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***In: The 20th International conference on Electrical Machines and Systems.
2017, Sydney, Australia: IEEE.***

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URL link to conference:

<https://doi.org/10.1109/ICEMS.2017.8056499>

Date deposited:

19/09/2017

Investigation of a Doubly Salient Halbach Array Linear Permanent Magnet Machine for Wave Energy Converters

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Abstract— In this paper a novel E-core Linear Variable Reluctance Vernier Hybrid Permanent Magnet (LVR-VHPM) machine with inherent magnetic gearing is proposed for use in the long stroke application of a wave energy converter. The proposed topology is a combination of a doubly salient flux reversal machine, a consequent pole machine and a surface mounted Halbach array Permanent Magnet (PM) machine. The stator teeth interact with horizontally and vertically magnetized PM and ferromagnetic poles in such a way as to maximize the flux density in the machine by minimizing flux leakage. The translator is segmented to ensure the most effective use of material for minimum mass.

A performance comparison study between the novel LVR-VHPM machine, a baseline linear Vernier Hybrid Permanent Magnet (VHPM) machine, a linear Halbach VHPM machine and a linear Consequent pole VHPM machine is used to show that the best result is achieved by the combined topology. All four designs consist of the same double sided E-core stators, segmented translators and an equal magnet mass.

Index Terms— Doubly salient, E-core, leakage flux, magnet mass, segmented translator, variable reluctance.

I. INTRODUCTION

The Vernier Hybrid Permanent Magnet (VHPM) machine is a member of Variable Reluctance Permanent Magnet (VRPM) family which are known to exhibit high torque or force density due to the reluctance variation and flux reversal characteristics of the slotted translator causing a magnetic gearing effect [1], [2].

Mueller and Baker performed performance analysis of a high shear stress linear version of the Vernier Hybrid Machine (VHM) for low speed applications like direct drive wind turbine generators or direct drive wave energy converters [1]. They used flux linkage map to analyze the performance of the VHM but did not attempt to reduce the heavy leakage flux at the poles. The VHM is less force dense than the transverse flux machines developed by Weh in [3] but has a simpler mechanical design and a 2D flux path around the machine which makes it a strong candidate for the direct drive high force application. It is proposed to be used in marine propulsion as a replacement of conventional PM synchronous machines by Hodge and Mattick [4]. The linear VHM machine has an advantage in marine applications because both the magnets and the coils can be mounted on the stationary stator, whilst the longer translator is made of only laminated steel. Baker [5] performed amplitude

amplification in a wave energy converter with an oversized translator that requires less force to generate the same power. To utilize the maximum energy from the wave, linear machines with oversized translator or stators and high constant active area are very important. Oversizing the translators for amplitude amplification has its own mass penalty [5].

Ji in [8] also proposed a high force dense single sided VHM with magnets and coils both mounted on the shorter mover. Though it achieved high force density, the thick salient stator core is too heavy and the magnet orientation (combination of two magnetization directions of magnets) make it more prone to demagnetization at high current density and temperature as horizontal magnets concentrate flux to the vertical magnets. Raihan in [6] proposed a much lighter segmented translator topology and improved the E-core VHPM machine with a higher force density, while the machine still suffered flux leakage from adjacent magnet poles.

In this paper a novel LVR-VHPM machine with doubly salient structure is proposed that incorporates a Halbach array of magnets with consequent poles and a segmented chamfered translator, as developed in [5]. The topology can be thought of as a combination of a VHPM with opposite polarity magnet poles [6], a consequent pole machine and a Halbach machine. Finite Element Analysis (FEA) results will present the transient characteristics including no-load flux linkage, back Electromotive Force (EMF), average force and cogging force. The proposed topology will be compared with the three component topologies to analyze the performance of the machine topologies for a fixed magnet mass.

II. METHODOLOGY

Four models with the same overall stator, chamfered segmented translator and a fixed magnet mass have been developed and analyzed in 2D FEA. Static and transient characteristics such as percentage of leakage flux, force per magnet mass and back EMF for a fixed axial length are compared. All the machines have equal translator and stator magnet pole pitch and magnet thickness is varied to give the required volume.

The active flux path for all the machines is vertical and assumed in the direction of y-axis, while all the flux in the x-axis is assumed to contribute to the leakage flux in the machine.

Fig. 1. Magnet orientation of single stator tooth set of the baseline VHPM model, derivation of d-axis and q-axis and no load flux contour.

III. MACHINE LAYOUT AND OPERATION

Four different topologies of double sided E-core VHPM machines are presented in this section. All the models consist of the same long segmented translator that can be connected with a heaving buoy to transform the wave motion into linear mechanical movement, as discussed in [6]. Double sided stators incorporate the PMs and three phase armature coils with a concentrated winding configuration. The flux path for all four machines is from top stator to the bottom stator across the translator. There is a non-magnetic material in between segmented translator teeth to make a coreless continuous translator.

