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Assessment, Calculation And Choice Of Design Data For Reversible Reciprocating Electric Machine

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Abstract

Nowadays in order to perform the reciprocating motion of the working mechanisms as well as to operate the electrical generators powered by internal combustion engines the rotary (rotational) electrical machines are used predominantly. This is achieved by the means of power transmission, complicating the design and reducing the efficiency of a drive. The use of electrical reciprocating machines allows to overcome these disadvantages. It should be noted that the cylindrical structures of reciprocating electric machines with permanent magnets, the efficiency of which reaches 93 - 95% are the most effective ones. However, the rarity and the lack of mass production for this type of machines and concrete recommendations for their design is conditioned by the necessity of research performance aimed at the search of optimal design solutions. The article describes the types of reciprocating electrical machines and offers the results of dynamic characteristics numerical simulation for the three versions of a reciprocating cylindrical machine design with the permanent magnets of 10 kW, with the translator oscillation frequency of 20 Hz and the stroke of 120 mm. The most effective design parameters of a reciprocating electrical machine are determined on the basis of its specific performance, such as: the power density per surface unit of an air gap W/m2; the specific power per unit of stator volume W/m3; specific power per unit of an electric machine weight, W/kg; specific power per unit of rare earth metals in use NdFeB, W/kg; power density per unit of copper weight in the stator windings W/kg. The shape analysis of EMF graph was also considered. It appeared on the stator windings in the generator mode to determine the most optimal design parameters of an electric machine performance with a minimum non-sinusoidal ratio. The next step of modeling is the testing and correction of a numerical model for anelectric reciprocating machine by its comparison with the real dynamic characteristics of a prototype.

Keywords: reciprocating electric machine, linear generator, linear motor, design choice

1. INTRODUCTION

Nowadays in order to perform the reciprocating motion of working mechanisms as well as the electrical generators powered by internal combustion engines the rotary (rotational) electrical machines are used predominantly. This is achieved by the means of kinematic transmissions, complicating the design and reducing the efficiency of a drive. The use of electrical reciprocating machines allows to overcome these disadvantages.

However, a low prevalence of this type of machines should be noted, despite the large number of its species [1,2,3,4,5].

The most promising ones are the cylinder structures of electric reciprocating machinery, whose efficiency reaches 93 - 95% [6], while the efficiency of the flat machinery makes only 60 - 62% [7]. This is achieved due to the lack of longitudinal edge effect at a closed magnetic conductor of reciprocating cylindrical machines [8].

Then the authors of the article consider only reciprocating electric machines with a closed magnetic conductor of cylindrical structure.

Among the various types of reciprocating cylindrical electric machinery it is advisable to allocate the machines with permanent magnets [8,9], which are characterized by the highest specific parameters [7], and are used already as the power units for hybrid vehicles, as well as independent supply sources (generators) [10,11], the efficiency and reliability of which is achieved due to the absence of additional mechanical gears at the operation of a linear generator in a single unit together with an internal combustion engine [12,13].

The use of permanent magnets in electrical machines based on rare earth metals makes it possible to reduce sharply the mass of an excitation system, and allows to obtain an electric machine of a non-contact type. The latter circumstance is decisive in the case of a linear generator selection as the source of energy for electric power systems of autonomous objects [12].

2. CLASSIFICATION OF RECIPROCATING ELECTRICAL MACHINES WITH PERMANENT MAGNETS

One of the possible classifications for reciprocating electrical machines with the permanent magnets is based on various design variants of a movable member shown by Figure 1 [12]:

a) movable element with movable coils;
b) movable element with permanent magnets.

