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Selection And Justification Of Design Parameters For Reversible Reciprocating Electric Machine

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Abstract

The article presents the technique of design parameters choice and substantiation for a reversible electric machine with reciprocating motion in the engine and generator mode. The aim of the study is to calculate the rational parameters of an electric machine to ensure maximum energy efficiency taking into account the given conditions. The concept of parallel simulation (Co-Simulation) is proposed. The concept is based on the data exchange between the programs Matlab/Simulink, CatiaV5 and a special program.

The concept makes it possible to exchange the data between the marked programs to improve the efficiency, accuracy, simulation and optimization of the parts structural dimensions.

The optimization block is developed in OptimizationToolbox application to determine the structural dimensions of a reciprocating electric machine stator and translator. The problem of the objective function optimization is solved in the application OptimizationToolbox of the program Matlab. The program that allows you to calculate the parameters of an objective function based on genetic algorithm is written by the language Matlab.

These values are placed in a 3D model of a linear electric machine in CAD CATIAV5 for later kinematic and strength calculation.

The modeling data in the software package Matlab-Simulink based on the programs written in Matlab are transferred to the project table Excel, which is synchronized with the CAD CATIAV5. CATIAV5 develops 3D models of an electric machine stator and translator. The strength calculations of a translator basis are performed and the fastening of magnets on a translator is carried out for the subsequent development of project documentation.

The developed method allows to determine the rational parameters of an electrical machine during a design stage, followed by an adjustment during the manufacture of an experimental sample.

Keywords: reciprocating electric machine, simulation, three-dimensional modeling, optimization, energy efficiency

1. INTRODUCTION

The energy strategy of Russia till 2030 is the development of a small-scale power engineering that creates an active trend for a widespread use of mobile and stationary power plants with the capacity up to 100 kW based on internal combustion engines that produce electric power for midget single users [3, 7, 8, 9, 10].

It is best to use a reversible reciprocating electric machine, built according to a modular principle as an electromechanical energy converter in such power plants (Figure 1) [1, 2]. This allows to scale a power plant scale by power for a specific task. Figure 1 demonstrates a general view of a developed reciprocating electrical machine which was determined on the basis of a patent preliminary analysis [6].

The analytical analysis of selected and published protection documents during a patent study allowed to reveal the strengths and weaknesses of various design solutions for a reversible reciprocating electric machine. The most efficient form of a reversible reciprocating electric machine implementation is a cylindrical structure with permanent magnets on a movable armature. Structurally, it is advisable to make a hollow anchor, with the surface-mounted magnets, forming a radial magnetic flux. The chosen form of implementation will provide the best technical and economic characteristics of a reversible reciprocating electric machine.

