Design of a Novel Air-Cored Permanent Magnet Linear Generator for Wave Energy Conversion

Rieghard Vermaak*, Maarten J. Kamper†

Abstract -- **An analytical design optimisation model of a novel air-cored permanent magnet linear generator is developed for wave energy conversion. The aim is to reach a design with dimensions optimised for minimum cost of the active material. The analytical results are verified with finite element analysis and compared to previous studies. The optimised machine shows considerable improvement over previous designs.**

Index Terms-- **Air-cored, direct drive, linear generator, permanent magnet, wave energy.**

I. Introduction

The ocean is a very attractive renewable energy source, not least because it covers around three quarters of the earth's surface [1] and energy can be extracted from the waves, tides, currents, temperature gradients and salinity gradients in the ocean [2]. Wave energy, in particular, is spatially more concentrated than both wind and solar energy [3]; it is also more persistent [3] and predictable than wind energy [4]. The global wave power resource has been estimated to be at least 1 TW, with a potential annual energy production of about 2000 TWh [1], [4]; this is comparable to the energy production from nuclear or hydropower in 2006.

Many different wave energy converters (WECs) have been proposed to harness this enormous energy resource. WECs need to be robust enough to handle the harsh conditions of the sea; they must also be maintenance free as far as possible, because maintenance at sea can be expensive, difficult and dangerous. Due to the variability of the waves, high part-load efficiency is also desirable for WECs [5].

Direct drive WECs using permanent magnet (PM) linear generators have received much attention in recent years [5-13]. Due to the elimination of any mechanical interface between the device and the electrical generator, maintenance and losses are kept to a minimum. Direct drive WECs also contain no hydraulic fluid, like many other WECs, which would need replacement or cause concern for the environment if leakage should occur. However, due to the slow speed of the waves, very large forces need to be reacted by these machines; this means that the devices are physically very large and hence their price per unit power is also high. The larger the machines, the more difficult it becomes for bearings to carry the load of the normal attraction forces in iron-cored machines, which means even more structural mass is needed.

The Archimedes Wave Swing (AWS) was the first device of this kind, developed in the Netherlands and first tested in the sea off the coast of Portugal in 2004 [6]. Other devices which followed the AWS and have also progressed to sea-trials were developed at Uppsala University [7] and Oregon State University [8]. These are of the longitudinal flux iron-cored type and suffer especially from high bearing loads and/or cogging force.

Some suggestions from Polinder et.al. [9] for overcoming problems associated with linear generators WECs include: increasing generator speed; investigating higher force density generator types; investigating air-cored machines; and using cheaper construction methods, like using concentrated coil windings.

A tubular machine from Trident Energy [10] and the C-Gen machine from Edinburgh University [11] are so far the only linear air-cored PM machines with concentrated windings which aims to reduce bearing loads and structural mass.

In this paper the design optimisation of a novel air-cored PM machine topology is considered. In the next section the machine is described where after the modelling and optimisation is considered. The optimised design is verified with finite element analysis (FEA) and then compared to previous designs.

II. The Linear Generator Concept

The proposed air-cored linear generator is shown in Fig. 1 and is also described in detail in [12]. Fig. 2 and Fig. 3 show the important dimensions and indicate the flux paths through the machine. This machine is essentially a number of linear double-sided (LDS) PM translator machines (as seen in [13]) arranged in a tubular topology. However, here the translator yokes are removed and the flux from any particular magnet circulates around the machine rather than coupling with the neighbouring magnets like in a conventional machine (see

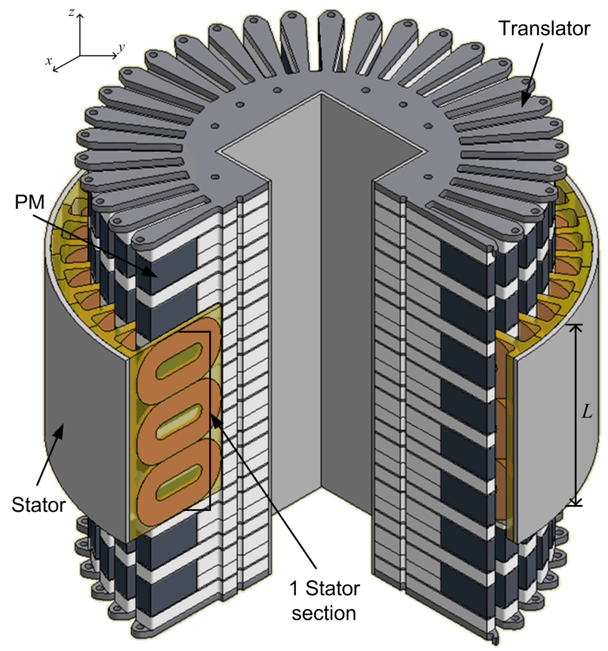

Fig. 1 Cut-out view of proposed linear generator.

