

68th Conference of the Italian Thermal Machines Engineering Association, ATI2013

Kinetic energy recovery system for sailing yachts: preliminary experimental results

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Abstract

SEAKERS (SEA Kinetic Energy Recovery System) is a research project, funded within the 7th EU Framework Program, whose goal is to develop an innovative device consisting in a model of a kinetic energy recovery system for sailing yachts, based on the conversion of wave-induced boat oscillations (heave, pitch and roll) into electric energy by means of a linear generator. The device aims at recovering as much kinetic energy as possible from the natural movements of a sailing yacht on the sea, therefore taking the view of a boat as a moving wave energy converter with energy harvesting capability. The boat's motions can be vertical oscillations due to the buoyancy in the presence of sea waves and rolling and pitching motions originated both by sailing in wavy waters and by the normal boat dynamics due to the sails' propulsion. This paper presents a brief description of the prototype of linear generator, which has been developed in the SEAKERS project, and reports about the first experimental tests carried out on the prototype. Two kind of tests have been performed on the generator, which can be classified as a linear permanent magnet switched reluctance generator: first, the possibility to use the prototype like an actuator has been investigated, in order to force the cursor to have a motion in phase with the external forcing, so as to recover more energy when the machine acts as generator. The behaviour of the actuator was examined in a static way, measuring the forces between cursor and stator, varying relative position of cursor and current in the coils. The second kind of tests has been performed to analyse the efficiency of the generator, for different external loads and translational velocities. The trend shown in these tests are then explained by an analytical model based on an electromagnetic circuit.

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Selection and peer-review under responsibility of ATI NAZIONALE

Keywords:

Wave energy recovery; energy harvesting; linear generator; sail yacht

1. Introduction

The aim of the SEAKERS project is the study and the experimental set-up of a prototype for the harvest of energy from wave motion on sail yachts with a main length of about 10-15 m. The energy harvest is carried out by a linear electric generator. This electric machine is composed of a stator, in-built to the hull of ship, and a cursor which can

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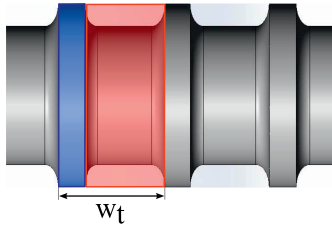


Fig. 1. Stator: tooth (blue) and cavity (red).

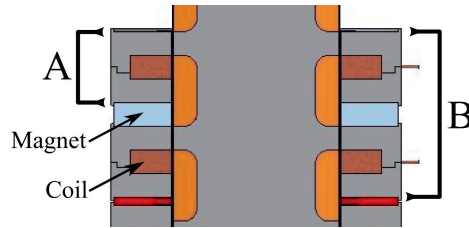


Fig. 2. Section of cursor and stator.

slide along the stator. Its motion is due to the inertial force between stator and cursor caused by the wave motion. In a previous paper the authors have discussed the theoretical energy recovery by a linearised system [1]; in this work a brief description of the electric machine developed by LABOR srl is given, and the results of experimental tests performed to investigate its behaviour, when operating both as generator and as a motor, are presented. The results are illustrated also by means of an analytical lumped-parameter model capable to describe the machine behaviour, and measured and calculated data are compared.

2. The electric machine

2.1. Stator

The stator has two main functions, a mechanical one that is to be a linear sliding guide for the mobile equipment and the other one is a magnetic function: it has to close the magnetic circuit due to permanent magnet to create a magnetic flux linked to the coils. The stator is made of pure iron (Type ARMCO, manufactured by AK Steel), and change of the magnetic flux linked to the coils (located in the slider) are induced by a series of teeth and cavities on the stator (Figs. 1 and 2). However these cavities are filled with resin to allow the cursor being guided by the external surface of the stator, without any additional components. To create the desired flux the stator has a tooth width of $h_t = 8$ mm and the width between two consecutive teeth is $w_t = 32$ mm which represent the stator pitch.

