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Linear Reciprocating Generator – Prototype Design and Simulation

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Abstract : Linear reciprocating generator is a very popular power converter for various hybrid vehicles which are discussed a lot in recent decades. This article presents a prototype design and electromagnetic simulation of a generator, which is designed to work with free-piston engine of about 15 kW. In order to increase power density presented generator has a flat inductor design with two flat stators on both sides. Inductor consists of permanent magnets and tooth concentrators between them. Each stator winding has concentrated tooth coils with fractional number of slots per phase per pole. Mechanical analysis was made in order to determine internal mechanical stress in longitudinal and transverse directions of inductor. FEM model for electromagnetic analysis was described. The model was used to evaluate the influence on generator performance of technological deviations in generator design and dimensions, which may occur during production and assembling.

Keywords : Linear electric machine, Reciprocating movement, Mechanical analysis, FEM-transient simulation.

1. INTRODUCTION

Linear reciprocating motors and generators are known for a long time, but in the last decades their application areas have been significantly expanded, one can see this in many publications [1]. Among such application areas there are wave energy converters, active suspension damping systems and linear electric machines embedded into external combustion engines (*e.g.* Stirling engine) and internal combustion free piston engines [2]. Moreover, in the latter case, the electric machine is used both in generator and motor modes to control piston position [3].

Free-piston energy converter (FPEC) transforms chemical energy of fuel into mechanical energy of a piston movement and then into electrical energy of electric generator. FPEC seems to be a perspective power source for use in autonomous installations including hybrid vehicles.

One of the popular FPEC designs is shown in Fig. 1. Here, the rod connecting pistons of two opposite combustion chambers acts as a movable part of a linear electric generator. Periodically repeating processes of ignition and compression in opposed combustion chambers provides reciprocating motion of the rod. Middle part of the rod contains a system of permanent magnets creating a number of alternating poles of excitation filed along the movement path. That is why the movable part of linear electric machine could be called an inductor. Stationary part around permanent magnets on the rod contains magnetic core and a system of electric coils forming an armature winding. Movement of the rod (inductor) provides inducing electromotive force in armature winding. Thus, energy released during fuel combustion is converted into thermal energy of a heated gas, which is then transformed into kinetic energy of a piston. Most of this kinetic energy is then converted into electrical one by means of a linear generator without any additional transformation of linear movement into rotational by means of mechanical gear. Main features of this concept are the elimination of the crankshaft and the crank rod, free piston dynamics (the piston movement is determined by the balance of forces acting on it), electrically operated valves

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and application of new cycles of fuel combustion (like a new environmentally friendly homogeneous charge compression ignition, HCCI).

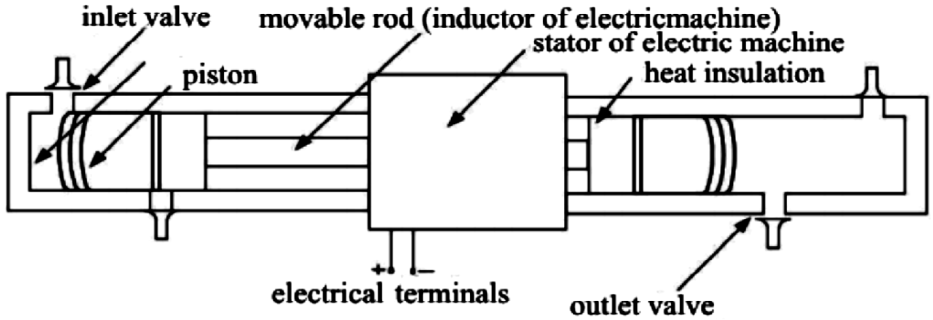

Fig. 1. Integrated free-piston motor-generator.

HCCI technology provides ignition of the air-fuel mixture in the cylinder through its compression. Unlike spark ignition and the combustion process in a diesel engine, HCCI technology allows to release the fuel energy through low-temperature combustion of the mixture in the entire volume of the combustion chamber without flame. Combustion temperature of homogeneous charge ignited by the compression is 1.5 - 2.0 times lower than the combustion temperature of the charge in the flame front of a classic petrol or diesel engines. As a result, fuel efficiency can be significantly improved and NOx and CO2 emissions can be reduced.