The financial assistance of the South African National Energy Research Institute towards this research is hereby acknowledged. Opinions expressed and conclusions arrived at, are those of the author and are not necessarily to be attributed to SANERI.

The authors are with the Department of Electrical and Electronic Engineering, University of Stellenbosch, Private Bag X1, Matieland, 7602, South Africa. (email: *rvermaak@ieee.org, †kamper@sun.ac.za).

978-1-4244-4175-4/10/$25.00 ©2010 IEEE

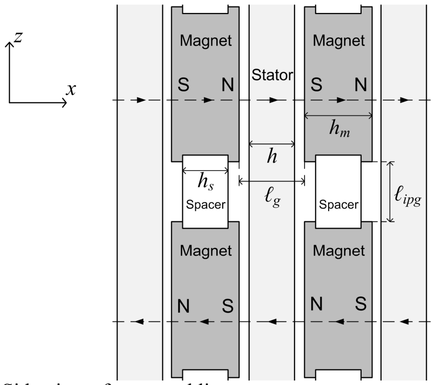

Fig. 2 Side view of proposed linear generator.

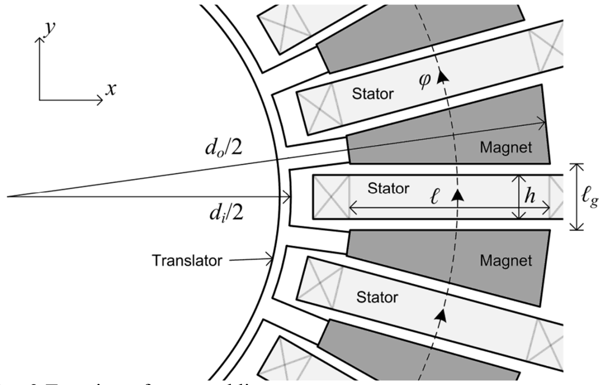

Fig. 3 Top view of proposed linear generator.

[12]). The advantages of this translator are:

1) Reduced mass and losses due to removal of the yokes;
2) Attraction forces on magnets are ideally zero and thus a reduction in structural mass can be expected;
3) The pair-wise flux coupling found in linear machines is eliminated and so ensures an even air gap flux distribution [12].

The air-cored stator uses non-overlapping concentrated coils which are easily machine wound and then cast into non-magnetic epoxy resin. The individual stator sections are inserted from the outside and can be connected in series or in parallel. The advantages of this stator can be summarised as:

1) It is easy to manufacture and therefore reduces cost.
2) Non-overlapping coils reduce copper mass and improve efficiency compared to overlapping coils [13].
3) The air-cored stator is lighter than an iron-cored stator [12].
4) There are no attraction forces between the PM translator and the stator.
5) There are no iron losses in the stator.
6) A very small armature reaction means reduced eddy current losses in the magnets.
7) There are no cogging forces and thus a high quality voltage waveform can be expected.

In [12] a comparative study was done between the novel topology and existing experimental iron-cored WECs. It was found that a greater active air gap area and power density can be achieved with the novel topology, but much more magnet material and copper is used and that efficiency can be adversely affected by high copper losses. However, due to the elimination of a steel translator yoke, the total translator mass is still comparable to that of the existing experimental machines; the overall mass of the air-cored stator is also less than the iron-cored stators, as mentioned before. These results were obtained while using machine parameters which matched those of the existing experimental linear WECs as closely as possible for comparison purposes and were thus not optimised for this topology. The focus of this paper is therefore on finding an optimised design.

III. Mathematical modelling

In [13] a model is developed for a LDS PM translator machine and shows how thrust is influenced for a variation in the per unit coil-side width κ and also in the number of active poles p for given machine dimensions and copper losses. Optimal values for κ and p are obtained independently of machine dimensions. Here the mathematical model is developed such that optimal dimensions for minimising costs associated with the active material in the machine can be obtained. The structural material and the thermal modelling of the machine are beyond the scope of this paper.

First the performance parameters and the dimensional parameters to be optimised are respectively defined in matrix-format by **U** and **X** as

$$\mathbf{U} = \begin{bmatrix} P_{dt} \\ v_s \\ \eta \end{bmatrix}; \qquad \mathbf{X} = \begin{bmatrix} L \\ \ell \\ h \\ h_m \\ d_i \\ d_o \end{bmatrix}, \tag{1}$$

where P_{dt} is the total power generated, v_s is the vertical velocity of the translator and η is the machine efficiency. The parameters of **X** are defined in Figs. 1-3.

