UDC 621.318 https://doi.org/10.20998/2074-272X.2023.6.12

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The mutual influence of exciting and induced currents in the circular solenoid – massive conductor system

Problem. *The flow of currents in the conductive elements of electrical systems is accompanied by the excitation of electromagnetic fields and the occurrence of induced currents. The excitation of the induced signals, in turn, leads to a change in the parameters of the actual exciting currents. The* ***purpose*** *of the work is to obtain analytical expressions for the quantitative analysis of the results of the mutual influence of the exciting and induced currents and to calculate their ratio depending on the geometric characteristics of the inductor systems.* ***Methodology***. *The analysis of the processes of mutual influence is carried out on the example of a widespread inductor system, where a flat circular solenoid is placed above the surface of a massive conductor. Analytical expressions for eddy currents excited in a massive conductor and numerical estimates of the effect of induced currents on exciting currents in a solenoid are obtained.* ***Results***. *It is shown that the influence of the induced current on the current in the solenoid is very significant at small distances between the solenoid and the surface of the massive solenoid. It has been found that an increase in the width of the solenoid winding leads to a significant increase in the influence of the induced current on the excitation current in the solenoid. It is shown that the inductance of the «circular solenoid - massive conductor» system drops with a decrease in the distance between the solenoid and the massive conductor and an increase in the radial dimensions of the solenoid, which requires an increase in the amplitude of the exciting current to maintain a given value of the magnetic flux in the system.* ***Originality***. *The scientific novelty of this work lies in the proposal of an analytical approach and obtaining numerical estimates of the mutual influence of conductors with exciting and induced currents.* ***Practical value***. *Estimates of the mutual influence of conductors with currents are of interest for the practice of designing structures of electrical systems for various purposes. Very promising in the direction further research is seen as carrying out experiments with measurements of the quantitative characteristics of the mutual influence of exciting and induced currents in various designs of electrical systems.* References 20, figures 3.

Key words: **circular solenoid, massive conductor, inductor system, eddy currents, inductance.**

В роботі одержано аналітичні вирази для кількісного аналізу результатів взаємного впливу збуджуючих та індукованих струмів і числові оцінки їх співвідношення в залежності від геометричних характеристик індукторної системи. Аналіз результатів взаємного впливу проведено на прикладі широко поширеної індукторної системи, де плоский круговий соленоїд є розташованим над поверхнею ідеалізованого масивного провідника, що подається моделлю з нескінченою електропровідністю. Показано, що вплив індукованого струму на струм у соленоїді зростає при зменшенні відстані між соленоїдом та поверхнею масивного провідника і збільшенні ширини обмотки соленоїда, що вимагає підвищення амплітуди збуджуючого струму для збереження заданої величини магнітного потоку в системі. Бібл. 20, рис. 3.

Ключові слова: **круговий соленоїд, масивний провідник, індукторна система, вихрові струми, індуктивність.**

Introduction. Common to all known electrotechnical systems, regardless of their design, is the presence of conductive elements, the flow of currents in which is accompanied by the excitation of the corresponding electromagnetic fields. The latter, from a physical point of view, is a material substance with the help of which energy is exchanged between conductive elements where currents flow. It should be emphasized that the mentioned process is a process of mutual influence determined by M. Faraday's well-known law of electromagnetic induction. The interpretation of this law in relation to the process of mutual influence shows that the fields of induced currents lead to a change in the parameters of the actual exciting currents. On the other hand, physically, the mutual influence and related corresponding changes in the electrodynamic characteristics of the ongoing processes can also be explained by the principles of the law of conservation of energy [1-3].

Problem definition. Modern requirements for energy saving require mandatory numerical estimates of the parameters of the processes taking place, taking into account the mutual influence of exciting and induced currents, which is necessary for the design of electrical devices of any purpose.

Literature review. As an object of research, it is possible to consider the tools of electromagnetic technologies of metal processing, called in the special literature «inductor systems» [4, 5]. The latter are designs of circular solenoids placed above conductive objects [6, 7].

