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New concept of a modern magnetodynamic installation based on the principle of superposition of pulsating electromagnetic forces

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Abstract
In this study, the principle superposition of the vertically directed pulsating electromagnetic forces, having the phase shift relative to each other ψphase = 2π/3, has been substantiated as an effectiveness method using of pulsating EM forces in magnetodynamic installation and EM pumps for increasing efficiency of their working. For practically using superposition of three pulsing EM forces principle and application in EM pump for molten metals has been developed original design of modern magnetodynamic installations with three-phase inductions channels and three-phase electromagnet. Developed and experimentally tested the original physical (on solid turns) and computer simulations model (by electric equivalent circuit) and shown validations of obtaining superposition of three vertical unidirectional pulsating electromagnetic forces in three-throw working area (Fem₁, Fem₂, Fem₃) at producing of triple DC component, creates pressure (∑Fem = 1.5jB₀C₀Cos(φ)) and minimal vibration component. It is shown that in comparison with the one/two-phase systems of create electromagnetic force (existing AC EM pump) the developed decision allows to create in three times higher value of the electromagnetic force/pressure.

Keywords: electromagnetic forces, superposition, magnetodynamic installation, pressure, modeling.

Introduction
Known on today existing magnetodynamic installations (MDI), as an induction channel furnace with electromagnetic pump, have a widely application in industrial casting production at melting and complex processing of non-ferrous and ferrous metals and alloys [1, 2]. Such equipment has been developed in the Physico-Technological Institute of Metals and alloys of National Academy of Sciences of Ukraine (PTIMA NASU).

The classic solution of MDI, for example by magnetodynamic installation for aluminum alloys MDN-6A, is designed with dual combined W-shaped channel, with two independently controlled inductors for each channel, and additional electromagnet, for creation of external alternating magnetic field (B). The poles of C-shape electromagnet are located in place connecting of bottom horizontal induction channels with central branches (pumping pipe), forming T-shaped working area (WA). The main working principle of this MHD-equipment is based on the interaction of AC electric current (I) with external AC magnetic field (B), to provide to generating of unidirectional pulsating electromagnetic force and pumping of the molten metal from WA, on metal duct, to casting molds as an EM pump [1].

The basic requirement for existent magnetodynamic installations (MDI) and EM pumps there are still in increasing pressure characteristics (pem - electromagnetic pressure), values of mass transferring flow rate (Q) at controlled electromagnetic casting (pouring). Additionally, at applying MDI for processing Al-alloys to need improve the hydrodynamic efficiency of physical methods influencing on melt for implement of the electrophysical melt processing due to action of high densities of AC current, the maximum value of the melt moving velocity, etc.

Issue of raising the operational characteristics of MDI can be solved by increasing the hydrothermal and hydraulic efficiency of working area (on example of traditional three-throw WA), where are to create of the electromagnetic pressure. Known, that in existing MDI for aluminium alloy the real coefficient transformation of the electromagnetic force to hydraulic pressure makes no more than 12%. Improving efficiency of existing MHD-pump possible due to decreasing of hydraulic resistance in WA by means optimizing of it configuration and geometry, eliminate the negative impact of electrodynamic effects, optimizing the spatial (in cross section) redistribution of current density j and magnetic field (B) [4]. However, by the theoretical calculation and estimations, such approaches (named below) can provide to increase the magnitudes of electromagnetic force (in WA) on 15 ± 25% and a hydraulic pressure up to 30%. But, increasing the amplitude values of the AC current density (j) in the WA is limited by critical values (for molten Al alloys - j < Jcritical(Al) = 25 A/mm²), that at the exceeding to make the risky appearing of the theta-pinch effect in melt into channel [3]. Increasing the intensity of the magnetic field in WA requires the development of expensive and large size complicated electromagnets, and can be provide to appearing negative “edge effect” [1].

A radical solution for increasing the efficiency of induction MHD-pump for molten metals, which use AC electrical power for induce of electric current and an external magnetic field, to consist in creation the conditions of vector superposition (addition) of several pulsating unidirectional electromagnetic forces in one local WA of MDI. Due to perform
increase the total component of electromagnetic force, which create the hydraulic (static) pressure in molten melt (static), at simultaneously decreasing useless action of vibration (pulsation) component.

**Presentation of the problem**

According to the canons of the MDI operating theory [1] the electromagnetic pressure there is as action result of the created in MDI of volumetric electromagnetic forces (EMF) (1) to output branch of three-throw working area WA (or cruciform working area for some known solutions MHD-pumps) [1]:

\[
F_{em.f} = \frac{df_{em}}{dV} = j \cdot B = J_m \sin(\omega t) \cdot B_m \sin(\omega t + \varphi) = 0.5(J_m B_m \cos \varphi) - 0.5J_m B_m \cos(2\omega t + \varphi) \quad (1)
\]

\[
p_{em} = \frac{1}{4ab} \int_V \text{Re}[JB^*]dV = 2JB_1 \cos \varphi \quad (2)
\]

where \( J_m \) and \( B_m \) – peak values of \( j \) (density of electric AC), \( A/mm^2 \), and \( B \) (magnetic field), \( T \); \( \varphi \) - angular frequency rad/sec; \( \varphi \) – angle of shift phase between \( j \) and \( B \), rad; \( p_{em} \) - electromagnetic pressure (2); \( Pa \); \( a \), \( b \) - the length and width \( WA \), \( m \); \( Re \) - real part of the vector product; \( V \) – volume of \( WA \), \( m^3 \); \( I \) - height of \( WA \), \( m \).