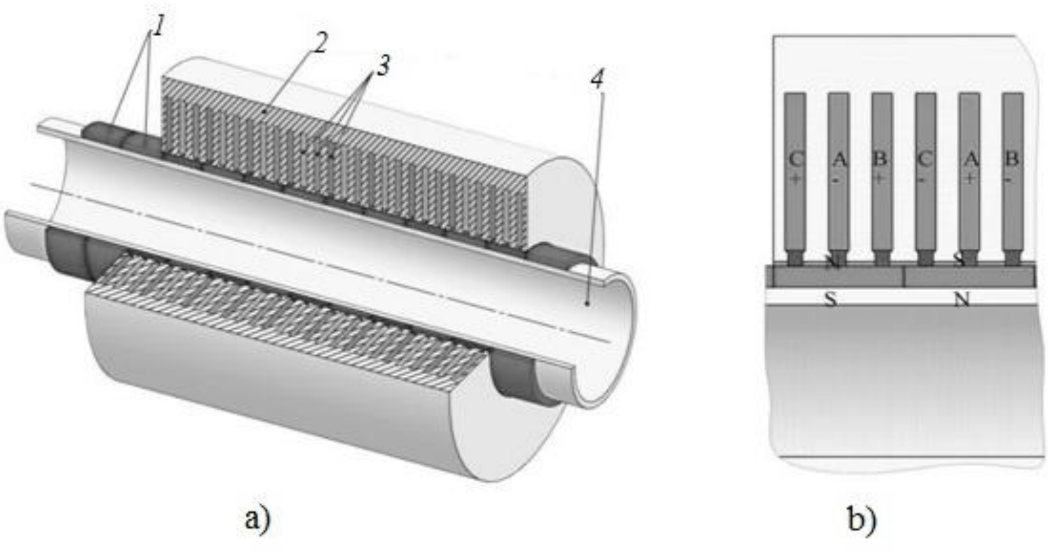

Fig. (1). The structure of a reciprocating electrical machine with radially-magnetized magnets on a movable element: a) general view; b) the diagram of permanent magnets phases and polarity; 1-annular permanent magnet; 2-frame yoke; 3-phase windings; 4-non-magnetic tube (titanium).

1. METHOD OF CHOICE AND JUSTIFICATION OF DESIGN PARAMETERS FOR A RECIPROCATING REVERSIBLE ELECTRIC MACHINE

To determine the rational design parameters of an electric reciprocating machine it is proposed to implement the concept of parallel simulation (Co-Simulation in foreign literature) [11, 12, 16].

This concept makes it possible to exchange the data between different programs in order to increase the efficiency, accuracy, simulation and optimization of the parts structural dimensions. In our case it is proposed to exchange the data between the programs Matlab/Simulink, and CatiaV5 through a specially written original program.

The development and optimization of a reciprocating electrical machine should be carried out with the calculation of the converter parameters, considering a linear machine and an inverter as a single system [13, 17, 19].

As a simulation environment of a reciprocating electric machine, a semiconductor converter and a control system selected the software package Matlab / Simulink and the library of SimPowerSystems blocks were selected, which is one of the many additional Simulink libraries, focused on the modeling of electrical devices. SimPowerSystems contains a set of blocks for the simulation of electrical devices.

Besides the model using SimPowerSystems blocks may also use the remaining Simulink libraries and the functions of MATLAB, including the optimization unit OptimizationToolbox, which provide almost unlimited possibilities for an electrical system modeling [5].

Thus, SimPowerSystems as the part of Simulink may be considered nowadays as one of the best packages for the simulation of electrical devices and systems [14, 21].

For a three-dimensional modeling, the strength and kinematic analysis of an electric machine parts the software CATIAV5 was chiosen. It is a comprehensive computer-aided design (CAD) system, the technological preparation of production (CAM) and engineering analysis (CAE), which includes the advanced three-dimensional modeling tools, the subsystems of software simulation concerning complex technological processes, the advanced means of analysis and a unified database of textual and graphical information [20].

2.1 SIMULATION AND RESEARCH OF A THREE-PHASE RECIPROCATING ELECTRIC MACHINE FOR A RECTIFIER LOAD

The integrated environment for Simulink engineering application creation within Matlab 2010 system models and studies different types of reciprocating reversible electric machine operation.

The external exciting mechanical vibrations acting on the reversible electric reciprocating machines are often unstable ones.

Thus, the operation of reciprocating reversible electric machines on a rectifier load followed by energy accumulation is reasonable.

The equivalent circuit is shown by Figure 2, where L_a, R_0 is the inductance and active resistance of the working coil; L_L, R_L is the inductance and load resistance, taking into account the rectifier resistance; E_v-EMF motion induced in the working coil during a magnet movement [4].