Prototype design

Synchronous machines with permanent magnets (SMPM) are the most frequently used type of electric machine among modern linear generators and motors [4-5]. In these designs, armature windings are placed on the stator while moving inductor contains permanent magnets as source of magnetic field. Permanent magnets along the inductor provides multi-pole alternating polarity excitation field. Permanent magnets can be either surface-mounted with magnetization direction normal to longitudinal axis of the rod or embedded into the inductor with magnetization direction coinciding with longitudinal axis. In latter case permanent magnets are separated by soft magnetic material which serves as flux concentrator. Besides, Halbach arrays of permanent magnets could be used at inductor surface which can produce multi-pole alternating magnetic field without any core, even without back yoke which leads to decreased inductor weight [6-7].

The stator of synchronous machine using permanent magnets excitation could be designed in two variants: in conventional style with slotted stator core and coils of armature winding located in these slots or in slotless style, which seems to be a perspective alternative to conventional one. Moreover, the whole electrical machine design could be flat or cylindrical, its inductor design could be single- or double-sided with one or two active air-gaps. The specific power which can be obtained in flat and cylindrical design is almost the same. However, the double sided inductor with two active air-gaps could be implemented in a flat design much easier than in cylindrical design [8].

Electric machine of this type has some advantages like lower mass of its movable part and higher performance. However, it suffers from problems with repeating impact forces acting on the inductor and permanent magnets cooling.

Due to the large impact forces produced in the combustion process the movable part experiences high mechanical stress. Besides, any possible deviation in the air-gap height on different sides of inductor creates an unbalanced traction force, which is almost proportional to the inductor displacement.

Inductor of linear electric machine does not only create excitation field, it also has to transfer impact forces and provide necessary and sufficient mechanical stiffness and strength. Therefore, the proposed inductor design must be analyzed concerning mechanical interaction of its different parts and its mechanical performance must be evaluated, particularly the strength and bearing capacity.

The proposed inductor design is shown at Fig. 2. Inductor consists of the following elements: steel poles, longitudinal guide tracks, two fastening plates, two rods (pistons) and a number of permanent magnets.

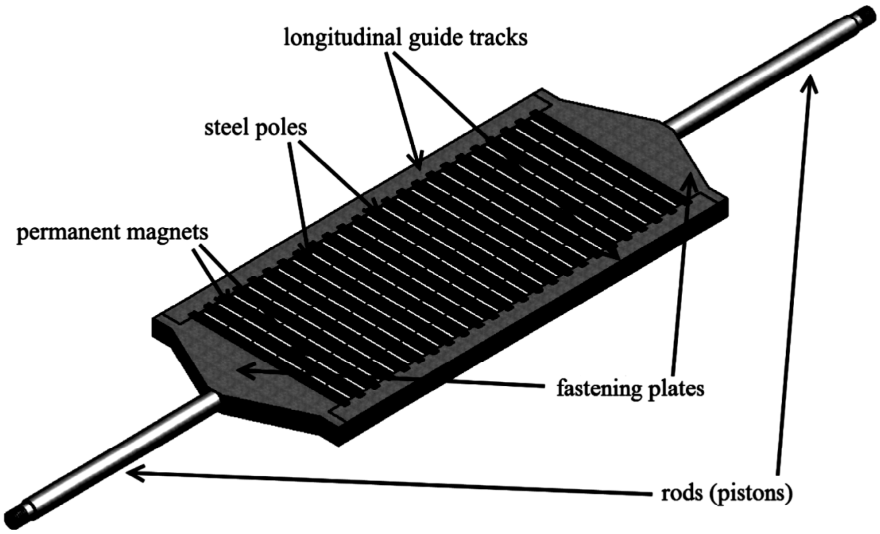

Fig. 2. Inductor design.

Steel poles of the I-beam shape are made of steel grade 10832 by means of milling from a solid rod. The poles provide mechanical strength of the inductor and at the same time it concentrates magnetic flux from inductor permanent magnets. Longitudinal guide tracks are made of non-magnetic stainless steel grade 12X21H5T and provide mechanical strength to the inductor. Guide tracks are also used as a frame bases for inductor assembling. Threaded holes M3 and special mounting surfaces are used to fix the steel poles to the guide tracks.