In equations (1) the constant component \( 0.5J_mB_m\cos(\varphi) \) to create the pressure but component \( 0.5J_mB_m\cos(2\omega t + \varphi) \), provides of doubled frequency vibratory action in melt \( (2\omega = 2\pi t) \). Thus, in the existing MDI for making hydraulic pressure in melt has been use only 50% of peak value of generated in WA MDI pulsating EMF [1].

By proposed in this study “concept” the improving efficiency of pulsing electromagnetic force transformation to hydraulic pressure in MDI (as in electromagnetic pumps for molten melts) there is possible at making superposition (vector summation) of three vertical directed pulsating electromagnetic forces \( (F_{em.f1}, F_{em.f2}, F_{em.f3}) \), which have phase shift relative to each other \( \psi_{phase} = 2\pi \). At them each pulsing EMF with own angle of phase shift can be create by localized single or two-phase alternating currents AC \( (I) \) and magnetic field \( (B) \), which also have a phase shift relative to each other \( \psi_{phase} = 2\pi/3 \).

Thus, the resulting superposition of three vertically unidirectional pulsating electromagnetic forces (PEMF) in one local WA provide to create in three time higher component of EMF, which make a hydraulic pressure in melt \( (\sum F_{em.f} = 1.5J_mB_m\cos(\varphi)) \), but vibrating useless action, due to phase shift angle to each other \( (2\psi_1 = 0, 4\pi/3, 8\pi/3) \), have a minimal values and cancel each (Fig. 1). For cases that \( I_1 = I_2 = I_3 = I_0 \) and \( B_1 = B_2 = B_3 = B_0 \) there is vibration component equal “0”.

\[
F_{em.f1} = (I_1 \cdot \cos(\omega t)) \cdot (B_1 \cos(\omega t + \varphi)) = 0.5 \cdot I_1 \cdot B_1 \cdot \cos(2\omega t + \varphi); \quad (3)
\]

\[
F_{em.f2} = (I_2 \cdot \cos(2\pi/3 + \omega t + \varphi)) \cdot (B_2 \cos(\omega t + 2\pi/3 + \varphi)) = 0.5 \cdot I_2 \cdot B_2 \cdot \cos(2\omega t + 4\pi/3 + \varphi); \quad (3)
\]

\[
F_{em.f3} = (I_3 \cdot \cos(4\pi/3 + \omega t)) \cdot (B_3 \cos(\omega t + 4\pi/3 + \varphi)) = 0.5 \cdot I_3 \cdot B_3 \cdot \cos(2\omega t + 8\pi/3 + \varphi)
\]

\[
\sum F_{em.f} = F_{em.f1} + F_{em.f2} + F_{em.f3} = 0.5 \cdot 3 \cdot (I_0 \cdot B_0) \cdot \cos(\varphi) = 0
\]

![Graph result of superposition](image)

**Fig. 1:** Graph result of superposition \( (\sum F_{em.f}) \) in three-throw one local working area (WA) of three unidirectional pulsating electromagnetic forces \( (F_{em.f1}, F_{em.f2}, F_{em.f3}) \), with phase shift between each one \( -120^\circ \) \( (\psi_1 = 0, \psi_2 = 2\pi/3; \psi_3 = 4\pi/3) \).

New original design for the three phase’s of magnetodynamic pump and furnace was developed to the technical implementation and experimental verification of the superposition principle (Fig. 2).

As opposed to existing MDI with W-shaped two induction channels, in the proposed here the new design and solution MDI have an induction channel with three vertically connected induction channels, which have one vertical pumping pipe (Fig. 2 and 3). Each from three induction channels to connected in the vertical plane on 120° angle each other (Fig.
Horizontal triple channel (Fig. 3) to consist of three horizontal slopes (Fig. 3), which connected at an angle of 90° with a central/vertical channel and with 120° angle relative to each other in a horizontal plane. In this case under central pumping channel/pipe to forming the three-throw one local working area (WA).

In addition, as opposed to existing, in new design MDI the three phase’s electromagnet (Fig. 3) has three poles, that there are directed at angle of 90° to three-throw WA and arranged horizontally from three sides at angle of 60° - relative to lateral horizontal channels and 120° angle relative to each other.