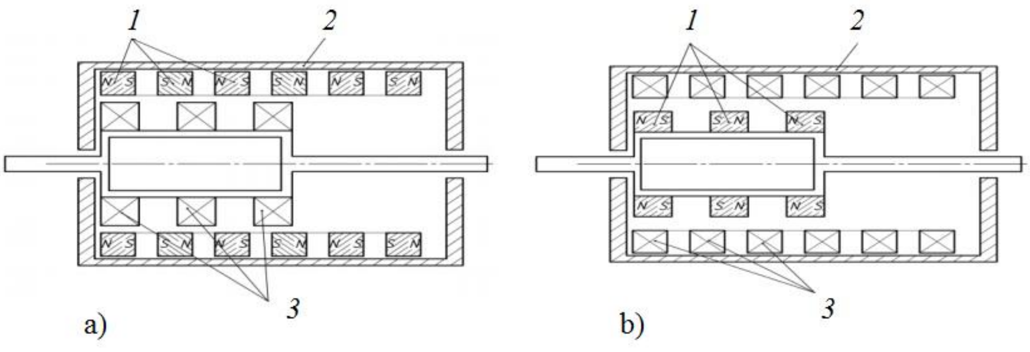

Fig. (1). – Possible designs of reciprocating electrical machines with permanent magnets 1 - permanent magnets; 2 - yoke; 3 - winding

The advantage of the structure shown by Figure 1, b is of the implementation of movable magnetic system made of annular permanent magnets with radial and axial magnetization in a so-called Halbach array [14]. Halbach array is a sequence of permanent magnets with cyclically variable angular orientation of a magnetization vector. At that, first of all, in the ideal case the magnetization vector is varies sinusoidally in space, thereby minimizing the pulsation of the clutch between teeth without the use of special measures in the form of cutting grooves, and secondly, the magnetic fluxes are closed in an electrical machine without scattering outside - it is the effect of self-screening [15]. The absence of reciprocating cylindrical electrical machines serial production with the permanent magnets and the specific recommendations for their design necessitates research aimed at the obtaining of some optimal design solutions and the analysis of electric machines dynamic characteristics. The final choice of the most efficient reciprocating electric machine with permanent magnets is determined by its specific parameters obtained after numerical simulation.

The aim of this work is the numerical analysis of dynamic processes in a reversible reciprocating electric machine and the revealing of the most effective design parameters of an electric machine based on the determination of its specific characteristics, as well as the analysis of EMF graph curves arising on the stator windings in the generator mode in order to determine the design parameters with a minimum non-sinusoidal ratio.

3. DESIGN SPECIFICATIONS OF RECIPROCATING ELECTRICAL MACHINE

Three variants of a linear electric machine embodiment were developed with the permanent magnets shown by Figures 2a, 2b, 2c, respectively. The main design parameters for three investigated variants are presented in Table 1.