In order to uniformly transfer driving force from the rod to the steel poles and permanent magnets fastening plates are used. The latter are made of non-magnetic stainless steel grade 12X21H5T. Each fastening plate contains special holes for fixing it to the longitudinal guide tracks by high-strength bolts and threaded holes for mounting rods. In order to avoid transmission of impact forces from the fastening plate to the steel poles and permanent magnets, the fastening plates are mounted with a guaranteed clearance. The rod is designed to transfer driving force from the primary mover to the inductor of electric machine. The rod is made of the same material as the fastening plates. Each rod has threaded ends for coupling it to the fastening plate of inductor and a junction of the prime mover.

Permanent magnets are used to provide magnetic flux in the steel poles. Permanent magnets of cuboid shape are made of an intermetallic compound Nd2Fe14B and are magnetized in the longitudinal direction of inductor. Permanent magnets grade N40UH is selected in accordance with its residual flux density and operating temperature.

Mechanical analysis

The purpose of mechanical analysis is to check mechanical strength of the inductor and evaluate its ability to withstand external loads like considerable alternating impact forces produced by prime mover and unbalanced traction force which occur between inductor and stator core in case of air-gap deviation. Two mechanical models were investigated. In the first model (*a*) concentrated external force is applied to the end of the rod along the longitudinal axis of inductor. In the second model (*b*) distributed force is applied to the steel poles in the transverse direction. During mechanical analysis the following parameters were determined: equivalent breaking stress, maximum displacement and minimal safety factor values.

For calculation of the inductor mechanical stress the following assumptions were made: material properties were assumed to be linear, permanent, homogeneous and isotropic. “Linear properties” mean that internal stresses under load are proportional to the load applied. “Permanent properties” mean that material properties are not temperature dependent (or the temperature is constant). “Homogeneous properties” mean that material properties are the same for the whole volume of each part. “Isotropic properties” mean that material properties are equal in all directions (along all axes).

The safety factor is calculated in accordance with the theory of material plasticity, *i.e.* safety factor equals to the ratio of the maximum equivalent breaking stress to allowable stress, while the latter is accepted as material yield strength.

Table 1 contains the results obtained from the mechanical analysis of two models. Maximum stress in the first model is equal to 427 MPa. Maximal stress in the second model is less than 31 MPa. Both are less than material yield stress. Fig. 3 shows distribution of internal stress in inductor. Fig. 4 shows displacement calculation. The maximum displacement in longitudinal direction is less than 0.09 mm and the maximum displacement in transverse direction is 0.009 mm. Fig. 5 shows the safety factors for the inductor. The least safety factor is equal to 3.6 and it takes place in the fastening plates.

Table 1. Results of mechanical analysis

	External force 10 kN acting along the axis of inductor movement	***Distributed external force 5 kN acting across the axis of inductor movement***
Equivalent breaking stress, MPa	417	31
Maximum displacement, mm	0.08	0.008
Minimal safety factor value, ul	3.6	8.1

