Emergency Generator Design for the Maritime Transport Based on the Free-Piston Combustion Engine

Dizajn brodskog generatora za nuždu kojeg pokreće motor sa slobodnim klipom

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DOI 10.17818/NM/2015/2.6
UDK 621.313:629.5
629.5:519.6
Original scientific paper / *Izvorni znanstveni članak*
Paper accepted / *Rukopis primljen:* 24. 4. 2015.

Summary

The paper concentrates on the challenge of creating a system of emergency power supply in maritime transport on the basis of a linear electrical generator operated by the free-piston internal combustion engine. Reluctance-flux electrical machine is used as an electromechanical converter. The aim of this paper is to study the interaction of the linear electrical machine and the internal combustion engine. The electrical generator's main parameters are determined.

KEY WORDS

Linear electrical generator
reluctance-flux electrical machine
free-piston combustion engine
mathematical modelling

Sažetak

Ovaj rad analizira pokušaj oblikovanja sustava električnog napajanja u nuždi u pomorskom prijevozu na osnovi linearnog električnog generatora kojega pokreće motor s unutrašnjim izgaranjem sa slobodnim klipom. Električni motor s magnetskim otporom služi kao elektromagnetski pretvarač. Cilj rada je istražiti međusobno djelovanje linearnoga električnog motora i motora s unutrašnjim izgaranjem. Određeni su glavni parametri električnog generatora.

KLJUČNE RIJEČI

linearni električni generator
električni motor s magnetskim otporom
motor sa slobodnim klipom
matematičko modeliranje

INTRODUCTION / *Uvod*

Application of modern life-saving appliances on ships is one of the main components of the crew and passengers safety. Nowadays the lifeboat is a vessel with a variety of communication, control and determination of geographic co-ordinates systems, which requires a sustainable and long-term emergency electrical power. The use of mobile generators or batteries is the solution to this challenge. Classical electrical generators have large dimensions and weight parameters, which makes them difficult to operate in small boats. The batteries are not good to use because they do not have sufficient energy performance. At the same time the use of additional equipment that controls the charge and capacity of elements is a problem. For these reasons, the development of a compact and economical source of electrical energy for use in lifeboats is a relevant scientific and technical challenge.

It is expedient to use linear electrical generators driven by internal combustion piston engines as auxiliary power source with a capacity of more than 4 kW in small vessels [1]. Application of the reciprocating electrical machines combined with engine's cylinder improves weight, size and power of the generator. A positive feature of the reciprocating generators is the absence of crank mechanism. It reduces the system inertia and accelerates the system response to fluctuations in the power consumed by the load. The cylinders do not have a mechanical connection and can be made independently. It allows building a generating system of electricity on a modular principle. Possibility of independent operation allows connecting and disconnecting separate modules, to optimize power generation system, to increase the capacity of autonomous power supply system [2-4].

The following goals of this research were formulated by analyzing the standby generator application and the demands for his energy, weight and size parameters:

- choosing the optimal type of electrical machine and variant of coupling of the combustion engine used in the generator;
- elaboration of the electrical machine construction used in the generator;
- elaboration of the control system for the generator to reach high energy, weight and size parameters.

GENERAL REQUIREMENTS FOR THE LINEAR ELECTRICAL MACHINE USED AS A POWER GENERATOR / *Opći zahtjevi za linearni električni motor koji se koristi kao generator*

Using the linear electrical machine as a generator has some peculiarities. Firstly, the power converter, which is used with electromechanical energy converter, must be able to work in both motoring and generating operation. Secondly, the battery shall be provided in the system. It must be able to accumulate enough energy to ensure the work of electromechanical energy converter during motor mode.

It is necessary to take into account some factors complicating the use of such generators:

- discreteness of magnetic fields in both stator and moving element (as an edge effect) reduces the energy transfer from the edge zone;
- weight of the movable construction is restricted, that limits the amount of available active material and the size of available area of the active air gap. It can limit the power of machine for given dimensions.

The electrical machine must be able to work in motor mode to ensure the start of the internal combustion engine. Switching modes should be realized dynamically at runtime.

We can mark the following main variants of coupling of the linear electrical machine with the free piston engine (fig.1) [4-6]. The simplest variant is the connecting of the linear generator with the cylinder of engine on single side with one free end (Fig. 1.1, a). Its advantage is the possibility of implementing both two-stroke and four-stroke engine of any type (Otto, Diesel, Trinkler) with controlled compression ratio and ignition moment.