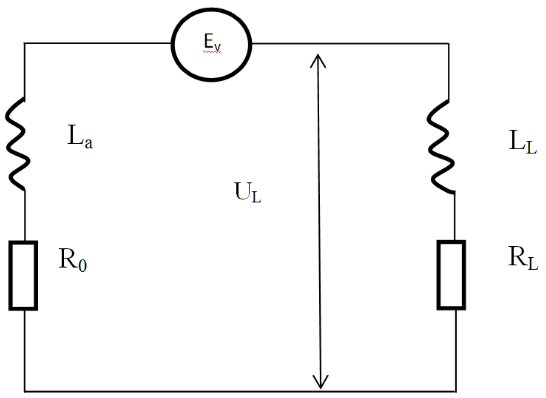

Fig. (2).-Equivalent circuit

The movement of magnets will follow the following regularity

$$x = x_m sin\omega t, \quad (1)$$

where x_m – the amplitude of magnet movement;
ω-angular frequency of magnet movement.

EMF movement of Ev is described by the following expression:

$$E_v = C_{MW}\frac{dx}{dt} = C_{mw}x_m wcoswt, \quad (2)$$

where C_{MW} – electromagnetic force ratio

$$C_{MW} = k_{MW}\frac{2\mu_0 lF_M w}{\pi k_\mu a}, \quad (3)$$

$where\ \ k_{MW}$ – electromagnetic force linearization coefficient;
μ_0 – the magnet permeability of vacuum $4\pi\cdot 10^{-7}$;
l – the circumference length of a magnet diameter D_M;
F_M – magnetomotive force of a magnet;
w-number of winding turns;
k_μ-saturation coefficient 1, 05;
a – parameter depending on a magnet and an air gap lengths.

The equation of a linear generator translator motion dynamics

$$F_{пр} - F_{эм} - F_{тр} - F_{пружж} = m\frac{d^2x}{dt^2},$$

where $F_{пр}$-actuator force (of an internal combustion engine, for example);

$F_{эм}$ – electromagnetic force of a linear generator;

$F_{тр}$ – friction powers;

$F_{пружж}$ – spring or other device force that reduces vibration;

m – translator weight.

A multi-step method of variable order was selected as an integration method- ode 23tb, using the formulas of numerical differentiation [21].

The mathematical model of a reversible three-phase reciprocating linear electric machine, shown by Figure 3, consists of a series branch of a generator own parameters operating on a rectifier diode bridge UniversalBridge, connected to an active and inductive load.

The main dimensions of an electrical machine were determined on the basis of a preliminary calculation, which will allow the production of a minimum capacity (10 kW) (Table 1).

Table 1. Preliminary dimensions of an electrical machine

Parameter	Value	Measuring unit
Air gap radius	100	mm
Translator active length	270	mm
Air gap	1, 5	mm
Stator active length	390	mm

On the basis of a developed simulation model for a three-phase reciprocating linear reversible electric machine the calculations of the dependences for produced electric power on the frequency of an electric machine translator (rotor) movement (Figure 4) were performed. The potential use of a developed linear generator is in the range of 3 to 16 kW, which allows to use this device in the field of a small-scale power engineering and hybrid vehicles.

During the design of machines it is important to provide the strength characteristics of parts and assemblies. The computed axial loads acting on an electric machine translator, depending on the translator frequency (figure 5), allow to perform a strength analysis of a translator shaft and the magnets attached to it.