Thus, multi-turn inductor systems in the classic magnetic pulse processing of metals, which became widespread in the second half of the last century, carried out effective deformation of massive metal workpieces. In the case of a sharp skin effect (high frequencies of active fields), production operations such as «crimping», «dispensing» and «flat stamping» have been successfully implemented [8-10]. It should be emphasized that the principle of operation of the presented electromagnetic technologies is based on the natural repulsion of conductors from the sources of the external magnetic field, which manifests itself as the so-called «magnetic pressure» [4, 11].

The tools of magnetic pulse attraction are single-turn inductor systems, the principle of operation of which is based on the suppression of Lorentz repulsion forces in low-frequency modes of excited fields, the use of magnetic properties of processed metals and Ampere's law on the force interaction of parallel currents [5, 12, 13]. The authors presented [14] various designs of tools, power sources and technological equipment of magnetic pulse attraction systems, protected by Ukrainian patents.

Inductor systems for induction heating of metal samples are presented in [5]. An analysis of the processes of excitation of electromagnetic fields by a cylindrical solenoid, in the inner cavity of which a massive conductive object is placed, was analyzed here.

Separation of tasks to be solved. A general drawback of the cited works, as well as recent publications based on calculation methods, for example [11, 15-17], should be considered the solution of the tasks in the approximation of the «given current», when the excited electromagnetic fields do not affect the characteristics of the sources, which are considered constant. This makes it possible to single out a significant part of the problems that need their solution and are dedicated to the study of the formation of exciting currents and voltages taking into account the action of excited fields [3, 7, 18].

The goal of the work is to obtain analytical expressions for the quantitative analysis of the results of the mutual influence of the exciting and induced currents and to calculate their ratio depending on the geometric characteristics of the inductor systems.

Basic ratios, analytical dependencies. The calculation model of the inductor system is shown in Fig. 1.

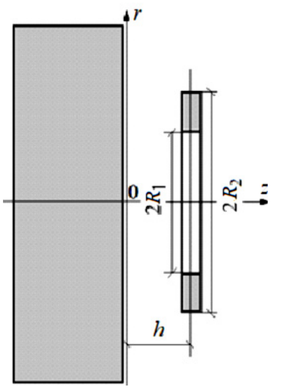

Fig. 1. Model of the inductor system with flat circular solenoid placed parallel to the surface of the massive conductor

Problem definition and assumptions to solving the problem:

1. A cylindrical coordinate system is acceptable.

2. We consider a massive conductor as one that conducts perfectly, which is practically admissible at sufficiently high frequencies of the active fields, and which can be realistically evaluated similarly to widely known works [1, 4, 16, 17].

3. The geometric dimensions of a massive conductor in $r \in [0, \infty)$ and $z \in (-\infty, 0]$ are infinite.

4. The solenoid is assumed to be axially symmetrical, i.e. $\partial/\partial\varphi = 0$, where φ is the azimuthal angle.

5. The azimuthal harmonic current $J(t) = J_m \sin(\omega t)$ flows in the solenoid winding with cyclic frequency ω that does not violate the accepted idealization of the conductor and with arbitrary amplitude J_m.

Note. Since an idealized model is adopted according to item 2, all characteristics of electromagnetic processes will be harmonic in time [16, 17].

6. According to the accepted geometric shape of the exciting current, the azimuthal component of the electric field strength $E_\varphi(t,r,z) \neq 0$, as well as the radial r and normal z components of the magnetic field strength vector $H_r(t,r,z) \neq 0$, $H_z(t,r,z) \neq 0$, respectively, are excited in the system [1, 2, 16, 17].

7. The evaluation of the characteristics of the mutual influence of the induced and exciting currents can be carried out, assuming that when the distance between the solenoid and the surface of the conductor varies, the average values of the normal components of the magnetic flux density, which are excited in the internal window of the solenoid, remain unchanged.

First, the relationships of a general nature.

The average value of the normal component of the magnetic flux density vector in the inner window of the solenoid, located at a distance h from the surface of the massive conductor, is described by the well-known relationship [18]:

$$\overline{B}_h = \Phi_h / S = \left(J_h \cdot L_h\right)/S\,, \qquad (1)$$

where Φ_h is the magnetic flux, S is the area of the internal window, J_h is the current in the winding, L_h is the inductance of the solenoid winding, which takes into account the presence of a massive conductor.