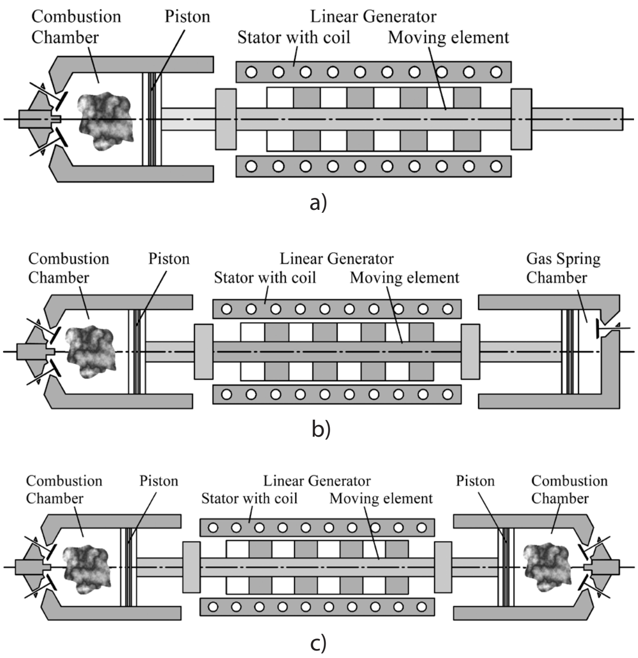


Figure 1 Electric generator based on free-piston internal combustion engine:
a) single side with one free end; b) single side with Gas Spring; c) both sides with opposite cylinders placement

Slika 1 Električni generator pokretan motorom s unutrašnjim izgaranjem sa slobodnim klipom: a) jedna strana s jednim slobodnim krajem; b) jedna strana s oprugom za plin; c) obje strane s cilindrima na suprotnim krajevima

The peculiarity of the free end system is that forces of linear electrical machine operating in the motoring mode move the piston during all strokes except power stroke. It is necessary to develop the force to overcome the inertia of moving parts of the system and opposing force generated by the compression stroke. To implement these strokes, energy must be stored in the energy accumulator. During a power stroke, linear electrical machine works as a generator. It must provide for the transfer of energy as a load and recharge energy storage to provide power at the next stroke. The limit of such system is the internal energy exchange between the system "electromagnetic field - power converter - energy accumulator" and moving part. To ensure system performance linear electrical machine must develop a major effort, that increases its weight and dimensions and, in some cases, make it unrealizable. The energy accumulator must have a significant capacity and be able to accept and give it during the strokes. It excludes the use of batteries and requires the use of supercapacitors.

The power converter must work with high currents and must be optimized for the capacity, which is bigger than the capacity supplied to the load. As a result, the cost of the system increases, its technical and economic parameters deteriorate.

One of the ways to improve the efficiency of generators is the exclusion of the energy exchange by electromagnetic field between the energy accumulator and the moving element and its realization within the mechanical system.

It can be achieved by connecting the free end of the linear electrical machine with the elastic element, which will accept the kinetic energy of the moving part and will store the part of the energy for the next compression stroke. In this case, the exchange of energy through the electromagnetic field is missed, which reduces the requirements for their efforts and storage capacity of electricity. It is advisable to use a gas spring as a mechanical energy accumulator (Fig. 1, b). The advantages of the gas spring are mechanical forces balance, which facilitates the design of supports as well as the reducing of the weight and dimensions of the linear electrical machine.

The further development of design with a gas spring is the disposition of engine cylinders at both ends of the linear electrical machine according to the oppositional scheme (fig. 1, c)

The double-cylinder engine of the oppositional scheme has a piston block composed of two pistons connected by a rigid rod. However, the using of such structure evolves difficulties connected with the implementation of the algorithm of energy storage and control the generator frequency.

STRUCTURE VARIANTS OF LINEAR REACTIVE RELUCTANCE-FLUX ELECTRICAL MACHINES / *Strukturalne varijante linearnih reaktivnih električnih motora s magnetnim otporom*

Analysis of possible implementations of the linear generator connected with combustion engine shows that the structure with free end has some disadvantages associated with the complexity of the control over the distribution of power and high norms of converter components subsystem. In the case of opposite cylinders, placement generator has simpler inverter, but it has a rather complex system and the control algorithm. The most efficient system of coupling the combustion engine and linear electrical generator is the gas spring structure because of the realization simplicity of mechanical subsystem and the simple control algorithm [4]. We will use it during our research.

It is necessary to choose the type of the electrical machine when designing electrical reciprocating machines for heavy conditions. The main criteria for choosing are structure simplicity and high relative indices.