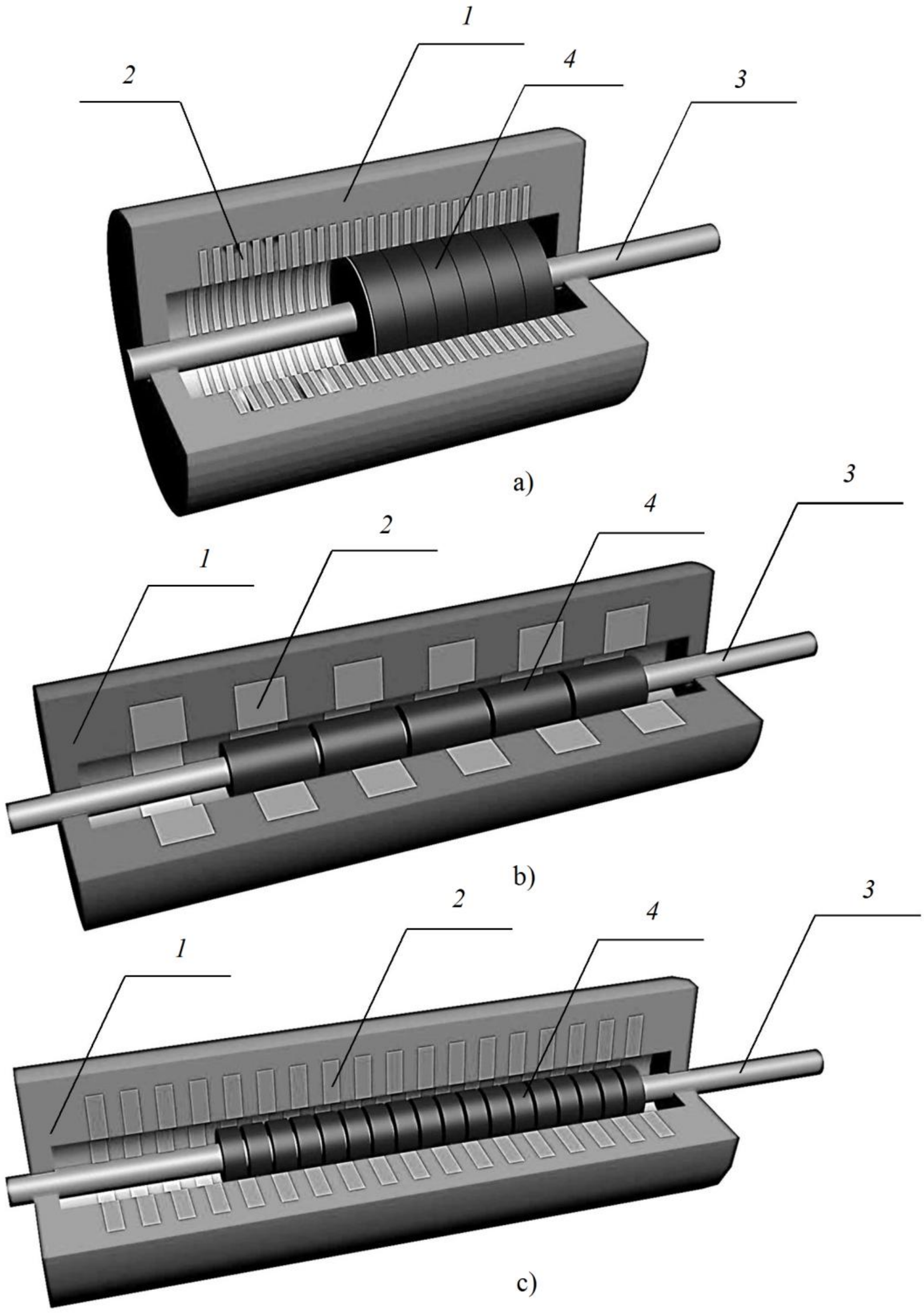

Fig. (2). – Investigated specimen of reciprocating electric machines *1* – stator yoke; *2* – stator copper winding; *3* – titanium hollow rod; *4* – annular permanent magnets NdFeB

Table 1. Main parameters of reciprocating electric machines

Parameter	Value by variants		
	Variant 1	Variant 2	Variant 3
Translator parameters			
Permanent magnet width, mm	24	72,8	18
Air gap between constant magnets, mm	0,75	5	3,5
External diameter of permanent magnet, mm	106	50	50
Inner diameter of permanent magnet, mm	100	25	25
Number of permanent magnets, pieces.	6	5	18
The length of permanent magnet base, mm	150	384	384
Outer diameter of permanent magnet base, mm	100	25	25
Diameter of hollow titanium rod, mm	25	25	25
Rod wall thickness, mm	5	5	5
Rod length, mm	500	750	750
Stroke length of translator, mm	120	120	120
Annular permanent magnet weight, kg	0,2	0,52	0,15
Permanent magnet base weight, kg	1	0,35	0,35
Rod weight, kg	1,5	1,1	1,1
Translator weight, kg	2,8	3,7	3,7
Translator oscillation frequency, Hz	20	20	20
Translator movement speed, m/s	4,8	4,8	4,8
Stator parameters			
Groove thickness for a phase winding placement, mm	5	42	14
Groove depth, mm	30	42	42
The distance between the winding grooves, mm	5	42	14
Number of grooves with windings, pieces	27	6	18
Stator active length, mm	270	504	504
Stator length, mm	360	594	594
Stator internal diameter, mm	112	75	75
Stator external diameter, mm	232	200	200
Winding weight, kg	0,4	4,2	1,4
Stator weight, kg	88,6	132,1	144,4
General parameters of electric machine			
Electric machine weight, kg	91,4	136	148,3

The investigated dynamic system is shown by Figure 3. It is assumed that NS translator of an electric machine performs a reciprocating motion and related to a rotor rotating shaft of an asynchronous electric motor 2 by the use of a reductor 3, a crank mechanism 4, and a split sleeve 5, which allows to disconnect the machine translator from a drive in the motor mode. At that the methods of electrical circuit theory are used for numerical calculation of transient and steady-state processes in the electrical circuit of the generator 6 and the analysis of its energy and dynamic characteristics. The control of loads is performed by the frequency control with a frequency converter 1. A fluid system with valves 7 is provided is provided to cool an electric machine.