According to the accepted problem definition, the influence of the induced current on the excitation processes of the electromagnetic field can be determined by the value of the average magnetic flux density from (1). The obvious statement is that the induced current has no effect if the massive conductor is «conditionally removed to infinity». In this case, the average magnetic flux density in the inner window of the actual solenoid depends on (1) at $h \to \infty$

$$\overline{B}_\infty = \Phi_\infty / S = \left(J_\infty \cdot L_\infty\right)/S\,, \qquad (2)$$

where Φ_∞ and L_∞ are the magnetic flux and inductance of the solenoid winding without a massive conductor, J_∞ is the current in the winding.

Now the equality of the averaged magnetic flux density values in (1), (2) allows finding the ratio between the currents in the solenoid winding in the presence of a conductive object and in its absence. In fact, this ratio determines the effect of the induced current on the current in the solenoid winding.

So,

$$\overline{B}_h = \overline{B}_\infty; \quad J_h / J_\infty = L_\infty / L_h; \quad J_0 = \left(L_\infty / L_h\right) - 1, \qquad (3)$$

where $J_0 = \Delta J / J_\infty$ and $\Delta J = J_\infty - J_h$ are the relative and absolute variations of the current in the solenoid winding due to the influence of the induced current.

The results in (3) are consistent with known dependencies. Indeed, the amplitudes of the currents in the windings are inversely proportional to their inductances [16].

In accordance with the set goal, let’s turn to the calculation model in Fig. 1, for which we write down the system of Maxwell equations in the space of Laplace images [1, 2, 16, 17]:

$$\begin{cases} \dfrac{\partial E_\varphi(p,r,z)}{\partial z} = \mu_0 p H_r(p,r,z); \\ \dfrac{1}{r} \cdot \dfrac{\partial}{\partial r} \cdot \left(r \cdot E_\varphi(p,r,z)\right) = -\mu_0 p H_z(p,r,z); \\ \dfrac{\partial H_r(p,r,z)}{\partial z} - \dfrac{\partial H_z(p,r,z)}{\partial r} = j_{\varphi 0}(p,r,z), \end{cases} \qquad (4)$$

where $E_\varphi(p,r,z) = L\{E_\varphi(g(t)t,r,z)\}$; $H_{r,z}(p,r,z) = L\{H_{r,z}(t,r,z)\}$; $j_{\varphi 0}(p,r,z) = \{j_{\varphi 0}(t,r,z)\}$, $j_{\varphi 0}(t,r,z)$ is the current density in the solenoid, $j_{\varphi 0}(t,r,z) = j_m \cdot g(t) \cdot f(r) \cdot \delta(z-h)$, $g(t)$ is the dependence in time, $f(r)$ is the radial dependence, $\delta(z-h)$ is the Dirac function [19].

Note. The system of Maxwell equations (4) is fundamental as the basic basis of problems in applied electrodynamics, but in combination with the also well-known relationships (1) – (3) it makes it possible to study the mutual influence of exciting and induced currents in the elements of inductor systems, which is necessary for the design of effective tools in magnetic pulse processing of metals.

Further solution of the given task will be carried out according to the adopted calculation model. The geometry of the inductor system and the accepted assumptions make it possible to apply the Fourier-Bessel integral transformation [19, 20]. For the L-image of the strength of the excited electric field $E_\varphi(p,r,z)$ we write that

$$\begin{cases} E_\varphi(p,r,z) = \int\limits_0^\infty E_\varphi(p,\lambda,z)\cdot\lambda\cdot J_1(\lambda r)\mathrm{d}\lambda; \\ E_\varphi(p,\lambda,z) = \int\limits_0^\infty E_\varphi(p,r,z)\cdot r\cdot J_1(\lambda r)\mathrm{d}r; \end{cases} \quad (5)$$

where $E_\varphi(p,\lambda,z)$ is the image of the electric field strength in the Fourier-Bessel space, λ is the integral transformation parameter, $J_1(\lambda r)$ is the Bessel function of the first order.

