DESIGN STUDY OF A TUBULAR LINEAR MACHINE WITH PERMANENT MAGNETS FOR WAVE POWER GENERATION

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***Abstract* - A non-dimensional analysis of a slotless tubular linear generator with longitudinal flux topology has been undertaken using a finite element method. Starting from an arbitrary initial design, design parameters were varied in order to maximise the electromotive force produced per unit cost of the generator. The influence of variation of design parameters on the cogging force has also been investigated.**

I. INTRODUCTION

In recent years linear generators have been proposed and studied in the context of marine wave power generators. The concept of such electrical machines is relatively simple. Moreover, there is no crank shaft or any rotary parts which make the design robust and suitable for direct drive conversion. A fairly recent concept is one of a tubular iron-core linear generator, the main advantage of which is the fact that stator elements are loop-closed around the permanent magnets mounted on the moving part of the machine. In this arrangement most of the available magnetic flux is utilised resulting in higher efficiency than that of a planar linear generator. However, the use of high performance magnets in such tubular generator structures would create extremely high cogging forces if a classical design with teeth were to be used [1]. These cogging forces need to be reduced in order to reduce the losses [2] and meet the support structure requirements [3]. The removal of iron teeth from the magnetic circuit in these generators appears to be a reasonable method to reduce the cogging forces; however, it will also reduce flux density through the coils and will therefore reduce the induced electromotive force (*emf*). For such generators to be shown to be competitive, the economic aspects need to be included; we have therefore undertaken a cost based study. Our aim was to understand the cost implications for a design that maximises *emf* while minimising the cogging force.

II. DESIGN STUDY

A finite element (FEM) electromagnetic analysis software package Magnet by Infolytica Corporation [4] was used to perform a non-dimensional analysis of the geometrical design parameters of a slotless tubular linear generator. In this design the N42 grade axial neodymium magnets, stacked in a flux concentrator configuration separated by M45 grade silicon steel spacers, form the moving part of the generator (slider). A 1mm air gap separates the slider from the stator consisting of 3-phase copper coil windings backed by a M45 grade silicon steel tube (Fig. 1). For all simulations SWG 20 copper wires were assumed, the number of turns dependent upon available space for the coils. The operational velocity was kept constant for each simulation.

In order to non-dimensionalise the design parameters, three 'base' design parameters were fixed to constant values and every other parameter was expressed as a per unit (*pu*) fraction of one or more of these base quantities. The base parameters themselves were also non-dimensionalised with respect to each other in order to facilitate a complete analysis. In the radial direction the stator radius (*St_r*) and the air gap (*Ag*) were selected to be the base design parameters. The slider radius (*R_r*), its complementary stator thickness (*St_t*), and the coil thickness (*C_t*) were defined as a *pu* fraction of a combination of the air gap and stator radii. In the longitudinal direction, the pole pitch (*PP*) was selected as the base design parameter. The magnet height (*M_h*), its complementary spacer height (*S_h*), and the stator iron-end extension (*St_I_ex*) were defined as a *pu* fraction of the pole pitch. Figure 1 shows half of the cross sectional geometry of a linear slotless generator and indicates the design parameters.

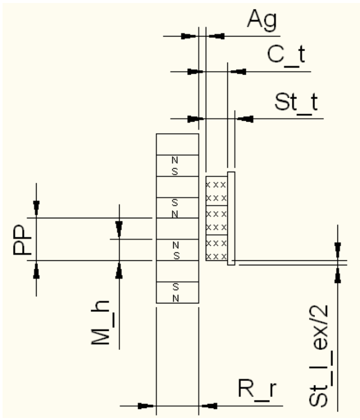

Fig.1. System with nonlinear elements

Table 1 summarizes all the non-dimensional design parameters used throughout this study, their non-dimensional ratios and the default values for these ratios.

In this study, the slider is assumed to be larger than the stator by a factor of 3, i.e. for each unit length of area of active power generation, 2 units of the slider length are inactive. To determine the relative cost of each generator design the mass of each material is weighted according to a cost factor and added together; this value is then used as an indication of cost. Magnets have been assigned a cost factor of 10 in relation to the other materials.

