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Optimisation of a tubular linear machine with permanent magnets for wave energy extraction

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Abstract

Purpose – The purpose of this paper is to optimise the cost-based performance of a tubular linear generator and to minimise cogging forces.

Design/methodology/approach – Optimisation of a tubular linear generator with longitudinal flux topology has been undertaken using a finite element method. The computational models used have been verified experimentally.

Findings – The use of an oversized stator linear generator design as opposed to an oversized translator design has the potential to increase the output electromotive force per unit material cost by 25 per cent for slotless iron core topologies and approximately 14 per cent for air core topologies. For cogging force minimisation, optimisation of the length of the stator core is an effective technique for both oversized stator and oversized translator constructions. Comparisons of magnet materials also indicate that the higher cost of rare earth magnets to ferrites is compensated by their superior specific performances.

Originality/value – In this paper, a broader range of design parameters than in previous investigations has been optimised for the slotless iron core and air core topologies. The result relating to cogging force reduction and cost savings (in particular) has the potential to make direct drive wave energy extraction a more competitive technology in terms of reliability and cost.

Keywords Generators, Energy sources, Water power

Paper type Research paper

1. 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, the lack of crank shafts or any rotary parts 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 known as the translator (or rotor). 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 (Janssen *et al.*, 2007). These cogging forces need to be reduced in order to reduce the losses (Kimoulakis *et al.*, 2009) and meet the support structure requirements

COMPEL: The International Journal for Computation and Mathematics in Electrical and Electronic Engineering
Vol. 30 No. 3, 2011
pp. 1056-1068

0332-1649
DOI 10.1108/03321641111110997

(Baker *et al.*, 2004). 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.

2. Design study

2.1 Design parameters optimised

A non-dimensional analysis of a slotless iron core and air core tubular linear generator with longitudinal flux topology has been undertaken using a finite element method (FEM). A study of the effects of magnet type, i.e. radial or axial as well as the magnet material used in the translator, has also been conducted. In linear generators either the translator or stator needs to be longer than the other, therefore the performance of oversized stator designs and oversized translator designs has been compared. Most linear generator designs use an oversized translator; however – since the translator contains all of the magnets and therefore has the largest influence on cost – an oversized stator design could be a more economical solution. Starting from an arbitrary initial design, design parameters were varied in order to maximise the EMF produced per unit material cost of the generator. The influence of variation of design parameters on the cogging force has also been investigated.

2.2 Computational model

A, FEM electromagnetic analysis software package MagNet by Infolytica Corporation was used to analyse these design parameters for slotless iron core and air-core tubular linear generators. In this design, N42-grade axial neodymium magnets, stacked in a flux concentrator configuration separated by M45 grade silicon steel spacers, form the translator. A 1-mm air gap separates the translator from the stator that consists of three-phase copper coil windings backed by a M45-grade silicon steel tube (Figure 1). For all simulations SWG 20 copper wires were assumed, the number of turns dependent upon available space for the coils. The translational velocity of the translator was assumed constant for each simulation.

2.3 Geometric optimisation

In order to non-dimensionalise the design parameters, three "base" design parameters were fixed (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. Figure 1 shows half of the cross-sectional geometry of a linear slotless generator and indicates the geometric design parameters. In the radial direction, the stator radius (St_r) and the air gap (Ag) were selected to be the base design parameters. The translator 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 steel-end extension (St_I_ex) were defined as a pu fraction of the PP.