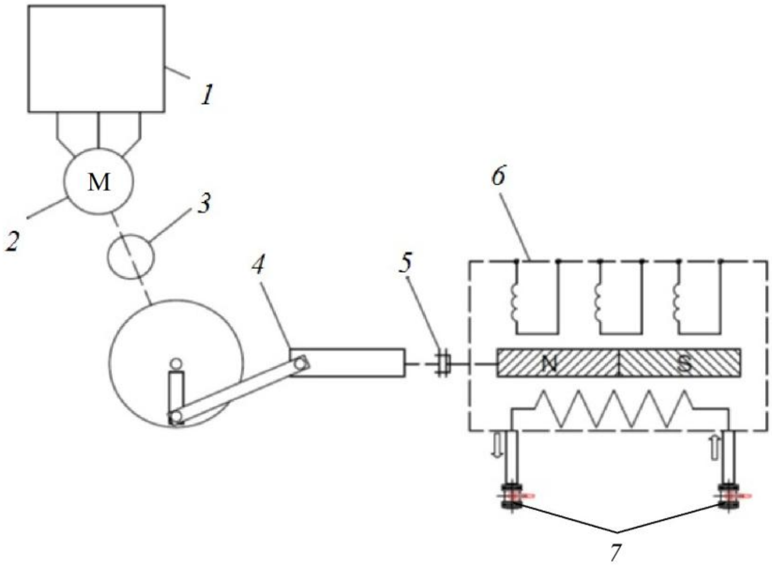

Fig. (3). – The scheme of investigated energy conversion dynamic system 1 - frequency converter; 2 - asynchronous electric motor; 3 - gear; 4 - crank mechanism; 5 - split sleeve; 6 - generator electric circuit; 7 - cooling system valves

In order to calculate the magnitude of a magnetic flux produced by the permanent magnets and linked to the stator coil, and the dependence of stator winding inductance according to the position of a translator, the calculation of a magnetic field in the active zone of a linear generator is performed by a finite element method. At that the following assumptions were used:

- The magnetic properties of the stator magnetic poles and the massive translator poles do not depend on the magnetic field value;
- The magnetic material is an isotropic one;
- The influence of eddy currents in a stator and a translator may be neglected and a field problem may be considered in the magnetostatic approximation.

In order to utilize the magnetic flux of permanent magnets more fully a combined magnetic system of ring magnets with a radial and axial magnetization as Halbach array was considered. The magnetic flux distribution is shown by Figure 4 [7]:

a) the design of the machine with ring magnets;
b) the magnetic flux lines.

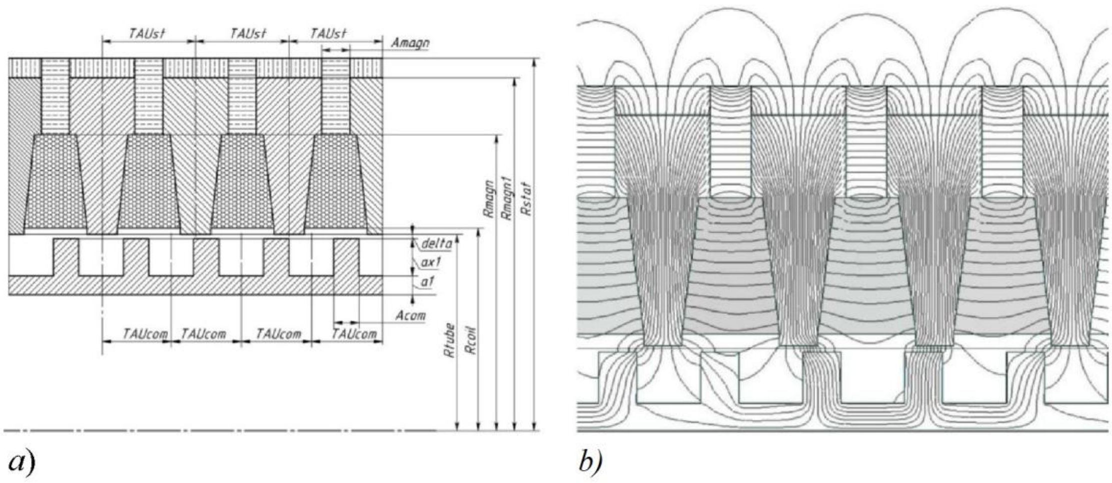

Fig. (4). – Magnetic flux distribution diagram for a reciprocating electric machine

The generator design is characterized by an axial symmetry that allows us to consider the field problem as a two-dimensional one in a cylindrical coordinate system.