Comparative analysis of electrical machines shows that synchronous machines with permanent magnets and reactive inductor machines correspond to these criteria. Electrical machines with permanent magnets have the best specific parameters, but the use of permanent magnets limit the area of application of this type of electrical machines under heavy duty conditions.

The permanent magnets retain their magnetic properties at temperature below 200°C. During the work of the reciprocating electrical machine with the combustion engine the temperature of the rotor can exceed 200°C. It reduces the reliability of the synchronous electrical machine with permanent magnets. In addition, shock stress and vibrations provide demagnetizing effect on the permanent magnet. Moreover, the high cost and complexity of mounting the permanent magnets impose additional economic and technological constraints.

In spite of the fact that reactive inductor machines have lower power density, we decided to design a heavy-duty reciprocating electrical machine based on reactive inductor machine. This choice was made due to the simplicity of design, high reliability and the ability to work in difficult conditions. Two types of linear reactive reluctance-flux electrical machines were examined: the cylindrical stator-to-rotor gap electrical machine and the plain stator-to-rotor gap electrical machine.

The flat stator-to-rotor gap electrical machine's disadvantages are the considerable consumption of active materials and the construction complexity.

The use of cylindrical stator-to-rotor gap electrical machine is optimal. However, it is necessary to consider that increase of the length of the translator needs to strengthen its flexing resistance because the air gap between the stator core and the moving element core must be minimum and it must be bordered only by the electrical machine's structure to improve efficiency of the reactive inductor machine.

The air gap is 0.2 mm in most reactive inductor machines. In cylindrical stator-to-rotor gap electrical machine the bush bearing provides the air gap.

THE MATHEMATICAL MODEL OF THE SYSTEM PROCESSES IN QUESTION / *Matematički model procesa predmetnog sustava*

The correct choice of structure type, parameters and principles of the control system determines the reliability and efficiency of the electric generator on the basis of a free-piston engine [7-9]. We should determine the operational frequency, the peak displacement of the moving element from the equilibrium state and the generated force.

For the purpose of this research due consideration of the mechanical and dynamic processes in the system "free-piston combustion engine - linear electrical machine – gas spring" [8-10] is required. Since the performing analysis is preliminary and its purpose is to define the requirements for the electrical machines, the system in question is represented as a single-mass system with one degree of freedom.

The piston force, the spring stiffness and the electromagnetic force act on the moving element. The dynamic equation has the following form:

$$m\ddot{x} = F_p + F_{em} - d \cdot \dot{x} - C_s \cdot x \quad , \qquad (1)$$

m – the moving elements mass, F_p – the piston force; F_{em} – the electromagnetic force; d – the dissipation factor; C_s –spring stiffness.

POWER STROKE MODEL AND DETERMINING THE PISTON POWER / *Model radnog takta i određivanje snage klipa*

To determine the piston power operating on the moving element it is necessary to concentrate on the dynamic pneumatic process in the engine. In the power generator with one cylinder and gas spring, the use of only a two-stroke working cycle is possible. In that case full cycle ends in one stroke of the piston. The description of dynamic pneumatic process was based on the approach outlined in the [8-10].

When the piston moves toward the combustion chamber after exhaust valve overlap, an adiabatic compression of the fuel-air mixture occurs. The following expression describes the dependence of the cylinder pressure from the piston moving in this mode:

$$P_{comp}(h) = P_0 \left[\frac{S_p h_p + V_{cc}}{S_p (h_p - h)} \right]^{k_a}, \qquad (2)$$

h – the piston position (piston position farthest from the combustion chamber is taken as zero); P_0 – the ambient pressing; V_{cc} – the combustion chamber volume; $S_з$, h_p – piston surface and piston-stroke, k_a – heat capacity ratio.

After the position corresponding to the desired compression ratio is reached the compressed air–fuel mixture in a gasoline engine is ignited and the power stroke starts. Isochoric heat supply occurs in the working medium and the pressure increases in the cylinder. The piston starts to move in the opposite direction. In this mode the pressure in the cylinder is described as:

$$P_{expan}(h) = P_{comb} \left[\frac{V_{cc}}{S_p (h_p - h) + V_{cc}} \right]^{k_a}, \qquad (3)$$

P_{comb} – cylinder pressure at the start of the expansion process

During the exhaust stroke, the exhaust valve is open. This action expels the spent fuel-air mixture through the exhaust valve. The cylinder pressure can be described as:

$$P_{scav}(h) = P_0 + \left(P_{comb} \left[\frac{V_{cc}}{S_p (h_p - h_{sc}) + V_{cc}} \right]^{k_a} - P_0 \right) e^{\frac{h - h_{sc}}{G_{sc}}}, \qquad (4)$$

h_{sc} – the exhaust valve position; G_{sc} – the exhaust intensity parameter.