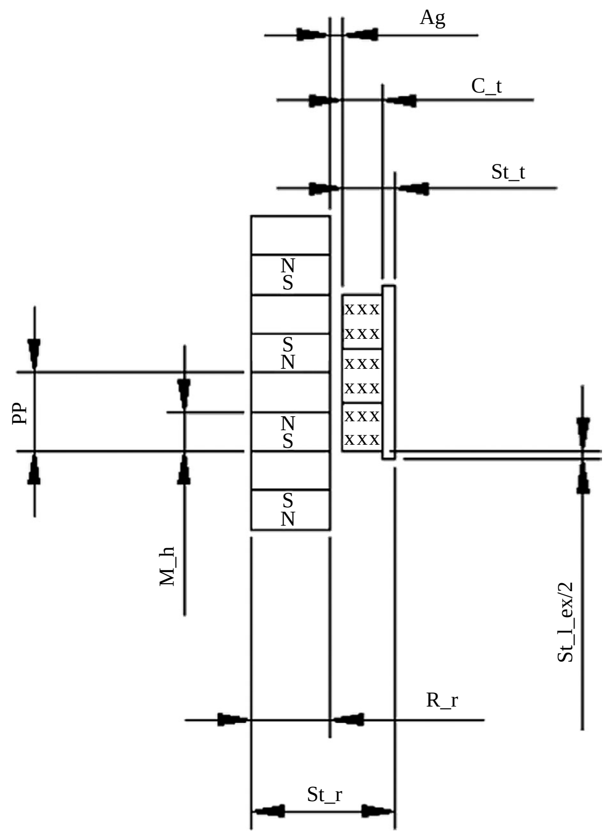

Figure 1.
Cross-sectional view of tubular slotless iron core generator

For the air-core construction, stator iron dimensions go to zero and C_t becomes the complementary of St_r and R_r. For the oversized stator layouts for both slotless iron core and air core constructions, the translator iron-end extension (R_I_ex) parameter has also been investigated. Table I summarizes all the non-dimensional design parameters used throughout this study, the non-dimensional ratios and their default values are specified.

The oversized component is assumed to be larger than the other by a factor of 2, since efficient utilisation of material is said to require that either translator or stator be equal to the stroke length (wave height) and the other twice this (Arshad *et al.*, 2003). To determine the relative cost of each generator design, the mass of each material is weighted according to its price. Table II summarises material costs based on 2009 market prices (NovaTorque, Inc., 2009).

A number of FEM models have been set up and run for different values of the design parameters. The ratio of EMF over unit material cost has been plotted against non-dimensional parameters for iron core oversized translator and stator (Figures 2 and 3) and for air core oversized translator and stator (Figures 4 and 5).

Figures 2-5 indicate that the EMF per unit material cost initially rises as the translator radius is increased. This can be explained by the increase in magnet volume

Design parameter	Symbol	Geoemtric parameter default value (mm)	Non-dimensional ratio	Non-dimensional ratio default value (pu)
Stator radius	St_r	11	(St_r − (1/2)Ag)/PP	1.75
Air gap	Ag	1		
Pole pitch	PP	6		
Translator radius	R_r	6	R_r/(St_r − (1/2)Ag)	0.57
Coil thickness	C_t	3	C_t/St_t	0.75
	St_t	4		
Magnet height	M_h	3	M_h/PP	0.5
Stator steel end extension	St_I_ex	0	St_I_{ex}/PP	0

Table I. Non-dimensional values of design parameters

Material	Price (USD/kg)
Neodymium magnets	55.50
Ceramic magnets	5.50
Electrical copper	8.80
Silicon steel	1.76

Source: NovaTorque, Inc. (2009)

Table II. Cost of generator materials

with corresponding larger amount of magnetic flux available. However, a further increment in R_r shows that an optimum value exists, after which a drop is observed. This nonlinear behaviour is due to a combination of factors: there is a reduction of coil dimensions, therefore a reduction in the number of turns, and for the iron core layouts there is also a reduction in the back steel thickness which saturates faster, thus reducing the magnetic flux that is concentrated through the coils. These in turn will reduce the EMF. Furthermore, increasing the magnet volume raises the cost as magnets are the most expensive components in our analysis.

A sharp increase in cogging force for the iron core topologies is also associated with increasing translator radius in Figures 6 and 7. This is expected as the cogging force is directly proportional to the intensity of the flux in the air gap (which is increased) and inversely proportional to the distance between the magnets and the back steel (which decreases).