Omitting the intermediate mathematical transformations, from the system (4), using the integral representation (5), we write the differential equation for the azimuthal component of the strength of the excited electric field [19, 20]:

$$\frac{\partial^2 E_\varphi(p,\lambda,z)}{\partial z^2} - \lambda^2\cdot E_\varphi(p,\lambda,z) = K(p,\lambda)\cdot\delta(z-h), \quad (6)$$

where $K(p,\lambda) = \mu_0 \cdot p \cdot j_m \cdot g(p) \cdot f(\lambda)$; $j_m = J_m / (R_2 - R_1)$ is the excitation current density;

$$g(p) = L\{g(t)\}; \quad f(\lambda) = \int\limits_{R_1}^{R_2} f(r)\cdot r\cdot J_1(\lambda r)\mathrm{d}r .$$

The general solution of the ordinary differential equation (6) can be represented by an expression of the form [19, 20]:

$$\begin{gathered} E_\varphi(p,\lambda,z) = C_1\cdot e^{\lambda z} + C_2\cdot e^{-\lambda z} + \\ + \frac{K(p,\lambda)}{\lambda}\cdot\eta(z-h)\cdot \mathrm{sh}(\lambda\cdot(z-h)), \end{gathered} \quad (7)$$

where $C_{1,2}$ are the arbitrary integration constants, $\eta(z-h)$ is the Heaviside step function.

Satisfying the boundary conditions at $z = 0$ ($E_\varphi(p,\lambda, z = 0) = 0$) and $z\to\infty$ ($E_\varphi(p, \lambda, z\to\infty) = 0$), we find a partial solution of equation (6). By substituting the coordinate $z = h$ into the obtained expression, we obtain an image of the electric field strength excited in the inner window of a flat circular solenoid:

$$E_\varphi(p,\lambda,z=h) = -\frac{K(p,\lambda)}{2\lambda}\cdot\left(1-e^{-2\lambda\cdot h}\right). \quad (8)$$

The integral representation of (5) taking into account (8) takes the form:

$$E_\varphi(p,r,z) = -\int\limits_0^\infty \frac{K(p,\lambda)}{2}\cdot\left(1-e^{-2\lambda\cdot h}\right)\cdot J_1(\lambda r)\mathrm{d}\lambda . \quad (9)$$

The connection of the L-image of the normal component of the magnetic field strength, which is excited, in the internal window of the solenoid in the presence of a massive conductor, with the $E_\varphi(p,\lambda,z)$ is found using the second equation from system (4):

$$H_z(p,r,z=h) = -\frac{1}{\mu_0 p}\cdot\frac{1}{r}\cdot\frac{\partial}{\partial r}\cdot\left(r\cdot E_\varphi(p,r,z=h)\right). \quad (10)$$

By integrating expression (10), we determine the dependence for the L-image of the magnetic flux:

$$\begin{gathered} \Phi_h(p) = 2\pi\mu_0\cdot\int\limits_0^{R_1} H_z(p,r,z=h)r\mathrm{d}r = \\ = -\frac{2\pi}{p}\cdot\left(r\cdot E_\varphi(p,r,z=h)\right)\Big|_0^{R_1}. \end{gathered} \quad (11)$$

Substituting (9) into (11) and opening $K(p,\lambda)$ from (6), we obtain that

$$\begin{gathered} \Phi_h(p) = J_m\cdot\frac{\mu_0\pi R_1}{(R_2-R_1)}\cdot g(p)\times \\ \times\int\limits_0^\infty f(\lambda)\cdot\left(1-e^{-2\lambda\cdot h}\right)\cdot J_1(\lambda R_1)\mathrm{d}\lambda. \end{gathered} \quad (12)$$

Since the time dependence of the magnetic flux, as follows from (12), is determined by the function $g(p)=L\{g(t)=\sin(\omega t)\}$, then $\Phi_h(t) \sim \sin(\omega t)$. And, therefore, expression (12) can be interpreted as a relationship between the amplitude values of the exciting current and the excited magnetic flux. That is,

$$\Phi_h = J_m\frac{\mu_0\pi R_1}{(R_2-R_1)}\int\limits_0^\infty f(\lambda)\left(1-e^{-2\lambda\cdot h}\right)J_1(\lambda R_1)\mathrm{d}\lambda . \quad (13)$$

The inductance of the analyzed system is defined as the ratio of the magnetic flux to the excitation current [16].