The force acting on the piston during the power stroke is determined using the expressions (1) - (4) as the product of the cylinder pressure by the surface of the piston in dependence on its position and direction.

POWER CONVERTER SUPPLYING RELUCTANCE-FLUX ELECTRICAL MACHINE AND ALGORITHM OF RESULTANT ELECTROMAGNETIC FORCE / *Pretvarač koji snabdijeva električni motor s magnetskim otporom i algoritam elektromagnetske sile koja se stvara*

The winding power of reluctance-flux electrical machine under the current is carried out by the single current. Therefore the converter shown on the figure 2 is used as its power. It consists of two single-phase half-bridge autonomous voltage invertors with independent connection of windings ($Q1$, $Q2$, $D1$, $D2$ и $Q3$, $Q4$, $D3$, $D4$) connected in parallel to the DC link [11]. Both the motor and generator mode of each module of the electric machine can be realized with the use of such converter.

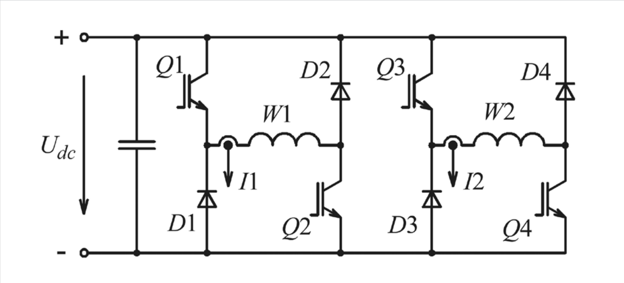


Figure 2 The power converter of the two-phase reluctance-flux electrical machine

Slika 2. Pretvarač dvofaznog električnog motora s magnetnim otporom

CONTROL SYSTEM STRUCTURE / *Struktura kontrolnog sustava*

Control system of linear electrical generator based on the free-piston engine is made according to the principles of descendant control (fig.3). Its structure and principles correspond to [12,13].

The loop controlling the position of the moving element is external. Required position of the moving unit is given to its input in the form of a sinusoidal signal with the working frequency and amplitude corresponding to the half-length of the power stroke. The velocity supplied as a reference to minor loop is the output loop position. Information from the sensor position of the movable element and its derivative is used as a feedback for these circuits. The force from the output goes on the input of the control system of the inductor electric machine. Depending on the position of the moving element, the value of the required winding currents to obtain a predetermined force is determined. The required winding current value is generated using the pulse-width modulation.

TECHNICAL SPECIFICATION FOR THE LINEAR ELECTRICAL MACHINE COUPLED WITH THE FREE-PISTON ENGINE / *Tehnička specifikacija linearnog električnog motora spojenog na motor sa slobodnim klipom*

The ratio between the cylinder and piston stroke cannot vary widely, because it leads to the deterioration of the engine characteristics in the combustion engine with crank mechanism. This ratio can vary over a considerable range in the free-piston engine. That is why three variants of the ratio of the diameter of the cylinder and the piston stroke with an equal amount of work are considered. For the electro-generating system of 10 kW the free-piston engine with working volume 400 cm^3 and a compression ratio of 8.8 was adopted.

The pressure at the beginning of the power stroke was determined so that the mechanical power was 14 kW at the operating frequency of 50 Hz. The dimensions and the figures of variants under the question are given in the table 1.

Table 1 Calculated parameters of the free-piston engine

Tablica 1. Izračun parametara motora sa slobodnim klipom

Variant	Piston diameter, мм	Piston-stroke, mm	Compressive ratio	Pressure in the beginning of the power stroke MP	Operating frequency, Hz
1	93	60	8.8	5.30	50
2	76	90	8.8	8.35	50
3	66	120	8.8	9.90	50

The high degree of interaction and mutual influence processes in the subsystem consisting of converter power, linear reactive inductor electric machine and its control system, is represented in the form of an electromechanical transducer and is replaced by a periodic link of the first order. The time constant of this link is equal to uncompensated time constant of the force control loop. Its value determines the speed of the force control loop and it is one of the electro-mechanic converter parameters.

Taking into account the parameters of modern semiconductor devices the converter modulation frequency in the selected power gains 10 kHz. Therefore, in subsequent calculations it was assumed that the time constant of the electromechanical converter is 0.5 ms.

The controller synthesis of linear electrical generator control system has been performed for the electromechanical converter variant described above and for the parameters of free-piston engine. PID and PI -regulators are used as speed and position controllers respectively.