A. Modelling a single stator section

The modelling of a single stator section is first considered, after which the modelling for the complete machine is considered. Because each one of the n_s stator sections is identical, the power P_d generated in one such stator can be calculated as $P_d = P_{dt}/n_s$. Two more required performance parameters, which are here also defined for only one stator section, are the developed thrust $F_d(\mathbf{X})$ and the copper losses $P_{cu}(\mathbf{X})$; these are determined as

$$\mathbf{G} = \begin{bmatrix} F_d(\mathbf{X}) \\ P_{cu}(\mathbf{X}) \end{bmatrix} = \frac{1}{n_s} \begin{bmatrix} 1/v_s \\ k(1-\eta) \end{bmatrix} P_{dt}, \tag{2}$$

where $k < 1$ is the ratio of the copper losses to the total losses in the machine. As explained in [12], only copper losses and the eddy-current losses P_e in the copper wire need to be considered and hence k is given as

$$k = \frac{P_{cu}}{P_{cu} + P_e}. \tag{3}$$

Formulas for calculating P_{cu} and P_e are given in [12], where it can be seen that the determining factor for P_e is the wire diameter d_w. The electrical frequency f_e, which also has an effect on P_e, depends on the wave speed and the magnet pole pitch. Due to constraints on the magnet pole pitch (discussed later) and the inherent slow wave speed, f_e is expected to be very low. Therefore, by adjusting the number of parallel strands in each coil turn, and so adjusting d_w, P_e can be designed to be very small. For the purpose of this study the value of k can thus be assumed in order to reduce the complexity of the problem. From experience a value of $k \approx 0.95$ has been found to be practically possible for low frequency machines.

1) Thrust calculation

Similarly as derived in [13], the developed thrust can be expressed as

$$F_d = k_w C_1 K_1, \tag{4}$$

where k_w is the winding factor, defined as

$$k_w = k_p k_d \,. \tag{5}$$

The pitch factor k_p and distribution factor k_d are defined in [13]. The machine constant C_1 is given by

$$C_1 = B_{p1}\sqrt{\frac{2\kappa k_f P_{cu}}{\rho_{cu}}}, \tag{6}$$

where B_{p1} is the peak fundamental air gap flux density, k_f is the copper fill factor and ρ_{cu} is the resistivity of copper. K_1, which is a function of **X**, is given by

$$K_1 = \sqrt{\frac{h\ell L}{(2+\delta)}}. \tag{7}$$

The end-turn to active stator winding length δ is given as

$$\delta = \ell_e / \ell, \tag{8}$$

where ℓ_e is the total end-turn length of a coil, given in [13] as

$$\ell_e = \frac{2\theta_c L}{\pi p}(1 - 0.586\kappa). \tag{9}$$

Here θ_c is the coil width in electrical radians.

It can be noted that K_1 can now be calculated from the required force of (2) and from (4) and (6) as

$$K_1 = \frac{F_d}{k_w C_1}. \tag{10}$$

2) Copper loss calculation

The copper losses can be expressed as

$$P_{cu} = K_2 C_2, \tag{11}$$

where C_2 is another machine constant given by

$$C_2 = \kappa k_f \rho_{cu} J^2. \tag{12}$$

The current density J must be selected in the design and plays an important role in the outcome of the design, as is pointed out in [12] and in the next section. K_2, which is also a function of **X**, is given by

$$K_2 = h\ell L(2+\delta). \tag{13}$$

Similar to (10), K_2 can be calculated from the required copper losses of (2) and from (11) and (12) as

$$K_2 = \frac{P_{cu}}{C_2}. \tag{14}$$

3) Winding active length calculation

The active stator winding length ℓ can easily be calculated by eliminating the common terms in K_1 and K_2 to find a new constant K_3 as

$$\frac{\sqrt{K_2}}{K_1} = K_3 = (2+\delta). \tag{15}$$

Substituting (8) into (15) and rearranging gives

$$\ell = \frac{\ell_e}{(K_3 - 2)} \tag{16}$$

and by substituting (9) into (16),

$$\ell = \frac{2\theta_c L}{\pi p (K_3 - 2)}(1 - 0.586\kappa) \tag{17}$$

According to (17), and since the optimal values for θ_c and κ are known (see [13]), there exists a unique relationship between ℓ and L for a given number of active poles. Hence, if L and p are chosen, ℓ can be determined from (17), and with ℓ known, h can be determined from (7) or (13). This leaves three of the dimensional parameters of **X** to be determined.

