An E-core Linear Veriner Hybrid Permanent Magnet Machine with Segmented Translator for Direct Drive Wave Energy Converter

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***Abstract*— This paper proposes a new topology of a Linear Veriner Hybrid Permanent Magnet (LVHPM) machine with E-core stators and a segmented chamfered translator, which is shown to give mass reduction and better magnetic flux path compared to existing designs. Linear Permanent Magnet (PM) generators have the capability to reduce the number of moving parts, providing a simpler mechanical drive train when used as an all-electric direct drive power take-off for wave energy converters. The translator can be directly connected to a heaving buoy, or similar, to translate linear motion from the ocean waves into electricity. In this paper, the electromagnetic performance including magnetic flux, back EMF, cogging, thrust force, thrust ripple as well as force density of the new segmented chamfered translator design is analyzed in Finite Element Analysis (FEA). The proposed design is compared with two different models and shown to produce the best performance among those models.**

Keywords*— *wave energy, linear generator, segmented chamfered translator, magnet mass, force density.

I. Introduction

Over recent decades, ocean wave energy has drawn researchers' attention due to its high relative density compared to other sources of renewable energy [1]. Using wave energy devices, it is possible to generate more than 2000 TWh energy per annum by exploiting the global wave energy resources [2]. Therefore, the focus on generating electricity by extracting wave energy is an important area of research.

Various types of wave energy converter have been proposed in the last few decades to extract energy from waves and convert it into electricity. A direct drive wave energy converter incorporating a PM linear generator is one option. The main significance of this system is that the intermediate mechanical systems such as pneumatic or hydraulic systems which are usually required to convert slow speed reciprocating motion into high speed rotary motion can be eliminated by connecting the generator's translator directly to the floating buoy. This may lead to an improvement of the system efficiency, reduction in complexity and elimination of maintenance requirements. It has also been shown that direct drive all electric power take-off system with amplitude amplification or magnetic gearing properties has potential [3].

Mueller and Baker presented Vernier Hybrid Machine (VHM) performance analysis in [5], that is a member of variable reluctance PM machine family and exhibits high force density due to the perfect reluctance variation and flux reversal characteristics of the slotted translator. A flux linkage map was used to analyse the performance of the VHM but no attempt was made to reduce the heavy leakage flux at the pole tip. The VHM is slightly less force dense than transverse flux machine's quoted by Weh in [6] but have a much simpler mechanical design and flux path. The VHM is thus a strong candidate for direct drive high force applications such as wave energy. It is proposed to be used in marine application replacing conventional PM synchronous machines by Hodge and Mattick [7]. Magnets and coils are mounted on the stator while the mover/translator is only laminated steel that gives the machine an advantage in long stroke applications.

A Linear Vernier Hybrid Permanent Magnet (LVHPM) machine with inherent magnetic gearing has been proposed for direct drive wave energy converter with high shear stress [4]. However, this machine suffers from bulky size, a large amount of copper in the coils due to the high rated MMF, a heavy translator and a high magnet volume. In this paper a baseline LVHPM machine is presented in Fig. 1 and an updated design of LVHPM machine is developed and optimized to give a smaller size and lower magnet mass. In addition, a segmented translator is proposed resulting in significant reduction in the translator mass while improving the performance. The initial LVHPM machine, which was based around separate stator C-cores, and a novel LVHPM, based around E–cores, are designed, analysed, optimized, and compared using Finite Element Analysis (FEA).The new topology is shown to produce higher back EMF and average force, all with a lower cogging force.

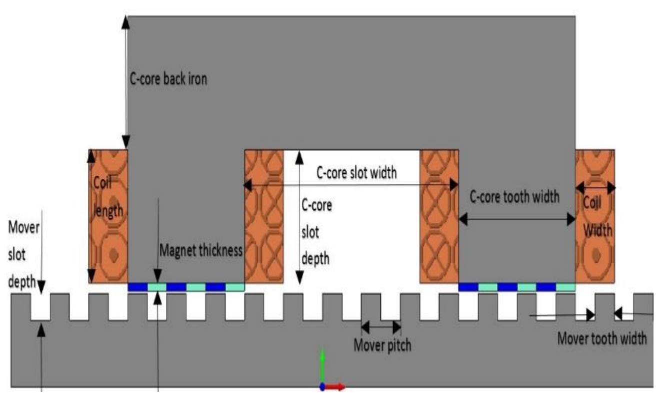

Fig. 1. Initial design of the single phase C-core LVHPM machine (Half)