4. CALCULATION OF RECIPROCATING ELECTRIC MACHINE DYNAMIC PARAMETERS

During the dynamic calculation the movable element parameters - movement S and velocity V were set by the following dependencies [7,16,17] whose graphs are shown by Figure 5 [7]:

$$S = L_{\text{шт}} \cdot \sin(2\pi t / f),$$

where $L_{\text{шт}}$ – movable element stroke;
f – frequency, Hz;

$$V = \frac{dS}{dt} = \frac{L_{\text{шт}} \cdot 2\pi}{f} \cos\left(\frac{2\pi t}{f}\right).$$

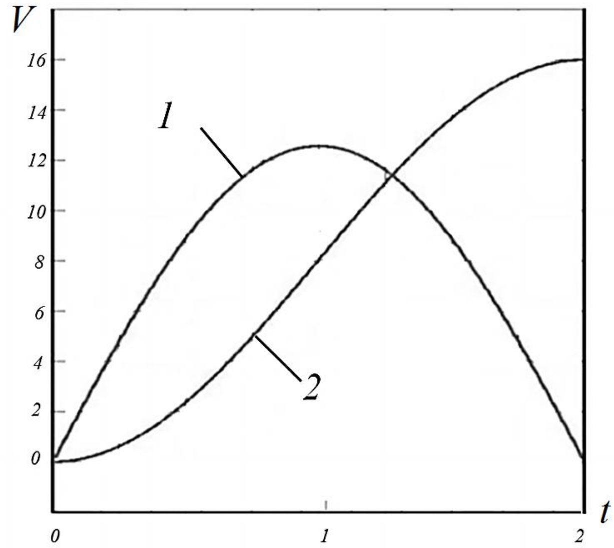

Fig. (5). – Graphs of the movable element movement *1* – velocity; *2* – movement

Unlike conventional electrical machines of translational motion, the movable element of an investigated dynamical system makes a reciprocating movement, i.e. during the motion of an armature there are the instants corresponding to the upper and lower position in which it is stationary with respect to a stator. These points do not produce the conversion of electromechanical energy that provides certain peculiarities for the shape of a generator idle running and for the passing of dynamic processes in the "generator - load" system. Let's consider the features of electromagnetic processes in a generator.

The problem was solved in the axisymmetric formulation. An axisymmetric finite element model of an electric machine was developed for this. It was based on the models presented in [6,18,19], which simulated a nonstationary problem of a movable element moving along a stator magnetic system. The eddy currents in the magnetic conductors and permanent magnets were not taken into account. As a machine load was purely active, then the electrical power of the machine P was calculated according to the following formula:

$$P = 2 \cdot f \cdot r \cdot \int_0^{T/2} I_{\text{сум}} dt,$$

where

$I_{\text{сум}}$ – total instant current, A;

r – equivalent resistance;

T – oscillation period, $T = 1/f$, c.

The model difference is the following: it contains two systems of differential equations for an electrical state of phases, as well as the system of magnetic state algebraic equations for the equivalent magnetic circuit:

$$(u) = (R_\varphi)(i_\varphi) + (L_\varphi)(Di_\varphi) + (K_E)(D\Phi_{11});$$

$$(R_{11})(\Phi_{11}) - (R_{12})(\Phi_{22}) = (K_F)(i_\varphi);$$

$$-(R_{21})(\Phi_{11}) + (R_{22})(\Phi_{22}) = (i_c);$$

$$(r_c)(i_c) + (L_i)(Di_c) + (L_c)(v)(i_c) = -(D\Phi_{22}) - (v)(\Phi_{22}),$$

where
(R_ϕ), (L_ϕ), (r_c), (L_c) – resistance and phase inductance matrices;
(i_ϕ), (i_c) – vectors (matrices-columns) of the instantaneous values for unknown phase currents;
D – time differentiation operator;
(Φ_{11}), (Φ_{22}) – vectors of the flow instantaneous values;
(K_F) – slot MMF matrix distribution;
(R_{11}), (R_{22}), $(R_{12}) = (R_{21})$ – the matrices of self and mutual magnetic impedancesof an equivalent circuit;
$(K_E) = (K_F^T)$ – the matrix of instant EMF values development in the phases containing nonzero elements $a_{n.n-1} = -\upsilon/2t_z$ and $a_{n.n+1} = \upsilon/2t_z$ [20].

