DOI: https://doi.org/10.15407/techned2024.01.012

ARKADIEV-MARKS CIRCUIT WITH RESONANT CHARGING OF CAPACITIVE ENERGY STORAGE IN MAGNETIC-PULSE INSTALLATIONS

Yu.V. Batygin*, S.O. Shinderuk, E.O. Chaplygin***, D.V. Fendrikov**
Kharkiv National Automobile and Highway University,
st. Yaroslava Mydrogo, 25. Kharkiv, Ukraine, 61002.
e-mail: 097931417e@gmail.com

The effective use of Arkadiev-Marx scheme with a resonant charging of capacitive storages in magnetic-pulse installations, as power sources, in technologies using the electromagnetic field energy is proposed and substantiated. It is found that during charging the maximum voltage amplitude at capacitor increases by number times equal to the quality factor of the charging circuit at the fundamental frequency of the harmonic expansion of exciting signal, but by ~34% less than possible maximum. The calculations of the characteristics of magnetic-pulse complex intended for the repair of damaged car bodies show the high efficiency of using the Arkadiev-Marx circuit with the resonant charging of capacitive storage. It is found that during the time of ~0.45 s the battery of 10 capacitors connected in parallel with total capacitance of ~100 μF can be charged up to voltage of ~7500 V with stored energy of ~2.8 kJ. The results of the work allow us to give recommendations on the practical increase in the efficiency of magnetic-pulse metal processing. References 16, figures 4.
***Key words*:** magnetic pulse processing of metals, Arkadiev-Marx circuit, series circuits, voltage resonance.

Introduction. The magnetic pulse processing of metals (MPMP by traditional abbreviation or electromagnetic metal forming, EMF by western terminology) relates without a doubt to the advanced technology of modernity. Here the contactless force effect on processing object, high productivity, wide opportunities for automating the production process, environmental friendliness and many other advantages take place. Physically the effectiveness of magnetic-pulse metal processing is due to the appearance of Lorentz force during the interaction of external magnetic field with conducting medium. The excited high-power electrodynamic forces are the magnetic pressure forces in classical special literature [1–2].

It should be noted that the natural repulsive action of Lorentz forces can be transformed into attraction. To do this, first of all, it is necessary to go to the region of sufficiently low operating frequency and, when processing the non-magnetic thin-walled metals, add an additional structural element that is an auxiliary screen. In the latter case, the attraction takes place as a force interaction between the exciting current and the current induced in the screen of metal [3–5]. In addition, as is known, the efficiency of force impact is determined by the amplitude of excited fields. Here the resonant effects, which significantly increase the level of generated electromagnetic energy, can play an important role [6].

Speaking about metal processing technologies with the use of electromagnetic field energy, it is necessary to mention the similar electrodynamic force effects in fundamental experiments, where the excitation of the strong and super-strong fields made it possible to form intense flows of charged particles that ultimately led to a new scientific direction known as plasma physics [7].

The power source is a mandatory component of equipment for any purpose, where the electromagnetic field energy is used. In MPMP, there are magnetic-pulse installations (MPI by traditional abbreviation). Basically, in the traditional version, they contain charging and discharging blocks. The first block (input) combines the step-up transformer, AC voltage rectifier and electronic control system. The second block as a discharging unit (output) is a serial active-reactive circuit in which a pre-charged capacitor is discharged at so-called inductor. The inductor along with the object being processed is a tool for performing a given production operation [1, 3, 4, 7]. Here, as mentioned above, in order to excite the attractive forces, it is necessary to go to low operating frequency. But when the implementation of technological process occurs with natural repulsion (magnetic pressure on the conductor), then the tools, i.e. inductors, should operate exclusively in the range of sufficiently high frequency of fields [1].

Returning to the charging block of capacitive storage devices in the traditional design of MPI, as disadvantages, we can point out its complication (rectifier, step-up transformer, etc.) and high cost.

ORCID: * https://orcid.org/0000-0002-1278-5621; ** https://orcid.org/0000-0002-6354-4174;
*** https://orcid.org/0000-0003-1448-6091

Recent theoretical and experimental works (for example, [6, 8]) in the field of creating the amplifiers of reactive electrical energy, based on resonant effects in active-reactive circuits, allow us to propose their use as charging units instead of traditional devices. In this case, the amplification of signal from external source occurs in the circuit of series connected active resistors, inductance coil (inductor) and capacitor (*RLC* circuit). Moreover the increase in voltage is due to the excitation of so-called "voltage resonance". The quantitative indicator of growth is equal to the quality factor of series circuit. As shown by theory and experiments, this indicator can practically reach very high values [6].

The possibilities for improving the efficiency of pulse systems are not limited to the above variants of chargers. Here one cannot ignore the well-known approaches related to the variation of load characteristics in discharge circuits (for example, these are the tools of magnetic-pulse technologies [9]), although capacitive energy storages still play a main role.