For the iron core topologies (Figures 2 and 3), the initial increase in EMF per unit material cost as a result of 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 for the same parameter displays an exponential fall with increasing coil thickness due to the corresponding increase in separation of stator steel with translator magnets (which increases leakage flux in the air gap).

An increase in magnet height (as a fraction of pole pitch), similarly shows an initial increase in EMF per unit material cost, due to an increase in magnet volume and therefore magnetic flux. However, after its peak value, other factors, such as an increase in reluctance of the silicon steel spacers, as well as larger increases in cost for

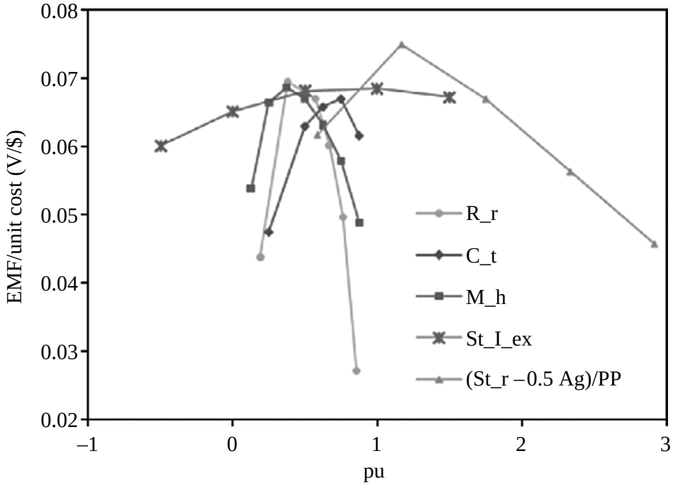

Figure 2.
EMF per unit cost for iron core oversized translator

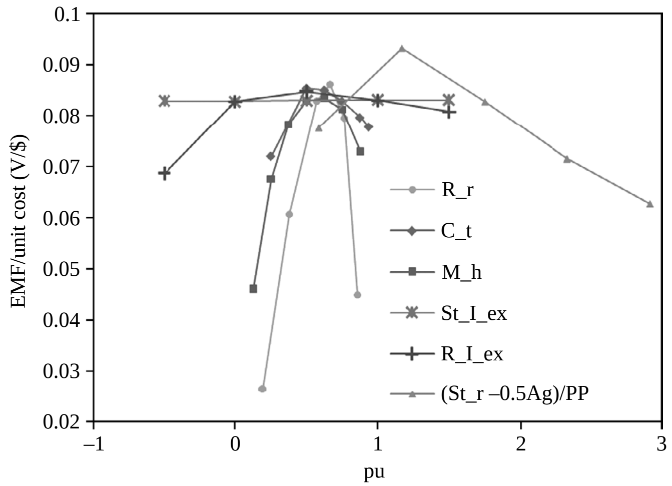

Figure 3.
EMF per unit cost for iron core oversized stator

a given increase in performance, lead to a decrease in this value. The cogging force for the iron core layouts is seen to increase linearly with increasing magnet height as expected. This is due to the proportionality between magnet volume and the cogging force (again due to an increase in magnetic flux in the air gap).

The optimum value of the iron extensions (both translator and stator iron extensions) 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 in the slotless iron core oversized translator topology has significant impact on cogging force characteristics. It is interesting to note that, due to force cancellation and reinforcement, the peak cogging force varies cyclically with increasing extensions. For the oversized stator layout, cogging forces are seen to reduce with stator iron