II. ANALYTICAL MODELLING AND ANALYSIS

A. Initial Design

The VHM is a variable reluctance, flux reversal machine that offers high power and force density with simple and rigid structural construction. In the initial design [5], there are two C-core stators facing each other, surrounding two sides of a laminated steel toothed translator. Translator teeth and slots are equal width while multiple magnet poles and armature coils are mounted on the C-core stator. Alignment and un-alignment between magnet poles and mover teeth produce maximum and zero flux linkage respectively. Moving the teeth to adjacent magnets produces a reverse flux flow around the machine. Physically displacing the translator by a short distance, the coils see a large change in magnetic flux, and a corresponding high back emf and force production - this phenomena is called magnetic gearing. This magnetic gearing is a non-contact method that enables direct drive machines to reach higher force density without conventional mechanical gearbox within limited size [3].

Fig. 1 presents the initial model of a Linear Vernier Hybrid Permanent Magnet (LVHPM) machine which is redesigned and analysed in FEA software in this section. The topology consists of an iron toothed translator and two stator cores with alternate polarity PMs mounted. Six PMs make up one stator pole with a concentrated winding mounted on an iron C-core. Due to the alternate magnet polarities in the adjacent poles, flux under translator tooth and slot (Fig. 2) produce forces in the opposite direction.

B. Reluctance Network and Shear Stress Calculation

Fig. 3(a) represents the reluctance network of a part of the C-core model, consisting of a pole pair and a translator pitch. The middle column consists of series magnet reluctance (S_{PM}) and reluctance of airgap under the translator tooth (S_t). The other branch consists of opposite polarity magnet reluctance in series with the translator slot reluctance (S_{slot}). Shear stress can be used to determine the maximum achievable force and thus the power capability of the machine. General peak shear stress can be expressed in terms of maximum flux density under each translator tooth by the following equation [5],

$$\sigma_{peak} = \frac{B_t t_m}{w_m}\left(\frac{B_r}{\mu_0\mu_r}\right)\left(1 - \frac{g+t_m}{\sqrt{(g+t_m)^2+0.25{w_m}^2}}\right) \quad (1)$$

Where, σ_{peak} is the maximum shear stress, B_t is the flux density under the tooth, μ_0 is permeability of free space, μ_r is relative permeability of rare earth magnets, g is the air gap length, t_m is the magnet thickness and w_m is the width of the magnet poles. If all the magnet flux passes though the airgap to the translator teeth, assuming an infinite depth of the slot, saturation limits the field strength under translator tooth. Equation (2) can give an approximation that relate the flux density under the tooth (B_t) to that at the flux density at the root (B_{root}) from [5],

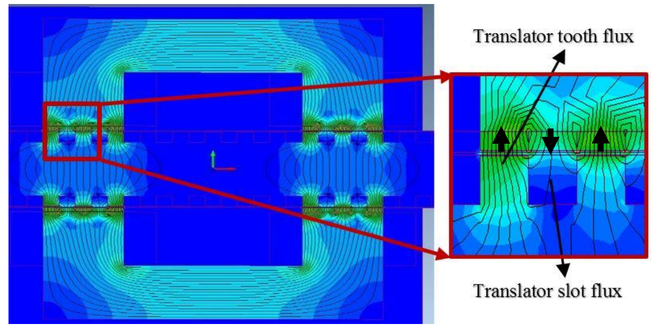

Fig. 2. FEA flux function of the initial C-core model

$$B_t = \frac{B_{root}}{1+\frac{g+t_m}{\sqrt{(g+t_m)^2+0.25{w_m}^2}}} \quad (2)$$

Peak force occurs when the translator teeth are aligned with the intersection between adjacent magnets and the peak shear stress can be expressed by combining (1) and (2) derived from the reluctance circuit of VHM (Fig. 3(a)),

$$\sigma_{peak} = \frac{B_r}{\mu_0\mu_r}\frac{t_m}{w_m}\left(\frac{B_{root}}{1+\frac{g+t_m}{\sqrt{(g+t_m)^2+0.25{w_m}^2}}}\right)\left(1 - \frac{g+t_m}{\sqrt{(g+t_m)^2+0.25{w_m}^2}}\right) \quad (3)$$

Where B_r =1.2, B_{root} = 1.9T (can be derived from Fig. 4 for rated field strength), w_m = 12mm and g = 1mm are used.