Calculations were performed for each of the variants under consideration. The moving parts mass of the system is 5 kg, the gas spring stiffness was determined from the resonance condition at the operating frequency. Figure 4 shows the results of the calculation for a piston stroke of 90 mm.

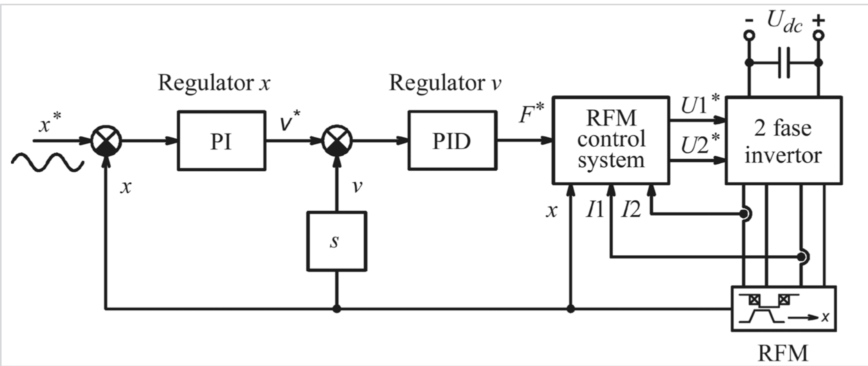
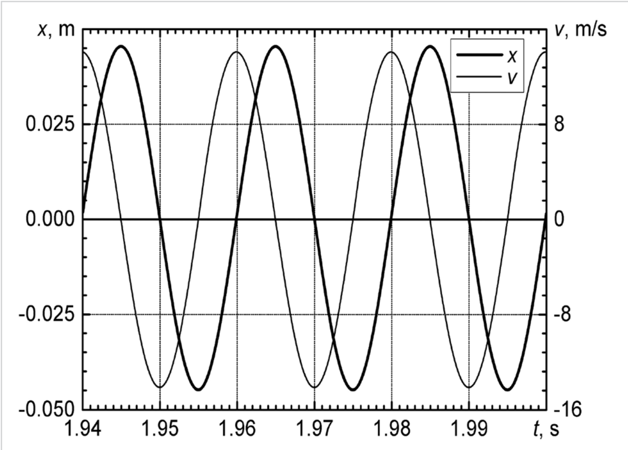


Figure 3 The control system structure

Slika 3. Struktura kontrolnog sustava



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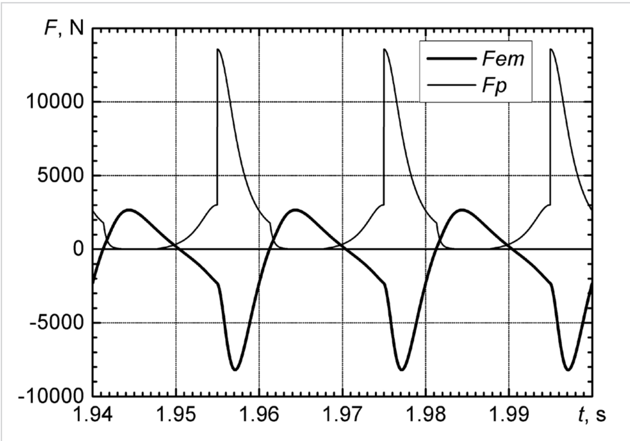

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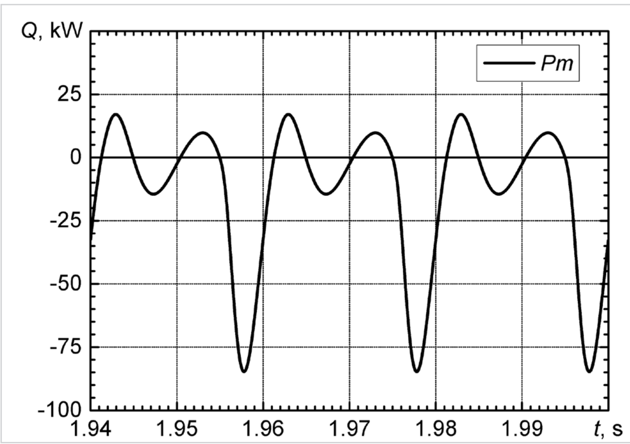


c)

