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A linear consequent pole Halbach array flux reversal machine

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Abstract

This paper presents a Linear Variable Reluctance Permanent Magnet (LVRPM) machine where the armature winding and inset Halbach array Permanent Magnets (PMs) are mounted on E-core stators. The Halbach array consists of a vertically magnetised PM pole and a salient ferromagnetic iron pole (split tooth) sandwiched between two horizontal PMs. The translator consists solely of laminations with salient iron poles. As a variable reluctance machine, it exhibits inherent magnetic gearing and a higher force and power density than the conventional synchronous PM machines. Finite Element Analysis (FEA) has been used to investigate the effect of machine parameters. The logical development of the LVRPM from the more conventional Vernier Hybrid machine is presented, including a near 50% reduction in magnetic flux leakage and a higher flux per unit magnet mass.

1 Introduction

High force and power density PM machines are of great interest, especially in low speed applications such as marine energy converters. For linear variants, it is beneficial for all the active components to be mounted within the stator.

Variable Reluctance Machines (VRM) operate by the reluctance variation due to the interaction between a slotted translator and a slotted stator. They can offer high force and power density [1]. Variable Reluctance Permanent Magnet (VRPM) machines shares the basic principle of linking flux between sets of PM and salient teeth [2-4]. Those machines generally consist of PM arrays with short pitch that move parallel to the slotted structure shown in Figure 1(a). Alignment and un-alignment between PM arrays and slotted structure produce high forces even for a small displacement, exhibiting the 'magnetic gearing' effect [5].

Different members of VRM offer specific advantages along with their own drawbacks. The Vernier Hybrid Machine (VHM) is a variable reluctance, flux reversal machine that offers greater power and force density whilst having a simple and rigid construction [2]. The transverse flux machine is generally known to offer high force density in air-cooled applications with relatively low magnet mass. In applications with high current densities, performance is limited by saturation and poor power factor, and the 3D flux path and translator mounted magnets can all cause problems in linear applications. The Flux Reversal Machines (FRM), also of the VRM family, offers a simple construction with a comparatively low specific torque. The Verniver Hybrid Permanent Magnet (VHPM) machine shown in Figure 1(a), shares the high force capability of TFM and simple construction of FRM [3]. The VHPM machine has proved to be suitable for low speed direct drive application due to high torque or force density, flux reversal / switching characteristics and inherent magnetic gearing properties [1, 5-7].

The VHPM machines suffers from high leakage and low power factor, which in a generator demands a higher power rating inverter drive than the real power extracted. Because of the adjacent PM arrangement in the VHPM machine, they are not

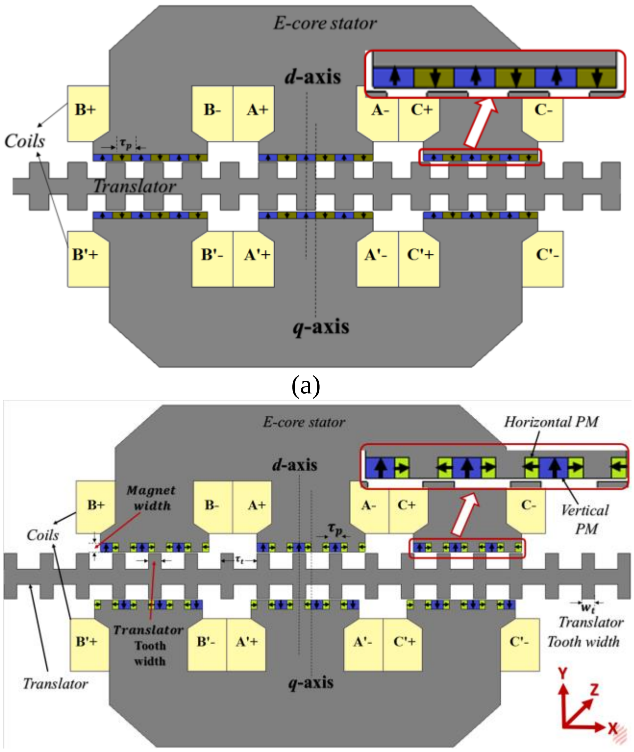

Figure 1: (a) Baseline VHPM machine (b) Proposed LVRPM machine with magnet orientation & three phase windings.

suitable to generate the same flux density as normal PM synchronous machines for a fixed PM volume [6].