By using (3) and approximation above, it is theoretically predicted from Fig. 3(b) that the maximum shear stress of around 126kNm^{-2} occurs at the magnet thickness of 4mm and a subsequent decline with further increase in the thickness while for a constant 12mm magnet width. The VHM design in [5] was taken as a baseline for initial investigation and further manual optimization. Fig. 1 shows all the dimensional parameters of the top half of a single core of the initial C-core design. Total number of magnets per stator tooth is 6. The peak back EMF found from (4),

$$E = N\frac{t_m B_r}{(t_m+g\mu_r)}v\pi L\frac{n}{2} \quad (4)$$

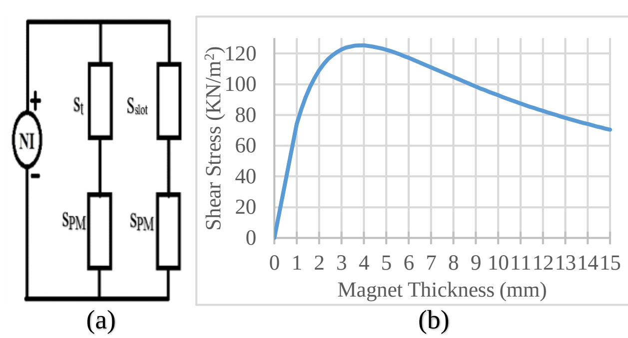

Fig. 3. a) Reluctance circuit of the C-core LVHPM machine b) Effect of magnet thickness on predicted shear stress.

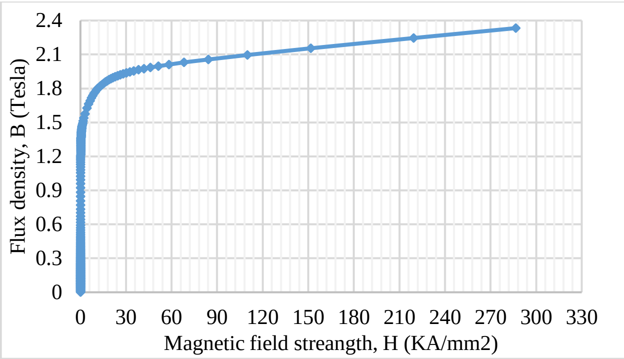

Fig. 4. B-H curve for the selected translator material in FEA

In (4), N is the number of turns, v is the velocity of the translator, n is the number of magnet per stator tooth and L is the axial length of the machine. Dimension parameters of the initial design VHM model are given in the Table I.

III. 2D FEA ANALYSIS & OPTIMIZATION

Initial design dimensions and detail about the VHM mentioned above was based on simple flux path and theoretical analysis of the equivalent circuit. Practically, there is significant difference with the finite element simulation results because of the fringing, leakage and interference between adjacent magnets in the stator tooth. At the beginning of the design process, a simulation mesh refinement study was done to find the suitable mesh size of each design parameters to get accurate results.

TABLE I. DIMENSIONS OF INITIAL DESIGN C-CORE LVHPM

Parameters	Values	Parameters	Values
Magnet pitch (mm)	12	Magnets per stator pole	6
Mover pole pitch(mm)	24	C-core slot depth (mm)	50
Magnet thickness (mm)	4	C-core slot width (mm)	72
Stator core back (mm)	50	Mover slot depth (mm)	10
Airgap (mm)	1	Mover core depth (mm)	50

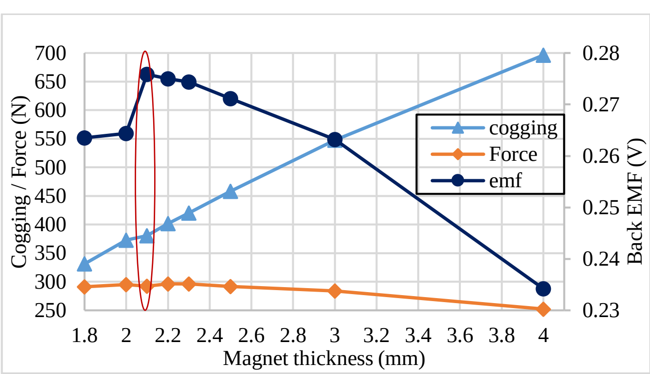

Fig. 5. Effect of magnet thickness on cogging, back-EMF and average force in a single phase C-core model