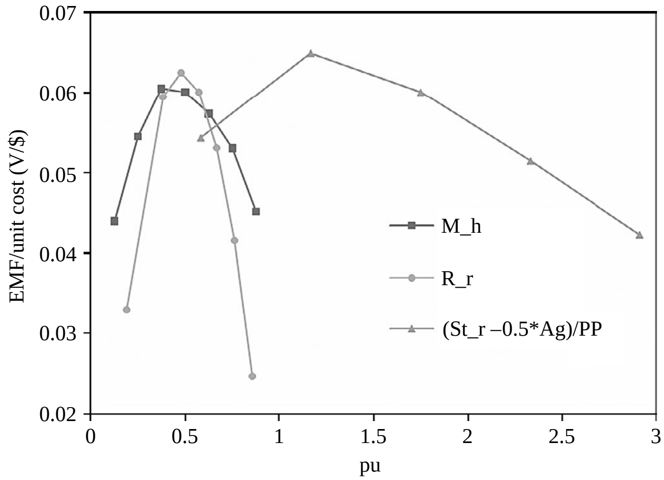

Figure 4.
EMF per unit cost for air core oversized translator

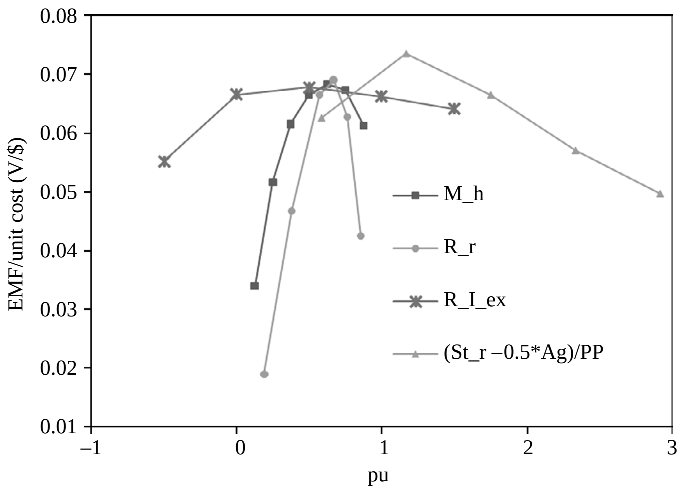

Figure 5.
EMF per unit cost for air core oversized stator

extensions, again due to increases in force cancellation. This appears to be a simple but effective approach to minimising cogging forces due to the finite length of the iron core (Figures 6 and 7).

Increasing the stator radius in relation to PP height also results in an initial increase in EMF per unit material cost, followed by a peak and then a decline. The initial increase is due to the larger magnet volume, which leads to larger magnetic flux. The decrease occurs due to lower subsequent increases in EMF as compared to increases in cost required for larger radius magnets, as well as (for the iron core layouts) due to increases in the distance between translator magnets and stator steel leading to flux leakage. The exponential fall of the cogging force (for the iron core constructions) with increasing stator radii is due to greater flux leakage in the magnetic circuit as the distance between magnets and the iron core increases.