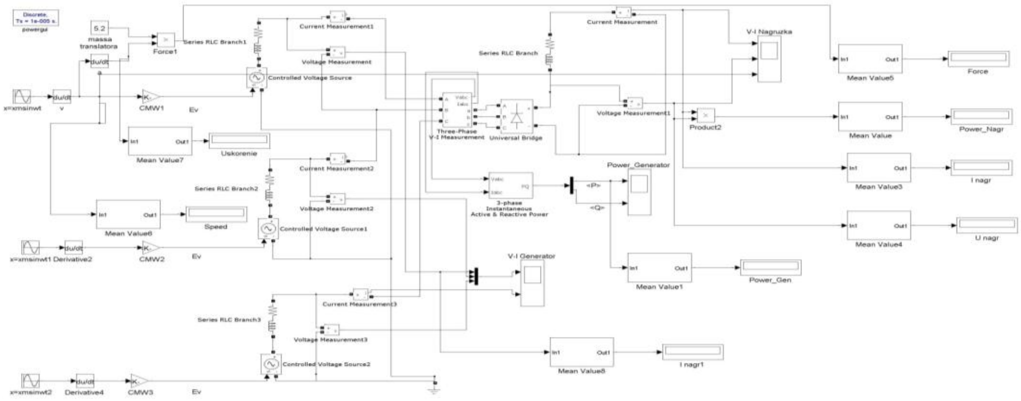

Fig. (3).-The model of a three-phase reciprocating reversible linear electrical machine

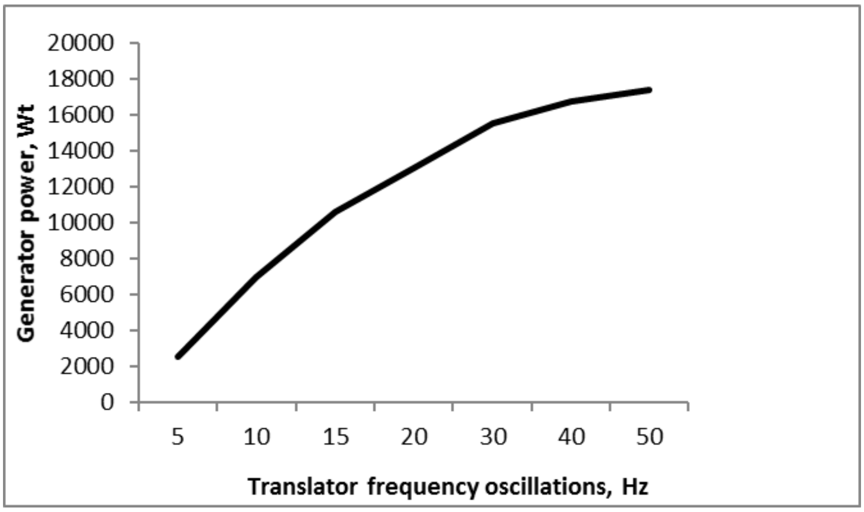

Fig. (4). The calculated theoretical dependence of the power produced by a generator from a translator frequency.

The provision of the necessary strength should be considered with the goal of a translator minimum weight provision of in order to achieve the best kinematic and dynamic characteristics.

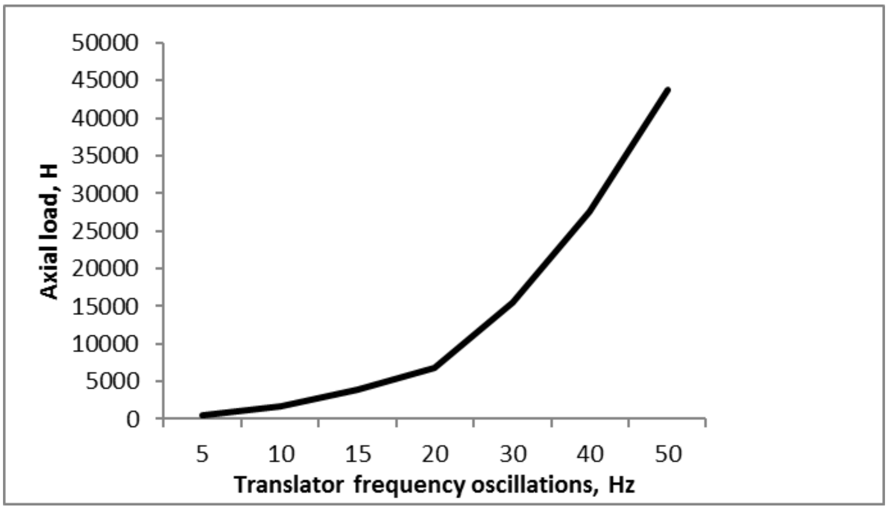

Fig. (5).-The calculated theoretical dependence of the axial load on a translator from the translator frequency

2.2 OPTIMIZATION UNIT TO DETERMINE STRUCTURAL DIMENSIONS OF A RECIPROCATING ELECTRICAL MACHINE STATOR AND TRANSLATOR

The optimization purpose of a reciprocating electrical machine design is the obtaining of maximum electric power by $P_в$ generator.