The vector of voltage instant values applied to the inductor winding determines the machine operation mode. For example, at a symmetric system of the power supply voltage it is expressed as follows:

$$(u) = \begin{pmatrix} U_m \sin \omega t \\ U_m \sin(\omega t - \frac{2\pi}{3}) \\ U_m \sin + \frac{2\pi}{3}) \end{pmatrix}.$$

After a series of transformations one may obtain:

$$(\Phi_{11}) = (a_{11})(i_\varphi) + (a_{22})(i_c);$$

$$(\Phi_{12}) = (b_{11})(i_\varphi)(\Phi_{22}) + (b_{22})(i_c),$$

where

$(a_{11}) = (A)(R_{11}^{-1})(K_F);$

$(A) = (R_{12}^{-1} R_{22} - R_{11}^{-1} R_{12})^{-1};$

$(b_{11}) = (B)(R_{12}^{-1})(K_F);$

$(b_{22}) = (B)(R_{22}^{-1});$

$(B) = (R_{12}^{-1} R_{11} - R_{22} R_{12})^{-1}.$

A system of equations is obtained:

$$\left.\begin{array}{r}(A_{11})(Di_\varphi) + (A_{12})(Di_c) = (u) - (R_\varphi)(i_\varphi)\\ (A_{21})(Di_\varphi) + (A_{22})(Di_c) = -(d)(i_c) - (v)(a_{11})(i_\varphi)\end{array}\right\}$$

where

$(A_{11}) = (L_\phi) + (K_E)(b_{11}),$

$(A_{12}) = (K_E)(b_{22}),$

$(A_{21}) = (a_{11}),$

$(A_{22}) = (L_c) + (a_{22}),$

$(d) = (r_c) + (L_c)(v) + (v)(a_{22}).$

The system is reduced to Cauchy form:

$$\left.\begin{array}{r}(Di_\varphi) = (K_1)(u) - (K_2)(i_\varphi) + (K_3)(i_c)\\ (Di_\varphi) = (K_4)(u) - (K_5)(i_\varphi) + (K_6)(i_c)\end{array}\right\}$$

where

$(K_1) = (A_{11}^{-1}) + (A_{11}^{-1})(A_{12})(A_A)(A_{21})(A_{11}^{-1});$

$(K_2) = (A_{11}^{-1})(R_\varphi) + (A_{11}^{-1})(A_{12})(A_A)(B_B);$

$(K_3) = (A_{11}^{-1})(A_{12})(A_A)(d);$

$(K_4) = -(A_A)(A_{21})(A_{11}^{-1});$

$(K_5) = (A_A)(B_B);$

$(K_6) = (A_A)(d);$

$(A_A) = (A_{22} - A_{21}A_{11}^{-1}A_{12})^{-1};$

$(B_B) = (A_{21})(A_{11}^{-1})(R_\phi) - (v)(a_{11}),$

or

$(DI) = (T_1)(u) + (T_2)(I),$

where

$$(I) = \begin{pmatrix} (i_\varphi) \\ (i_c) \end{pmatrix}; \ (T_1) = \begin{pmatrix} (K_1) \\ (K_4) \end{pmatrix}; \ (T_2) = \begin{pmatrix} (K_2) & (K_3) \\ (K_5) & (K_6) \end{pmatrix}.$$

The above equation is solved numerically with the respect to the vector of all currents. From this vector the phase current vectors are revealed:

$$(i_c) = (S_S)(I),$$

where

$(S_S) = -(R_{21})(S_{TB}) + (R_{22})(S_{TA});$
$(S_{TA}) = ((a_{11})...(a_{22}));$
$(S_{TB}) = ((b_{11})...(b_{22})).$