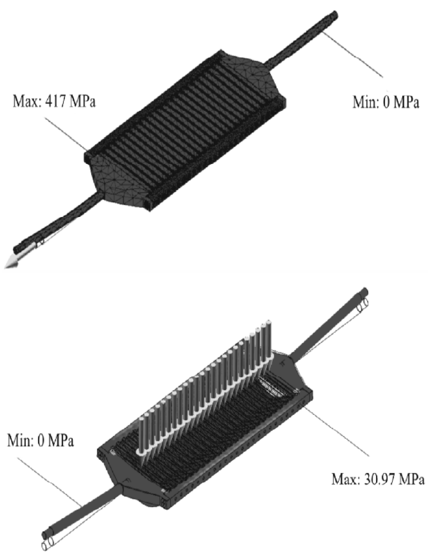

Fig. 3. Equivalent stress calculation

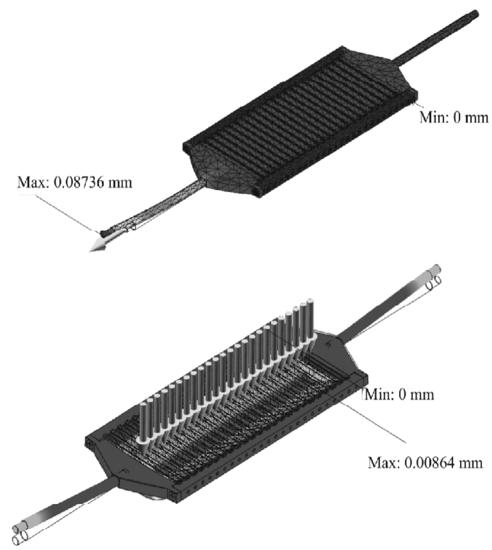

Fig. 4. Displacement calculation

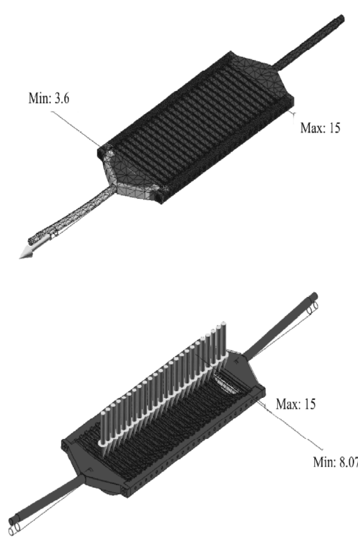

Fig. 5. Safety factor calculation.

Mechanical analysis proved that proposed inductor design provides strength of all details. Considering that calculations were made for a peak load one could be sure that under working load the inductor strength will be provided too.

Generator performance evaluation

Modern engineering software allows us to build high accuracy mathematical models of electric machines in order to predict its performance and obtain characteristics at the design stage even before prototyping [9]. This saves a lot of money as one can test numerical models and correct design errors before making final prototype. Usually rough analytical models are used for optimization procedures when engineer evaluates a number of design variants for a short time, but the final design must be simulated with a high accuracy model in order to ensure its performance before prototyping. And nowadays the most reasonable model of electric machine should be based on a Finite-element method (FEM) of electromagnetic field analysis [10-11].

Such FEM model of proposed design was built for electromagnetic analysis of linear reciprocating generator. Fig. 6 shows a fragment of FEM model which allows to take into account real dimensions of a complex linear generator active zone, material properties with saturation of stator teeth and inductor field concentrators, mutual position of stator and inductor cores while calculating magnetic field distribution and electromagnetic forces for any core position.

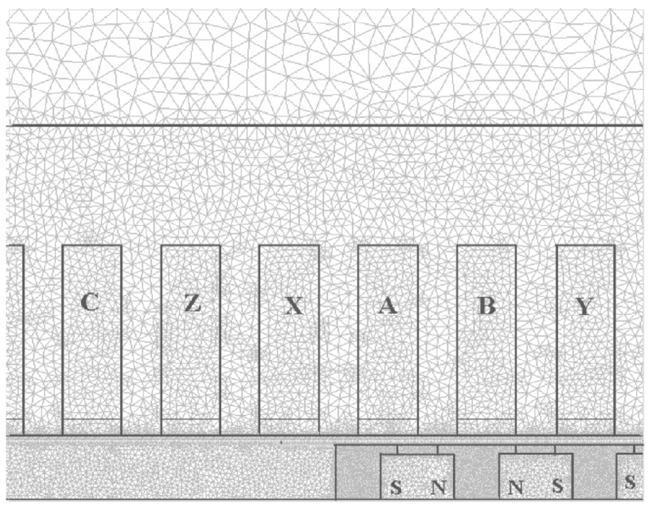

Fig. 6. Fragment of a FEM model of a flat linear generator with double-sided stator.

Fig. 7 shows a fragment of FEM model in more details to demonstrate finite element structure of the model. In order to provide high accuracy of electromagnetic force evaluation the air-gap zone of generator should be simulated by at least four layers of finite elements while contour for air-gap flux density and electromagnetic force evaluation is located in the middle of the air-gap height and is separated from both inductor and armature core by two layers of fine elements.