According to [4], the maximum electromagnetic power which may be obtained from a generator will be the following

$$P_в = \frac{1}{2} E_{vm} i_m cos\varphi. \quad (4)$$

Taking into account the expression (2), we shall obtain the following:

$$P_в = \frac{1}{2} C_{MW} x_m \omega cos\omega t i_m cos\varphi. \quad (5)$$

Let us analyze the expression. The increase the oscillation frequency x_m amplitude and the transition frequency of the translator ω is a trivial solution and is limited by a performance specification and the strength characteristics of the machine. The generator current i_m is limited by the stator winding section and the cooling conditions of an electrical machine. During the operation on a resistive load $cos\varphi \approx 0,9$ may be taken.

According to the expression (3) the electromagnetic force coefficient includes the structural dimensions of an electrical machine stator and translator, and the magnetomotive force of magnets. This multiplier of the expression (5) may be taken as an objective function that needs to be maximized subject to the imposed constraints on its input parameters.

Let's expand the objective function based on the equations (7-12). The resulting function (6) is introduced in the optimization block for the Optimization Toolbox application.

Table 2 demonstrates the parameters included in the objective function, the limits imposed on them taking into account the designation features and technical specifications, as well as the designations adopted in the application OptimizationToolbox.

$$C_{MW} = (1 - \alpha * ln\left[1 + \frac{1}{2\alpha}\right])\frac{2\mu_0 \pi D_M H_c L_M w}{\pi k_\mu \alpha b_м} \rightarrow max \tag{6}$$

$$l = \pi D_M, \tag{7}$$

where l-circumference length of a magnet diameter.

$$F_M = H_c L_M, \tag{8}$$

where H_c – the coercive force of a magnet, N/m;
L_M – magnet height.

$$w = \frac{k_{cu} * hокна * bокна}{Sм}, \tag{9}$$

where k_{cu} – the stator slot filling factor;
$hокна$ – stator slot height;
$bокна$-stator slot width;
$Sм$-conductor section in a stator.

$$k_{MW} = 1 - \alpha * ln\left[1 + \frac{1}{2\alpha}\right] \tag{10}$$

$$\alpha = \frac{a}{b_м}, \tag{11}$$

where α – relative parameter,
$b_м$ – magnet width.

$$a = \frac{1}{\pi}\left[\frac{\mu_0}{\mu_r} L_M + 2\delta\right], \tag{12}$$

where a-conventional thickness of magnets and gaps divided by π;
δ-air gap;
μ_r-magnetic permeability of a magnet.

Table 2. Objective function parameters

Value name	Designation in OptimizationToolbox application	Limits
C_{MW}	Maximized value	
μ_0	$4\pi*10^{-7}$	
μ_r	$1, 41*10^{-7}$	
D_M	X(1)	$(195\text{-}205)*10^{-3}$ m
L_M	X(2)	$(3\text{-}6)\text{-}10^{-3}$ m
$h_{окна}$	X(3)	$(25\text{-}45)\ 10^{-3}$ m
$b_{окна}$	X(4)	$(5\text{-}10)\ 10^{-3}$ m
k_{MW}	X(5)	0.6-0.9
α	X(6)	0.045-0.05
a	X(7)	$(1.2\text{-}1.4)*10^{-3}$

The problem of an objective function optimization is solved by the application Optimization Toolbox of the software Matlab. The program written by Matlab language allows you to calculate the parameters of an objective function based on a genetic algorithm.