TABLE I
DESIGN PARAMETERS

Design Parameter	Symbol	Non-Dimensional Ratio	Default Value (*pu*)
Stator radius Air Gap Pole Pitch	*St_r* *Ag* *PP*	$\frac{St\_r - 0.5 * Ag}{PP}$	1.75
Slider Radius	*R_r*	$\frac{R\_r}{St\_r - 0.5 * Ag}$	0.57
Coil Thickness	*C_t*	$\frac{C\_t}{St\_r}$	0.75
Magnet Height	*M_h*	$\frac{M\_h}{PP}$	0.5
Stator Iron End Extension	*St_I_ex*	$\frac{St\_I\_ex}{PP}$	0

A number of FEM models have been set up and run for different values of the design parameters. Some of the results are presented in the following graphs. The ratio of *emf* over the unit cost and the ratio between the peak cogging force and the *emf* have been plotted against our non-dimensional parameters (Fig. 2 and Fig. 3). The unit cost is expressed here in kg for reasons explained before.

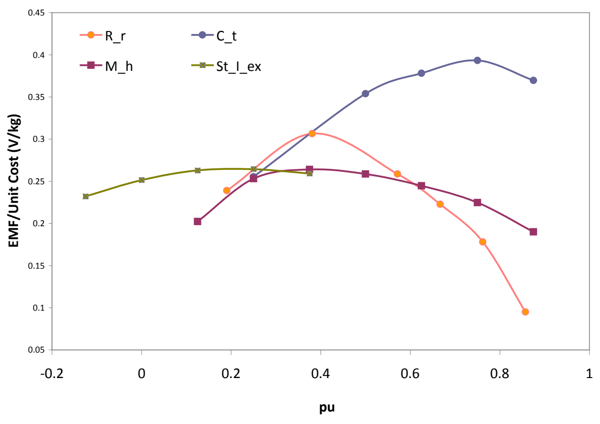

Fig. 2. *Emf* per unit cost of selected design parameters

From the results it can be noted that the *emf* per unit cost initially rises as the slider radius is increased (Fig. 2). This can be explained by the increase of the magnet volume and therefore more magnetic flux available. However, a further increment in *R_r* shows that an optimum value exists, after which the ratio drops. This nonlinear behaviour is due to a combination of factors: there is a reduction of coils dimensions, therefore a reduction in the number of turns, and a reduction in the back steel thickness which saturates faster, thus reducing the magnetic flux that is concentrated through the coil. This in turn will reduce the *emf*. Furthermore, increasing the magnet volume raises the cost as magnets are the most expensive components in our analysis. Regarding the cogging force variation (Fig. 3), a sharp increase is observed, which has been expected as the force is directly proportional to the intensity of the magnetic field (which is increased) and inversely proportional to the distance between the magnets and the back steel (which decreases).

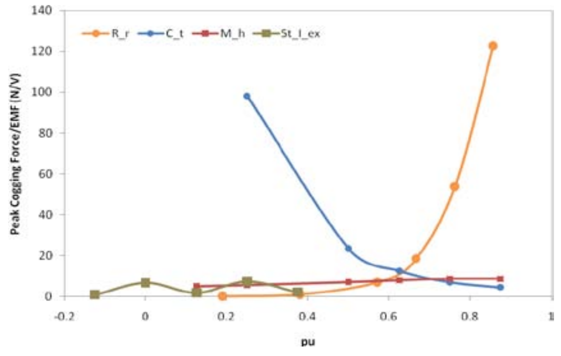

Fig. 3. Cogging force per unit *emf* produced for selected design parameters

The initial increase in *emf* per unit cost as a result of the increasing coil thickness (as a fraction of the stator thickness) is due to the associated increase in the number of turns. The turning point occurs when the drop of flux through the coil due to saturation of a thinning stator steel starts to dominate the response. The cogging force displays an exponential fall with increasing coil thickness due to the corresponding increase in separation of stator steel with slider magnets.

The optimum value of the stator end silicon steel extension is determined by the length required to channel maximum flux around the coils in order to generate maximum *emf*. The effect of extending the stator steel ends is most apparent on the cogging force characteristics. It is interesting to note that, due to force cancellation and reinforcement, the peak cogging force varies cyclically with increasing extensions. This could prove to be a simple but effective method of minimising cogging forces (Fig. 3).

III. CONCLUSIONS

A slotless linear generator has been optimised in order to give maximum power per unit cost using FEM. Non-dimensional optimum values for the most important geometrical design parameters have been determined. The study has also revealed how changing stator steel end extensions can minimise cogging forces.

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