The FEM-model presented at Fig. 6 and Fig. 7 simulates only upper half of generator cross-section, while generator has double-sided design. This is due to generator's symmetry relative to the middle plane of inductor, hence magnetic field is identical in upper and lower half of cross-section. The use of symmetry feature allows to significantly decrease analyzing area and reduce calculation time for magnetic field analysis.

Presented FEM model allows to analyze magnetostatic fields, which means that initial conditions of magnetic field analysis should contain all sources of magnetic field. Besides permanent magnet MMFs, which are reproduced automatically by material properties of corresponding PM blocks, one should define current density in each block corresponding to armature winding in stator slots. During generator operation instant values of armature phase currents are determined by instant value of phase electromotive force (EMF) and impedance of corresponding electric branch which includes load impedance, phase resistance and phase reactance of end turns leakage. The latter cannot be reproduced by 2-dimensional model and should be evaluated separately and introduced in electric branch circuit. While phase EMF calculated as a phase linkage derivative takes into account both excitation and armature reaction fields, slot leakage and differential leakage fields. This means that magnetostatic field calculation should be fulfilled many times on the period of inductor movement during one stroke.

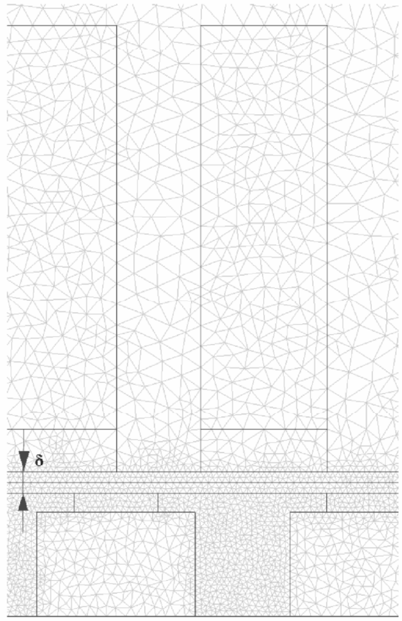

Fig. 7. Fragment of FEM model demonstrating finite element structure with a flux density evaluation contour at the middle of the air-gap.

Instant values of phase currents on the period could be obtained from differential equations of generator electric branches. As these equations are non-linear one should use one of numerical approximation methods. One period of inductor movement will require hundreds calculations of magnetic field at different inductor position and different phase current values. In order to provide transient analysis with relatively simple magnetostatic FEM model one should use some script language, which allows to build FEM model automatically, perform field calculation and evaluation of output variables, while using it in numerical approximation algorithm of differential equations analysis.

FEM-transient simulation

Program for FEM-transient simulation was made with Lua script language and implemented the following algorithm. For a given law of inductor speed variation on a period of one stroke the total time span is divided into a rather big number of small time intervals at which instant phase current values should be estimated. Example at Fig. 8 covers half period, which is equal to 10 ms at 50 Hz frequency and it is divided into 80 time intervals.

Let us consider calculation sequence at $(t+1)$ time interval. Initial conditions are based on instant values of phase flux linkages Ψ_t and currents i_t at the previous time interval t. Corresponding inductor position is determined by given law of inductor speed variation and time interval t. The first magnetic field calculation at current time interval $(t+1)$ is made for a new inductor position with phase currents $i_{i+1}^{(0)}$ obtained from the previous time interval currents i_t. In the simplest case, new currents could be found as $i_{i+1}^{(0)} = i_t$. As a result of this first field calculation the values of phase flux linkages $\Psi_{t+1}^{(0)}$ are evaluated.

After that new phase current values $\hat{i}_{t+1}^{(1)}$ are calculated based on a Kirchhoff equation for each phase:

$$\left(-\frac{\Delta\Psi_{t+1}^{(0)}}{\Delta t}\right)+\left(-\mathrm{L}\frac{\Delta\hat{i}_{t+1}^{(1)}}{\Delta t}\right)+\left(-\mathrm{R}\cdot\hat{i}_{t+1}^{(1)}\right) = 0.$$

where $\Delta\Psi_{t+1}^{(0)} = \Psi_{t+1}^{(0)} - \Psi_t$, $\Delta\hat{i}_{t+1}^{(1)} = \hat{i}_{t+1}^{(1)} - i_t$, Δt is a time interval.