The feasibility of genetic algorithms use to solve the problems of this type arises due to the following reasons: the implementation of a simple but quite effective calculation scheme, the possibilities of use under continuous and discrete character of variables, the principal possibility of constraints consideration, the absence of requirements for continuity, differentiability and unimodality of optimization criterion, determining the global extremum of an objective function. An essential feature of this approach is that it may be used in combination with classical techniques.

The optimization pack allows you to set another minimization function, which will be used after the end of the algorithm operation. As an additional feature, which allows you to specify the value of an objective function the *fmincon* function is selected built in Matlab in order to implement the algorithm with the given constraints, based on the method of sequential quadratic programming [21].

Figure 6 shows the visualization of calculations based on the genetic algorithm. The negative value of an objective function is expressed by the fact that it is necessary to take its negative value during the maximization of the objective function in the program Matlab. As you see from the graph, the solution is achieved at a half of populations (the default value is 100). The resulting value C_{MW} = 17, 79 N/A is introduced into the model of a three-phase linear reversible electric machine (Figure 3).

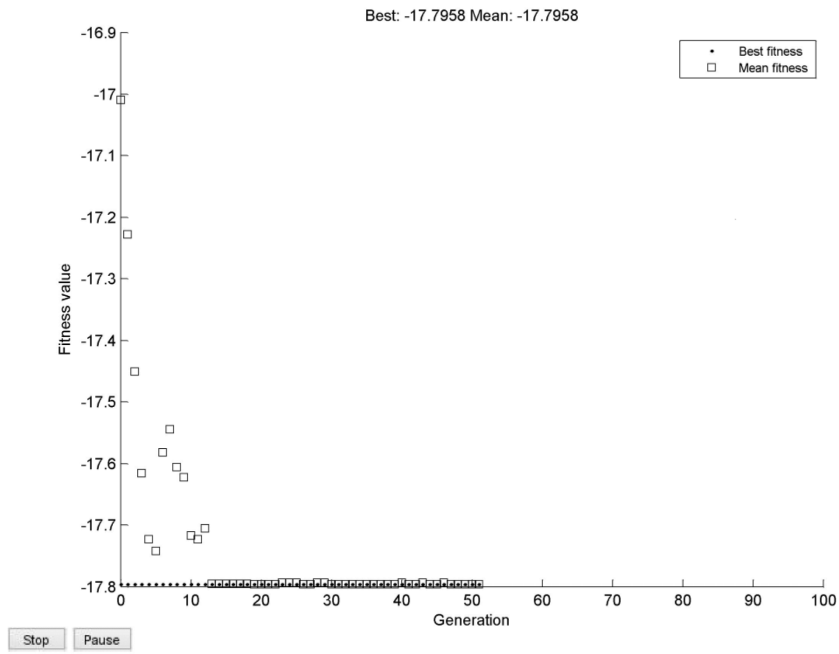

Fig. (6).-The graph of the objective function value (fitness value) change depending on the number of populations (Generation).

The calculated parameters based on the presented optimization method are summarized in Table 3.

Table 3. Calculated parameters of objective function

Value name	Designation in OptimizationToolbox application	Calculated values
C_{MW}	Maximized value	17, 79
μ_0	$4\pi*10^{-7}$	
μ_r	$1, 41*10^{-7}$	
D_M	X(1)	$197*10^{-3}$ м
L_M	X(2)	$3\cdot10^{-3}$ м
$h_{окна}$	X(3)	$30\cdot 10^{-3}$ м
$b_{окна}$	X(4)	$5\cdot10^{-3}$ м
k_{MW}	X(5)	0, 88
α	X(6)	0.045
a	X(7)	$1.2\cdot10^{-3}$

These values are placed in a 3D model of a linear electric machine in CAD CATIAV5 for later kinematic and strength calculation.