In the traditional version of MPI, the capacitors of the charging and discharge circuits are the same, since the same electrical energy storage devices are charged and discharged. This fact imposes the significant restrictions on the variability of the operating frequency of generated fields. That leads to certain difficulties when performing the specified production operations. It is possible to expand the variability if, in a magnetic-pulse installation, the battery of several capacitors is made according to Arkadiev-Marx circuit [10, 11]. In this case, the charge is produced at parallel connection, and the discharge takes place at series connection of individual capacitors. For each of them, the capacitance will be inversely proportional to their number. Accordingly the range of permissible operating frequency and the production capabilities of magnetic-pulse technological processes are growing. Note that, unlike the classic Arkadiev-Marx circuit, the capacitors connected in parallel are charged by exponentially growing sinusoidal voltage. The problem of "connecting-disconnecting" the specified number of capacitors in power electronics is solved by modern high-speed synchronous switches (for example, thyristor switches) with the microsecond or millisecond ranges depending on the operating frequency of charge or discharge [12, 13].

The purpose of this work consists in the proposal and justification of the efficiency of Arkadiev-Marx circuits with the resonant charging of capacitive storage devices in magnetic-pulse installations, as power sources, in the technologies using electromagnetic field energy.

Principle of action, problem statement. The equivalent circuit of magnetic-pulse installation with connected electric load in the form of inductor system as a tool for performing a given production operation is shown in Fig. 1, *a*.

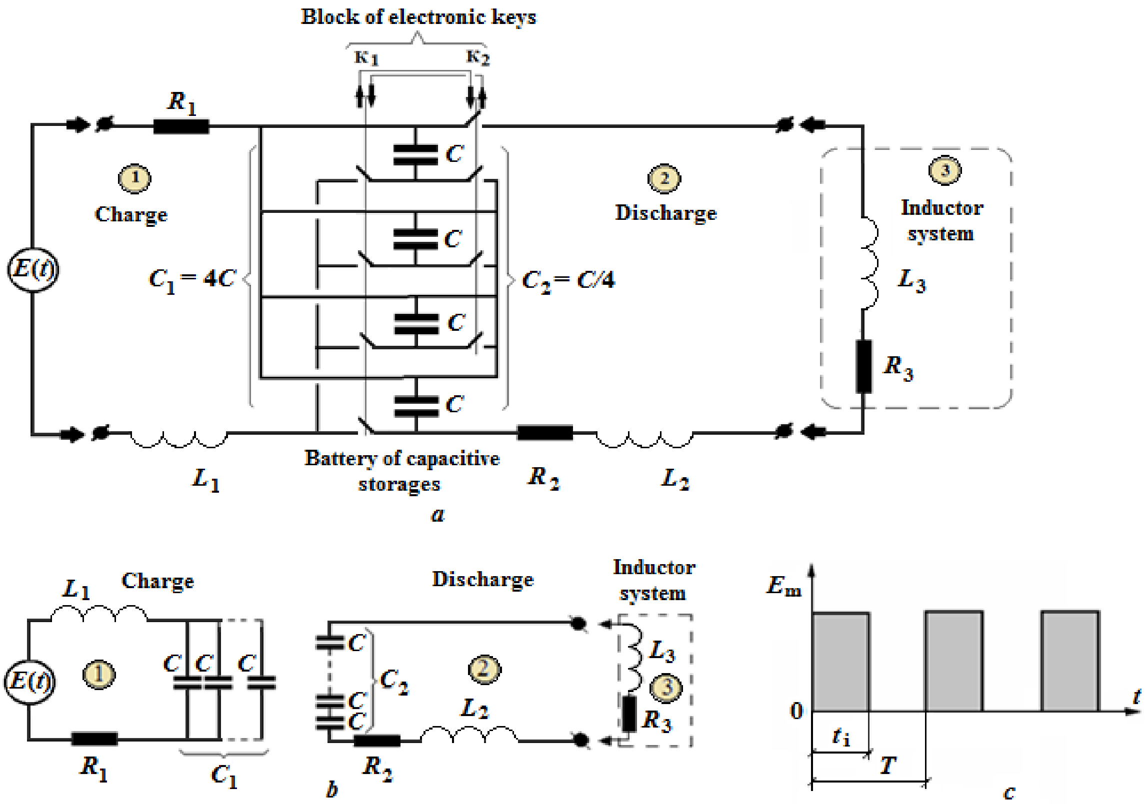

Fig. 1

In Fig. 1: the capacitive energy storage devices consist of n identical capacitors C; the charged capacitor C_1 and discharged capacitor C_2 are conventionally separated. The calculation models of charging and discharging are shown in Fig. 1, *b*. C_1 and C_2 are the resulting capacitance of batteries formed by combinations of n individual capacitors with capacitance C when they are connected in parallel (charging circuit) and in series (discharge circuit) so that $C_1 = n \cdot C$ and $C_2 = C/n$. Thus capacitors C are charged in their parallel combination (this is C_1), and the same previously charged capacitors are discharged, but already in their serial combination (this is C_2).