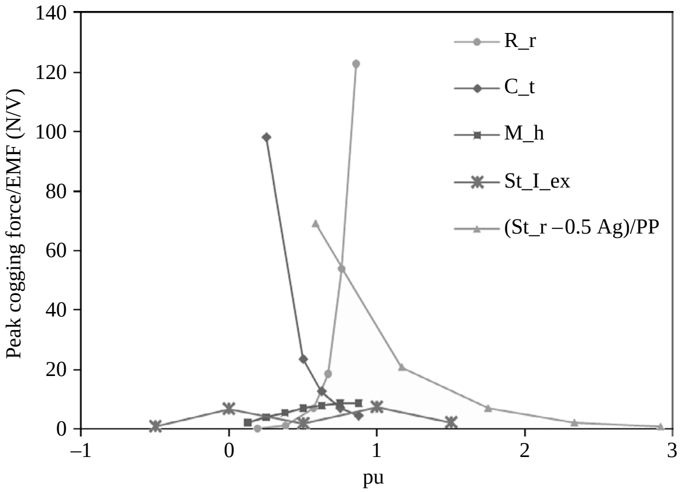

Figure 6.
Cogging force per unit EMF for iron core oversized translator

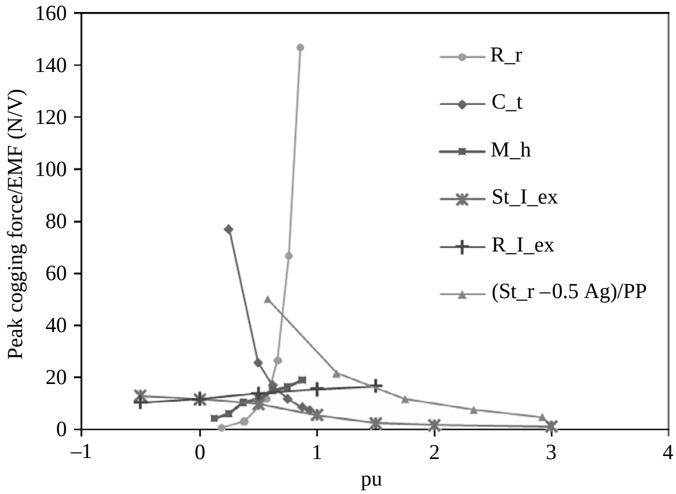

Figure 7.
Cogging force per unit EMF for iron core oversized stator

It is apparent from the optimisation results that the oversized stator topologies (Figures 3 and 5) has superior cost-based performance to oversized translator topologies (Figures 2 and 4). Iron core oversized stator designs in particular give increases in EMF per unit material cost of around 25 per cent compared to iron core oversized translator designs. The lack of cogging forces associated with the air core oversized stator topology also makes this a competitive design to the iron core oversized translator topology as a result of the reduced structural support requirements and smaller losses. However, the extra costs of the power electronics required to bypass inactive coils in oversized stator designs need to be considered in order to obtain the actual cost reductions that can be obtained in practice.

2.4 Magnet type and magnet material comparison

The influence of the orientation of magnetic domains inside magnets was also explored in this investigation. In particular, translators using radial magnets were compared with those consisting of axial magnets. Radial magnets magnetised in the radially outward and radially inward direction were stacked alternatively and separated by silicon steel spacers. The axial magnets were, again, stacked in a flux concentrator configuration with steel spacers between adjacent magnets. The default geometric design parameters of the four layouts were used in the analysis. Figure 8(a) shows the EMF per unit cost obtained. It is clear that axial magnets give a superior performance compared to radial magnets. This could be due to the flux concentration that takes place in the spacers, which effectively forces flux out of the translator and into the air gap. It is also apparent that oversized stator topologies show better performance for both magnet types, though the difference is less when radial magnets are used. Cogging forces are, as expected, seen to decrease when radial magnets are used (Figure 9(a)). This is due to the lower amount of flux in the air gap.

The effects of the magnet material used in the translator have also been addressed in this study. The use of high-strength rare earth magnets such as neodymium magnets in linear generators has become possible due to recent reduction in prices. The low-cost alternative to these expensive magnets are ferrite (or ceramic) magnets (Danielsson *et al.*, 2003). The relative performance of the four linear generator