A. Baseline VHPM model

The Vernier Hybrid Machine (VHM) is a variable reluctance, flux reversal machine that offers high power and force density with simple and rigid structural construction. A single phase of a simple linear E-core baseline VHPM model is shown in Fig 1. Each stator tooth has magnets of opposite polarity sitting side by side. Perfect alignment and un-alignment between magnet poles and translator teeth produce maximum and zero flux linkage respectively. Moving the teeth to the adjacent magnets reverses flux flow around the machine. Physically displacing the translator by only a short

Fig. 3. Magnet orientation of single stator tooth set of the consequent pole VHPM model, derivation of d-axis and q-axis and no load flux contour.

distance, the coils see a 180 degree change in magnetic flux - so called magnetic gearing. This provides a non-contact method that enables direct drive machines to reach higher force density without conventional mechanical gearbox within limited size [5]. Though it possess high force density, the leakage flux is a weakness for this type of machine. Heavy leakage flux between the adjacent magnets in the single phase stator teeth of the baseline VHPM model is shown in Fig. 1. The main flux is being drive by the leftmost magnet. The right hand set of magnet poles can be seen to be almost 100% leakage

It is showed from the reluctance network of the C-core baseline model [6] that a 4mm magnet thickness gives maximum shear stress (Fig. 2). The base line model consists of an E-core stator with three active faces with a segmented translator, 4mm thick and 12mm wide magnets.

B. Consequent pole VHPM model

In a consequent pole machine, alternate magnet poles are replaced with iron teeth. Leakage flux can be reduced as compared to the baseline model and thus the main flux is increased. In addition, the effective air gap is also minimized which reduces the reluctance of the equivalent magnet circuit resulting in improved power density. A c-core Consequent pole topology has been implemented in a linear VHM in [7]. Therefore, a consequent pole E-core linear VHM with segmented translator is presented in Fig. 3. Three magnets with the same magnetization direction are mounted on each stator tooth and three consequent poles operate as the opposite polarity while the concentrated winding is wound around the tooth. The long laminated translator with salient teeth is sandwiched between the stator sides which offers a robust structure to produce and transfer the thrust force.

The operation principle of the E-core LVHPM machine with consequent pole is similar to that of the baseline LVHPM machine in which the consequent poles act as the missing polarity. Magnets on the top stator are

Fig. 2. a) Reluctance circuit of the C-core LVHPM machine b) Effect of magnet thickness on predicted shear stress.

Fig. 4. Magnet orientation of single stator tooth set of the Halbach VHPM model, derivation of d-axis and q-axis and no load flux contour.

magnetized vertically upward and the bottom magnets are magnetized downward. During the first half of an electrical cycle, the translator teeth are aligned with the top magnets and the bottom consequent poles. The pattern is repeated in the opposite direction for the second half of the cycle. In one complete electrical cycle, flux reaches two opposite maximum values during two alignments and two minimum values when unaligned. Therefore, magnetic gearing occurs due to a rapid change in flux linkage with short translator displacement.

C. Halbach VHPM model

Fig. 5 shows a detailed picture of the E-core VHPM model with the Halbach magnet orientation and the segmented translator. The working principle is same as the baseline VHPM model. Instead of fully vertically magnetized magnets, it incorporate the Halbach orientation. Each magnet pole consists of a set of 3 magnets: a vertically magnetized magnet sandwiched between two horizontally magnetized magnets facing each other. Adjacent vertically magnetized magnets are

Fig. 5. Magnet orientation of single stator tooth set of the proposed LVR-VHPM model, derivation of d-axis and q-axis and no load flux contour when translator teeth are align with d-axis.

Fig. 6. Single phase no-load flux linkage (ψ_{PM}) and back EMF of upper and lower stator coils of the LVR-VHPM model

separated by two horizontal magnets facing opposite to each other. The advantage is the inclusion of effective reluctance equivalent to the air gap between adjacent magnet poles to reduce the leakage. Fig. 4 presents the no load flux linkage contour plot. It is clear that the leakage is reduced compared to the baseline model, where all magnet poles now contribute to the main flux. Substantial leakage, especially in the right hand magnet poles, is still evident.

D. Combined LVR-VHPM model

Fig. 5 presents a single phase of the proposed model which is a combination of the consequent pole and Halbach topologies. Magnets are magnetized in vertical and horizontal directions on a salient E-core stator that is made of laminated iron core. Segmented translator sits in the middle of the double sided stators. A PM array of three identical sets of magnets are mounted on the inner face of each stator tooth. Each PM array consists of a vertically magnetized PM and a ferromagnetic split tooth sandwiched between two horizontally magnetized PMs facing each other. When the translator teeth are aligned with the vertical magnets, the unaligned ferromagnetic teeth concentrate the flux from horizontal magnets and add with the flux flowing from the vertical magnets. When the mover teeth align with the ferromagnetic teeth, the horizontal magnet poles concentrate the flux to the ferromagnetic teeth and the adjacent vertical magnets sum the flux. The resultant flux is directed across the translator teeth to the opposite stator pole. The horizontal magnets also acts as an effective air gap between vertical magnets and ferromagnetic split poles that results in a reduction of the leakage flux. The no load flux function contour for this topology is shown in Fig. 5. Compared to figs 1, 3 and 4, there is a substantial reduction in leakage flux across adjacent stator poles. Each magnet pole contributes equally to the main flux path.