1.3 3D MODEL DESIGN OF A LINEAR ELECTRIC MACHINE IN CAD CATIAV5

The modeling data of the software package Matlab-Simulink based on the programs written in Matlab are transferred to the project table Excel, which is synchronized with the CAD CATIAV5. 3D models of an electrical machine stator and translator are developed in CATIAV5.

The force block in the model of a three-phase linear reversible electric machine (Figure 3) calculates the axial loads on an electric machine translator, which are transferred on the oscillograph Scope. The block ToWorkspace records the obtained values to the file «nagruzka».

The program file export, integrated in this model after the calculation unloads the obtained values in the form of a design Excel-table that is synchronized with the CAD CATIAV5.

The general view of an electric machine is shown by Figure 7. Titan as the material of the magnets-NdFeB (neodymium-iron-boron) is chosen for a translator base from a built-in library. The weight of a translator calculated in CAD CATIAV5 makes 5.2 kg. In similar works the translator weight makes about 10 kg [6, 15, 18].

The figure 8 represents the strength analysis of a magnet mounting on an electric machine translator. The maximum mechanical voltage on a mount makes 7.72 MPa, which must be considered when you choose the method of mounting on a translator basis.

The figure 9 provides a strength analysis of an electrical machine translator basis. The presence of axial loads only is assumed. The maximum mechanical stress made 110 MPa, which allows the use of titanium as the material of a translator base taking into account its mechanical properties.