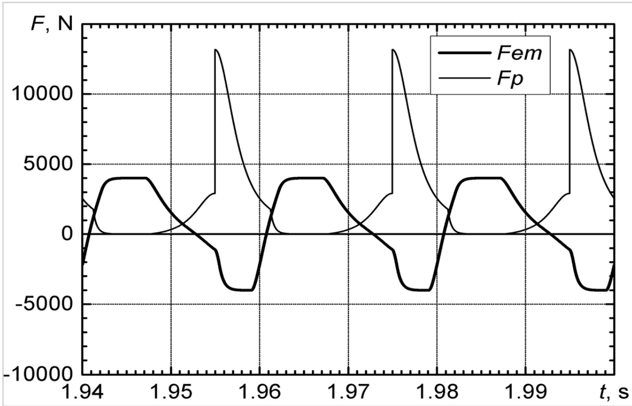
Figure 4 Results of the calculation for a piston stroke of 90 mm a) displacement and speed of the moving element; b) the force acting on the piston and the electromagnetic force; c) instantaneous mechanical power

Slika 4. Rezultati izračuna za hod klipa od 90 mm a) istisnina i brzina pokretnih dijelova; b) sila koja djeluje na klip i elektromagnetska sila; c) postignuta mehanička sila

As evident from these results, the linear electric machine must develop force in the range from 8600 N to 2600 N with used free piston engines parameters. Electric machine, designed for such efforts will have considerable weight and dimensions.

The calculation of processes developed by the limited electromagnetic force was made to optimize the electromechanical converter. It was found that the system retains functionality while limiting forces to +/- 3000 N. However, the situation when electrical machine cannot ensure the power take-off from the system can emerge if the parameters of the process in the engine cylinder or other factors are changed.

In this case, there is a risk of uncontrolled growth of fluctuations and emergency operation of the system. Therefore, to ensure reliable operation the electromagnetic force limit must be set to 20-30% over the limit value. Fig. 5 shows the results of calculation of processes developed by the limited electromagnetic force of +/- 3000, and figure 6 shows the results of calculation of processes developed by the limited electromagnetic force of +/- 4000 N.



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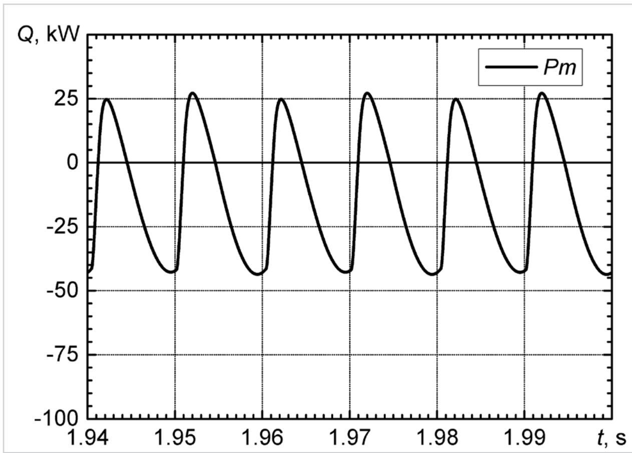
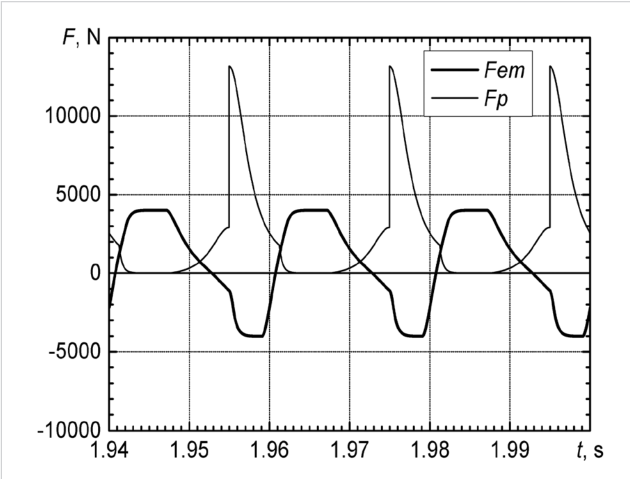


b)

Figure 5 The results of calculation of processes developed by the limited electromagnetic force of +/- 3000 and a piston stroke of 90 mm: a) force acting on the piston and the electromagnetic force; b) instantaneous mechanical power.