According to the ideas in formed in three-throw WA (Fig. 3) at the interaction of mutually perpendicular horizontal electric currents I*1, I*2, I*3 with three alternating magnetic fields (B1, B2, B3), in pole gap of three poles electromagnet, at switching the windings in three-phase electricity network by a “triangle” - formed three pulsating electromagnetic forces directed vertically (Fem.f.1, Fem.f.2, Fem.f.3). The AC I1 (I1* = I1 + I2) has induced by the first and second inductors, I2 (I2* = I2 + I3) by second and third inductors and I3 (I3* = I3 + I1) by first and third inductors at switching of each coils to three-phase electrical network by a “star”.

Each one electromagnetic force there are to changing in dynamic mode (Fig. 4) in time intervals - t = π/2 + ψi, equal to 1/3 period (T1 = 2π/3 = ψi). Next, the process generation and changing for each electromagnetic force (directed vertically) continues in a time cycle - 2π, 4π, etc.

The model/simulator as a solid coil was developed for experimental verification of proposed idea (Fig. 5). Such model to consist of three horizontal slopes, which were made from aluminum plate 10 mm thick, height up to 80 mm, connected in the horizontal plane at an angle 120°). All three horizontal slopes of physical simulation model was connected at 90° angles to central cylindrical aluminum rod (diameter 40 mm), forming in result three-throw WA MDI (Fig. 5), 3-phase’s electromagnet of simulation model was performed from three not connected each other horizontal magnetic cores (cross section 70×90 mm and a length of 400 mm), with the single layer low voltage windings (30 turns), and withal are used as the inductors.

For induce of AC in model used induction method at placing by two turns (coil) of copper cable (cross section 120 mm²) on each inductor. The ends (clamps) each copper cable has connected to the ends of the horizontal slopes of
model, forming shorted secondary coils in each of the three electric circuits by "star" (Fig. 5). Powering of the electromagnet/inductors in the model the low-voltage transformers from MDN-6A and voltage from 20 to 80 Volts used. For experimental measuring and recording the electromagnetic force impact, the central vertical rod of solid model/simulator was attached to strain gauges sensor, which measured the weight equivalent of ponderomotive force action (F = mg).

At the experimental test of solid simulation model has been performed at creation in the poles gap of electromagnet magnetic field in range from 0.01 to 0.15 T, and the AC current in the horizontal coil respective to own magnet pole 0.4 to 2 kA. The registered in solid simulation model the triplex electromagnetic force, in weight equivalent, has been amounted from 2.1 to 8.5 kg (20 ÷ 84 Newton). In comparisons with equivalent of two-phase model operation (simulation existing MDI with one pulsing EMF, - 2.3 ÷ 2.4 kg, or 21 ÷ 22 N) the new method and design of 3-phases MDI was in 3.5 ÷ 3.8 times effectively by ponderomotive power (greater than on ≈ 200 ÷ 280%). Obtained result to shown possibilities to increasing the hydraulic pressure in liquid aluminium from 30÷35 (in existing) to 90 ÷ 100 kPa (1 bar) or no less than 3.5 meter (1.25 meter against existing today) in new developing 3-phases MDI for aluminium alloys.

![Fig. 5: Experimental model of the triplex inductions channel with three-throw WA (aluminum plate)](image)

![Fig. 6: The results of computer simulation creating a superposition of three pulsating electromagnetic forces (the equivalent electric circuit) (B = 0.1 T, I = 2 kA, f = 50(60) Hz).](image)

For analytical testing principle of three pulsating electromagnetic forces superposition, the computer / physical model (Simulink model - Matlab 7.0), based on an equivalent electric circuit, was developed and successfully tested. At testing computer electric equivalent model the real parameters of inductors and electromagnet (in range of electric currents from 2 to 12 kA and magnetic field 0.01 to 0.3 T – accordingly to analogue with MDN-6A) was used. The result of computer simulation (Fig. 6) has confirmed the principle of superposition three-pulsating electromagnetic forces and found, that the vibration component of EMF was not more than 5 % from the triplex constant unidirectional electromagnetic force, created in three-throw one local working area developing 3-phases EM pump for molten melts and metals.

**Conclusion**

Theoretical, analytical and experimental modeling (using physical and computer simulation) showed efficiency of the developed method of superposition of three pulsating electromagnetic forces in the original developed design of three-throw working area prototype of new design magnetodynamic installations for molten metals for heating, stirring, holding, processing and electromagnetic pumping, dosage and low pressure casting technologies. Shown, that in comparison with existing MDI for aluminium alloys (MDN-6A), by superposition principle to possible increase the hydraulic pressure in molten metals in 3 times from 30 kPa to 100 kPa, at same electric current density (j) in inductions channel and intensity of magnetic field (B) into electromagnet poles gap. New principle of superposition to provide the maximally using of pulsation electromagnetic forces power for transformation its energy to moving molten metals in AC EM pump due to optimal assuming useful and canceling useless components of pulsating EM forces. Obtained technical and theoretical results can be applied at creation new effectively design of modern magnetodynamic installations for non-ferrous and ferrous metals and alloys in modern foundry and casting industries.

**References**