

PERFORMANCE AND DESIGN OF A SINGLE-PHASE LINEAR SYNCHRONOUS GENERATOR USING FINITE ELEMENT METHOD

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ABSTRACT

This paper presents a general proposal to design and calculate the performance of a tubular permanent magnet linear generator treated here on the basis of the Finite Element Method. Optimizing the linear generator dimensions reduces the cogging force, which occurs due to the interaction between stator teeth and the permanent magnets. The generated AC voltage is analyzed and evaluated for both no load and load cases to take the armature reaction effects on the air gap flux density. A repetitive routine is followed to calculate the output AC voltage from the change of flux and the speed of the single-phase linear generator. The AC output voltage is calculated for different resistive loads, and hence, the linear generator load characteristic is obtained. The designed linear generator is capable to generate an output power of 5.3kW with AC output voltage of 222V with an efficiency of 96.8% at full load of 23.8A. The full load current is chosen based on the thermal properties of the coil wire insulations.

I. INTRODUCTION

In general, AC linear electric generators in addition to rotary AC generators are electromagnetic energy conversion devices, which develop short travel progressive linear motion or rotating in a specific speed, respectively. The main applications of the linear generator are the free piston applications, pen recorders, machine tool sliding tables, compressors, factory automation and material control systems [1], [2]. The main advantages of a linear generator (LG) over a conventional one are its compactness and higher efficiency. Among the various configurations of linear generators, the tubular permanent magnet (PM) is superior to the flat design in terms of volume compactness and symmetry, which helps to analyze in two dimensions only. The tubular structure has less leakage flux and is better in utilizing the material that leads to a higher electromotive force (emf). This is one of the main design factors. In spite of these advantages, the PM-LGs schemes in general have a high cogging force to deal with. The cogging force is produced by the interaction between the PMs and the slotted iron structure and the finite length of the stator core. These factors have different periods of one-slot pitch and one-pole pitch, respectively [4] [5]. The

cogging force produces a pulsating force ripple resulting in vibrations and acoustic noise, which is detrimental to the linear generators. The cogging force problem can be alleviated with proper optimization of the dimensions of stator and translator. As a result, proposal of methods to reduce the cogging force are presented and evaluated in this paper.

II. PM-LG PROTOTYPE STRUCTURE

In this paper, a tubular PM-LG prototype scheme is presented in which the design approach based 2D finite element method (FEM). The main design parameters are the emf AC voltage across the stator coils and the cogging force. To reduce the cogging force, the stator and the translator elements of tubular PM linear generator are optimized separately to get the desired values of the AC output voltage. Its stator length is effectively chosen to give a minimum cogging force. The PM length, the PM depth, the coil volume and teeth depth are varied over wide ranges and in each time, the output AC voltage and the cogging force are calculate by FEM. The proposed tubular PM-LG scheme have slotted structure and axially (z-axis) magnetized PMs as shown in Fig. 1. The stator of the tubular PM-LG consists of three non-opened slots, which contain the coils

and the core iron laminations, which have a fill factor of 95%. The translator part consists of four PMs of NdFeB material, which are magnetized in the axial direction (in the motion direction), mild steel spacers between the PMs acting as a pole shoes and a non-magnetic material (stainless steel) of the shaft, which is connected, to the external device (prime mover) in the generator operation to provide the oscillatory motion. It can be seen from Fig. 1, that the tubular PM-LG has equal slot and pole pitches (τ_s equals τ). The main dimensions of the PM-LG scheme are listed in Table I. The stator slots are semi-closed with constant slot depth d_s and opening slot width of s_o . The slot opening height is 2 mm and a slope height of 3 mm. This construction of the stator slots enhances the PM-LG performance. It results in a reduction in the cogging force as it is to be demonstrated in the following sections. Due to symmetry of the generator around z-axis, the 2D FEM is sufficient to analyze it.