Slika 5. Rezultati izračuna procesa koji nastaju uslijed ograničene elektromagnetske sile od +/- 3000 i hoda klipa od 90 mm: a) sila koja djeluje na klip i elektromagnetska sila; b) postignuta mehanička snaga

The similar calculations were made for a piston stroke of 60 mm and 120 mm. As a result, it was determined that the electrical machine must ensure the force from -18200 N to 8000 N with the piston stroke of 60 mm. The limited system maintains the availability to the force of +/- 8000 N. The limited force must be +/- 10000 N to ensure the correct work



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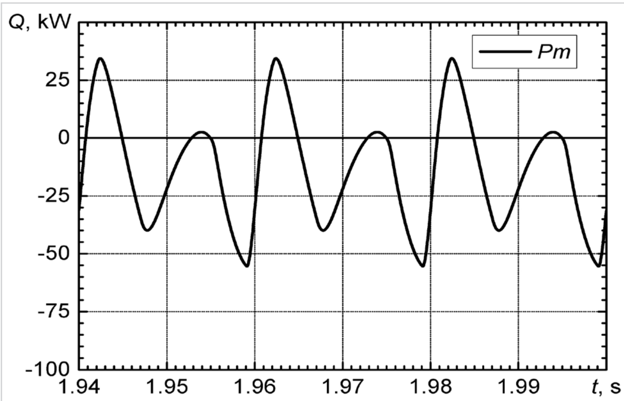


b)

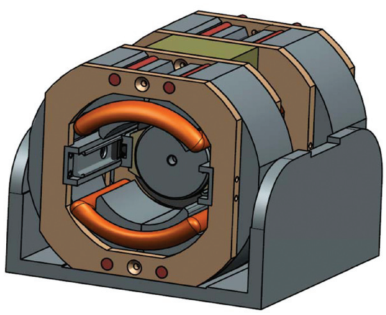
Figure 6 The results of calculation of processes developed by the limited electromagnetic force of +/- 3000 and a piston stroke of 90 mm a) force acting on the piston and the electromagnetic force; b) instantaneous mechanical power.
Slika 6. Rezultati izračuna procesa koji nastaju uslijed ograničene elektromagnetske sile od +/- 3000 i hoda klipa od 90 mm: a) sila koja djeluje na klip i elektromagnetska sila; b) postignuta mehanička snaga

of electrical generator. When the piston stroke is 120 mm the developed force is in the range of -4300 – 1500 N. The minimum and operational limited force read +/- 1800 N and +/- 2200 N respectively.

Analysis of the results shows that the increase of piston stroke reduces the force developed by the electric machine for the same operational volume of the cylinder and the oscillation frequency. As the mass and the size of linear reluctance-flux electrical machine depend on realized force, it can be rational to increase the piston stroke. The piston stroke of 90 mm is the most efficient in terms of the mass and size minimization of the electrical machine. The reluctance-flux electrical machine was designed; the figure 7 shows its 3D model. This model consists of two equal units.

This electrical machine has a complex configuration. Consequently, it is appropriate to use the 3D modelling to determine the electromagnetic field distribution and the developing forces.

To verify whether the electrical machine size and the electromagnetic load have been determined correctly, the calculation of electromagnetic field distribution was made



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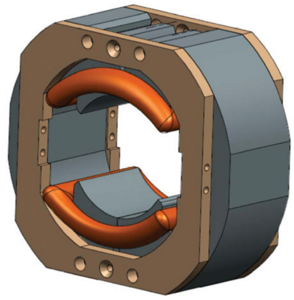

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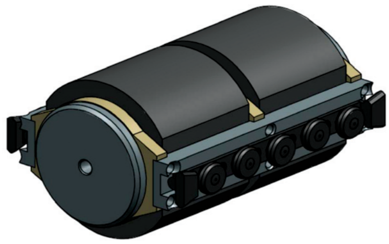
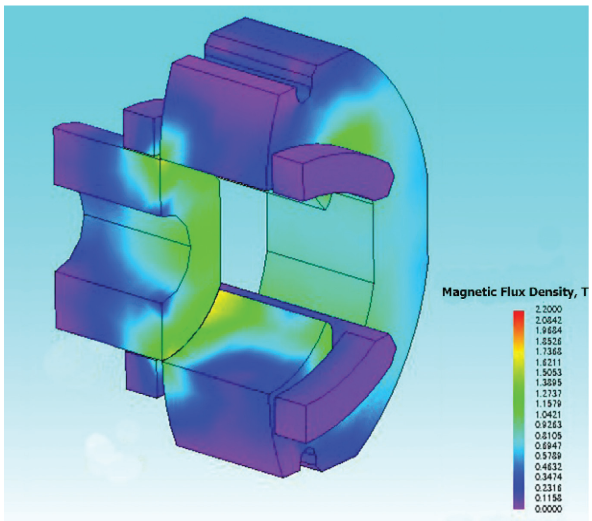


c)

Figure 7 The reluctance-flux electrical machine 3D model: assembled unit; b) stator; c) moving element
Slika 7. 3D model lektričnog motora s magnetskim otporom: a) sastavljena jedinica; b) stator; c) pokretni dio

using the software program COMSOL. Figure 8 shows the displacement distribution in the active elements of one of two units of the electrical machine model. There are two positions of the moving element.