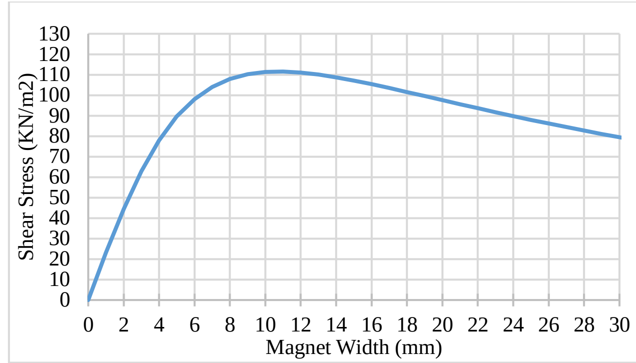

Fig. 6. Effect of magnet width in the predicted shear stress with optimized magnet thickness.

The flux path is symmetric and so to reduce computation time, only a single side of a single phase C-core model is analysed, separated by a field normal boundary condition.

A. *Magnet Height Optimisation*

Magnet height has been studied using FEA and it is shown in Fig. 5 that a magnet height of 2.1mm gave best results in terms of cogging, back EMF and active force while keeping the magnet width constant at 12mm. This can theoretically be proved from (3) and shown in Fig. 6, which gives maximum shear stress for a 2.1mm thick magnet at a magnet width of close to 12mm and thus maximum average force. Normally force and back EMF are expected to increase with magnet thickness in conventional PM machines. In this LVHPM machine, however, with opposite polarity adjacent magnetic poles, the magnetic flux leakage is prevalent as magnet thickness increases further from 2.1mm. Thus average force and back EMF started to reduce in the FEA results of Fig. 5. Again, if the magnet thickness is reduced further down from 2.1mm, demagnetization of the magnets for the rated current became an issue.

B. *Translator Teeth Study*

Different combinations of tooth and slot have been analyzed whilst keeping the mover pitch constant and equal to the stator pole pitch. Two optimization methods regarding the translator teeth have been investigated to improve the performance of the designed model.

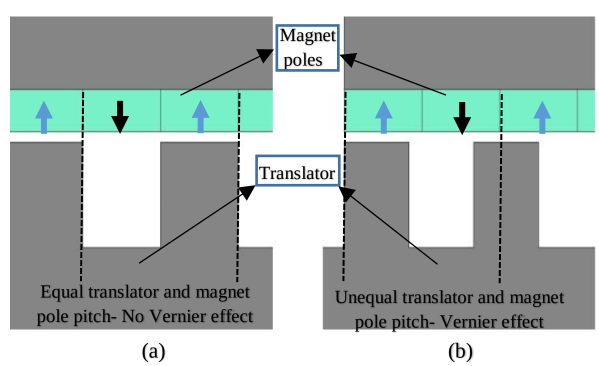

Fig. 7. Translator tooth and slot analysis with a fixed magnet pole pitch.

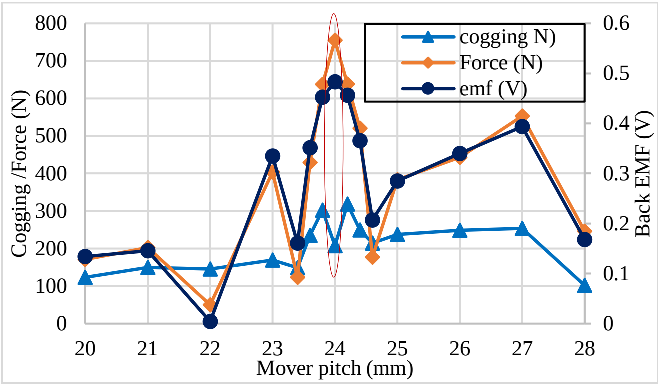

Fig. 8. Translator pitch analysis with equal translator tooth and slot of the LVHPM machine

1) Varying translator pitch fixing tooth and slot width:

In a *Vernier* machine, the translator and stator pole pitch should not be equal, so the alignment of magnets and teeth across the machine does not occur concurrently. Cogging under each tooth should be shifted a certain amount and thus overall cogging was thought to be reduced. Fig. 7(b) represent the vernier action in VHM where translator pitch and magnet pole pitch are not equal. After analyzing the vernier action for varying mover pitch it is concluded that the Vernier action is not an effective cogging reduction tool for the respective model. Fig. 8 shows the cogging, back EMF and average force of a single phase C-core VHM varying with difference in the mover pitch. During the analysis, mover tooth and slot width were kept equal. It is clear from the Fig. 8 that a mover pitch of 24mm will produce the best performance in terms of force, back EMF and minimum cogging.