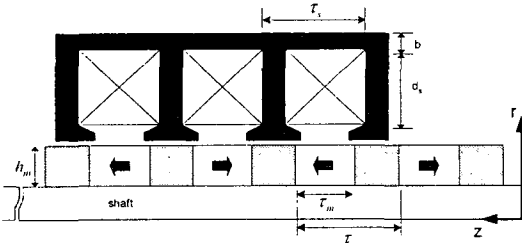


Fig.1 axi-symmetric sketch of the tubular PM-LG

Table I The actuator Specifications

Part	Item	Symbol	Value (unit)
Stator	Slot pitch	τ_s	55 (mm)
	Slot width	s_w	30 (mm)
	Slot opening	s_o	10 (mm)
	Slot depth	s_d	30 (mm)
	Turns/coil		95 (mm)
	Back-iron thickness	b_i	11 (mm)
Translator	PM force	H_c	883 kA/m
	Pole pitch	τ	55 (mm)
	PM length	τ_m	Variable
	PM width	h_m	variable
Air gap	Mechanical air gap	g	1 (mm)

III. FIELD AND FORCE CALCULATIONS

The governing equation of the tubular PM-LG prototype is given on the basis of using the magnetic vector potential, A as [6]:

Where, J_o is the exciting current density of the

$$\nabla \times [\nu(\nabla \times A)] = J_o + J_m \quad (1)$$

stator coil that is zero for generating mode, J_m is the equivalent magnetization current density of the PM and can be written as:

$$J_m = \nabla \times (\nu \mu_o M) \quad (2)$$

Where, ν is the magnetic reluctivity, μ_o is the free space permeability, and M is the magnetization vector intensity of the PM. Using the FEM, the cogging force densities are calculated using Maxwell Stress Method as [7]:

$$f_n = -\frac{1}{2\mu_o} (B_n^2 - B_t^2), \quad f_t = \frac{1}{\mu_o} B_n B_t \quad (3)$$

Where, B_n is the normal magnetic flux density to the integral surface, B_t is the tangential magnetic flux density to the integral surface. The generated AC voltage electromotive force (emf) at stator coils terminals is calculated from Faraday's law of magnetic induction as:

$$emf = -N \frac{d\phi}{dz dt} \quad (4)$$

where N is the number of turns per coil, ϕ is the flux passing in each turn in time t , z is the position of the translator with respect to a specific reference.

IV. CURRENT DENSITY CALCULATION

The current of the output circuit of the PM-LG depends on the cross-section of the coil wire. For most electrical machines, the insulation class F is assumed for the stator coil windings with a temperature rise of θ_w equal to 115 °C [8]. The heat is transferred to the environment through the external surface of the PM-LG prototype scheme ($\pi D_o 2p\tau$). The winding temperature rise θ_w is related to the copper loss p_{cu} in the coil by means of the overall heat transfer coefficient h_c [9] as,

$$p_{cu} = h_c \theta_w \pi D_o 2p\tau \quad (5)$$

And at the same time, the copper loss is related to the current density as in the following equation:

$$p_{cu} = \rho_{cu} V_{cu} J^2 \quad (6)$$

Where, D_o is the outer diameter of the stator, $2p$ is the number of poles, ρ_{cu} is the copper resistivity, V_{cu} is the volume of copper and J is the current density. Solving eqns. 5 and 6, one

can get the appropriate current density in the coil conductors as:

$$J = \sqrt{\frac{h_c \theta_w \pi D_o 2 p \tau}{\rho_{cu} V_{cu}}} \quad (7)$$

V. COGGING FORCE REDUCTION APPROACH

The main variable dimensions are optimized in order to minimize the cogging force value. The variables treated here are the PM dimensions, the coil dimensions and the slot opening length. These variables are considered separately in the following sections:

A. PM Dimensions Effects

The PM length is varied over wide ranges with different PM width h_m , and the cogging force is calculated each time and plotted in Fig. 2. The corresponding root mean square of the no-load back emf induced voltage in the stator coils are plotted in Fig. 3. Examining Fig. 2, it is clear that the cogging force curve has a minimum for each value of the PM width h_m . This minimum value always occurs when the PM length (τ_m) equals 22 mm. The cogging force in general increases with the increase of the PM width. The generated output AC voltage increases with the increase of the PM dimensions. For each magnet width, increasing PM length causes the emf to saturate to a constant value as shown in Fig. 3. It can be seen that the optimal PM length (τ_m) equals 22 mm.