In this paper a variant of the VHPM is presented and investigated which employs consequent poles separating arrays of Halbach magnets. The Halbach arrays have the property of producing high airgap flux density and the consequent pole can reduce the fringing flux that reduce the leakage flux [10]. So a significant improvement of the airgap flux density and hence the power factor can be achieved by combining both these concepts [11, 12]. PM array development and optimisation of structural parameters of the proposed LVRPM machine for maximum thrust force are analysed in this paper. The comprehensive comparisons of the electromagnetic performances of the two machines are conducted under similar operating conditions. It is shown that the proposed machine has the potential to offer improved force density and better PM utilisation than the surface mounted variant. Some important common parameters for both machines have been presented in Table 1.

Parameter	Value
Number of stator teeth	6
Pole pairs per stator tooth	3
Number of active translator teeth	20
Air gap length	1mm
Stator pole pair pitch (PPP)	24mm
Translator pitch	24mm
Number of turns	108
Translator speed	1.2m/s
Machine length	180mm

Table 1: Main common parameters of the two machine.

2 Machine Topologies and Operation principles

2.1 Baseline Vernier Hybrid Permanent Magnet model

Figure 1(a) shows a three phase VHPM machine [8, 9], where double sided three phase E-cores are used as opposed to single phase C-cores [9]. The E-core stators encompass a salient translator that consists of only laminated steel and equal size slots and teeth. Multiple magnet poles and armature coils are mounted on the E-core teeth. Alignment and un-alignment between magnet poles and translator teeth produce maximum and zero flux linkage respectively. Peak force occurs when the translator teeth are aligned with the intersection between adjacent magnets. It was shown by mathematical derivation in [9] that the magnet thickness of 4 mm provides a maximum shear stress and thus maximum force.

2.2 Linear Variable Reluctance Permanent Magnet model

Figure 1 (b) presents the double sided LVRPM machine, which is adopted from a combination of consequent pole and Halbach

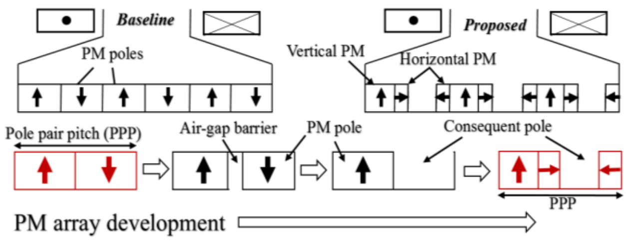

Figure 2: Schematics of PM array development of proposed LVRPM machine from baseline VHPM machine.