2) Varying translator tooth/slot combination with constant translator pitch:

An alternative method of investigating the effect of translator teeth and slot widths is performed by fixing the pitch to an optimized constant value whilst changing the tooth and slot widths. In this paper the translator pitch has been fixed at 24mm after the analysis in the previous subsection and translator tooth and slot width are varied to analyze the cogging, back EMF and force of the machine presented in Fig. 9. It has been found that a combination of 10mm tooth / 14mm slot and 6mm tooth / 18mm slot both provide convincing results with a high force and back EMF. While 6mm tooth would be saturated very early and provide worse cogging. On the other hand 10mm tooth and 14mm slot provides reasonable force with a minimum cogging and the combination has been chosen for the further machine design analysis and optimization.

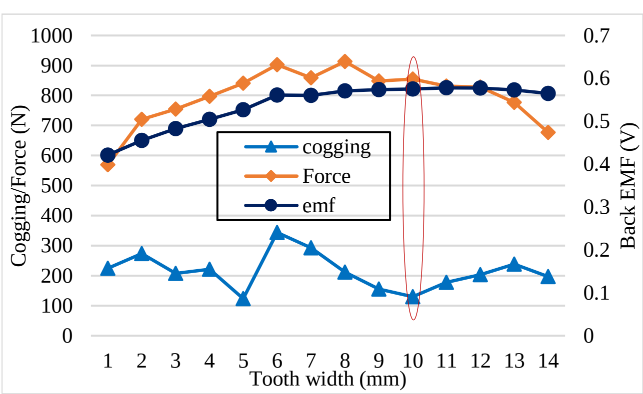

Fig. 9. Tooth width analysis of the VHM with constant translator pitch

IV. Machine Layout Development

A. *Integrated 3-Phase E-core Design*

Fig. 10 (a) shows the baseline C-core VHM. Three separate C-core units of the VHM have been integrated together to make 3-phase integrated C-cores that reduces the active volume of the machine, whilst increasing the robustness and mechanical stability–Fig. 10(b). After FEA simulation, magnetic flux distribution shows that the integrated C-core design act as 2 separate E-cores. So the integrated C-core design is converted into 2 isolated sets of E-core models –Fig. 10 (c). Another advantage of isolating 2 E-cores is a reduction in stator volume