After introducing a new integration variable $y=\lambda R_1$ and the necessary identical transformations, we obtain the formula for the inductance at an arbitrary distance from the inductor to the massive conductor:

$$L_h = \frac{\mu_0\pi R_1^2}{(R_2-R_1)}\int\limits_0^\infty f(y,R_{1,2})\frac{1-e^{-y\cdot\left(\frac{2h}{R_1}\right)}}{y^2}J_1(y)\mathrm{d}y, \quad (14)$$

where $f(y,R_{1,2}) = \int\limits_y^{y\cdot\frac{R_2}{R_1}} x\cdot J_1(x)\mathrm{d}x$

The limit transition in (14) at $h\to\infty$ gives an expression for the inductance of the actual inductor winding without a massive conductor:

$$L_\infty \approx \frac{\mu_0\pi R_1^2}{(R_2-R_1)}\int\limits_0^\infty \frac{f(y,R_{1,2})}{y^2}J_1(y)\mathrm{d}y. \quad (15)$$

Let's return to the relative value of the current change in the solenoid winding under the influence of induction effects in a massive conductor. Substitute dependencies (14), (15) into the corresponding formula from the set of relationships (3). We obtain an expression that quantifies the effect of the induced current on the exciting current in the solenoid winding:

$$J_0=\frac{\Delta J}{J_\infty}=\left(\frac{L_\infty}{L_h}-1\right), \qquad (16)$$

where $$\frac{L_\infty}{L_h}=\frac{\displaystyle\int_0^\infty \frac{f(y,R_{1,2})}{y^2}\cdot J_1(y)\mathrm{d}y}{\displaystyle\int_0^\infty f(y,R_{1,2})\frac{\left(1-e^{-y\cdot\frac{2h}{R_1}}\right)}{y^2}\cdot J_1(y)\mathrm{d}y}.$$

Analysis of the effect of the induced current on the exciting current in the solenoid. Numerical evaluations by the found analytical expressions were obtained using standard programs (in particular, NIntegrate) from the Wolfram Mathematics – 7.10 package.

Graphs illustrating the functional dependence (16) are shown in Fig. 2.

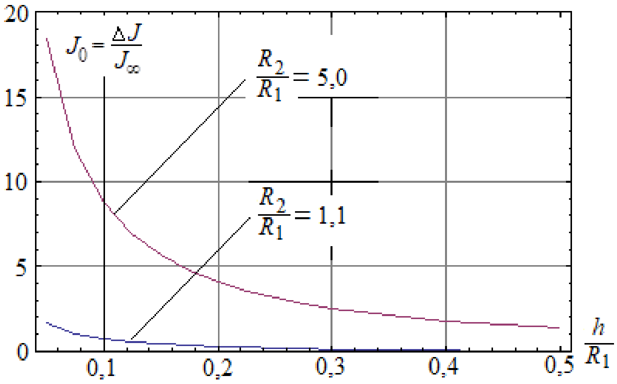

Fig. 2. Dependence of the current increase in the solenoid on the distance between it and the surface of the massive conductor

The results of the calculations showed that the influence of the induced current on the value of the current in the solenoid winding is mainly determined by the following factors:

- the influence on the exciting current increases when the distance between the solenoid and the massive conductor decreases and falls when the latter increases, which is fully consistent with a qualitative physical representation of the electromagnetic processes taking place;
- the influence of the excitation current largely depends on the geometry of the solenoid, that is, on the ratio between its external and internal dimensions;
- for a fairly thin solenoid ($R_2/R_1\approx1.1$) when $h/R_1>0.3$ the influence of the induced current is very insignificant, but when $h/R_1<0.05$ the influence of the induced current leads to an almost twofold increase in the current in the solenoid;
- an increase in the width of the solenoid winding leads to a significant increase in the influence of the induced current on the excitation current;
- a comparison of the calculation results for a «thin» and «wide» solenoid shows that an increase in the width of the winding leads to a significant distortion of the excitation current for fairly small and practically the most interesting ratios of the distance between the solenoid and its internal size.