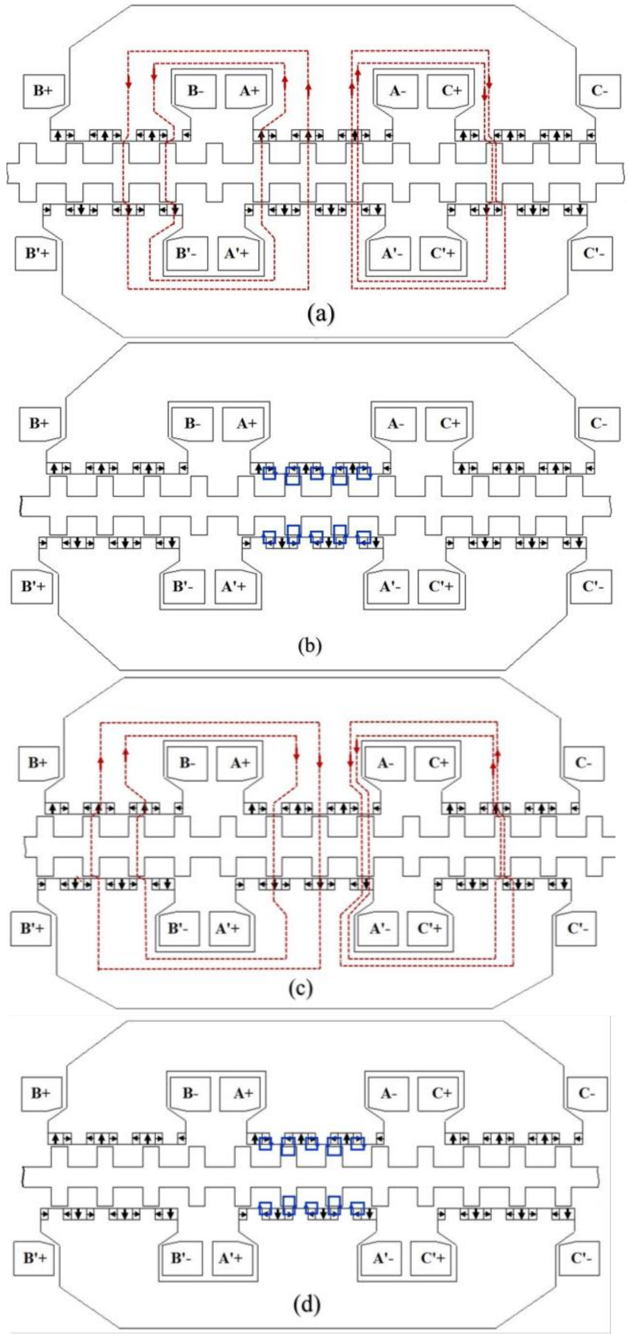

Figure 3: Operation principle at different translator positions. (a) Position a (b) Position b (c) Position c (d) Position d.

array configuration to utilise the magnet poles efficiently, thus reducing the leakage and fringing flux. Figure 2 represents the development of PM array of the LVRPM model. One PM array has three magnets with different magnetization directions and a ferromagnetic pole piece (split tooth). Each magnet array consists of a surface mounted vertically magnetised *pole* magnet and two oppositely directed horizontally magnetised *transition* magnets. The pole magnets are magnetised towards the stator iron core, and the transition magnets oppose each other through the split tooth. In the double sided machine, the centre line of the pole magnet of the upper stator must align with the split tooth of the bottom stator and vice versa. To ensure this, the bottom stator must be offset left by the distance of one transition pole width.

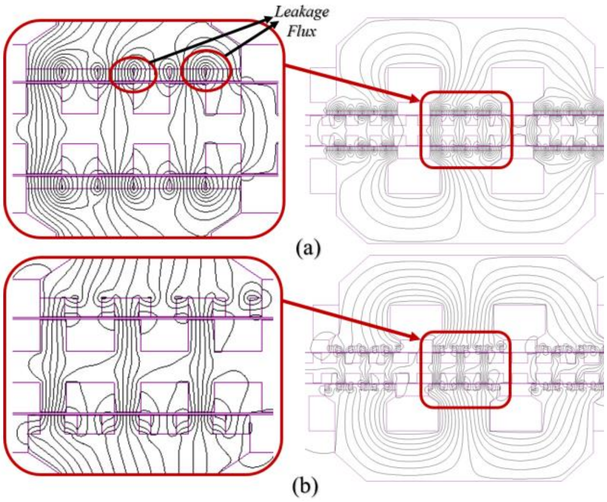

Figure 4: No load flux linkage path (a) VHPM machine (b) Proposed LVRPM machine.

The proposed machine consists of three phase windings that each produces a two-pole magnetic field. Due to the slotted structure, these magnetic fields are modulated by 20 active translator teeth (10 on each side). Finally these modulated magnetic fields interact with the magnetic fields produced by the 18 PM arrays (9 on each side) to produce the thrust force. Maximum thrust force is produced when the middle of the translator teeth are aligned with the middle of the transition magnets and minimum force is produced when the translator teeth are align with the PM poles and split teeth.

Figure 3 demonstrates the operation principle of the proposed machine in four typical translator position in terms of phase A (middle phase). Figure 3(a) represents the **positive maximum** flux linkage (d-axis) in phase A where the translator teeth are align with the PM poles of top stator and split teeth of bottom stator. Flux linkage of phase A becomes zero when the translator moves quarter of its pitch (q-axis), as shown in Figure 3(b). This position will give a negative maximum back EMF in the phase winding as the rate of change of flux with position is a maximum. Figure 3(c) shows a relative displacement of half a translator pitch from the initial position. This time translator teeth under phase A are aligned with split teeth of top stator and vertical PM poles of bottom stator and thus produce a **negative maximum** flux linkage and zero Phase back EMF. Fourth typical translator position is the displacement of three quarter of the translator pitch relative to the starting point shown in Figure 3(d). This position is identical with the position b, when the flux linkage becomes minimum while the back EMF of phase A becomes positive maximum.

To further understand the flux distribution of the machine, the flux from transition magnets allow the flux to be concentrated in the iron poles and add up with the PM poles flux resulting in a greater flux per pole. As shown in Figure 4(b), the vertically magnetised PMs produce the main flux, while the transition PMs reduce the leakage flux around the edges of PM. Peak force is produced when the translator teeth are aligned with the horizontal magnet along the q-axis of the machine.