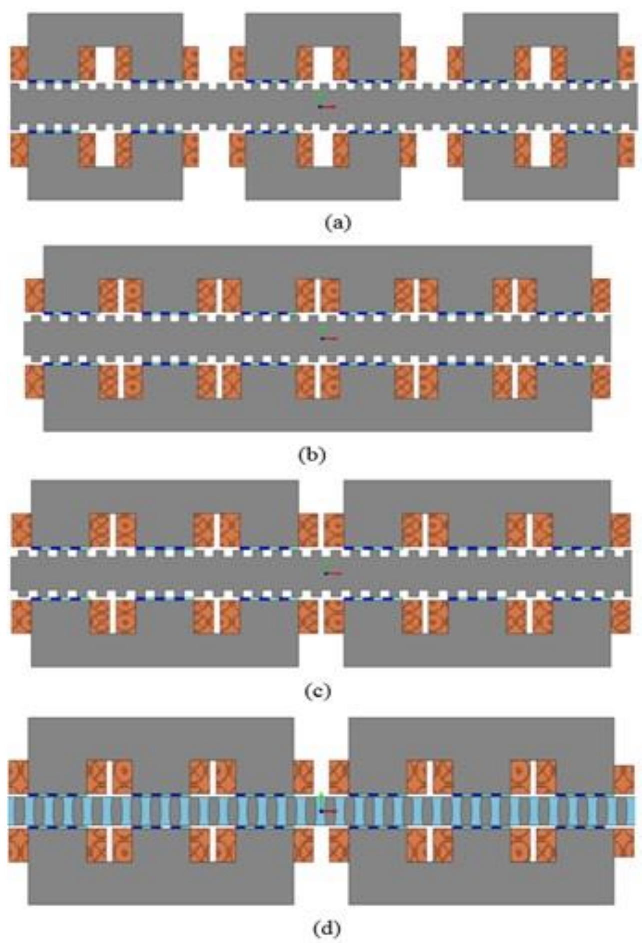

Fig. 10. 3-Phase VHM a) Initial C-core design b) Modified integrated C-core design c) Isolated E-core design d) Improved E-core with segmented translator.

by eliminating the interconnection iron which does not provide a useful flux path. Isolating the two E-cores is also found to increase the back EMF of the machine by almost 12% (Table II). Neighbouring E-cores are also mechanically shifted by 180 electrical degrees and the combined cogging forces of 2 adjacent sets of E-cores is much less than each of them individually. The resultant lower cogging and force ripple improve the performance of the machine.

B. Translator Teeth Optimisation

In this LVHPM machine configuration, all the useful flux travels straight through the translator, as shown in Fig. 2. There is no useful flux travelling through the translator core back but there is some leakage slot flux linking through the translator core. The translator can hence be redesigned without the core-back to consist only of flux carrying pieces. The translator tooth tips start to saturate at the rated current, and so the body of the translator teeth are chamfered to provide reasonable surface that reduces saturation by minimising flux density in the teeth compared to the straight teeth. After the study on translator teeth, segmented translator with a chamfering angle of 10 degrees (from perpendicular to tooth axis) chosen for the optimum performance based on rated current density and maximum thrust force and back EMF. Fig. 11 presents the translator structure after the development of segmented chamfered teeth without a translator core in the middle.

After all the design development and analysis, Fig. 10 represents the structure of-C-core baseline model -Fig. 10(a), isolated E-core LVHPM model -Fig. 10(c) and improved E-core model with segmented chamfered translator -Fig. 10(d).

FEA results of cogging force, Back EMF and the average thrust force over an electrical cycle of the three model designs have been presented by the Fig. 12, Fig. 13 and Fig. 14 respectively. All the models have been simulated with rated MMF to get the rated thrust force in FEA.

The machine average force, cogging, and back EMF comparison graph clearly show the performance comparison of each of the models. Average thrust force and cogging force of C-core and E-core maintain a close relation to each other while the improved E-core proves to reduce cogging by almost 50% and improve force approximately 15% due to the optimum dimensioned magnet poles and segmented chamfered translator

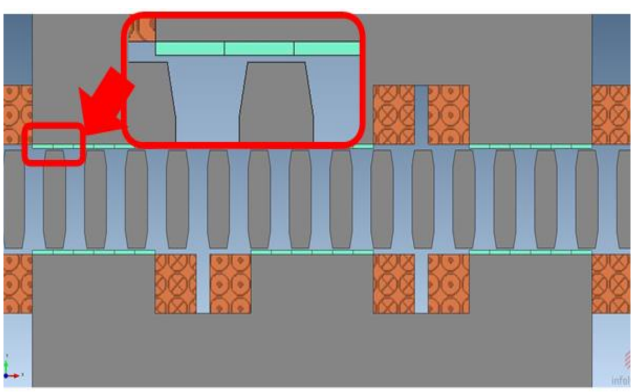

Fig. 11. Translator structure of the improved segmented chamfered E-core

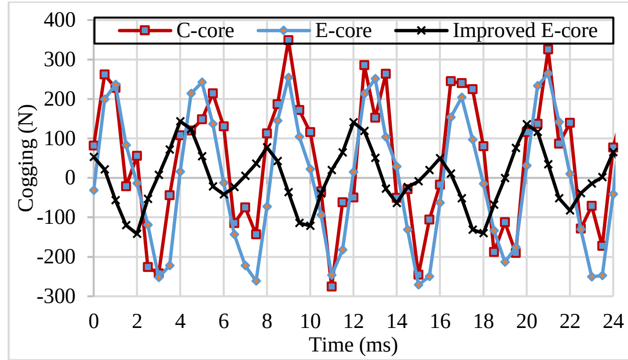

Fig. 12. Cogging force comparison between C-core baseline model, initial E-core model and the improved E-core model over an electrical cycle.