Fig. 6 presents the no load flux linkage and back EMF from two coils of the same phase. It is noticeable from the graph that both the coil fluxes are reversal in nature.

Fig. 7. Leakage flux density plot in the x-axis over an electrical cycle for all four VHPM models.

Flux linkage of the upper coil is slightly higher in the positive axis than the bottom coil in the first half cycle while the bottom coil has higher negative flux component for the second half. This is because alignment of translator teeth with the vertical magnet links slightly more coil flux than the alignment with ferromagnetic teeth. Fig. 6 shows the translator teeth aligned with vertical magnets of top stator and ferromagnetic teeth of bottom stator. Top stator has slightly lower leakage than bottom stator and thus higher active flux linkage. The back EMF - rate of change of flux ($d\psi/dt$) remains almost same for both stator coils.

IV. FEA RESULT & COMPARISON

This section describes the electromagnetic performance of all the models using Finite element Analysis (FEA) software. Under loaded and unloaded condition all the models have been simulated by using 2D FEA. Rated Magneto Motive Force (MMF) for all the models was 3000A-turns. The proposed model is designed to generate a rated force of 4.4kN at the rated speed of 1.2m/s. Important machine parameters and specifications for all four models are listed along with the achieved results in the Table. I.

Fig. 7 shows the leakage flux over a complete electrical cycle for all four models. It is very clear from the plot that the novel LVR-VHPM model has almost 50% less leakage than the baseline model.

Fig. 8 quantitatively compares the electromagnetic performance of the described VHPM models. Machine parameters like, translator pitch, translator teeth height, axial length, magnet material, magnet volume, air gap and number of turns of the coils as well as the material properties have been kept the same for all four models. 2D transient FEA analysis has been performed with and without a constant MMF to find the static characteristics i.e. back EMF, cogging force, thrust force, no load flux linkage etc. for all four models. Fig 8 (a) shows that the proposed model has the highest back EMF which is almost 50% higher than the baseline VHPM model.

Fig. 8. Comparison between Novel LVR-VHPM model, Baseline VHPM model, Halbach VHPM model and Consequent pole VHPM model a) no load back EMF, b) rated force, c) cogging force and d) no load flux linkage.

From Fig. 8(d), the proposed LVR-VHPM machine has shown maximum flux linkage compared with the rest of the models. Reduced leakage and high active magnetic flux allow the proposed machine to achieve very high thrust force while maintaining minimum cogging. The novel magnet orientation on the double sided salient stator also proved to provide the maximum force density for the same amount of PM usage and the rated MMF for a low speed operation.

TABLE I
COMPARISON TABLE AND DESIGN SPECIFICATION OF PROPOSED LVR-VHPM MODEL, BASELINE VHPM MODEL, HALBACH VHPM MODEL & CONSEQUENT POLE VHPM MODEL

Machine Parameters	Baseline VHPM model	Consequent pole VHPM model	Halbach VHPM model	Novel LVR-VHPM model
Average Force (N)	3278	3252	2850	4420
Cogging (N)	508	372	326	270
Back EMF (V)	16.2	20.4	13.7	24.4
Force/magnet mass (KNkg ⁻¹)	2.14	2.13	1.86	2.89
Magnet mass (kg)	1.53	1.53	1.53	1.53
Translator pole pitch (mm)		24	24	24
Electrical frequency (Hz)	24	50	50	50
Translator speed (m/s)	50	1.2	1.2	1.2
Axial length (mm)	30	118	118	118
PM height (mm)	4	8	4	6

Table I presents the summary of the transient performance of four VHPM models. From the comparison table, a column chart showing the per unit performance for all the models is shown in fig. 9. It is very clear from the chart that the proposed model contribute to the best performance.

V. CONCLUSIONS

A Vernier Hybrid Machine has been adopted to reduce leakage flux and improve machine performance. The proposed topology has a combination of consequent pole and a Halbach magnet configuration. Horizontally magnetised magnets are used to guide adjacent vertically magnetised magnet flux, resulting in an increase of flux per pole due to minimized leakage. The novel model is proved to produce the highest back EMF and thrust force, while giving the lowest cogging force for a fixed magnet mass across a range of similar topologies. The novel topology can produce high force and power density and output voltage at the low speeds encountered in wave energy converters.

Fig. 9. Per unit performance comparison between all four VHPM models.

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