Remarks. The possible example of MPI with Arkadiev-Marx circuit is given for illustrative purposes. In the circuit batteries C_1 and C_2 are formed by 4 separate capacitors C. It should be added that in a similar way one can form any batteries with arbitrary number n of separate capacitors C, which are presented in Fig. 1, *a* and *b*.

Principle of operation. The battery of energy storage devices with capacitance C_1 is charged in circuit $R_1L_1C_1 - 1$ by external source $E(t)$ with closed switch K_1 and open switch K_2 to given voltage $U_{C0}(t)$. The subsequent discharge occurs when switch K_1 is open and switch K_2 is closed in circuit $(R_2 + R_3)$ $(L_2 + L_3)$ $C_2 - 2$. Here the electric load is connected in the form of inductor-tool (circuit $R_3L_3 - 3$).

Formulation of problem. The formulation of problem and the assumptions made are determined by the purpose of this work with addition about the possible time dependence of power source voltage in the charging circuit.

The processes in the charging and discharge circuits of the proposed circuit proceed independently from one another. This allows us to consider them separately from each other. The calculation models of charging and discarding, according to which the processes occur, are shown in Fig. 1, *b*.

The power supply voltage is represented by unipolar periodic sequence of rectangular pulses. The time dependence of excitation voltage is shown in Fig. 1, *c*, where T is the pulse repetition period, t_i is the duration of each pulse, E_m is the pulse amplitude.

Remarks. The accepted assumption is of interest for practice when the power supply generates the rectangular voltage pulses with given amplitude-time parameters. For example, for independent MPI in electromagnetic hammer mode, it can be a battery with periodic disconnection of charging circuit.

The duration of the pulses of supply power is arbitrary. The repetition frequency in the sequence is equal to the natural resonant frequency of charging circuit 1: $\omega_1 = 2\pi/T$.

In order to avoid energy losses, the charging and discharge circuits are made with the minimum possible resistances and, accordingly, sufficiently small damping factor: $\delta_{1,2}/\omega_{1,2} << 1$, where $\delta_{1,2}$ are the damping factors, $\omega_{1,2}$ are the frequency of the charging and discharge circuits, respectively.

The electric load as a solenoid (inductor-tool for performing a given production operation) is connected to the electrical output of proposed MPI circuit, the inductance of which is much greater than the inductance of MPI in discharge, that is $L_3/L_2 >> 1$.

Remarks. The last two assumptions are typical requirements for the equipment of magnetic-pulse technologies introduced into modern industrial production [1, 3, 4, 7].

Calculated relationships. When solving the problem, we will use the operator method to calculate the electric circuits. Because the charge and discharge are independent, the electromagnetic processes occurring in the circuits can be considered separately (Fig. 1, *b*).

<u>Charge (equivalent circuit in Fig. 1, *b* on the left).</u>

As mentioned above, the capacitive storage is charging at parallel connection of separate n capacitors C, then $C_1 = n \cdot C$.

The differential equation in voltage across capacitor $U_C(t)$ in Laplace-space at zero initial condition $\left\{U_C(0) = \frac{dU_C(0)}{dt} = 0\right\}$ has the form [14]:

$$p^2 U_C(p) + 2\delta_1 \cdot pU_C(p) + \omega_1^2 \cdot U_C(p) = \omega_1^2 \cdot E(p), \tag{1}$$

where p is the Laplacian operator; $U_C(p) = L\{U_C(t)\}$; $E(p) = L\{E(t)\}$; $\delta_1 = L_1/2R_1$ is the damping factor; $\omega_1 = \frac{1}{\sqrt{L_1 \cdot C_1}}$ is the natural frequency of the circuit.

Solution of equation (1) permits to find L-image of the charging voltage through capacitor [15]:

$$U_C(p) = F(p) \cdot E(p), \tag{2}$$

where $F(p) = 1/(p+\delta_1)^2 + \omega^2$; $\omega = \sqrt{\omega_1^2 - \delta_1^2}$.

The original function from its Laplace transform of expression (2) can be written as the convolution of functions [15]:

$$U_C(t) = F(t) * E(t), \tag{3}$$

where $F(t) \leftrightarrow F(p)$; $E(t) \leftrightarrow E(p)$ are the originals of factors in (2).

According to formulation of the problem, the energy dissipation is minimal; this means that the value of relative damping factor is sufficiently small ($\delta_1/\omega_1 << 1$) and the frequency of excitation signal is equal to the natural frequency of studied resonant circuit $\left(\omega \approx \omega_1 = \frac{1}{\sqrt{L_1 \cdot C_1}}\right)$. In this case, the expression for $F(p)$ in (2) can be simplified. After passing to the space of originals, we obtain the following dependence [15]:

$$F(p) \approx \frac{1}{\omega_1} \cdot \frac{\omega_1}{(p+\delta_1)^2 + \omega_1^2} \leftrightarrow F(t) = \frac{1}{\omega_1} \cdot e^{-\delta_1 \cdot t} \cdot \sin(\omega_1 \cdot t). \tag{4}$$

The convolution of functions in expression (3), taking (4) into account, with phase dependence instead of time dependence in expanded form, is presented by

$$U_C(t) = \omega_1 \cdot \int_0^t e^{-\delta_1 \cdot (t-\tau)} \cdot \sin(\omega_1 \cdot (t-\tau)) \cdot E(\tau) d\tau, \tag{5}$$

where $\delta_1 = \delta_1/\omega_1$ is the relative damping factor.

