20} - I_{10}L_{10}M(z)}{L_{10}L_{20} - M^2(z)}. \tag{2.11}$$

From these relationships we will obtain the value of the mutual inductance, with which the current in the lower and upper rings is equal to zero:

$$M_1(z_1) = L_1 \frac{I_{10}}{I_{20}}; \quad M_2(z_2) = L_2 \frac{I_{20}}{I_{10}}.$$

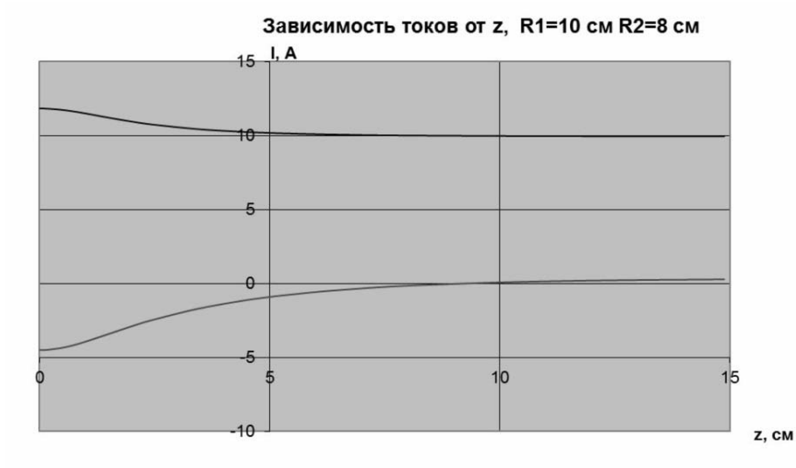

Fig. 1: Graphs of currents in the lower ring (upper curve) and in the upper ring (lower curve) with the initial values of current strength in the lower ring – 10 A and the value of current strength in the upper ring – 2 a.

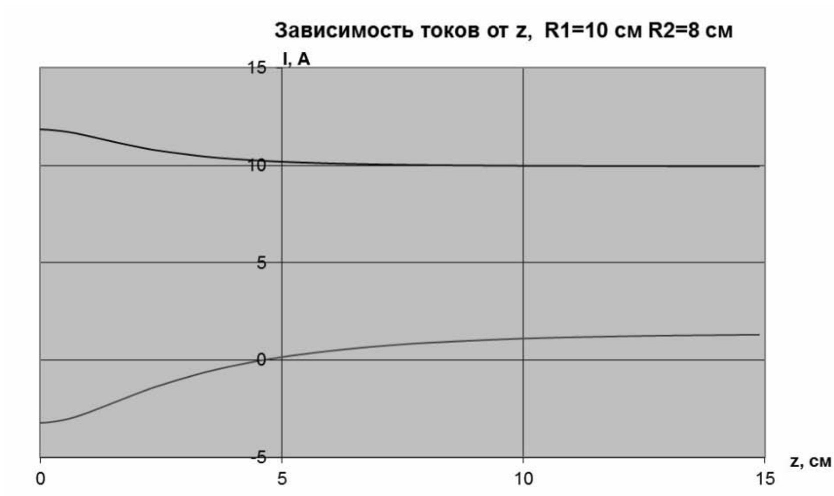

Fig. 2: Graphs of currents in the lower ring (upper curve) and in the upper ring (lower curve) with the initial values of current strength in the lower ring – 10 A and the value of current strength in the upper ring – 5 a.

Thus, assigning different initial values of inductances and currents frozen in them, it is possible to assign current zeros in that or other ring with different distances between them.

In Fig. 1 and Fig. 2 are depicted the drawings calculated by (2.11) formulas $I_1(z)$, also, $I_2(z)$ with different initial values of currents in the rings of radii $R_1 = 10$ cm, $R_2 = 8$ cm (radii of the section of wires $a_1 = a_2 = 0{,}1$ cm). It is evident that at the specific distance from the lower ring the current in the upper ring reverses the sign. They coincide at the great distance of direction of flow in the rings, and they are attracted. They are opposite on – smaller than the direction, and they are repulsed. Consequently, the point, at which the current in the upper ring reverses the sign, is a coordinate of potential well.