This differential equation was transformed into algebraic one by finite differences.

Next magnetic field calculation for $(t+1)$ time interval is made for the same inductor position but with new approximation of phase currents $i_{t+1}^{(1)} = i_{t+1}^{(0)} + k_r \cdot \Delta\hat{i}_{t+1}^{(1)}$, where k_r is a relaxation factor (this value significantly affects on convergence of the iterative process). As a result of this magnetic field calculation the new values of phase flux linkages $\Psi_{t+1}^{(1)}$ are evaluated which allows to calculate flux linkage changes $\Delta\Psi_{t+1}^{(1)} = \Psi_{t+1}^{(1)} - \Psi_t$, phase EMFs $e = -\Delta\Psi_{t+1}^{(1)} / \Delta t$ and voltage drops on phase and load impedance at phase currents . Then Kirchhoff equation for each phase is used to check maximum residual (error of left and right side of Kirchhoff equation). In case the maximum residual of all phase equations is more than allowable error, the iterative process for the current time interval $(t+1)$ is continued. In case the maximum residual is less than allowable error, the obtained instant values of phase currents and flux linkages are saved and algorithm goes to the next time interval.

Simulation results

Based on field calculation results for each time interval one can evaluate not only phase currents and EMFs but also magnetic flux density and magnetic permeability in any part of magnetic circuit (in the air-gap, in teeth and yokes of magnetic cores, in permanent magnets) and longitudinal and transverse components of electromagnetic force acting on active parts of generator (inductor, for example) and structural elements.