The amplitude-time dependence of excitation voltage from the sequence of rectangular oscillating pulses (Fig. 1, *c*) can be represented by Fourier series in cosines of multiple arcs [14, 15]:

$$E(t) = \frac{2}{\pi} \cdot E_m \cdot \sum_{k=0}^{\infty} \delta_k \cdot E_k \cdot \cos\left(\omega_k \cdot \left(t - \frac{t_i}{2}\right)\right), \tag{6}$$

where $E_k = \sin(\omega_k \cdot t_i/2)/k$, $\omega_k = 2\pi k/T$ are the amplitudes and relative frequency of the harmonics of spectrum analysis, respectively; $\delta_k = \begin{cases} 0.5, & k = 0, \\ 1.0, & k \neq 0 \end{cases}$ – is the Kronecker-Cappelli symbol [15].

Let us substitute expansion (6) by expression (5).

After integration, taking into account that $\delta_1/\omega_1 << 1$, we obtain the following amplitude-time dependence for voltage across the capacitor:

a) the fundamental harmonic corresponding to voltage resonance,

$$U_{C-\text{main}}(t) \approx \frac{2}{\pi} \cdot Q_1 \cdot E_m \cdot \left(1 - e^{-\delta_1 \cdot t}\right) \cdot \sin\left(\omega_1 \cdot \left(t - \frac{t_i}{2}\right)\right), \tag{7}$$

where $\omega_1 = 2\pi / T = (\sqrt{L_1 \cdot C_1})^{-1}$ is the resonance frequency, $Q_1 = (\omega_1 \cdot L_1)/R_1 = 1/(\omega_1 \cdot C_1 \cdot R_1)$ is the quality factor of charging circuit at the resonant frequency

b) higher harmonics

$$U_{C-\text{high}}(t) \approx -\frac{2}{\pi} \cdot E_m \cdot e^{-\delta_1 \cdot t} \cdot \sin(\omega_1 \cdot t) \cdot F\left(\frac{t_i}{T}\right), \tag{8}$$

where $F\left(\frac{t_i}{T}\right) = \frac{2}{\pi} \cdot \sum_{k=0,2...}^{\infty} \delta_k \cdot \left(\frac{\sin\left(\omega_k \cdot \frac{t_i}{2}\right)}{k}\right)^2$ – is the quantitative indicator of the contribution of higher harmonics (taking into account the constant component of exciting signal) in the formation of charging voltage at capacitor.

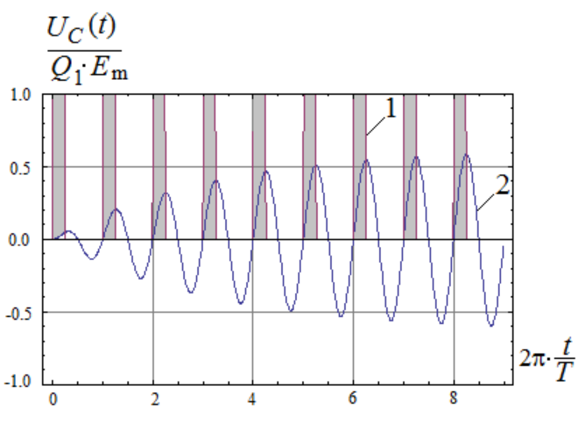

Fig. 2

Let us analyze the obtained results.

- Regardless of time characteristics of power source voltage, the harmonic signal is excited at capacitor. The time dependencies of voltages in charging circuit are shown in Fig. 2, where 1 relates to excitation signal from power source, $t_i/T = 0.1 \to 0$; 2 corresponds to voltage across capacitor.

Remarks. The time dependence on the relative (time/period) length t_i of pulses in input voltage – t_i is set by multiplier $\sim\sin\left(\omega_1 \cdot \left(t - t_i / 2\right)\right)$, but not by directly proportional multiplier (t_i/T). This follows from the solution of corresponding differential equation, and is explained by the fact that, in the end, the charge physically occurs at basic resonant frequency of sinusoidal (not constant) voltage.