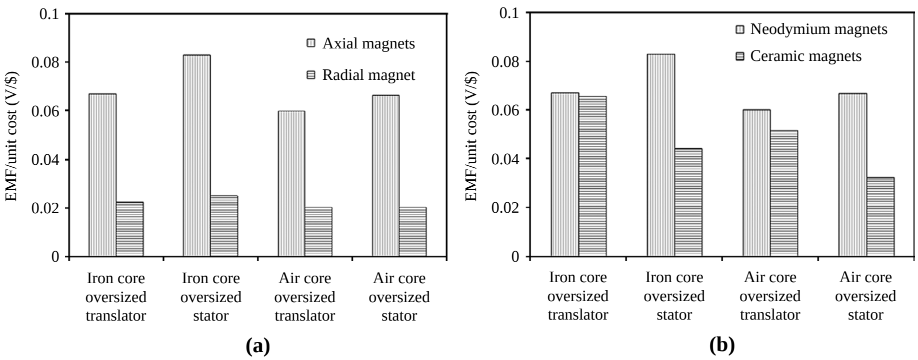

Figure 8.
EMF/unit cost comparison of (a) magnet type and (b) material

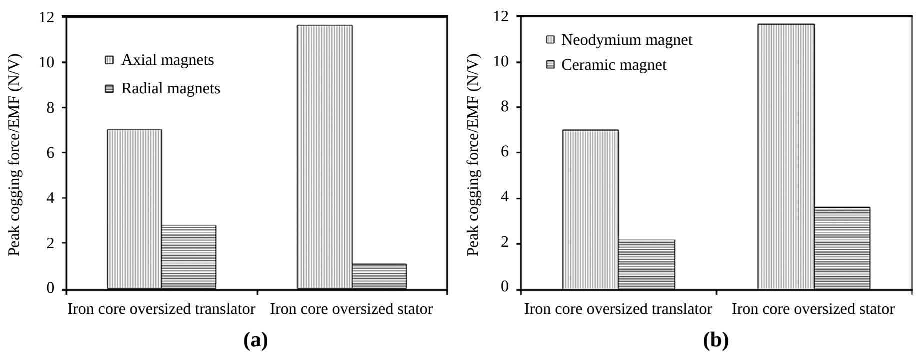

Figure 9.
Cogging force per unit EMF comparison of (a) magnet type and (b) material

topologies when either neodymium or ceramic magnets (grade C11) are used have been compared. The cost (per kg) of ceramic magnets has been assumed to be \$5.50 (NovaTorque, Inc., 2009). Figure 8(b) reveals that the reduction in costs makes ceramic magnets competitive when used in oversized translator designs. The performances of these machines exceed that of oversized stator constructions using ceramic magnets. This can be explained by the increase in flux gained through the use of more magnets and also the cost reductions of the ceramic magnets. Infact, not only do ceramic magnets cost less per unit weight than copper, a larger translator also provides greater flux and hence a more cost-effective machine. However, compared to rare earth magnets, the use of weaker ceramic magnets would require an increase in magnet volume and hence generator weight for a given power rating. This would add to the support structure costs and could be an issue in deep water. Furthermore, Neodymium magnets are seen to still give far superior performances for the oversize stator topologies. Cogging forces (Figure 9(b)), as expected, decrease with weaker magnets due to a decrease in the amount of magnetic flux in the air gap.

3. Experimental verification

3.1 Experimental method

In order to validate the FEM analyses conducted, experimental verification was used to confirm the accuracy of the computational settings and modelling. The prototype generator was to be coupled to a point absorber and tested in a wave tank, therefore constraints due to the size of the wave tank available for testing, size of waves that could be generated, the budget and ease of manufacture determined the design of the test device.

Figure 10 shows the iron core test generator. Tables III and IV summarise the design parameters of the prototype generator. An oversized translator design was selected.

An air core design with identical dimensions (but without stator iron) was also fabricated to demonstrate the effect of a reduction in cogging forces on the system (Figure 11).

As expected, the flux patterns obtained from FEM simulations of the two designs indicated that magnetic flux will be channelled by the iron core (Figure 12).