The vector of instant flow values in the yoke parts may be written as follows:

$$(\Phi_{22}) = (S_{TA})(I).$$

The vector of induction instant values in the gap parts:

$$(B_{22}) = (DI)(\Phi_{22}),$$

where (DI) – the matrix of derivatives development concerning the coordinate with non-zero elements

$$a_{n.n-1} = -1/2t \ ; \ a_{n.n+1} = 1/2t \, .$$

The force which makes an impact on the translator is determined as the product of a transposed matrix (B_{22}^T) on the matrix of rod currents (i_c):

$$F = \left[(DI)\left((S_{TA})(I)\right)\right]^T \left((S_S)(I)\right).$$

In order to take into account the translator movement speed changes the matrices of the corresponding coefficients become the functions of the translator velocity, and the system of equations is added by the following equation:

$$F - F_c = mdv/dt \, ,$$

where m – moveable parts weight;
F_c – movement resistance force.

5. RESULTS OF DYNAMIC PROCESS NUMERICAL SIMULATION FOR RECIPROCATING ELECTRICAL MACHINE AND THE SELECTION OF THE MOST EFFECTIVE DESIGN PARAMETERS

According to the results of numerical simulation the analysis of EMF graph curve was taken into account. This curve appeared on the stator windings in the generator mode to determine the most optimal design parameters of an electric machine performance with a minimum non-sinusoidal ratio.

According to the graph shown in Figure 6, it is seen that the EMF graph on the stator windings has the minimum ratio of nonsinusoidality for the first option.

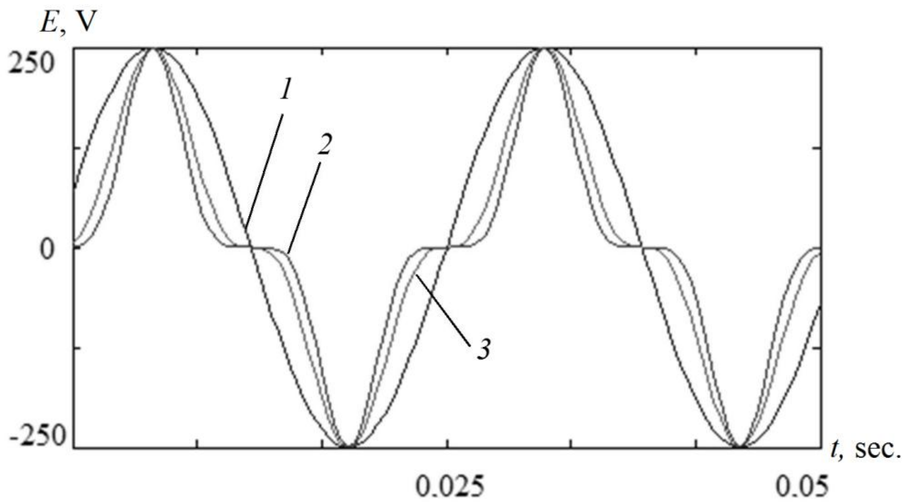

Fig. (6). – EMF graphs appearing at the stator windings in a generator mode for the three variants of a reciprocating electric machine 1 - the first variant; 2 - the second variant; 3 - the third variant

After the calculations the following specific characteristics of electrical machines were obtained with the oscillation frequency of 20 Hz and a translator working stroke of 120 mm, shown in Table 2.

Table 2. Specific characteristics of a reciprocating electric machine

Specific characteristic	Value by variants		
	Variant 1	Variant 2	Variant 3
Power density per area unit of an air gap, W/m2	4310	6980	8460
Specific power per unit of stator volume W/m3	657100	530516	530516
Power density per unit of an electrical machine weight, W/kg	109,4	73,5	67,4
Specific power per mass unit of rare earth metals in use NdFeB, W/kg	8333	3846	3704
Specific power per mass unit of copper in the stator windings W/kg	925	396	411

6. SUMMARY

On the basis of the above specific characteristics and taking into account the specific characteristics of EMF graphs curve on the stator windings in the generator mode, one may conclude that the first embodiment of an reciprocating electric machine is the most preferred one.

7. CONCLUSION

Thus, the obtained specific characteristics based on analysis of EMF graph curve appearing on the stator windings in the generator mode, allow us to determine the most effective design parameters of a reversible reciprocating electric machine. The next step is the testing and the modeling of a reciprocating electric machine numerical model by its comparison with the real dynamic characteristics of a prototype.

CONFLICT OF INTERESTS

The author confirms that the presented data do not contain any conflict of interest.

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