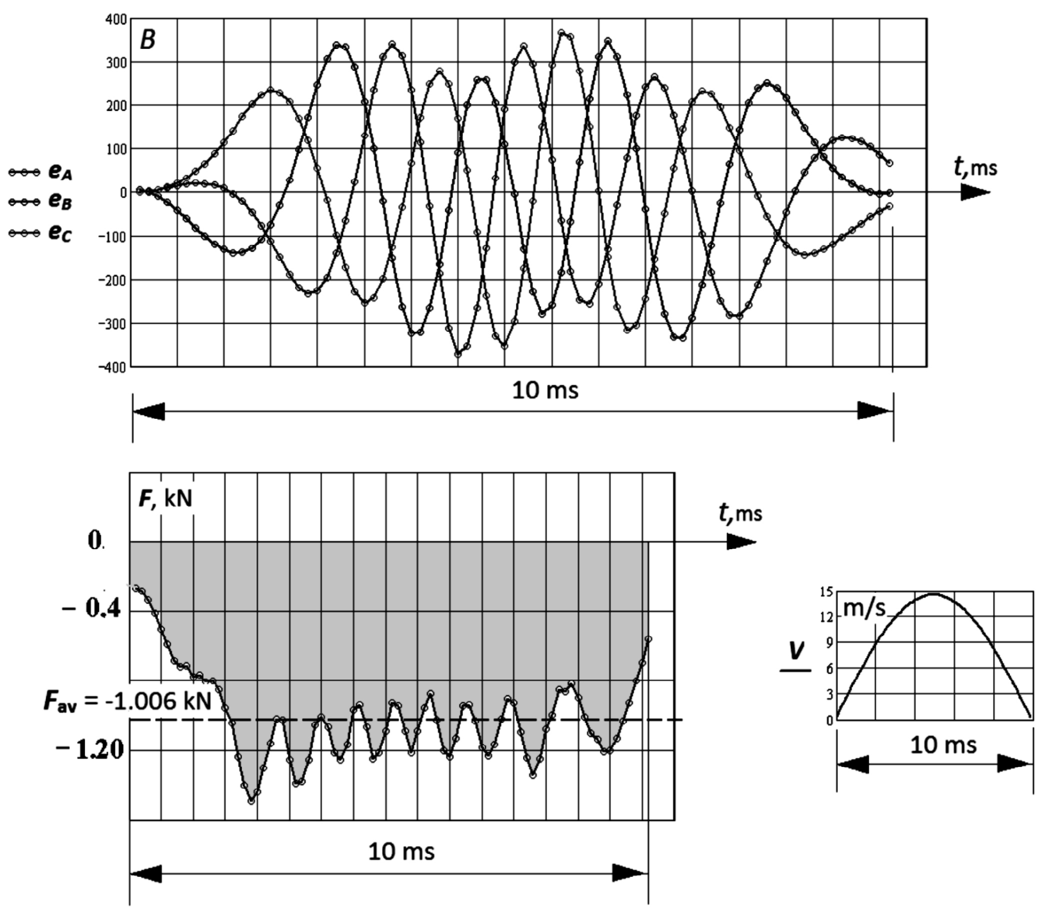

Fig. 8. Linear generator operating condition simulation at sinusoidal law of inductor speed variation

Fig. 8 shows some results of linear generator operating condition simulation. Inductor is reciprocating with sinusoidal law of speed variation, balanced phase of load impedance is equal to 10 Ohm. For this operating condition Fig. 8 shows time domain variation of phase EMF and electromagnetic force acting on inductor due to excitation field interaction with armature reaction field.

Electromagnetic analysis of air-gap deviations

Abovementioned FEM model can be used not only for electromagnetic analysis of initial linear generator design for selected shapes, dimensions and material properties, it can also be used to evaluate generator performance at various deviations. For example, technological deviations during prototyping could lead to air-gap height variation in longitudinal and transverse direction of linear machine. In order to predict prototype generator performance one can use electromagnetic model with accurate field calculation.

In case of air-gap deviations electric machine magnetic circuit can not be considered symmetrical relative to middle plane, so FEM model in that case should take into account the total cross-section of linear generator. While the algorithm of operating condition analysis is the same and the program of FEM-transient analysis could be used without changes.

A number of numerical experiments were performed in order to evaluate the influence of non-symmetric position of inductor relative to upper and lower stators on generator performance. When inductor is displaced from intermediate position between stators towards upper or lower stator the unbalanced electromagnetic force affects moving inductor attracting it towards the nearest stator core (unbalanced traction force). Numerical experiments have shown that this unbalanced traction of inductor is determined mainly by excitation magnetic field of inductor and weekly depends on armature reaction field. Moreover, it was demonstrated that such unbalanced traction force in dynamic mode of operation could be evaluated with sufficient accuracy by magnetostatic field analysis.

Table 2 contains calculation results of specific unbalanced traction force f_δ (traction force per unit of inductor surface) for some fixed inductor position at different inductor displacement $\Delta\delta$ relative to the balanced position at which the upper and the lower air-gap is equal to 1 mm. Each time calculations were made for two operating conditions: no-load condition with zero stator current and rated load condition. Rated load condition corresponds to a balanced three-phase load at which maximum stator slot current density is equal to 5 A/mm^2. FEM model supposes uniform distribution of current density per stator slot. For slot filling factor $k_{fill} \approx 0.5$ the value of RMS phase current density equals to $5\,(\sqrt{2})\text{-}1\,(k_{fill})\text{-}1 \approx 7.1$ A/mm^2.

Table 2 contains also values of electromagnetic force acting in longitudinal direction fz. At no-load condition this electromagnetic force is determined only by stator core slotting, while at load condition it is determined by interaction of excitation field and armature reaction field. One can see in Table 2 that in both cases this electromagnetic force fz does not significantly depend on inductor displacement.

Table 2. Calculation results

$\Delta\delta$, mm	J_{max}, A/mm^2	f_δ, N/mm^2	f_z, N
0.125	0	0.055	0.708
	5	0.051	-7.719
0.250	0	0.108	0.771
	5	0.103	-7.638
0.375	0	0.163	0.737
	5	0.157	-7.595
0.500	0	0.219	0.797
	5	0.212	-7.468

The unbalanced traction force is almost proportional to inductor displacement value. Hence, one can use rather simple method of evaluation of air-gap deviation effect on resulting unbalanced traction force and corresponding torque, which is produced by this force.