2.2. Cursor

The slider is composed of three ring-shaped modules each corresponding to one phase (B module in Fig. 2). They are mounted one above the other with a separating ring of PVC, but the second phase in the middle is mounted in the opposite direction to reduce magnetic flux leakage. The PVC ring has two functions, one is to allow a magnetic separation of the phases and the other is to shift the magnetic circuit of the phases. Each module is composed by two rings of iron (ARMCO) with a C shaped section (A module). In this way the iron rings form a series of tooth and cavities with a width of about $w_t/4$. The permanent magnets are placed between these iron rings. A single coil is placed in every cavity and an electric phase is composed by two coils, where a coil is wrapped around the first branch of the magnetic circuit and the other around the second one. Furthermore the two coils are connected in series in such a way that the electric current goes clockwise in one of the two and counterclockwise in the other. Three versions of coils have been prototyped and tested, with different number of turns and wire section (table 1).

Table 1. Characteristic of the coil used in the tests.

Type of coil	N. of turns	d [mm]	R [Ω]
1	400	0.63	5
2	136	1.15	0.5
3	200	0.8	1.6

The magnets are uniformly distributed and are mounted between the two C shaped rings, with the magnetization direction parallel to the sliding direction; their characteristics are summarized in table 2.

Table 2. Main characteristic of permanent magnets

Material	NdFeB
Dimension	15x15x8 mm
Remanence Br	1.29-1.32 T
Coercive force Hc	955 kA/m
Energy product BH	330 kJ/m

2.3. Magnetic flux trend

Permanent magnets generate a magnetic induced field \mathbf{B} in the cursor and when the teeth of the stator are aligned to the cursor teeth the magnetic field is induced to the stator and a magnetic flux concatenates the coils. The flux linked to a phase is the sum of the fluxes linked to every coil of the same phase.

To represent the magnetic behaviour of the electric machine three different magnetic circuits are considered, one for each phase. The circuit is formed by a variable flux generator that represents the permanent magnets while all the air gap between stator and cursor is represented by a variable reluctance (Fig. 3). From the geometrical configuration of the electric machine a simple and intuitive trend for the flux can be obtained. If we consider the cursor with the first tooth aligned with a tooth of the stator we can represent the variation of flux linked to the coil along the main dimension of the stator x with a sinusoidal trend. The three electric phases have the same trend but there is a phase shift δ [2,3].

$$\Phi_1(x) = \frac{3}{4}\Phi_p \left[\cos(\omega x) + \frac{1}{3} \cos(3\omega x) \right] \quad (1)$$

$$\Phi_2(x) = -\frac{3}{4}\Phi_p \cos \left[\cos(\omega(x - \delta)) + \frac{1}{3} \cos(3\omega(x - \delta)) \right] \quad (2)$$

$$\Phi_3(x) = \frac{3}{4}\Phi_p \left[\cos(\omega(x - 2\delta)) + \frac{1}{3} \cos(3\omega(x - 2\delta)) \right] \quad (3)$$

With the same thinking for the flux we obtain the trend for the total reluctance that represents the sum of all reluctances in series along the magnetic circuit:

$$R_1(x) = \frac{R_p}{2} \left[1 - \left(\cos(2\omega x) - \frac{1}{9} \cos(6\omega x) \right) \right] + R_{min} \quad (4)$$

$$R_2(x) = \frac{R_p}{2} \left[1 - \left(\cos(2\omega(x - \delta)) - \frac{1}{9} \cos(6\omega(x - \delta)) \right) \right] + R_{min} \quad (5)$$

$$R_3(x) = \frac{R_p}{2} \left[1 - \left(\cos(2\omega(x - 2\delta)) - \frac{1}{9} \cos(6\omega(x - 2\delta)) \right) \right] + R_{min} \quad (6)$$

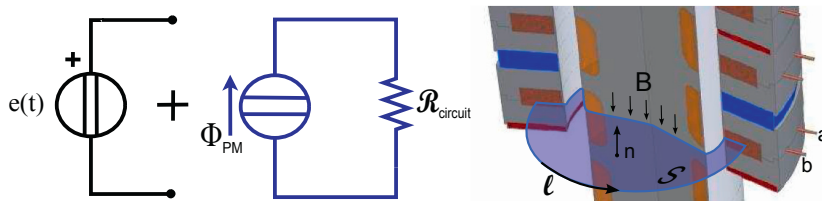


Fig. 3. Electric and magnetic circuit linked to the generator.