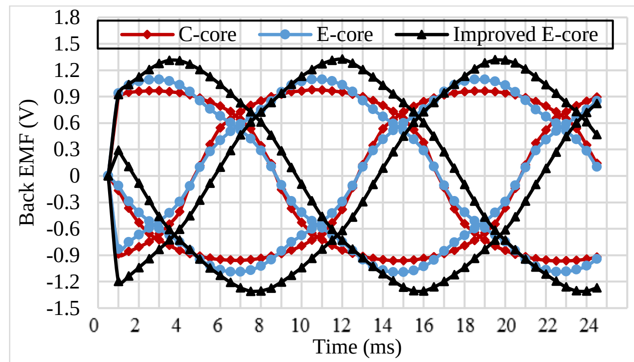

Fig. 13. Back-EMF comparison between C-core baseline model, initial E-core model and the improved E-core model over an electrical cycle.

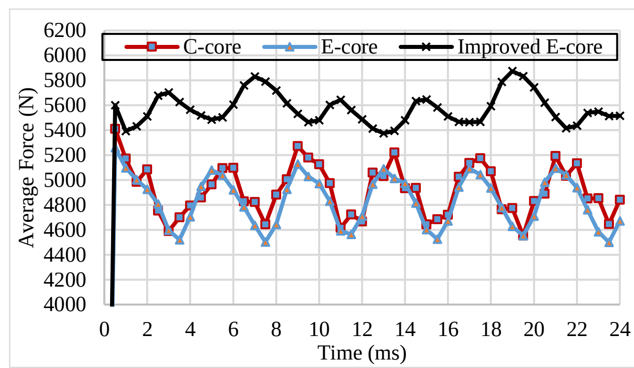

Fig. 14. Average thrust force comparison between C-core baseline model, initial E-core model and the improved E-core model over an electrical cycle.

modelling. The E-core model proved to provide higher back EMF than the baseline C-core model, but the improved E-core model produces maximum back-EMF due to the greater magnetic flux density and reduced leakage across the air-gap to the segmented chamfered translator.

After a full investigation of the design parameters, stator teeth, coils, translator teeth, slots and ultimately combining 3 phases within new E-core model, Table. II derived the comparison between the initial C-core VHM model, E-core VHM model and the final segmented improved E-core model of LVHPM machine.

TABLE II. COMPARISON TABLE BETWEEN BASLINE C-CORE MODEL, INITIAL E-CORE MODEL AND THE IMPROVED E-CORE MODEL

Parameters	**C-core VHM**	**Isolated E-core VHM**	**Improved E-core LVHPM**
Magnet poles width (mm)	4	4	2.1
Active machine length (mm)	792	724	724
Axial Length (mm)	100	100	100
Stator core back (mm)	50	50	45
Stator teeth height (mm)	50	50	35
Mover height (mm)	70	70	30
Mover speed (m/s)	1.0	1.0	1.0
Average Force (N)	4920	4838	5576
Force ripple (N)	860	750	490
Cogging (N)	625	535	226
Back EMF / turns (V)	0.98	1.1	1.3
Magnet mass (Kg)	2.55	2.55	1.34
Stator mass (Kg)	82.7	83.2	68.3
Translator mass (Kg)	44	44	12.5

Fig. 12, Fig. 13, Fig. 14 and Table. II show that, the improved E-core LVHPM machine presents superior results in terms of thrust force and back EMF with minimum cogging.

V. CONCLUSION

A novel E-core LVHPM machine has been developed from the baseline C-core LVHPM machine for direct drive wave energy converter. A new type of chamfered segmented mover has also been developed and analyzed in FEA regarding the magnetic flux path for optimal performance. Leakage magnet flux has been greatly reduced by using optimized magnet dimensions, introducing segmented translator teeth and chamfered tooth tips ensured the maximum useful flux carrying capability. Magnet mass and mover mass are also greatly reduced in the improved E-core design. Compared to the baseline, the final design is shown to deliver 14% of higher force and use 48% less PM material, and have an active mass of 78% of the baseline design. It is also proved to possess improved performance and economically feasible. Finite Element Analysis (FEA) shows, it has the merit of lower magnet mass, rigid and compact stator design with higher force density, thrust force and back EMF, while maintaining lower cogging force and force ripple over the existing model.

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