4) Magnet height calculation

The magnet height h_m must be designed such that the required air gap flux density is obtained. As also explained in [12] and shown in Fig. 3, the magnets are slightly tapered from the inside to the outside of the machine. This means that the magnet height on the outside (h_{mo}) will be greater than the magnet height on the inside (h_{mi}). The average value of the magnet height can be used in calculations, and as such h_m will refer to the average magnet height.

From the formula for peak induced flux density B_p given in [12], h_m can be expressed as

$$h_m = \frac{B_p \ell_g}{\mu_0 H_c \left(1 - B_p / B_r\right)}, \tag{18}$$

where B_r and H_c are the magnet residual flux density and coercivity respectively and ℓ_g is defined in Fig. 3 and given by

$$\ell_g = h + 2g, \tag{19}$$

where g is the gap between the stator and the translator PMs.

5) Active mass calculation

The active mass consists of the permanent magnets and the stator copper. The PM mass is given by

$$M_m = \gamma_{fe} \tau_m h_m \ell L. \tag{20}$$

where γ_{fe} is the PM density. The magnet to pole width ratio τ_m is given as

$$\tau_m = \theta_m / \theta_p, \tag{21}$$

where θ_m and θ_p are the magnet pitch and pole pitch respectively. A typical value for τ_m that can be used in the design is $\tau_m = 0.7$. After ℓ and h_m have been calculated from L with (17) and (18), the magnet mass can thus be obtained from (20).

The copper mass is given by

$$\begin{aligned} M_{cu} &= \gamma_{cu} \kappa k_f h\ell L(2+\delta) \\ &= \gamma_{cu} \kappa k_f K_2, \end{aligned} \tag{22}$$

where γ_{cu} is the copper density. Substituting (14) and (12) into (22) gives the equation for copper mass as

$$M_{cu} = \frac{P_{cu}\gamma_{cu}}{\rho_{cu} J^2}. \tag{23}$$

It can be noted that the copper mass is independent of **X** and only influenced by the choice of J.

B. Modelling the complete machine

When considering the complete topology with n_s stator sections, outside diameter d_o and inside diameter d_i, it can be shown that

$$d_o = \frac{n_s}{\pi}\left(\ell_g + h_m\right) + \ell \tag{24}$$

and

$$d_i = d_o - 2\left[\ell + \left(\frac{4\kappa L}{3p}\right)\right]k_\ell, \tag{25}$$

where k_ℓ is a factor which takes into account the open space between the translator and the end windings. From (24) and (25) it is evident that for any given value of **X** and p, d_o and d_i depend only on the number of stator sections n_s.

C. Dimensional constraints

To ensure minimum leakage flux between adjacent magnet poles, the design of the machine is subjected to the following constraints, as also given in [14]:

$$
\begin{aligned}
&h_m > \ell_g \\
&\ell_{ipg} = \frac{L}{p}\left(1-\tau_m\right) > \ell_g,
\end{aligned}
\tag{26}
$$

where ℓ_{ipg} is the inter-polar gap as defined in Fig. 2.

For construction purposes, it is also important to ensure that the minimum magnet height is greater than spacer height h_s as

$$h_{mi} = \frac{\pi}{n_s}\left(d_o - 2\ell\right) - \ell_g > h_s. \tag{27}$$

IV. Design optimisation

A. Specification and constant parameters

It is decided to design a 2 kW machine with an efficiency of 90 %. The translator speed, which depends on the wave speed, is chosen to be a value of 0.76 m/s, which is the same as in [8]; this is for comparison purposes in a later section. This gives

$$\mathbf{U} = \begin{bmatrix} P_{dt} \\ v \\ \eta \end{bmatrix} = \begin{bmatrix} 2000 \\ 0.76 \\ 0.9 \end{bmatrix}. \tag{28}$$

The value of **G** of (2) depends on n_s, which is a variable in the optimisation; **G** will thus be calculated for a range of different values of n_s.

From experience, k of (3) is taken as k = 0.95. For the windings, κ = 0.37 and $\theta_c = 4\pi/3$ are selected according to [13] and k_f = 0.45 is also selected from experience.

For the permanent magnets, NdFeB magnets of grade N48 are chosen. A study in [14] shows that by using the highest magnet grade, a reduction in magnet mass can be achieved with only a marginal increase in cost. Some of the other constant parameters used in the design are given in Table I.

TABLE I Constant parameters.