- The fundamental harmonic of voltage at capacitor (7) contains factor $-2/\pi$; this means the decrease in amplitude value by ~ 34% in comparison with excitation signal.
- The amplitude of fundamental harmonic of voltage at capacitor includes the product of source supply voltage E_m and quality factor of charging circuit at fundamental frequency of the harmonic expansion of excitation signal Q_1; this means the increase in charging voltage by ~Q_1 times.
- When reaching the stationary state, the charging voltage at fundamental frequency reaches its maximum ($U_{C-\text{main,max}} \approx (2/\pi)\cdot Q_1\cdot E_m$), the amplitude of higher harmonics tends to zero as $e^{-\delta_1 \cdot t}\Big|_{t \gg \frac{1}{\delta_1}} \to 0$.
- The contribution of higher harmonics to the formation of voltage at capacitor is minimal with short duration of excitation pulse in periodic sequence of their repetition ($t_i/T \to 0$) and is maximum with the duration of excitation pulse approaching to the signal repetition period ($t_i/T \to 1$). The dependence of the quantitative indicator of contribution of higher harmonics to the formation of voltage at capacitor on the time characteristics of excitation voltage is shown in Fig. 3.

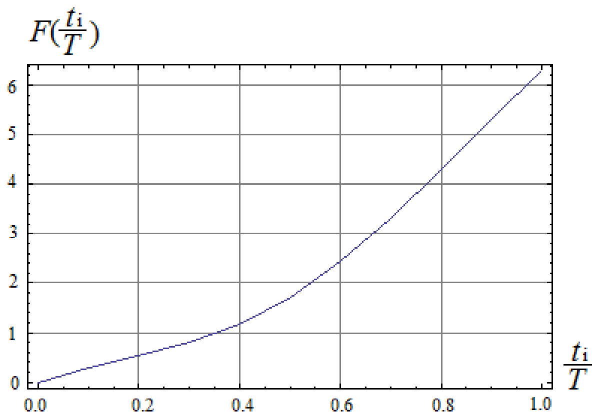

Fig. 3

<u>Discharge (equivalent circuit in Fig. 1, *b* on the right).</u>

The capacitive storage is discharging at series connection of identical separate n capacitors C, then $C_2 = C/n$.

When performing the calculations, we assume that the entire battery, like each individual capacitor, is charged up to amplitude value $U_{C0} = (2/\pi)\cdot Q_1\cdot E_m$ after reaching of which the discharge of all capacitors occurs simultaneously.

The main characteristics of discharge circuit are described by the following dependencies:

a) the total initial charging voltage at the battery

$$U_{C02} = n \cdot U_{C0} = n \cdot \left(\frac{2}{\pi} \cdot Q_1 \cdot E_m\right), \tag{9}$$

b) stored energy

$$W_0 = \frac{C_2 \cdot U_{C02}^2}{2} = \frac{2C_2}{\pi^2} \cdot \left(n \cdot Q_1 \cdot E_m\right)^2 \tag{10}$$

c) frequency of discharging signal

$$\omega_2 = \frac{1}{\sqrt{\left(L_2 + L_3\right) \cdot C_2}}. \tag{11}$$

Note that the resonant frequency of discharging signal increases by a factor of n compared to the frequency when individual capacitors are connected in parallel. The last fact can be compared with the well-known circuits for magnetic pulse installations, where the capacitance at the charge and discharge is the same [1, 3, 4, 7].

Second, as following from the above relations, the energy stored in capacitor bank, when they are connected in parallel (charge), is equal to the energy when they are connected in series (discharge). That is the corresponding law of conservation of energy is satisfied; this indicates the validity of noted relationships [14].

Thus the oscillatory discharge of capacitor in voltage resonance mode starts immediately after the end of its charge. At $\sqrt{\frac{(L_2+L_3)}{C_2}} >> 0.5\cdot(R_2+R_3)$ the current in the circuit is described by known exponentially decaying harmonic time dependence [14]:

$$J_2(t) \approx \frac{2}{\pi}\cdot\frac{n\cdot E_m}{(R_2+R_3)}\cdot\frac{Q_1}{Q_2}\cdot e^{-\frac{1}{2Q_2}\cdot\omega_2\cdot t}\cdot\sin(\omega_2\cdot t), \tag{12}$$

where $\varphi = \omega_2 \cdot t$ is the current phase, t is the time from the moment of charge beginning, $Q_2 = (\omega_2 \cdot (L_2 + L_3))/(R_2 + R_3) = 1/(\omega_2 \cdot C_2 \cdot (R_2 + R_3))$ is the quality factor in the representations according to the voltage resonance in discharge circuit.