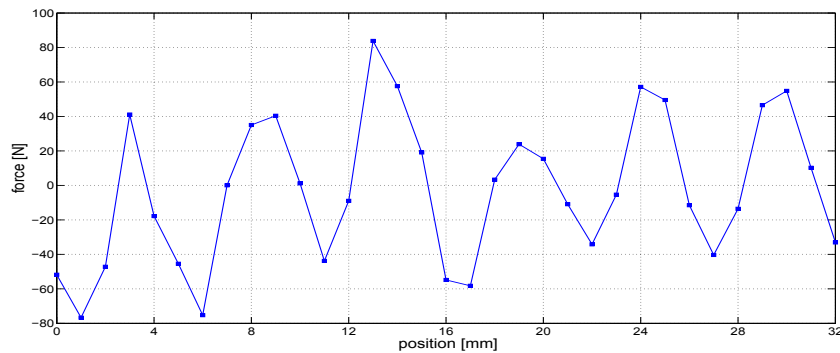


Fig. 4. Cogging force

3. Tests

3.1. The actuator

Supplying a voltage to the coils the electric machine can work like an actuator. This behaviour is investigated in a static way in order to have a force mapping for different operating conditions. This investigation is required because of the possibility to use the actuator to move the slider and force it in order to have a motion in phase with the inertial force. In this way the generator spends a little amount of energy in order to recover later a larger amount of the available energy.

Another aspect investigated is the magnetostatic force due to the permanent magnets, i.e. the cogging force. This force must be large enough to balance the gravitational force acting on the cursor because, for reasons related to the particular frequency of the forcing input, there is no mechanical system (springs) to provide the required force [1].

3.1.1. Test

To perform the measurements, coils have been fed with different currents from a maximum negative value to the same positive value with a specific step and for a specific time frame. All parameters are chosen and controlled by the computer with a LabVIEW[®] acquisition program. For each current the force is measured and data are saved in a log file. This kind of test has been repeated for all positions of interest, with the stator shifted from zero (which was chosen arbitrarily) to the relative final position that correspond to a stator pitch. For the tests a step of 1 mm has been selected, with a total of 33 positions where the behaviour of the prototype is investigated. The instruments used for this test were:

- Caliper: to measure the relative position between stator and cursor.
- Load cell: to measure the relative force between stator and cursor.
- Current generator: to feed and control the current to the coils.
- Chassis: to allocate the electric machine and allow the relative motion between stator and cursor.

3.1.2. Results

Cogging force. Tests were performed with a current step that also allows a measure at zero current in order to evaluate the magnetostatic force due to the permanent magnets. The results show a periodic trend with an amplitude approximately constant, as illustrated in Fig. 4.

Actuator forces. The other measurements represent the trend of force as position and current are varied, and an example is shown in Figs. 5, 6 and 7. The first one shows the superposition of two different periodic trends while the variation of current shows a linear trend outside the central plateau where only the cogging force is active.

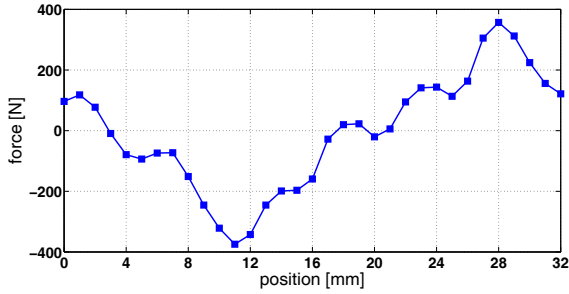
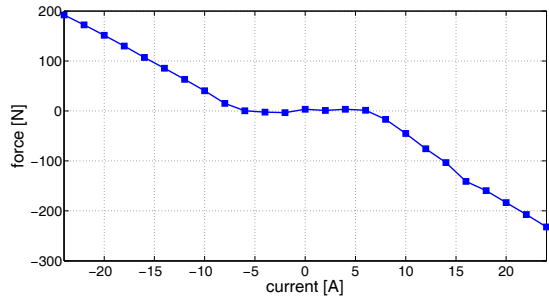
Fig. 5. Trend of measured force for a fixed current along x .

Fig. 6. Trend of force at a fixed point as the current fed is varied. The effect of residual magnetization of iron core has been deleted.