2.3 Motivation for the new machine topology

The surface mounted VHPM model topology works well, although inspection of the flux contours generated by FEA shows significant flux leakage between adjacent magnets as they are magnetised in opposite direction (Figure 4(a)). The poles and translator teeth are connected via a low reluctance iron stator path and high reluctance air gaps. Some magnet pairs contribute almost zero to the main flux as almost all the flux leaks though the air gap and does not contribute to the active machine force. To reduce the leakage between adjacent magnet poles and increase the reluctance path between them, the new topology of LVRPM model has been developed. It is shown in Figure 4(b) that in the LVRPM machine, horizontal transition magnets work as an affective flux barrier between vertical pole magnet and the ferromagnetic pole. The horizontal magnets guide the flux to pass through the split iron tooth towards the effective flux path that results reduced leakage.

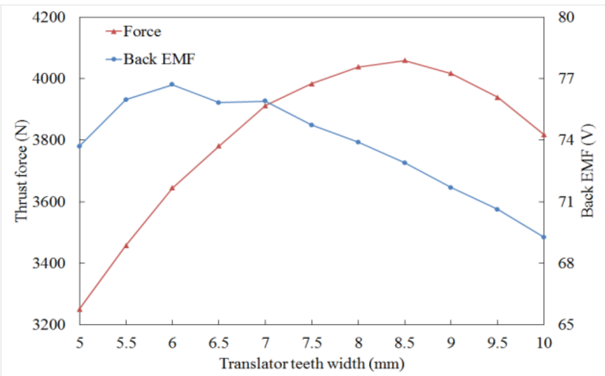

Figure 5: Thrust force and back EMF variation with translator teeth width.

3 Detailed design of the LVRPM model

3.1 Translator tooth width

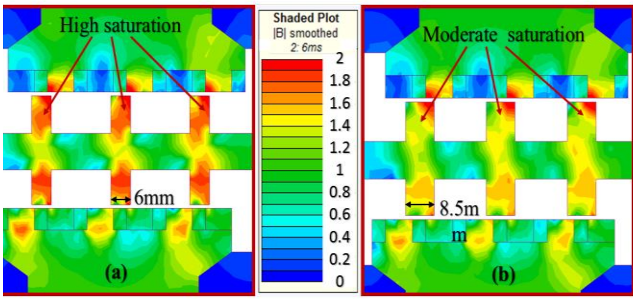

Figure 6: Effect of magnetic flux saturation on translator teeth at rated current (a) 6mm (b) 8.5mm.

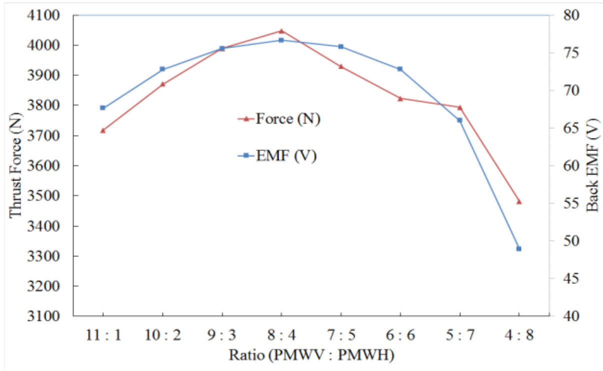

Figure 8: Thrust force and back EMF variation with the ratio

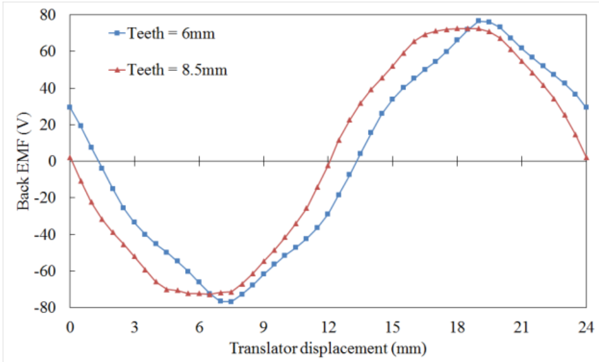

Figure 7: Phase-A back EMF for different translator teeth width.