Taking into account the values of the quality factors and frequency (11), the dependence for discharge current (12) is reduced to a form which is more convenient for subsequent numerical evaluations

$$J_2(t) \approx \frac{2}{\pi}\cdot\frac{E_m}{R_1}\cdot e^{-\frac{1}{2Q_2}\cdot\omega_2\cdot t}\cdot\sin(\omega_2\cdot t). \tag{13}$$

The energy of magnetic field in inductor-tool is equal to [14]:

$$W_{L_3}(\varphi) = \frac{2}{\pi^2}\cdot L_3\cdot\left(\frac{E_m}{R_1}\right)^2\cdot e^{-\frac{1}{Q_2}\cdot\omega_2\cdot t}\cdot\sin^2(\omega_2\cdot t). \tag{14}$$

Under assumptions of the problem as it follows from expression (14), the energy reaches its maximum when $(\omega_2 \cdot t_{\max}) \to \pi/2$. In this case we have:

$$W_{L_3\max} = \frac{2}{\pi^2}\cdot L_3\cdot\left(\frac{E_m}{R_1}\right)^2\cdot e^{-\frac{\pi}{2Q_2}}. \tag{15}$$

Let us calculate the part of the energy stored in the capacitors of capacitive storage by (10) which is transformed into the magnetic field energy of inductor-tool (14). Expression (14) should be divided by expression (10). Taking into account the dependencies previously obtained, after analogous transformations, we obtain the expression for the relative energy of magnetic field in inductor-tool:

$$\frac{W_{L_3}(t)}{W_0} = \frac{L_3}{L_1}\cdot e^{-\frac{1}{Q_2}\cdot\omega_2\cdot t}\cdot\sin^2(\omega_2\cdot t). \tag{16}$$

To estimate by the maximum and using expression (15), we can write that $W_{L3\max}/W_0 = (L_3 \cdot e^{-\pi/2\,Q_2})/L_1$.

Let us analyze the results following from (14)–(16).

- The energy in inductor-tool is generated by the harmonic function decaying exponentially in time (15).
- The amplitude of magnetic field energy in inductor-tool depends only on resistance R_1 of charging circuit elements (14, 15), but is independent on resistance of discharge circuit R_2.
- The value of resistance R_2 affects only the degree of signal attenuation in discharge circuit, since it is included in expression for its quality factor.
- Since the electromagnetic field energy in inductor-tool and the electromagnetic energy stored in capacitor are interconnected by directly proportional relationship between the inductance of inductor itself and the inductance of charging circuit (16), the operation of the proposed circuit can be conditionally interpreted as the operation of a transformer with primary winding L_1 and secondary winding L_3.
- In practice, relation (16) gives a possibility to achieve a certain efficiency of stored energy conversion directly into the energy of conductive object processing.

Example of calculation. Using the obtained dependencies, we determine the parameters of magnetic-pulse complex with resonant charging of the capacitive energy storage devices connected by Arkadiev-Marx circuit. This complex can be used, e.g., for repair technologies of modern vehicles.

When performing the calculations, we are focused on characteristics of the operating magnetic-pulse complex based on MPI-2 installation and created at the Kharkov National Automobile and Highway University (Ukraine) for production operations relating to contactless repair of damage in the metal coatings of car bodies.

Note that the proposed example of magnetic-pulse complex of a similar purpose should be independent and operate on a constant-voltage source, for example, car batteries with output voltage up to ~100 V [16].

Magnetic-pulse complex with resonant charging of the capacitive energy storage devices connected by Arkadiev-Marx circuit. The schematic diagram of equivalent circuit is represented in Fig. 1, *a*.

1. The charging circuit (Fig. 1, *b*, on the left).

1.1. The storage battery with voltage E_m = 96 V is a power source.

Remarks. The combination of 4 batteries connected in series with voltage of ~24 V for any one of them is possible.

1.2. The electronic switch that provides the formation of rectangular voltage pulses (meanders) with repetition rate equal to the natural frequency of charging circuit – 1 (qualitative time dependence is presented in Fig. 1, *c*).

1.3. Capacitors: 10 units (n = 10), each capacitor has capacitance $C_0 = 10\cdot10^{-6}$ F and total capacitance at their parallel connection $C_1 = n\cdot C_0 = 100\cdot10^{-6}$ F.

1.4. Solenoid with inductance $L_1 = 15\cdot10^{-3}$ H.

1.5. Resistance of current-conducting elements $R_1 \approx 0.1\ \Omega$.

1.6. Natural resonant frequency of the circuit $\omega_1 = \dfrac{1}{\sqrt{L_1\cdot C_1}} = 816.497$ Hz, $f_1 \approx 130$ Hz.

1.7. Quality factor of the circuit – $Q_1 = (\omega_1\cdot L_1)/R_1 = 1/(\omega_1\cdot C_1\cdot R_1) \approx 122.5$.

1.8. The voltage of fundamental resonant harmonic at capacitors in steady state mode $U_{C0} = (2/\pi)\cdot Q_1\cdot E_m \approx 7485$ V.

Remarks. The rise time under stationary conditions is determined by inequality $t_e > L_1/R_1$. In this case, the rise time $t_e \approx 0.45$ s provides the deviation of voltage from the amplitude of not more than ~5% under steady-state conditions.

1.9. Stored energy $W_0 = (C_1\cdot U^2_{C0})/2 \approx 2801$ J.

Summary. During ~0.45 s the battery of 10 capacitors connected in parallel with total capacitance of ~100 F can be charged up to voltage of ~7500 V (taking into account ~5% deviation from the steady-state amplitude). The stored energy should be ~2.8 kJ.