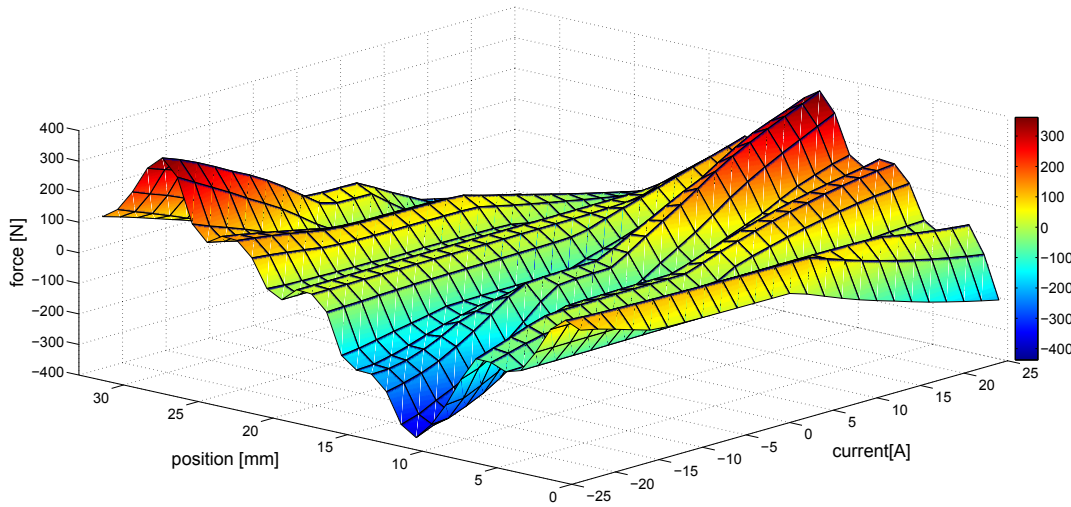


Fig. 7. Trend of force as both current and relative position are varied.

3.1.3. Analysis

The magnetostatic force, F_{tot} , acting on a target in a magnetic circuit, containing a coil and a permanent magnet, is given by the sum of three components [4]:

$$F_{tot}(x, i) = \underbrace{\frac{1}{2} i^2 \frac{dL_{coil}(x)}{dx}}_1 + \underbrace{\frac{1}{2} \frac{d(R_{PM}\Phi^2)}{dx}}_2 + \underbrace{N_{coil} i B}_3 \quad (7)$$

where L_{coil} is the inductance (defined as $L_{coil} = N^2/R_{coil}$), N_{coil} is the number of turns, Φ is the flux generated by the PM and R_{coil} is the total reluctance of the magnetic circuit linked to the coils, while R_{PM} is the reluctance of the magnetic circuit linked to the PM. The displacement of the slider is indicated by the x -parameter and i is the current. The three components are the following:

1. F_{coil} : Reluctance or magnetization force generated by a current carrying coil in a magnetic circuit. The direction of the force is always such that it tends to increase the inductance and hereby decreases the reluctance R_{coil} . Its trend is shown in Fig. 8.
2. F_{PM} : Reluctance or magnetization force generated by a permanent magnet. The reluctance force generated by the permanent magnet always tends to decrease the reluctance, R_{PM} , of the total circuit.

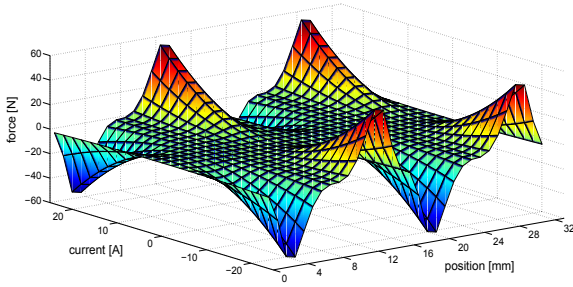
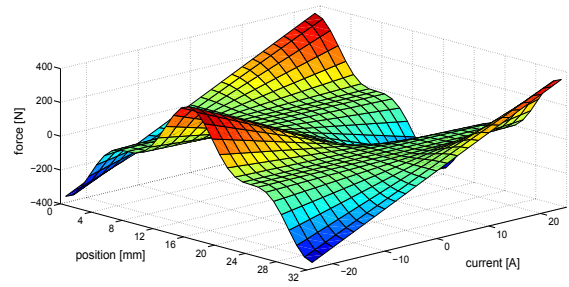
Fig. 8. Trend of F_{coil} Fig. 9. Trend of $F_{lorentz}$