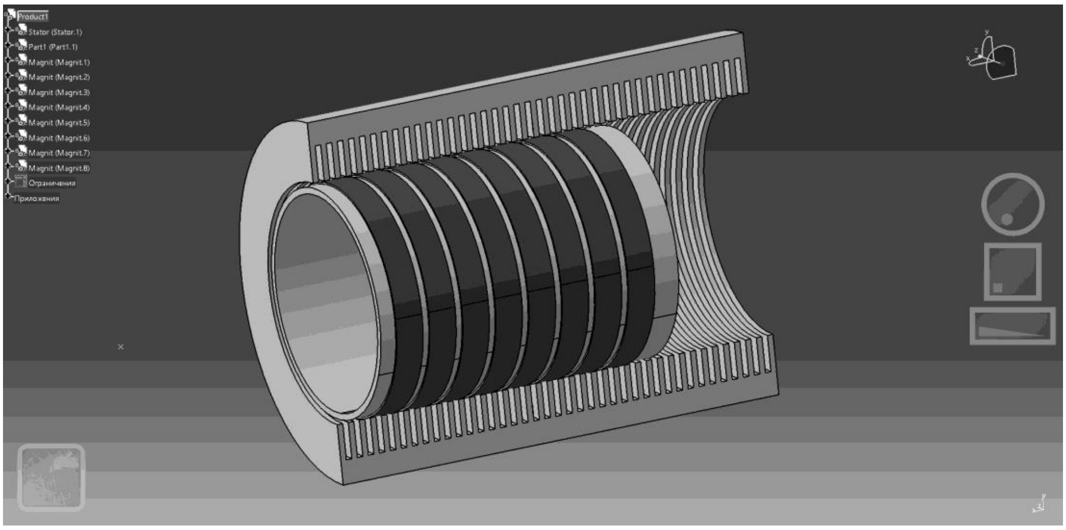

Fig.(7).-3D model of a linear oscillator in the program Catia V5

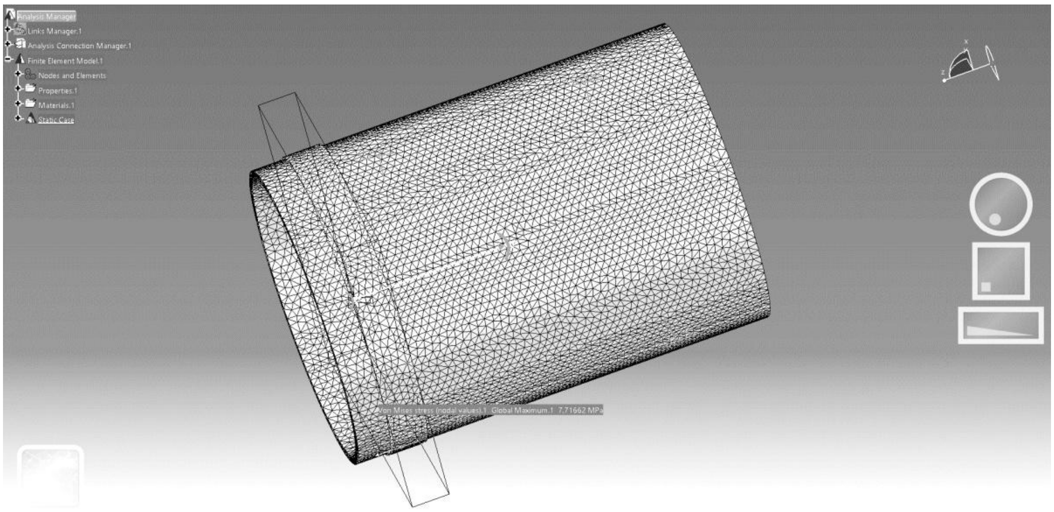

Fig. (8).-The performance of a structural analysis for a magnet mounting on an electric machine translator

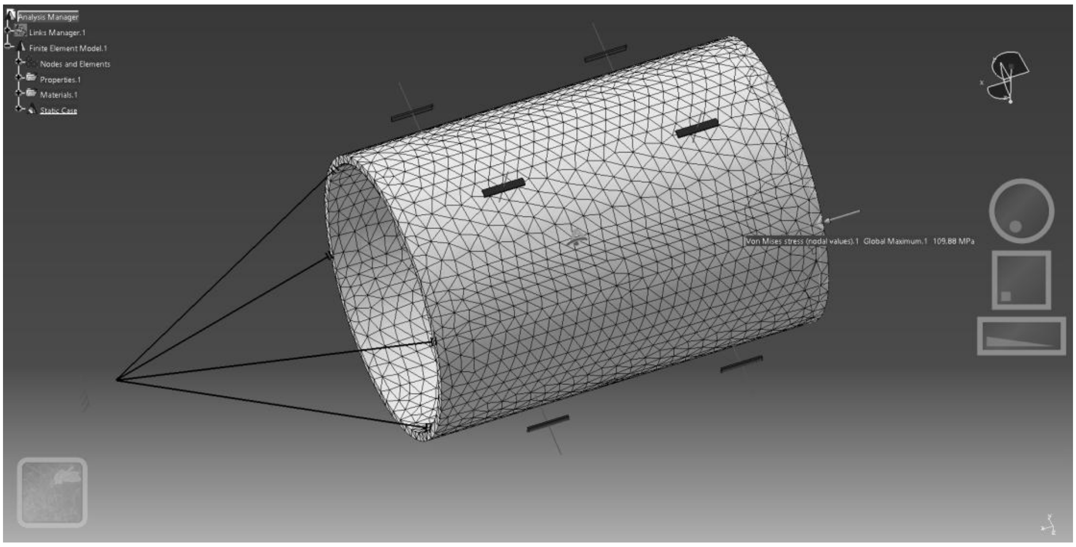

Fig.(9).-The performance of an electric machine translator strength base

2. CONCLUSION

The concept of parallel simulation (Co-simulation) based on the data exchange between the programs Matlab/Simulink, and CatiaV5 is proposed.

The optimization block in the application Optimization Toolbox is developed to determine the structural dimensions of a reciprocating electric machine stator and translator.

The developed method allows to determine the rational parameters of an electrical machine at the design stage, followed by the adjustment during the manufacture of an experimental sample.

The results obtained in the course of a mathematical and numerical modeling for a reciprocating electrical machine show the effectiveness of various software systems use in order to increase the effectiveness of the design parameters projecting and optimization.

CONFLICT OF INTERESTS

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

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