B. Slot Opening Effects

To increase the flux change with respect to the translator position, the slot is slightly closed as in semi-closed slot technique. Increasing the flux change results in an increase in the generated AC voltage across the stator coils as expected from eqn. (4). Generally, the cogging force in case of semi-closed slot is smaller than that of the opened slot. The effect of slot opening s_o on the cogging force, F_c and the generated output emf, V_o is shown in Fig. 4. The voltage, V_o is directly proportional to the slot opening s_o , while there are fluctuations for the F_c values. When s_o varies, the flux linking the coil changes as the PM passes through the slot, affecting the output voltage V_o . It is observed that decreasing the length of the slot

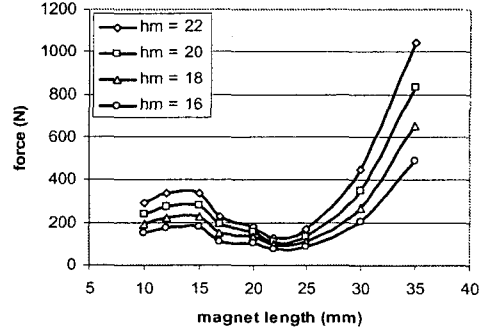


Fig. 2 The cogging force versus

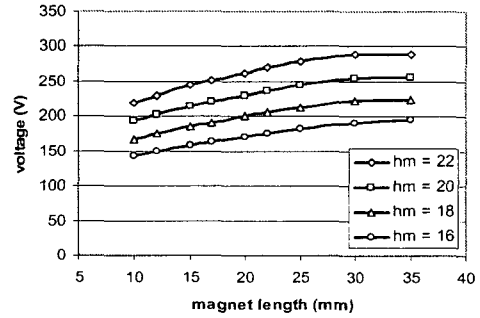


Fig. 3 The output voltage versus

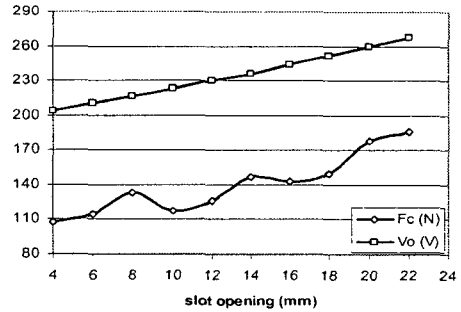


Fig. 4 Slot opening effects; $\tau_m = 22$ mm, $h_m = 20$ mm, $b_i = 11$ mm

opening leads to the increase of the iron path for the magnetic flux. This in turn decreases the F_c . It is found that for this application the suitable the slot opening is around 12 mm.

C. Slot Width Effects

To optimize the coil dimensions, the slot width s_w is varied and its effects on the cogging force F_c as well as on the output voltage V_o is shown in Fig. 5. Changing the slot width, s_w inevitably affects the number of the coil turns. The cogging force F_c has a minimum at a slot width of 34 mm as shown in Fig. 5. The corresponding V_o and F_c are 258 V and 97.5 N, respectively.

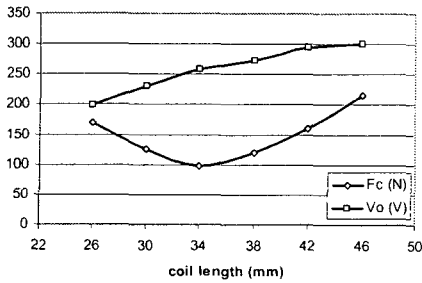


Fig. 5 Effects of slot width, $s_0 = 12$ mm

VI. WEIGHT AND CURRENT CALCULATIONS

After optimizing the overall dimensions of the tubular PM-LG prototype scheme, its weight is calculated. The stator weighs 20.85kg, while the translator weighs 5kg. It is clear that the moving part is not so heavy. The moving part in any machine should be as light as possible to enhance the electric machine performance. The weight of the PM's should be small, as the PM material is the most expensive one in the design. Using 5, 6, and taking the copper conductivity of 58 MS/m, h_c equals 24.3 W/($^{\circ}$ C.m²) and θ_w equals 115 $^{\circ}$ C [9], the current density of the copper conductor can be calculated. The calculated current density J is 3.5 A/mm². The coil cross-section area equals 1020 mm², and taking the coil fill factor equals 0.7, the net copper cross-section area equals 714 mm². If the conductor cross-section is considered to be 1.6x4.25 mm² (for design purpose), the number of turns per coil is about 105 turns. From the calculated current density of the conductor and the conductor cross-section, the appropriate full load current of the generator is 23.8 A.