Table 3. Parameters used for the evaluation of the forces

$\Phi_p[Wb]$	$R_p[10^6 H^{-1}]$	$R_{min}[10^6 H^{-1}]$	$R_{PM}[10^6 H^{-1}]$
0.0009	6.5	1.4	2.4

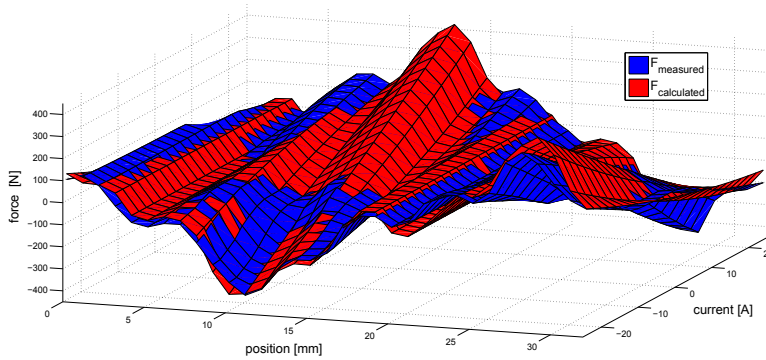


Fig. 10. Comparison between measured and calculated forces

3. $F_{Lorentz}$: Lorentz force. It is the mutual force between the current carrying coil and PM-induced field. Lorentz force have the form $\mathbf{F}_{Lorentz} = q\mathbf{v} \times \mathbf{B}$. This equation is rewritten with the aim of depending upon the electromagnetic parameters which are known in our case, as in the following equation shown below, which is represented here for the first phase:

$$F_{Lorentz,1} = NilB_{stator} = \frac{\Phi_1(x)k_{rid}}{S_{stator}}Nil \quad (8)$$

where k_{rid} is a parameter which reduces the value of $\Phi_1(x)$ in order to consider only the component of B that actually produces a force along x , and l is the perimeter of coils in the magnetic field. Its trend is shown in Fig. 9.

These expressions for the forces are calculated in Matlab® with the parameters given in table3. From the comparison of measured and calculated forces we can see that the largest contribution is due to the Lorentz force. For that reason the actuator can be seen as a linear permanent magnet synchronous motor [5].

3.2. The generator

The main function of the electric machine in the SEAKERS device is obviously to generate electric energy thanks to the relative motion between stator and cursor. This behaviour is investigated by a dynamic test in order to evaluate the performance of the generator in terms of power output and efficiency.

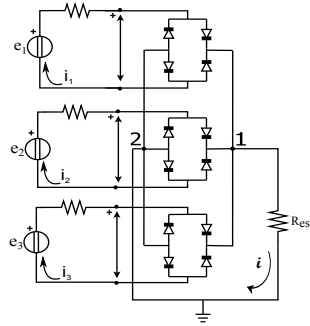


Fig. 11. Circuitual representation of generator and its rectifier.

3.2.1. Test

The experimental apparatus is composed by a fixed chassis where the cursor is mounted and a mobile frame, connected to the stator through a load cell which provides data for the total force acting on the stator. The external force is managed directly by the motion control system, while the three phases of the generator are connected to a variable load, through a voltage rectifier to get a single DC voltage output (Fig. 11).

The coils used in this test have 100 windings per coil, for a total of 200 windings per each phase, diameter 0.80 mm and a total resistance of about 1.6 Ω . The only major modification is the number of magnets, which was increased to 13, to increase the magnetostatic force, too low with 11 magnets to contrast gravity.

The mobile part of the test bed connected to the stator is controlled by a control system which is programmed in LabVIEW[®] that impose a motion with a triangular waveform, with constant speed area and smoothed corners to avoid sharp acceleration. Another program has been developed for data acquisition.

Tests have been performed varying two parameters, i.e. external load resistance (R_{ext}) and relative translational speed. For each resistance connected, several speeds have been tested. Structural limitations suggested to use 0.2 m as semi-amplitude of the triangle waveform, while speed has been varied from 0.05 m/s to 0.55 m/s with a step increase of 0.05 m/s. Each profile has been tested for a minimum of 30 to 50 periods. As soon as a cycle with variable speed is finished, load resistance is changed. Resistances tested are 0.33 Ω , 1.12 Ω , 5.1 Ω , 15 Ω , 30 Ω and 75 Ω .