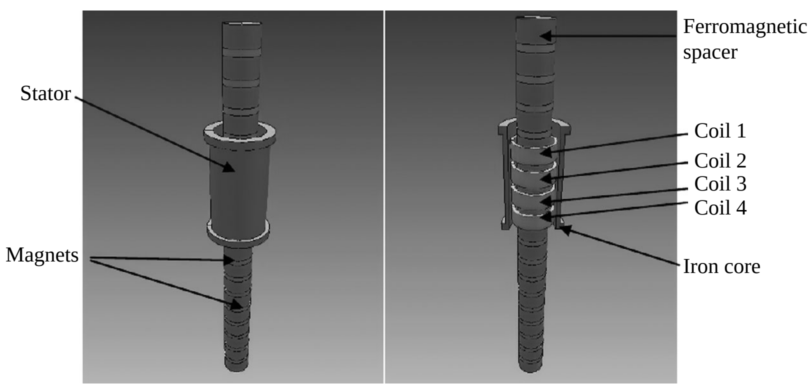

Figure 10.
Slotless iron core test generator design

Design parameter	Value
Translator length (mm)	320
Stator length (mm)	76
Number of coils	4
R_r (mm)	11
St_r (mm)	20
Air gap (mm)	2
Coil height (mm)	11
M_h (mm)	4
PP (mm)	16
Number of pahses	1
Number of poles	20
Number of turns per coil	21

Table III.
Test generator design parameters

Componets	Material
Magnets	N35 Neodymium
Silicon steel	Black mild steel
Conductor	SWG20 Copper

Table IV.
Test generator materials

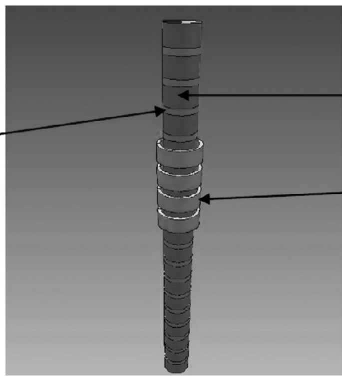

Figure 11.
Air core test generator

3.2 Experimental results

The EMF generated by the device during tank testing was monitored using an oscilloscope. The theoretical EMFs were calculated through FEM simulations of prototype generator models subject to the experimentally measured heave motions of the device.

Figure 13 shows the theoretical and experimental EMFs for the iron core generator moving with an amplitude of 0.039 m at 0.88 Hz. Figure 14 shows the same data for the air core generator moving with a heave motion amplitude of 0.0503 m at 0.88 Hz. The incident wave used in each case had an amplitude of 0.025 m and frequency of 0.88 Hz.

It is interesting to note that for this wave condition the peak EMF, and therefore power, is greater for the air core generator due to a larger heave amplitude and therefore velocity. The lower heave amplitude for the iron core generator is due to the added damping experienced due to the friction generated as a result of cogging forces