Figure 5 shows the translator teeth investigation for maxium thrust force and peak back EMF. The translator tooth width has been varied during a design study from 5 mm to 10 mm with increments of 0.5 mm. In this figure, it is clearly visible that the maximum force is achieved at a tooth width of 8.5mm, whereas the peak EMF is achieved at 6 mm. The thinner tooth increases the rate of change of flux with position and hence back emf, but also saturates in the presence of an armature field and the force is reduced by more than 12% compared to 8.5 mm tooth. Figure 6 shows the saturation in the translator teeth at rated current for the two width. Iron laminations become severely non linear above a flux density of 1.5 T and so performance deteriorates. Figure 7 shows the back emf profile, where the 8.5 mm tooth provides lower but more sinusoidal back EMF than for 6mm, elminating the presence of higher order harmonics. The translator tooth width has been selected as 8.5 mm.

3.2 Magnet width

A design study of the magnet dimensions has been performed to achieve maximum thrust force and back EMF. As the transition magnets play a very important role for the performance of the machine, the ratio of the width of PM pole and transition magnet has been investigated for optimal performance. The stator pole pair pitch (PPP) has been kept constant at 24 mm and the vertical PM poles and split teeth are kept equal in width for every steps of change in the magnet width ratio. The horizontal transition magnets width has been varied from 1mm to 8mm while the PM poles and split teeth are varied from 11mm to 4 mm with increments of 1 mm.

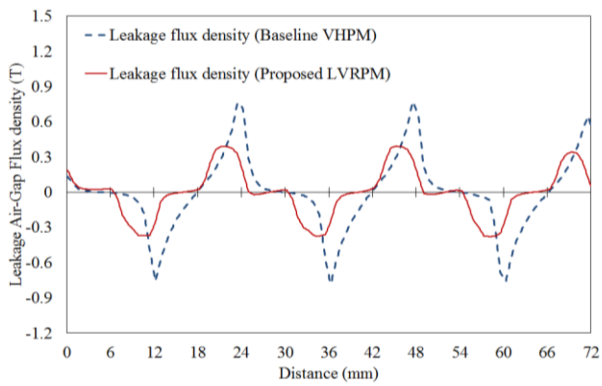

Figure 10. Leakage air gap flux density comparison between initial VHPM model and the proposed LVRPM model.

It can be seen from Figure 8 that the thrust force increases almost linearly to reach a maximum at the PM width ratio of 8:4. Above this, the thrust force drastically reduces. Again the back EMF follows similar pattern with a peak at 8:4 ratio. So the final horizontal magnets and the vertical PMs width are chosen to be 4mm and 8mm respectively for maximum thrust force application.

4 Performance analysis

4.1 Flux linkage and flux leakage

Figure 9 presents the no load air gap flux density distribution of the proposed LVRPM machine and the surface mounted VHPM machine. It is plotted on the middle of the air gap over the active length of the translator. Both the machines are designed and analysed based on the same size, electrical loading and magnetic loading. The proposed model provides higher flux linkage due to the higher air gap flux density compared to the baseline model. It can also be seen from Figure 3 that the proposed model has higher flux lines linking the phase windings than the baseline model while the baseline model suffers from significant leakage

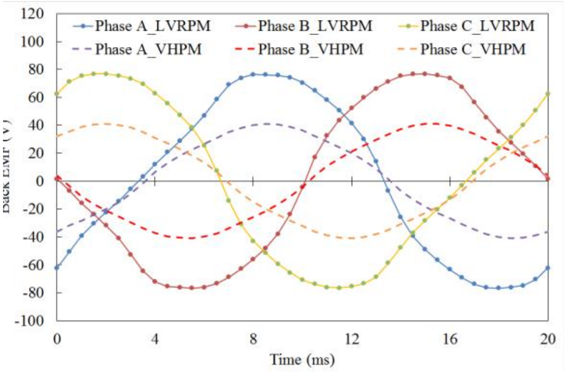

Figure 11: Three phase back EMF for the proposed LVRPM machine.

flux and saturation in the interface region between PM and iron stator. All the flux in the vertical Y-axis are assumed to be active flux as they link the translator and stator while the flux in the horizontal X-axis (axis of motion) are assumed as leakage flux. In the proposed model, significant leakage is substantially reduced and converted into active flux by the use of the horizontal transition magnets. Figure 10 compares the no load leakage air-gap flux density under the middle stator tooth for both the machines. It plots the no load air gap flux density in the X-axis for both machines. It shows that the proposed model has the capability to reduce the leakage flux by approximately 50% compared to the VHPM model and thus produce higher airgap flux density.