3.2.2. Results

It can be assumed from general considerations on the linear generator that, as an ideal first approximation (without losses), the dynamic behaviour of the linear generator is expressed by the following simple relationship:

$$m\ddot{x} + F_{em} = F_{in} \quad (9)$$

where the terms represent:

- x : relative position between stator and slider;
- F_{em} : electromagnetic braking force, which can be seen as $F_{em} = c_{em}\dot{x}$, where c_{em} is the electromagnetic damping coefficient depending on the characteristics of the electromagnetic braking: $c_{em}(t) = e(t)i(t)/\dot{x}^2(t)$;
- F_{in} : external forcing.

The instantaneous efficiency can therefore be expressed as:

$$\eta_{tot} = \frac{E_{out}}{E_{in}} \implies \eta_{tot} = \frac{\int_t^{t+T} v i dt}{\int_t^{t+T} F_{in} \dot{x} dt} \quad (10)$$

where output voltage and current have been introduced (respectively, v and i). In order to get an indirect measurement of the efficiency, it will be necessary to measure directly F_{in} , v and i . Trends of measured data along time are reported in Fig. 12, while the total efficiency value is reported in Fig. 13.

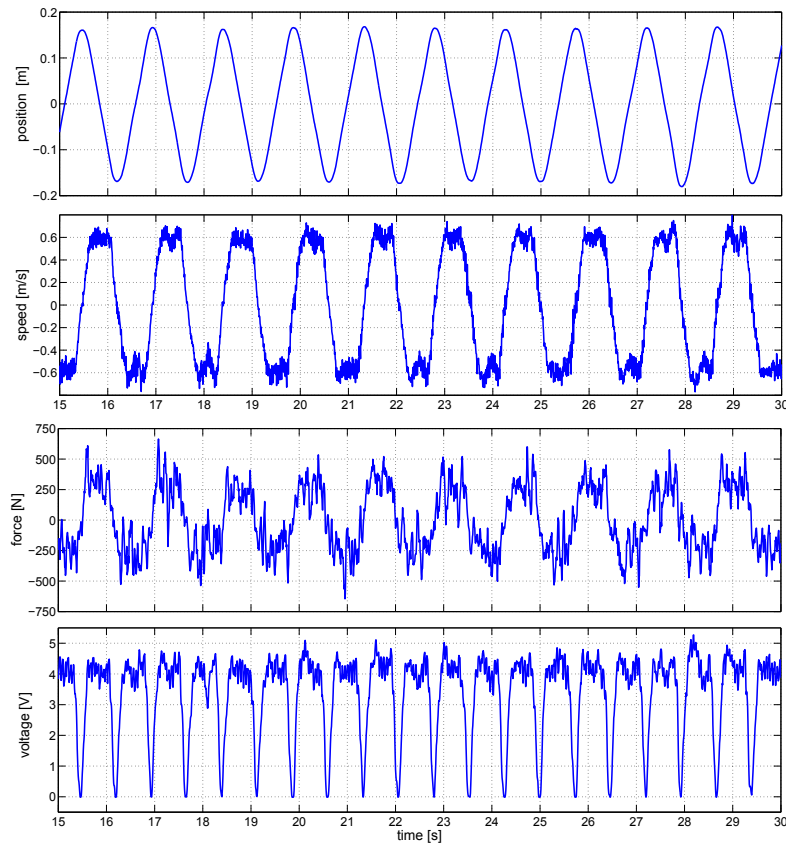


Fig. 12. From top to bottom: stator relative position and velocity, force, rectified voltage, for fixed values of load resistance and translational speed.