For comparison: the maximum charging voltage and the largest stored energy of MPI-2 (designed in Kharkov National Automobile & Highway University) are 2 kV and 2 kJ, respectively.

2. Discharge circuit (Fig. 1, *b*, on the right).

2.1. Capacitors: 10 units (n = 10), with capacitance $C_0 = 10\cdot10^{-6}$ F and total capacitance at their-series connection $C_1 = C_0/n = 1.0\cdot10^{-6}$ F.

2.2. Let us specify the inductance of the tool as $L_3 = L_1 = 0.015$ H and $L_3 >> L_2$, then the internal inductance of the installation can be neglected (the internal inductance of MPI-2 is ~$0.4\cdot10^{-6}$ H).

Remarks. The inductance of the tool is not always determined by its design according to a given production operation. This value can be varied by introducing so-called matching device. The device, in principle, is a step-down air-cooled transformer with the multi-turn primary winding connected to discharge circuit, and with the single-turn secondary winding, to the output of which the power single-turn solenoid is connected. This solenoid is in fact the tool of force impact on processed object. It should be noted that the matching device can significantly increase the current in operating zone and thereby significantly increase the amplitude of generated electrodynamic force [6].

2.3. Resistance with current-limiting resistor $R_2 = 100\cdot R_1 = 10.0\ \Omega$ (by practical experience of magnetic-pulse installations [1, 6]).

2.4 The natural resonant frequency of discharge circuit with load is equal to $\omega_2 = 1/\sqrt{L_3\cdot C_2} = 8164.97$ Hz, $f_2 = 1299.49 \approx 1300$ Hz (the operational frequency of the complex with MPI-2 is equal to ~ 1500 Hz).

2.5. The quality factor of the circuit $Q_2 = (\omega_2\cdot L_3)/R_2 = 1/(\omega_2\cdot C_2\cdot R_2) \approx 12.25$.

2.6. The time dependence of the magnetic energy generated in the inductor-tool is given in Fig. 4.

Summary. The magnetic energy oscillating in time with maximal ~2500 J is generated in the inductor-tool. The frequency is ~1300 Hz. These characteristics are mainly determined by the inductance of dis-

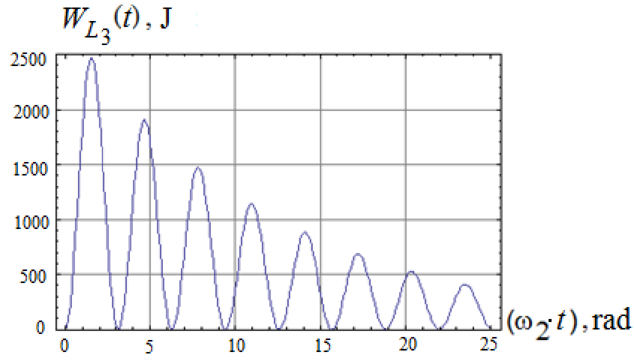

Fig. 4

charge circuit. The inductance rise makes it possible to increase the maximum of generated energy, but with corresponding decrease in the frequency of flowing current.

Conclusion.

1. The effective use of Arkadiev-Marx circuit with the resonant charging of capacitive storages in magnetic-pulse installations, as power sources, in the technologies using electromagnetic field energy is proposed and grounded.

2. As found, during charging the maximum voltage amplitude at capacitor increases by number times equal to the quality factor of charging circuit at fundamental frequency of exciting signal, but by ~ 34% less than possible maximum.

3. It is revealed that during discharging the energy in inductor-tool is generated by harmonic function exponentially decaying in time and its amplitude depends only on resistance of the elements of charging circuit.

4. It is shown that the operation of proposed circuit during discharging of capacitive storage can be conditionally interpreted as the operation of transformer with primary winding L_1 (inductance of charging circuit) and secondary winding L_3 (inductance of inductor-tool); this permits to achieve a certain efficiency of stored energy conversion directly into energy of processing of given conductive object.

5. The calculations of the magnetic-pulse complex using Arkadiev-Marx circuit (similar to operating complex created at the Kharkiv National Automobile&Highway University) and the resonant charging of the capacitive storage devices designed to repair damaged car bodies illustrate the efficiency of proposed solution.

1. Psyk V., Rich D., Kinsley B.I., Tekkaya A.E., Kleiner M. Electromagnetic forming. A review. *Journal of Material Processing Technology*. 2011. No 211. Pp. 787-829.

2. Altenbach H., Konkin V., Lavinsky D., Morachkovsky O., Naumenko K. Deformation analysis of conductive metallic components under the action of electromagnetic fields. *Engineering Research*. 2018. Vol. 82. No 4, Pp. 371-377. DOI: https://doi.org/10.1007/s10010-018-0285-x .

3. Bay F., Jeanson A.-C., Zapata J.A. Electromagnetic forming processes: material behaviour and computational modelling. *Procedia Engineering*. 2014. Vol. 81. Pp. 793-800. DOI: https://doi.org/10.1016/j.proeng.2014.10.078.