4.2 Back EMF

The FEA simulation of back EMF for both models at a constant speed of 1.2 m/s are compared in Figure 11. As the proposed machine has reduced the leakage flux by almost 50%, it can be seen that the achieved back EMF is almost double compared to the baseline model. The back EMF of the baseline models are symmetrical and almost sinusoidal, while the proposed model has slightly distorted back EMF due to the higher order harmonics. Reducing the leakage results in a more square wave flux density distribution in the airgap (Figure 9). Harmonic content is thus higher. The three phase EMF are still symmetrical and shifted by 120 from each other°.

4.3 Thrust force and cogging

Figure 12(a) shows the cogging force waveform for both machine models. By using the new machine topology the cogging is reduced by 54%. It is shown in Figure 12(b) that the number of cogging cycles is reduced by half. In the proposed machine, the dominant cogging harmonic is 3rd order. For the baseline model, its 6th order harmonic due to the six cogging cycles. Again for the proposed machine all the higher order harmonics and especially the 4th and 12th are comparatively lower than the baseline model. By comparing the dominant order harmonic and higher order harmonics, it is clear that the LVRPM machines provides much lower cogging compared to the VHPM machine.

Figure 13 compares the FEA thrust force variation of the proposed LVRPM machine and the baseline VHPM machine with current. Current was applied in phases that were aligned with the d-axis. It can be seen that the thrust force increase almost linearly until 20A for LVRPM machine and 29A for baseline VHPM machine. The increase of thrust force is gradually clipped after that rated armature current level for both machines.

For a fair thrust force comparison between two machines, the rated armature current for both machines has been chosen as 20A and the PM mass remains the same for both machines. Figure 14 shows the rated thrust force comparison for both the machines. It can be seen that the average thrust force for the LVRPM machine is 4.1 kN, whereas the baseline VHPM machine provides almost 30% less force for the same rated current.

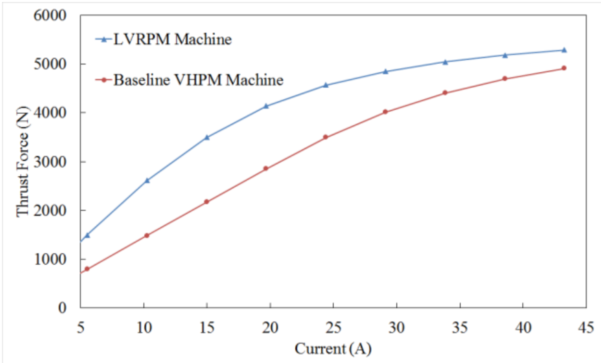

Figure 13: Thrust force variation with armature current for LVRPM machine and baseline VHPM machine.

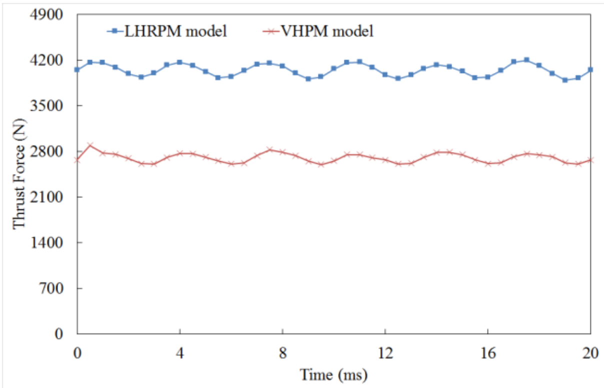

Figure 14: Thrust force at rated armature current for LVRPM machine and baseline VHPM machine at rated current.

4 Conclusion

A Linear Variable Reluctance Permanent Magnet machine has been developed from a surface mounted magnet Vernier Hybrid Machine. A new Halbach magnetic pole arrangement consist of a vertical PM poles and a consequent pole sitting in the middle of two horizontal transition poles has been proposed and a design study carried out for optimal performance. The proposed machine has the advantage of flux concentration properties of the Halbach array machine and the leakage reduction properties of the consequent pole machines which boost the active flux density of the machine. It is shown that at rated current the proposed machine provides almost 30% higher force and a 12% higher back EMF. The improvement stems from the almost 50% reduction in magnet leakage. Therefore the proposed model exhibits greater advantage in generating high force and power at low speed long stroke application like marine energy generation.

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