VII. PM-LG PERFORMANCE

The PM-LG is simulated under load conditions to calculate the generator performance and taking the armature reaction effect into consideration. After completing the first loop, the internal back-generated emf is calculated and from the simple equivalent circuit, the load current can be calculated. The AC output power and copper and core losses are then determined so the efficiency of the alternator can be calculated. In the next the flux is calculated again from PMs and currents of the winding. This newly flux is compared with the original flux comes from PMs only. If the flux change exceeds a predetermined threshold, the entire process with the voltage calculation is repeated

[10]. This routine flow chart is depicted in Fig. 6. The calculation routine is repeated with different resistive loads. The terminal voltage and output power of the linear generator are plotted in Fig. 7. As it can be seen that, when the load resistance value increases, the output power is decreased due to the decrease of the load current. At the same time, the AC output voltage is going to the open circuit value with decreasing the load. For different load resistance, the load characteristics of the linear generator treated here are shown in Fig. 8. For the calculated full load current of 23.8A, the output power of the generator is 5.3kW, with a terminal voltage of 222V. From the no load and full load voltage values the generator regulation becomes 11.7%. The corresponding efficiency of the generator is 96.8%. The considered losses are copper and core losses only of 147W and 26W, respectively. It is worth to mention that the core losses are calculated for power and higher frequency values. The iron core loss is calculated for different frequencies using the iron silicon steel data sheet tables provided from the manufacturer.

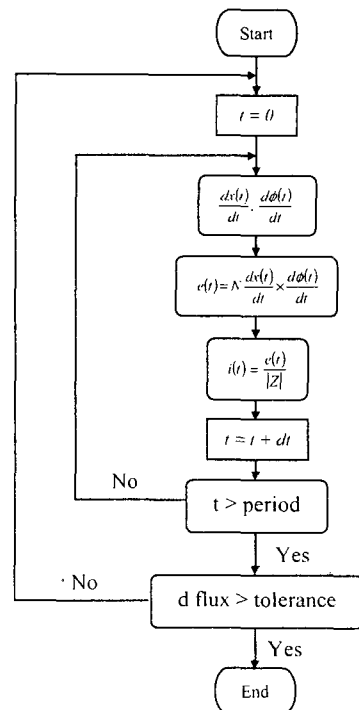


Fig. 6 Output voltage algorithm routine

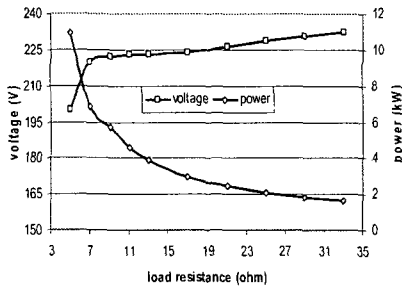


Fig. 7 Simulated output power and terminal voltage

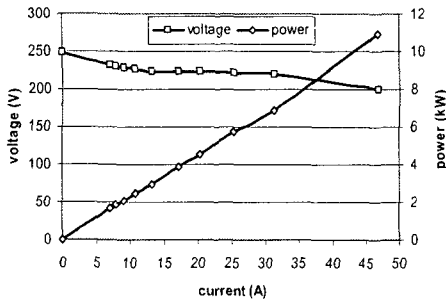


Fig. 8 Load characteristics of the linear generator

VIII. CONCLUSIONS

A tubular permanent magnet linear single-phase AC synchronous generator was designed using a two-dimensional finite element method (Maxwell 2D software by Ansoft Corporation[®]). The design based on minimizing the cogging force and maximizing the output induced voltage of the linear generator prototype treated here. Optimizing the linear generator dimensions and using the optimal length for both the stator core and permanent magnet reduced the cogging force. The current density of the permanent magnet linear generator prototype was also calculated based on the thermal capacity of the copper wire; and hence the output power of the linear generator was calculated. The linear generator was analyzed under various resistive loads to take the armature reaction effect in the analysis calculations. A repetitive routine was used for each load value to calculate the AC output voltage and hence, the load characteristic was obtained. The efficiency of the designed tubular linear generator was calculated to be 96.8% at full load current of 23.8A with output voltage of 222V_{rms}. The output power of the designed

single-phase linear synchronous generator is around 5.3kW at full load conditions.

ACKNOWLEDGMENT

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