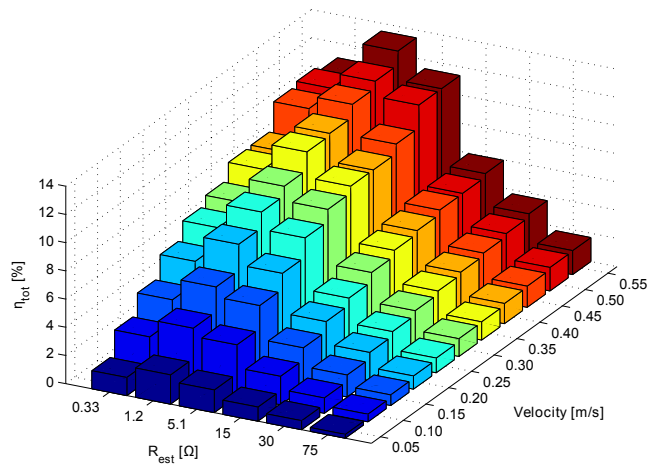


Fig. 13. Total efficiency trend

Total efficiency can be seen as the product of an electric efficiency and a mechanical efficiency. The first one takes into account losses in the coils and in the rectifier, while the second one considers the losses due to eddy current and friction between stator and cursor. Their value is represented in Figs. 14 and 15.

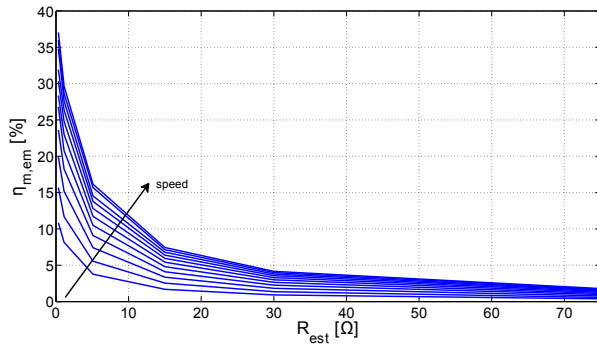


Fig. 14. Magneto-mechanical efficiency

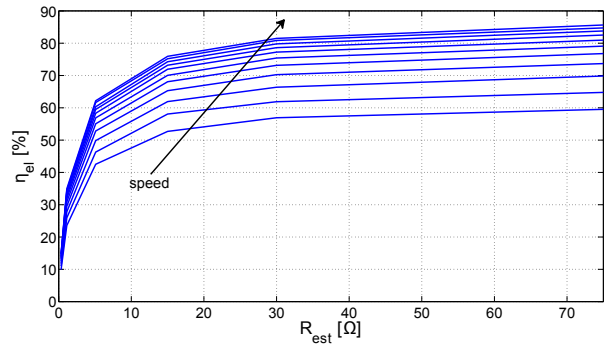


Fig. 15. Electric efficiency

3.2.3. Analysis

To reproduce the dynamic behaviour of forces and generated voltage a model in Simulink has been implemented according to the following considerations.

Voltage. The working principle of the generator is identified as the Lenz-Faraday law, $e_i = -d\Phi_i/dt$, where e_i is the voltage generated at the end of a winding and Φ_i is the concatenated magnetic flux. For the first phase:

$$e_1(t) = -\frac{d\Phi_1}{dt} = \frac{3}{4}\Phi_p\omega\dot{x}\frac{N}{2}[\sin(\omega x) + \sin(3\omega x)] \quad (11)$$

Voltage trend for the other phases is only shifted of about 120° one from the other. The prototype was also fitted with a rectifier, converting into positive current and summing the three phases to the nodes (junctions) 1 and 2 where the voltage is measured.

Dynamic behaviour. With a detailed analysis of forces acting on the linear generator the dynamic equation, which includes the possible energy losses, can be rewritten as:

$$m\ddot{x} + F_{em,r} + W + F_{PM} + F_{att} + F_{em,ec} = F_{in} \quad (12)$$

- $F_{em,r}$: real electromagnetic braking force. The real force has a lower value than the ideal one mainly due to two sources of energy loss: the first one is the hysteresis effect on the magnetization of the core, and the second one is due to eddy currents.
- W : weight force. The moving part of the generator is subject to the gravitational force.
- F_{PM} : magnetostatic force. This term has already been described in the previous section.
- F_{att} : dynamic friction force. It represents the effect of friction between the two surfaces in movement. For the prototype there is not a detailed knowledge of this term, thus it is represented in the model as follows: $F_{att} = -\text{sgn}(\dot{x})H_{att}$, where H_{att} is a constant value deduced from the measured data.
- $F_{em,ec}$: electromagnetic braking force due to eddy currents. Eddy currents in the stator determine a magnetic flux opposed to the one that created them, with the effect of decreasing the braking force. The force can be expressed as: $F_{em,ec} = c_{em,ec}\dot{x}$, where also $c_{em,ec}$ is deduced from measured data.