Let us examine the task, when the axes of two rings from the superconductive circular conductors coincide and are directed length wise Oz, in this case reference point O combined with the center of the first ring. Let us find currents in the rings and force of interaction of rings depending on the coordinate of the center of the second ring z, if with $z = z_0$ current in the second ring it is absent, and in the first it is equal I. Radii of rings r_1 r_2 are considerably more than radii a_1 and a_2 the section of wires.

Then in the first ring

$$I_1(z) = I\frac{b_1b_2 - 4f(\kappa_0)f(\kappa)}{b_1b_2 - 4[f(\kappa)]^2}. \tag{2.12}$$

And the secondly

$$I_2(z) = 2Ib_1\sqrt{\frac{r_1}{r_2}}\frac{f(\kappa_0) - f(\kappa)}{b_1b_2 - 4[f(\kappa)]^2}. \tag{2.13}$$

The force of interaction of the rings

$$F(z) = \mu_0 I^2 g(\kappa)\frac{[b_1b_2 - 4f(\kappa_0)f(\kappa)][f(\kappa_0) - f(\kappa)]}{[b_1b_2 - 4[f(\kappa)]^2]^2}\frac{b_1|z|}{r_2}. \tag{2.14}$$

Here μ_0 – magnetic constant, $b_1 = \ln(8r_1/a_1) - 2$ and $b_2 = \ln(8r_2/a_2) - 2$, A

$$\kappa = \kappa(z) = 2\sqrt{\frac{r_1r_2}{(r_1+r_2)^2 + z^2}}, \qquad \kappa_0 = \kappa(z_0) = 2\sqrt{\frac{r_1r_2}{(r_1+r_2)^2 + z_0^2}}.$$

In the expressions (2.12)–(2.14) the functions figure

$$f(\kappa) = \frac{1}{\kappa}[(1-\kappa^2/2)K(\kappa) - E(\kappa)], \qquad g(\kappa) = \kappa\left[K(\kappa) - \frac{1-\kappa^2/2}{1-\kappa^2}E(\kappa)\right],$$

where $K(\kappa)$ and $E(\kappa)$ – the complete elliptic integrals of the 1st and 2nd kind:

$$K(\kappa) = \int_0^{\pi/2}\frac{d\theta}{\sqrt{1-\kappa^2\sin^2\theta}}, \qquad E(\kappa) = \int_0^{\pi/2}\sqrt{1-\kappa^2\sin^2\theta}\,d\theta.$$

As an example let us take the following radii of rings: $r_1 = 10$ cm and $r_2 = 8$ cm, and radii of the section of wires – $a_1 = a_2 = 0{,}1$ see. Let with the distance $z_0 = 5$ cm between the centers of rings the current strength in the first ring compose $I = 10$ A, and the secondly current is absent. Dependences $I_1(z)$, $I_2(z)$ and $F(z)$, calculated by formulas (2.12)–(2.14), are depicted in graphs (ris.3, Fig. 4 and Fig. 5) Current in the first ring I_1 is equal $I = 10$ to A with $z = \pm z_0$ and $z \to \pm\infty$. Current in the second ring I_2 is turned into zero with $z = \pm z_0$. Positive values I_2 correspond to identical directions of flow in the rings, and negative– opposite. Finally, the positive values of force F correspond to the repulsion of rings, and negative – to attraction. It is obvious that with $z = \pm z_0$ it becomes zero, in this case the rings are located in the position of stable equilibrium. Force F is absent also with $z = 0$ (when the planes of rings coincide), but in this case equilibrium – is unstable.