4. Du L., Li X., Xia L., Zhang X., Lai Z., Han X., Li L., Cao Q. Numerical and experimental verification of an iterative coupling method for analyzing the Lorentz-force-driven sheet metal stamping process. *The International Journal of Advanced Manufacturing Technology*. 2021. Vol. 115. No. 7-8. Pp. 2161-2173. DOI: https://doi.org/10.1007/s00170-021-07268-z .

5. Kudasov Y.B., Surdin O.M., Platonov V.V., Kozabaranov R.V., Maslov D.A., Makarov I.V., Svetlov A.S., Popov E.Y. Metal plate deformation under magnetic field pulse of complex shape. *Journal of Applied Physics*. 2019. vol. 126. No 8. Pp. 084901. DOI: https://doi.org/10.1063/1.5108823 .

6. Batygin Yu.V., Shinderuk S.O., Chaplygin E.O., Fendrikov D.V. Double-circuit resonant electric power amplifier for magnetic-pulse processing of metals. *Tekhnichna Elektrodynamika*. 2022. No 3. Pp. 29–36. DOI: https://doi.org/10.15407/techned2022.03.029.

7. Shneerson G.A, Dolotenko M.I., Krivosheev S.I. Strong and superstrong pulsed magnetic fields generation. Berlin: Walter de Gruyter, 2014. 429 p.

8. Lykhovyd Yu.M. The resonant power amplifier. Patent 103215 Ukraine. 2015. (Ukr)

9. Batygin Yu.V., Shinderuk S.O., Chaplygin E.O. Mutual influence of currents in a flat inductor system with solenoid between two massive conductors. *Electrical Engineering & Electromechanics*. 2021. No 6. Pp. 25-30. DOI: https://doi.org/10.20998/2074-272X.2023.6.12

10. Mesyats G.A. Pulse energy and electronics. M: Nauka, 2004. 704 p. (Rus)

11. Gladkov V.S., Magda I.I., Melnikov P.N., Rudakov V.V. Megavolt frequency pulse generator with a half-maximum duration of 30 ns. *Pribory i tekhnika eksperimenta*. 2009, No 3. Pp. 53-58. (Rus)

12. Wu Sh., Cui Sh. Pulsed alternators technologies and application. Springer International Publishing AG, part of Springer Nature, 2021. 276 p.

13. Kondo M., Lim S., Koita T., Namihira T., Tokoro Ch. Application of electrical pulsed discharge to metal layer exfoliation from glass substrate of hard-disk platter. *Results in Engineering*. 2021. No 12. Pp. 100306.

14. Thomson J.J. Elements of the mathematical theory of electricity and magnetism. Publisher: Wentworth. 2016. 510 p.
15. Kantorovic L. Mathematics for natural scientists. fundamentals and basics. N-Y: Springer, 2016. 526 p.
16. Bazhynov O.V., Smyrnov O.P., Sierikov S.A., Dvadnenko V.Y. Synergetic automobile. Theory and practice. Kharkiv, 2011. 236 p. (Ukr)

УДК 621.318

СХЕМА АРКАДІЄВА-МАРКСА З РЕЗОНАНСНИМ ЗАРЯДОМ ЄМНІСНИХ НАКОПИЧУВАЧІВ ЕНЕРГІЇ В МАГНІТНО-ІМПУЛЬСНИХ УСТАНОВКАХ

Ю.В. Батигін, С.О. Шиндерук, Е.О. Чаплигін, Д.В. Фендриков
Харківський національний автомобільно-дорожній університет,
вул. Ярослава Мудрого, 25. Харків, Україна, 61002.
e-mail: 097931417e@gmail.com

Запропоновано та обґрунтовано ефективне використання схеми Аркадьєва-Маркса з резонансним зарядом ємнісних накопичувачів у магнітно-імпульсних установках як джерелах потужності у технологіях з використанням енергії електромагнітних полів. Отримано, що при заряді максимальна амплітуда напруги на ємності збільшується в число разів, що дорівнює добротності зарядного контуру на основній частоті гармонічного розкладання збуджуючого сигналу, але на ~34% нижче можливого максимуму. Розрахунки характеристик магнітно-імпульсного комплексу, призначеного для ремонту пошкоджених автомобільних кузовів, показали високу ефективність використання схеми Аркадьєва-Маркса з резонансним зарядом ємнісних накопичувачів. Так, отримано, що за час ~0.45 с батарея з 10 паралельно з'єднаних конденсаторів загальною ємністю ~100 мкФ може бути заряджена до напруги ~7500В у разі запасеної енергії ~2.8 кДж. Результати роботи дають змогу надати рекомендації щодо практичного підвищення ефективності магнітно-імпульсної обробки металів. Бібл. 16, рис. 4.

Ключові слова: магнітно-імпульсна обробка металів, схема Аркадьєва-Маркса, послідовні контури, резонанс напруг.

Надійшла 02.11.23
Остаточний варіант 18.12.2023