For example, let us consider torque which is produced at inductor displacement as shown in Fig. 9 when inductor is tilted relative its main longitudinal axis – inductor roll.

In order to make necessary calculations one need to know inductor active zone dimensions (length L_{ind} = 0.276 m and width B_{ind} = 0.120 m) and maximum and minimum air-gap height on opposite inductor edges max and min.

For a rated air-gap height $\delta = 1$ mm and inductor edge displacement by 0.5 mm (on opposite edges inductor is displaced in opposite directions) the maximum unbalanced force according to data of Table 2 is equal to 210 N/mm^2. While we are considering inductor roll relative to its longitudinal axis, the specific unbalanced traction force is changing linearly from zero value at inductor center to maximum value at inductor edge equal to $f_{\delta}^{0.5} = 0.210.10^6$ N/m^2. At that resulting torque produced by such unbalanced traction force can be calculated as follows

$$M = 2L_{ind} \int_0^{0.5\,B_{ind}} \left(\frac{f^{(0.5)}}{0.5\,B_{ind}} . \,x\,dx \right) . \,x = 4\frac{L_{ind}}{B_{ind}} f_{\delta}^{(0.5)} . \frac{x^3}{3} \Bigg|_0^{B_{ind}\,0.5}$$

$$= \frac{1}{6} L_{ind}\; B_{ind}^2 . f_{\delta}^{(0.5)}$$

For a given dimensions of inductor active zone the value of torque is equal to 139.1 Nm.

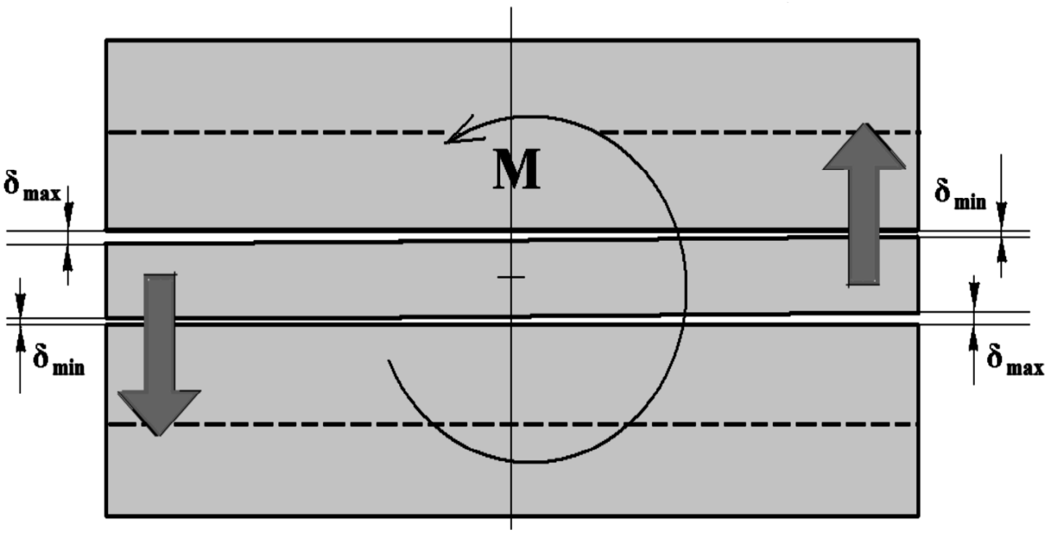

Fig. 9. Torque calculation at inductor roll.

Obviously, such approach can be used for any known variation of air-gap height between inductor and stator cores in any direction.

2. CONCLUSION

Linear reciprocating electric machine is presented which use flat inductor and double-sided stator design. Stator winding is made multi-pole with a fractional number of slots per phase per pole $q = 2/5$. Inductor contains permanent magnets with longitudinal direction of magnetization and alternate polarity. Permanent magnets are located between flux concentrators made of soft magnetic material. Mechanical analysis was made in order to determine internal mechanical stress in longitudinal and transverse directions of inductor. FEM model for electromagnetic analysis was described which was used to evaluate the influence on generator performance of technological deviations in generator design and dimensions which may occur during production and assembling.

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