$\rho_{cu} = 1.7 \times 10^8$ Ωm	$\kappa = 0.37$	$B_r = 1.37$ T	$g = 2$ mm
$\gamma_{fe} = 7580$ kg/m^3	$k_f = 0.45$	$H_c = 1021$ kA/m	$\tau_m = 0.7$
$\gamma_{cu} = 8230$ kg/m^3	$k_w = 0.875$	$B_p = 0.7$ T	$h_s = 10$ mm

B. Design optimisation

The objective function, $F(\mathbf{X})$, that has to be minimised in the design optimisation, subject to the performance constraints of (28) and the dimensional constraints of (26) and (27), can thus be expressed as

$$F\left(\mathbf{X}\right) = w_1 M_m\left(\mathbf{X}\right) + w_2 M_{cu}, \tag{29}$$

where w_1 and w_2 are weighting factors. Although M_{cu} is not a function of **X**, it does depend on J, and according to (12)-(17), the dimensions in **X** are dependent on the choice in J. Including M_{cu} in the objective function is therefore essential for obtaining the optimal **X** for minimising $F(\mathbf{X})$.

In deciding on w_1 and w_2, the magnet and copper price and labour costs associated with fixation of the magnets and winding the copper wire should be considered. Although the cost per unit mass is significantly more for magnets than for copper, the fixation of the magnets will be far less labour intensive than manufacturing the stators. The magnets will each simply be slid into place in this machine, while the copper wire needs to be stranded, wound into coils and then cast into resin. Using non-overlapping concentrated coils reduces labour compared to overlapping winding layouts, but is still a time consuming process compared to fixation of the magnets in this case. For now, as it is difficult to quantify these labour costs, it is deemed sufficient to select $w_1 = w_2$. It is therefore assumed that the sum of the material and labour costs are the same for both the magnets and the copper. This will have to be refined when more experience is gained with the construction of this machine.

From the model derivation in Section III it is clear that 4 different variables, namely n_s, L, p and J, must be selected before the objective function can be calculated. The mathematical model and a program to vary these parameters are implemented in the Python programming language. For every combination of n_s, L, p and J, the constraints of (26) and (27) are checked and the objective function calculated. If the constraints are violated, the solution to the objective function is marked as invalid. From all the valid solutions, the one which gives the minimum value of $F(\mathbf{X})$ is selected as the optimum design.

C. Results

The result show that both the magnet and copper mass, and thus the objective function, are decreased for a higher number of stator sections up to $n_s \approx 55$, as is shown in Fig. 4. For higher numbers of n_s the objective function increases again. It can be noted, though, that $F(\mathbf{X})$ changes very little for $50 < n_s < 70$; as such, any value of n_s in this range will be a good choice. A higher number of n_s will only have the disadvantage of increased labour costs in manufacturing more stator coils and fixing more magnets. A value of $n_s = 54$ was chosen for the purpose of comparing the results to a previously investigated machine. The optimum machine dimensions for this choice in n_s are given in Table II.

Another interesting result is that the minimum number of poles (p = 4 per stator section) is each time obtained for an optimal design. Fig. 5 shows how some of the dimensional parameters and magnet mass of the chosen design varies as L is varied for different pole numbers. In Fig. 5 only the flux constraints of (26) are imposed and it can be seen that the minimum magnet height and inside diameter of the machine quickly become negative as the active length L is increased; this clearly invalidates the design.

In Fig. 6 only valid designs satisfying both the flux and dimensional constraints of (26) and (27) are shown for different current densities, again as L is varied. It can be seen that the higher J becomes, the fewer valid solutions there are. The maximum J which yields only one valid solution gives both the minimum copper mass (from (23)) and the minimum magnet mass.

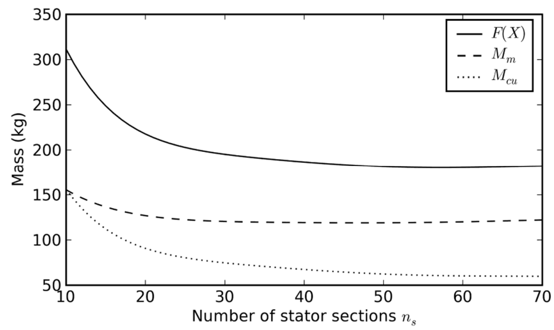

Fig. 4 Objective function value for a variation in n_s.