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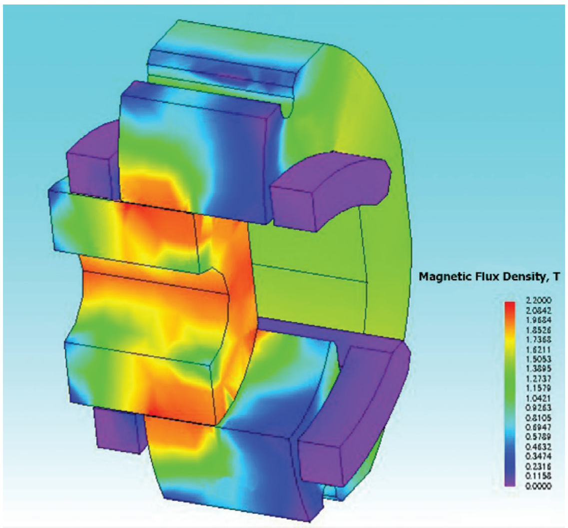

b)

Figure 8 The displacement distribution when the moving element is a) in the extreme position; b) in the intermediate position.

Slika 8. Raspodjela istisnine kad je pokretni element u a) ekstremnom položaju; b) srednjem položaju.

The graphs of the electromagnetic force were made after a series of calculations for different combinations of the moving element positions and the current in the windings (fig.9). The analysis of 3D modelling results shows that the electrical machine can obtain the force sufficient for the stable work of system provided the amount of current does not exceed the limit value.

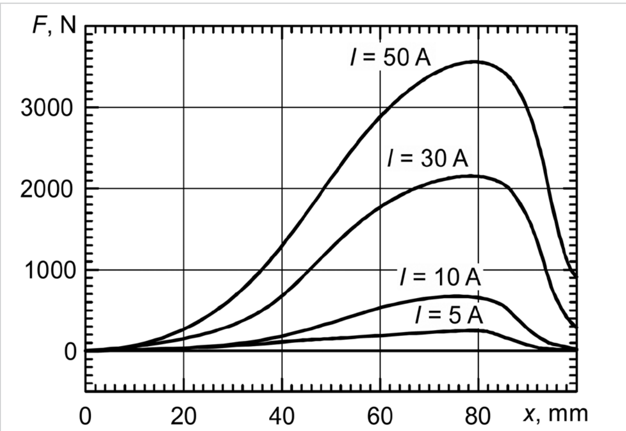

Figure 9 The calculation results of the electromagnetic force acting on the moving element, depending on its position and the current in the stator windings

Slika 9. Rezultati izračuna elektromagnetske sile koja djeluje na pokretni dio, ovisno o njegovom položaju i struji u namotajima statora

CONCLUSION / *Zaključak*

The use of the electrical generators based on free-piston combustion engines improves the weight, size and energy parameters of the emergency power supplies on the rescue vehicles.

The positive feature of the reciprocating generators is the absence of the crank mechanism. It reduces the system inertia and accelerates the system response to fluctuations in the power consumed by the load.

The most efficient coupling of the free-piston engine and the linear electrical generator is the gas spring structure because of the realization simplicity of mechanical subsystem and the simple control algorithm.

During the work of the reciprocating electrical machine coupled with the combustion engine the temperature of the rotor can exceed 200°C. It reduces the reliability of the synchronous electrical machine with permanent magnets. The hits and vibrations provide demagnetizing effect on the permanent magnet during the reciprocating movement of the moving element. Therefore, the use of reluctance-flux electrical machine is efficient.

The augmentation of the piston stroke allows reducing the requirements of the electrical machine force. The 400-sm2 system with the piston stroke of 90 mm has the best mass and size figures for the electrical generator output power of 10 to 12 kW. The developing force must be 3500 – 4000 N.

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The work is done by the authors as part of the agreement _ 14.579.21.0064 about subsidizing dated 20.10.2014. The topic is "Development of experimental model of reversible electric machine reciprocating power 10-20 kW heavy-duty" by order of the Ministry of Education and Science of the Russian Federation, Federal Targeted Programme (FTP) "Researches and developments in accordance with priority areas of Russian science and technology sector evolution for 2014 - 2020 years". The unique identity code of applied researches (the project) is RFMEFI57914X0064.