The value of the parameters used in the simulation are reported in table 4 while the comparison between measured and calculated data for the force and the voltage, with $R_{est} = 0.33 \Omega$ and $\dot{x} = 0.45 \text{ m/s}$ is shown in Fig. 16.

4. Conclusions

In the first kind of tests, with the machine controlled as an actuator, a simple relation between current and cursor position has been deduced. The control system will be designed taking these data into account, since it must be able

Table 4. Parameters used for the evaluation of dynamic forces and generated voltage

Φ_p [Wb]	R_{int} [Ω]	R_{diode} [10^6 H^{-1}]	V_{diode} [V]	H_{att} [N]	$c_{em,ec}$ [N s/m]
0.0012	1.6	0.3	0.7	95	180

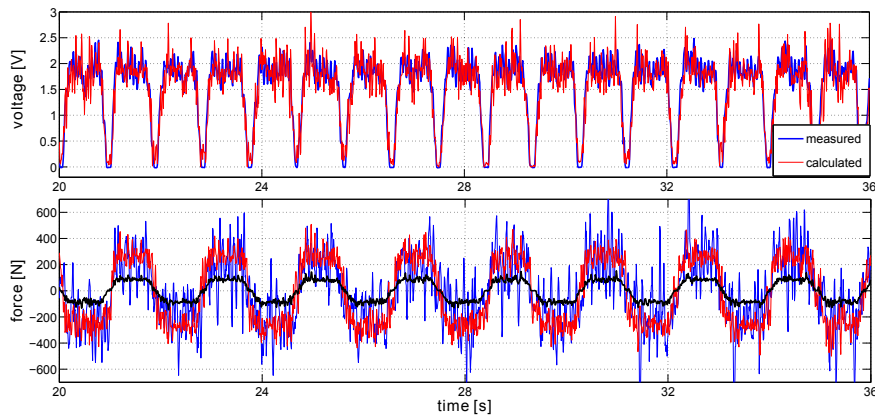


Fig. 16. An example of comparison between measured and calculated data in the dynamic tests. The curve in black represents the component $F_{em,r}$, that is responsible for the voltage generation.

to make the electric machine work briefly as an actuator in order to recover the largest amount of energy possible. In order to have a short lead time for the control system unit it is possible to consider only the effect of the Lorentz force.

For the second kind of tests some considerations can be deduced from the Simulink model where all the energy losses have been evaluated independently, introducing some efficiency parameters to represent them. From the results obtained it is possible to deduce that some changes must be implemented in the system in order to reduce energy losses when the machine works as a generator. A large amount of losses is due to friction and eddy current: the first one may be due at least partially to an imperfect experimental set-up and for this reason the experimental conditions must be reassessed in order to delete all systemic errors; eddy currents, on the other hand, represent a particular large amount of energy loss, in particular in the stator iron core, which can be deleted only if the stator is made of ferrite or of thin laminated sheets of iron, with insulating glue or paper between the sheets. Electrical losses can be dealt with more simply by means of an improved rectifier and a better configuration of coils. After these changes other tests need to be done in order to verify a better efficiency in generation, as well as the proper operation of the electronic control of the cursor motion. Then, the overall energy recovery system (generator, accumulator and control system) must be reassessed and other tests will be needed in order to verify the performance of the systems, particularly with reference to the simulation of actual navigation conditions.

References

- [1] Guizzi GL, Manno M, Manzi G, Salvatori M, Serpella D. Preliminary study on a kinetic energy recovery system for sailing yachts. *Renewable Energy* 2014;62(0):216–25.
- [2] Thorburn K, Leijon M. Farm size comparison with analytical model of linear generator wave energy converters. *Ocean Engineering* 2007;34:908–16.
- [3] Danielsson O. Wave energy conversion, linear synchronous permanent magnet generator. Ph.D. thesis; Uppsala University; 2006.
- [4] Laro DAH. Mechatronic design of an electromagnetically levitated linear positioning system using novel multi-DoF actuators. Ph.D. thesis; Delft University; 2009.
- [5] Boldea I, Nasar SA. Linear electric actuators and generators. Cambridge, UK: Cambridge University Press; 1997.