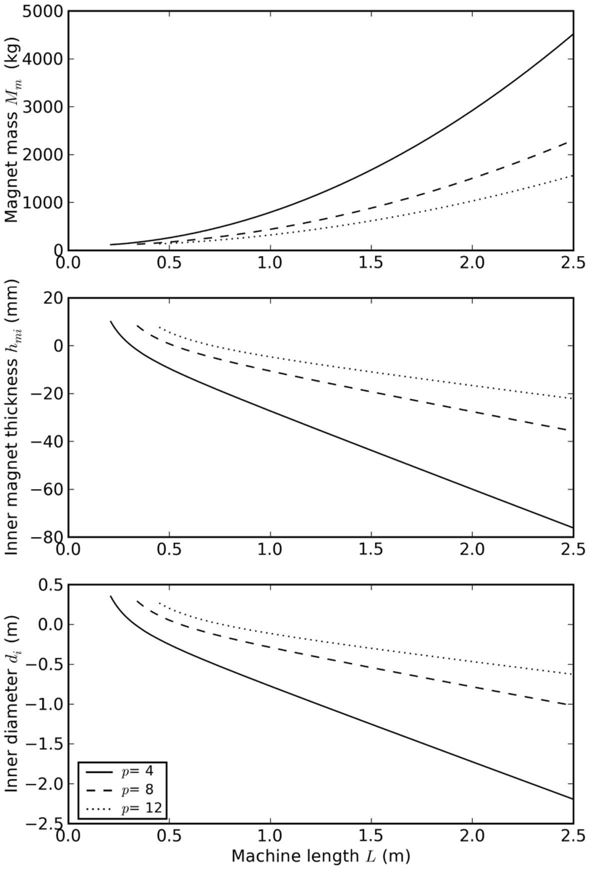

Fig. 5 Variation in PM mass and machine dimensions for a variation in active length L (J = 1.25 mm^2). Only flux constraints are imposed.

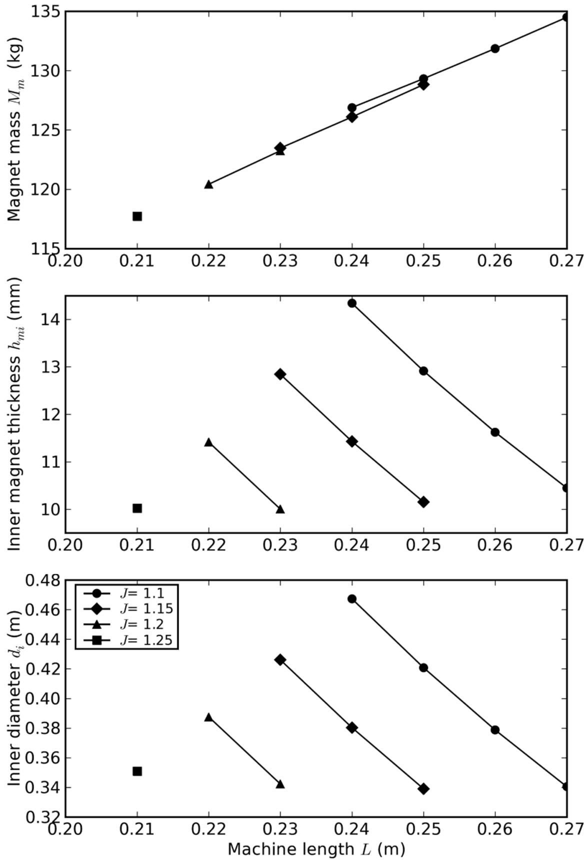

Fig. 6 Variation in PM mass and machine dimensions for a variation in active length L (p = 4). All flux and dimensional constraints are imposed.

TABLE II OPTIMUM DESIGN PARAMETERS.

$n_s = 54$	$\ell = 116$ mm	$h_m = 17$ mm	$M_m = 114$ kg
$p = 4$	$h = 11$ mm	$h_{mi} = 10$ mm	$M_{cu} = 59$ kg
$L = 0.21$ m	$\ell_g = 15$ mm	$h_{mo} = 24$ mm	$J = 1.25$ A/mm^2
$w_1 = w_2$	$\ell_{ipg} = 16$ mm	$d_i = 0.35$ m	$d_o = 0.66$ m

V. FINITE ELEMENT ANALYSIS

One stator section with periodic boundary conditions was implemented in the FE package Infolytica Magnet 6. 2D magneto-static simulations were done at the average magnet thickness in order to verify the analytical design.

In order to do this, the wire diameter and the number of coil turns N and strands n_c had to be selected. Selecting these values also then enables analytic values of the induced voltage, winding resistance, P_{cu} and P_e to be calculated from the equations in [12]. With d_w = 0.6 mm, N = 45 and n_c = 10, all the stator sections are connected in series (parallel circuits a = 1) to obtain values as given in Table III. There is overall a very good agreement between the FEA and analytical values. Plots of the induced voltage and generator force are shown in Fig. 7. These figures confirm the good quality of the voltage and force waveforms (force ripple of 1 %). Fig. 8 shows a flux density colour plot of two poles.

With the optimised dimensions, f_e = 14.5 Hz (at v = 0.76 m/s), which is low as initially assumed. The phase reactance X_{ph} was obtained at this frequency from the FEA and is also given in Table III. With X_{ph} = 0.018 p.u., previous assumptions that the reactance for the air-cored machine is very small is confirmed.