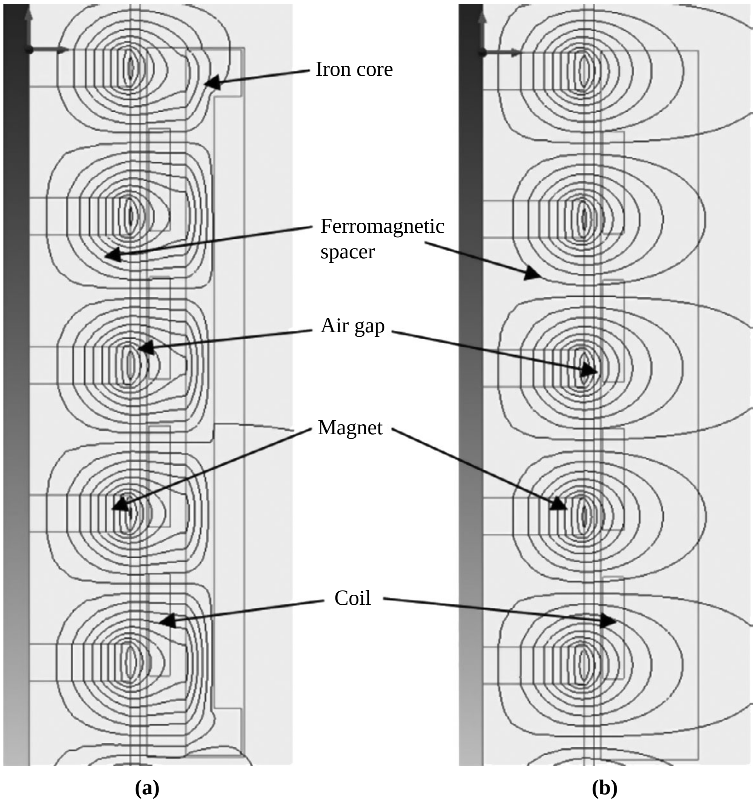

Figure 12.
Flux patterns of (a) iron core and (b) air core designs

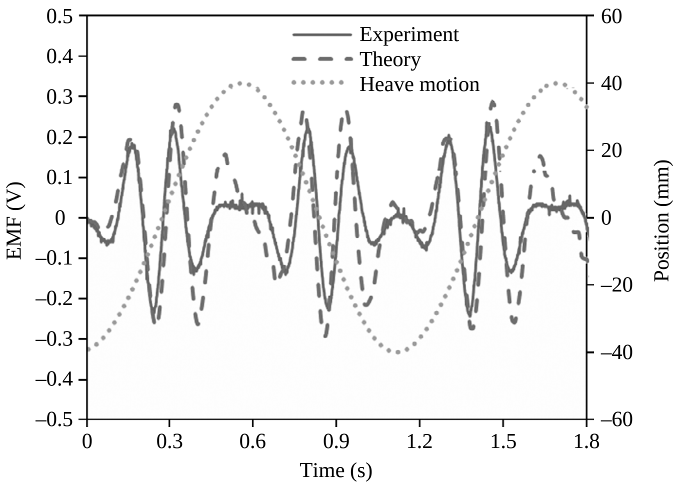

Figure 13.
Experimental and theoretical EMF for the iron core generator experiencing a heave motion of 0.039 m amplitude at 0.88 Hz

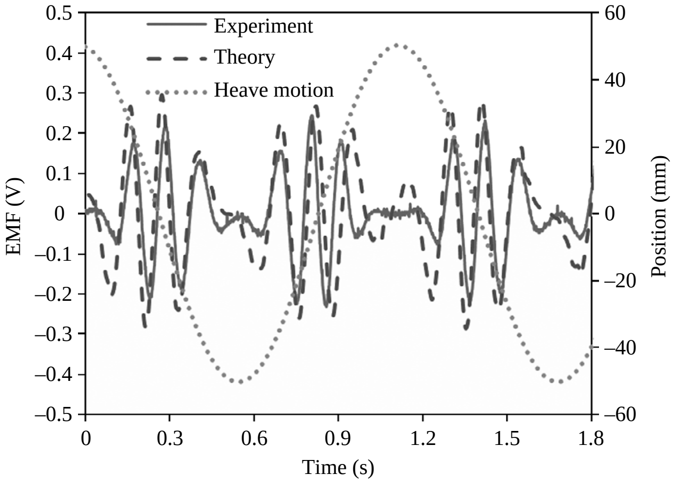

Figure 14. Experimental and theoretical EMF for the air core generator experiencing a heave motion of 0.0503 m amplitude at 0.88 Hz

as well as due to a lack of rigidity of the translator which resulted in unbalanced radial magnetic forces leading to contact between the translator and the stator.

The theory and experiments show good correlation. The difference in measured output EMF between the theoretical and experimental results is attributed to the translator not being rigid and centrally aligned within the stator. The resulting vibrations which occur in the horizontal plane are not taken into account in the computational models and are believed to cause the differences observed, especially apparent at the peaks of heave motion.

4. Conclusions

Finite element modelling was used to conduct a cost-based optimisation of slotless iron core and air core topologies for both oversized stator and oversized translator constructions of a tubular linear generator. This focused mainly on the optimisation of non-dimensional geometric design parameters, but also included comparison between different magnet materials and types. The results indicate that an oversized stator topology using rare earth axial magnets is the most suitable, as a consequence of its high cost-based performance. The experimental results of prototype linear generators were used to confirm the accuracy of the computational models used in the design optimisation.

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