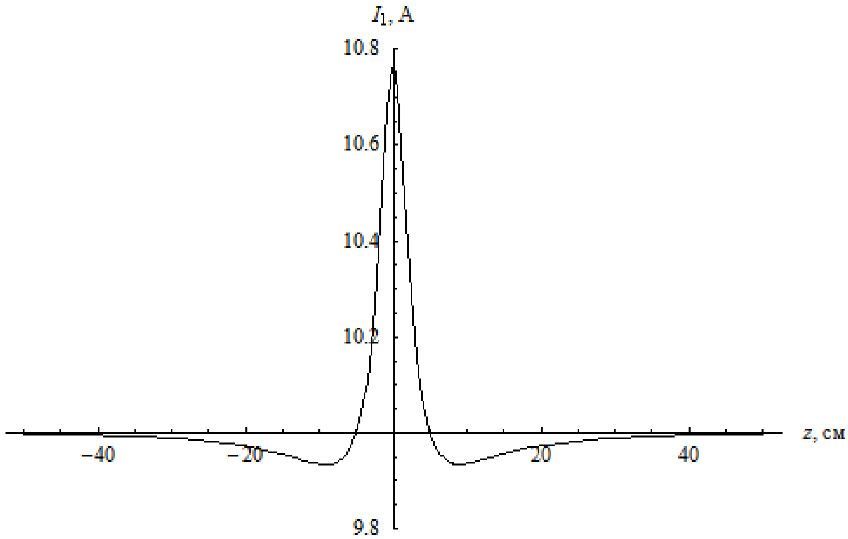

Fig. 3: Dependences $I_1(z)$

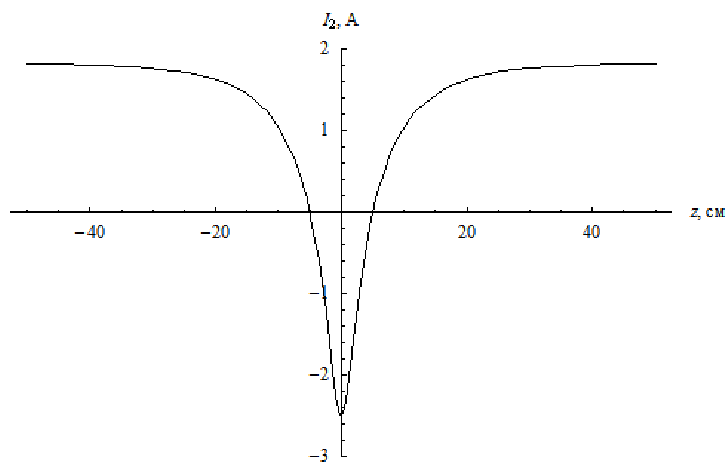

Fig. 4: Dependences $I_2(z)$

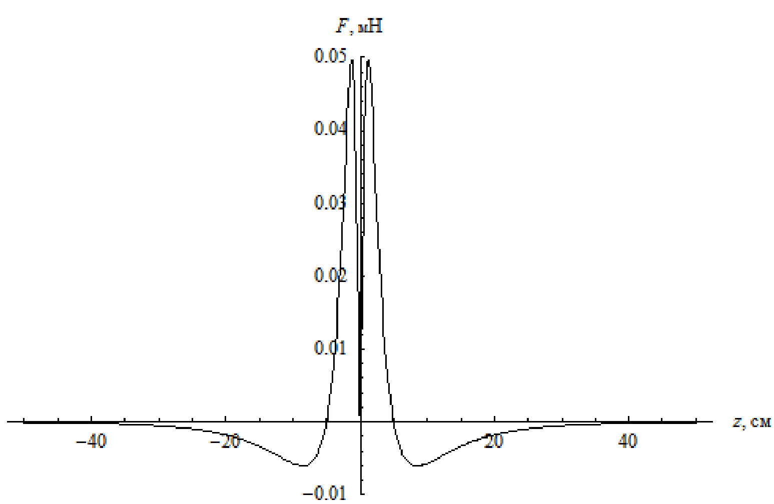

Fig. 5: Dependences $F(z)$

III. Conclusion

Work examines new physical phenomenon potential well on the superconductive rings. This phenomenon indicates that two superconducting the rings of different diameter, in which are frozen the flows, can be found with respect to each other in potential well, when their rapprochement or removal leads to the appearance of restoring force. The distance between the rings, which determines this pit, corresponds to the minimum of potential energy of the system of the connected rings. This phenomenon can find a practical use for creating the standards of force and highly sensitive instruments for its measurement, such as gravimeters and accelerometers.

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