The eddy current losses obtained (given in Table III) with the choice of n_c and the low f_e discussed here is also very low as assumed in Section III. P_e could also even be further decreased by increasing n_c.

TABLE III ANALYTIC DESIGN AND FEA PERFORMANCE PARAMETERS.

d_w = 0.6 mm; N = 45; n_c = 10; a = 1.	Analytic	FEA
Peak air gap flux density B_p (T)	0.7	0.7
Peak induced phase voltage E_p (V)	262	272
Phase resistance R_{ph} (p.u.)	0.10	0.10
Phase reactance X_{ph} (p.u.) at f_e = 14.5 Hz	-	0.018
Developed shear force F_d (kN)	2.625	2.754
Developed power P_d (kW)	1995	2093
Copper losses P_{cu} (p.u.)	0.09	0.1
Eddy current losses P_e (p.u.)	0.01	-
Efficiency η (%)	90	-

VI. COMPARATIVE STUDY

In [12], a machine with the novel topology of this paper, called N1, was investigated. Dimensions of another existing machine were imposed on this machine and were as such not optimised. It was shown that with J = 1 A/mm^2 a power output of 2 kW could be achieved with η = 90 % (ignoring P_e). Now, the optimised 2 kW machine of this paper has an active length L which is 27 % shorter, but an outside diameter which is 10 % greater. More importantly though, the optimised machine uses 10 % less PM material and 26 % less copper, which is a significant improvement. Note that this machine also has a 90 % efficiency, which includes the effect of P_e, unlike the previous machine.

The optimisation was also done for a 2 kW machine with a lower efficiency of 85 %. Now a 35 % reduction in magnet mass and 46 % reduction in copper mass can be realised, while also reducing the machine active length L by 31 %. The results of this study are given in Table IV where the dimensions of N1 in [12] are taken as unity.

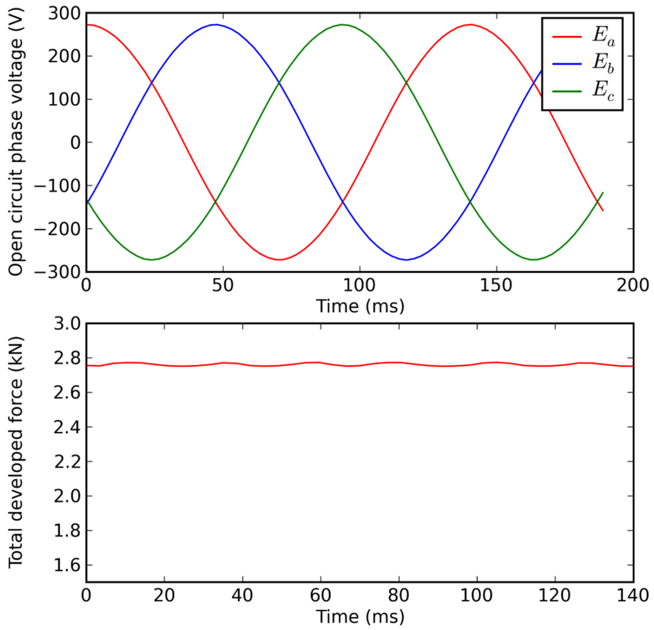

Fig. 7 Phase voltage and force obtained from FEA.

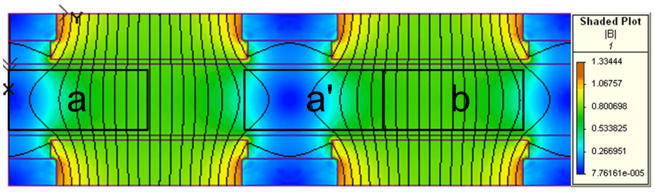

Fig. 8 Flux density colour and flux contour plot of two poles.

TABLE IV 2 kW MACHINE COMPARISONS.

Machine	N1 [12]	Optimised 1	Optimised 2
Efficiency η	90 %	90 %	85 %
Active length L (p.u.)	1	0.73	0.69
Outside diameter d_o (p.u.)	1	1.1	1.03
Active magnet mass M_m (p.u.)	1	0.90	0.65
Copper mass M_{cu} (p.u.)	1	0.74	0.56
Total active mass (p.u.)	1	0.84	0.62

VII. CONCLUSION

In this paper an analytical model is developed for the purpose of optimising the dimensions of a novel air-cored linear PM generator WEC for minimum cost of the active mass. The analytical results obtained are verified with FEA and shown to be accurate. A significant reduction of 16 % in overall active mass is obtained; this reduction becomes even more as the efficiency constraint in the optimisation is lowered. The proposed optimisation procedure is fast, because it is analytically based; the results also prove that it is effective.