Finally, we present the results of numerical estimates of the inductance of the «circular solenoid – massive conductor» system with normalization to the value of the inductance of a single isolated solenoid. The estimation data, as well as the results of direct calculations for currents, are also quantitative indicators of the influence of induction effects on the ongoing electromagnetic processes.

The results of calculations of the inductance of the «circular solenoid – massive conductor» system are presented in Fig. 3.

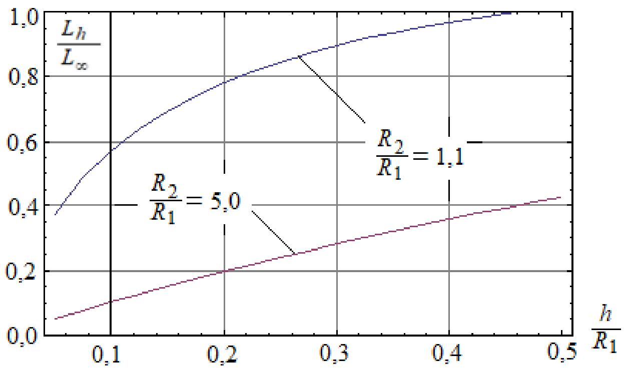

Fig. 3. Inductance of the «circular solenoid – massive conductor» system

It follows from the calculations that the inductance, as a proportionality factor between the excited magnetic flux and its exciting current, falls when the distance between the solenoid and the massive conductor decreases. Its largest value occurs at $h/R_1\to\infty$ (single solenoid). It should also be noted that the inductance increases with an increase in its width.

As a result, these facts mean the need to increase the amplitude of the current feeding the solenoid winding, in order to maintain the constant value of the magnetic flux while reducing the distance between the solenoid and the massive conductor.

From a physical point of view, the obtained results can be explained by the superposition of oppositely directed fields of the source current and the current induced in an ideal conductor. Moreover, the value of the «counter current» in the solenoid winding naturally decreases compared to the source current, which is due to the presence of the distance between the solenoid and the metal h. Obviously, when $h\to0$, the superposition of the source current and the «counter current» gives a zero result and the inductance of the system under study is $L_{(h\to0)}\to0$. The latter means the need for a significant increase in the source current to maintain a constant value of the excited magnetic flux.

Conclusions.

A theoretical analysis of the processes of excitation of eddy currents in a massive conductor by the field of a flat circular solenoid was carried out, numerical estimations of the influence of induced currents on the excitation currents in the solenoid were performed.

It is shown that the influence of the induced current on the current in the solenoid is very significant at small distances between the solenoid and the surface of the massive conductor.

It was found that an increase in the width of the solenoid winding leads to a significant increase in the influence of the induced current on the excitation current in the solenoid.

It is shown that the inductance of the «circular solenoid – massive conductor» system decreases with a decrease in the distance between the solenoid and the massive conductor and an increase in the radial dimensions of the solenoid, which requires an increase in the amplitude of the exciting current to maintain the given value of the magnetic flux in the system.

Conducting experiments with measurements of quantitative characteristics of the mutual influence of exciting and induced currents in various designs of electrical engineering systems is seen as a promising direction for further research.

Acknowledgments. The work was carried out and financed within the scope of research work under the state budget topic, state registration No. 0121U109610, code for program classification of expenditures and crediting 2201040: «Development of an energy-efficient machine complex for the transport support of the Armed Forces and the National Guard of Ukraine».

Conflict of interest. The authors declare no conflict of interest.

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Received 05.03.2023
Accepted 09.05.2023
Published 02.11.2023

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How to cite this article:
Batygin Yu.V., Yeryomina O.F., Shinderuk S.O., Chaplygin E.O. The mutual influence of exciting and induced currents in the circular solenoid – massive conductor system. *Electrical Engineering & Electromechanics*, 2023, no. 6, pp. 67-71. doi: https://doi.org/10.20998/2074-272X.2023.6.12