FEA also confirms previous assumptions of a high quality voltage waveform, which is advantageous for converter-fed control purposes. The air-cored WEC is also shown to have a very low internal reactance and low (high quality) force ripple.

The mechanical design and construction of a prototype WEC is currently under way, which will enable practical testing of the machine.

VIII. REFERENCES

[1] T.W. Thorpe, "A brief review of wave energy: A report produced for The UK Department of Trade and Industry.," ETSU-R120, May 1999.

[2] A.F.de O. Falcão, "The Development of Wave Energy Utilisation," 2008 Anual Report, International Energy Agency implementing agreement on ocean energy systems (IEA-OES), eds. A. Brito-Melo and G. Bhuyan, Feb. 2009.

[3] J. Falnes, "A review of wave-energy extraction," *Marine Structures*, vol. 20, pp. 185-201, 2007.

[4] T.W. Thorpe, "Wave Energy: 2007 Survey of energy resources," World Energy Council, Sep. 2007.

[5] M.A. Mueller, H. Polinder, and N. Baker, "Current and novel electrical generator technology for wave energy converters," in *Proc. IEEE IEMDC*, vol. 2, Antalya, Turkey, 2007, pp. 1401-1406.

[6] H. Polinder, M.E.C. Damen, and F. Gardner, "Design, modelling and test results of the AWS PM linear generator," *Euro. Trans. Electr. Power*, vol. 15, pp. 245-256, 2005.

[7] O. Danielsson, M. Eriksson, and M. Leijon, "Study of a longitudinal flux permanent magnet linear generator for wave energy converters," *Int. J. Energy Res.*, vol. 30, pp. 1130-1145, May 2006.

[8] J. Prudell, M. Stoddard, T.K.A. Brekken, and A. von Jouanne, "A novel permanent magnet tubular linear generator for ocean wave energy," in *Proc. IEEE ECCE*, San Jose, CA, 2009, pp. 3641-3646.

[9] H. Polinder, M.A. Mueller, M. Scuotto, and M.G. de Sousa Prado, "Linear generator systems for wave energy conversion," in *Proc. 7th European Wave and Tidal Energy Conference*, Porto, Portugal, 2007.

[10] P.C.J. Clifton, R.A. McMahon, and H.P. Kelly, "Design and commissioning of a 30 kW direct drive wave generator," in *Proc. IET 5th Int Conf. Power Electronics, Machines and Drives*, Brighton, UK, 2010, 6 p.

[11] N. Hodgins, A. McDonald, J. Shek, O. Keysan, and M. Mueller, "Current and future developments of the C-GEN lightweight direct drive generator for wave & tidal energy," in *Proc. 8th European Wave and Tidal Energy Conference*, Uppsala, Sweden, 2009, pp. 352-359.

[12] R. Vermaak and M.J. Kamper, "Novel Permanent Magnet Linear Generator Topology for Wave Energy Conversion," in *IET 5th Int. Conf. Power Electronics, Machines and Drives*, Brigthon, UK, 2010, 6 p.

[13] M.J. Kamper, "Comparison of linear permanent magnet machine with overlapping and non-overlapping air-cored stator windings," in *Proc. IET 4th Int. Conf. Power Electronics, Machines and Drives*, York, UK, 2008, pp. 767-771.

[14] J.A. Stegmann and M.J. Kamper, "Design aspects of medium power double rotor radial flux air-cored PM wind generators," in *Proc. Energy Conversion Congress and Exposition*, San Jose, 2009, pp. 3634-3640.

IX. BIOGRAPHIES

Rieghard Vermaak was born in Worcester, South Africa, in May 1985. He received the B.Eng. degree in electrical and electronic engineering from the University of Stellenbosch, South Africa in 2008. He is currently working towards the M.Sc.(Eng.) degree in the Department of Electrical and Electronic Engineering at the University of Stellenbosch.

His current research interests are wind- and ocean wave power generation and grid integration of renewable energy systems.

Maarten J. Kamper received the M.Sc.(Eng.) degree in 1987 and the Ph.D. (Eng.) degree in 1996 both from the University of Stellenbosch, Stellenbosch, South Africa.

He has been with the academic staff of the Department of Electrical and Electronic Engineering, University of Stellenbosch, since 1989, where he is currently a Professor of electrical machines and drives. His research interests include computer-aided design and control of reluctance, permanent magnet and induction machine drives. Prof. Kamper is a South African National Research Foundation Supported Scientist and a Registered Professional Engineer in South Africa.