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Comparison of flux switching and modulated pole linear machines for use with a free piston

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Abstract—This paper investigates the design of direct drive linear generators for use in Free Piston Engines. Flux switching, modulated pole and surface mounted magnet machines are individually modelled and optimized to react the force of the engine with minimum magnet mass. The mass of magnet used in each design is found to be heavily dependent on the copper loading in the machine and the flux produced at no load. The modulate pole or transverse flux machine, which in other applications gives an extremely efficient use of magnet, is here shown to be more effective than conventional machines but less effective than the flux switching machine.

Keywords—Piston, Linear Machine, Renewable Energy, Permanent Magnet Machine, Transverse Flux, Flux Switching, Magnetic Flux, Finite Element Analysis, Design Optimization.

I. INTRODUCTION

A free piston engine generator is an internal combustion engine where the mechanical output from the piston is coupled directly to a linear generator. Eliminating all the rotary components from the machine, such as the crankshaft and con rods, has the potential to drastically reduce the engine mass. Further, the compression ratio and velocity profile is no longer constrained and advanced combustion strategies become possible. When compared to a conventional four cylinder internal combustion engine, the number of moving parts is drastically reduced. This engine can hence be developed for lightweight or small space applications, such as the range extender for an electric vehicle.

The success of the engine is dependent on the development of an electrical drive train which can convert linear motion of variable frequency, variable amplitude, into electrical power. This direct drive solution consists of a linear generator and power converter.

From an electromechanical perspective, linear electrical machines operate in an identical manner to their rotary counterparts. The active area of a linear machine is parallel to the direction of motion, as opposed to the circumferential as in a rotating machine. As such, all electrical machine topologies can be built as linear machines. The moving part of the machine, known as the rotor in conventional machines, is referred to as the translator in a linear machine. In this paper a number of alternative linear machines are investigated against a specific free-piston engine [1] in Fig.1 with the corresponding engine specifications in Table 1

Fig. 1 Single piston free-piston engine [1]

- ①exhaust poppet valves;
- ②scavenging ports;
- ③common rail fuel supply;
- ④linear alternator;
- ⑤bounce chamber;
- ⑥bounce chamber pressure control valves;
- ⑦turbocharger compressor;
- ⑧turbocharger turbine.

Table 1

Stroke	152.4mm
Translator mass	$\leq 6\text{Kg}$
Operation	Two-stroke
Nominal compression ratio	15:1
Speed	25Hz
Boost force	1500N

The average speed of the free piston engine is 7.62m/s where as a 3000rpm electrical machine with an active diameter of 200mm has an air gap speed of 30 m/sec. Direct drive machines for the free piston engine therefore require the development of electrical machines with air gap speeds an order of magnitude lower than found in many rotary machines. As mechanical power is the product of velocity and force, high force density machines are required if the size of the electrical machine is limited. This naturally leads the designer to consider permanent magnet topologies.

Modulated pole machines are those where the flux resulting from a current carrying coil is modulated by a toothed structure to make a number of distinct North and South Poles. The orientation of the electrical and magnetic circuit is such that it is possible to adjust the coil area and tooth area separately. The number of electrical poles can thus be increased independently of the coil slot area. If each electrical pole interacts with an individual permanent

magnet, increasing the pole number increases the force output. Transverse flux and flux switching machines can both be classified as members of this family of machines, and have been shown elsewhere [13] to be capable of producing high force density operating under air cooled conditions. A number of alternative topologies are studied here, where the orientation and position of the magnets is altered.

Unlike in rotary machines, in order to maintain a constant active area over the entire mechanical cycle, the translator and stator must be different length. All machines in this paper have copper windings and a translator longer than the stator. Machines are designed with five electrical cycles per oscillation in one engine stroke – hence the overhang between the translator and stator must be five pole widths.

In this study, the five topologies being studied are three Surface Mounted (SM) Moving Magnet Machines, a Modulated Pole Machine (MPM), and a Flux Switching (FS) Machine.

The SMs have axial, radial and Halbach Array of magnets on the translator and a three phase windings on the stator.

The MPM has flux concentrated magnets on the translator and three transverse winding stators.

The FS machine has purely iron translator, with magnets and transverse windings attached to the stator for each phase.

II. DESIGN AND OPTIMISATION METHODOLOGY

The five topologies of electrical machines are designed and analyzed in static solution for a specific free piston engine, which fixes some parameters such as stroke length and pole pitch. Other parameters need to be considered such as translator mass, magnet volume, coil area and machine steel structure. To make the electrical machine design realistic other parameters are set as constants, such as air gap, shaft radius and current density.

Whether designing from a generator or motor point of view, the copper loading and no load flux loading are the two key aspects on machine force capacity. As the equations shown below:

$$EMF \propto N \times d\Phi_{no\ load}/dx \times v \quad (1)$$

$$F \propto \text{copper loading} \times \Phi_{no\ load} \quad (2)$$

$$\text{Copper loading} \propto MMF \times L_{coil} \quad (3)$$

Where EMF is the electromotive force (m/s), N is number of coil turns, $\Phi_{no\ load}$ is no load flux linkage (Wb) produced by magnet, x is displacement (m), v is velocity (m/s), F is force (N) related the air gap between translator and stator, copper loading is a measure of the copper usage (Am) in the coils, MMF is magnetic motive force (A) which is composed of current per coil and turns of coil, L_{coil} is the active coil length (m) i.e. the length of a single turn.

In this paper the aim is to compare the magnet usage and copper loss for the five machines i.e. the no load flux

linkage and the copper loading. Normally when it comes to the comparison between the machines with the same copper loading (Am), the ratio of force to magnet mass can fully distinguish the machine performance. However, when comparing machines with radically different coil configurations and turn length, fixing current density (A/mm²) is more realistic. For instance, in the transverse flux machine, the coil length per turn of coil is a function of the stator length, whereas in the surface mounted machine it relates to translator circumference. Also the turn number per slot is very different. What is more, when the machine is in the process of optimization, the machine iron volume and coil volume are changed simultaneously, which makes it harder to maintain the same copper loading for all the machines. In this paper the authors have chosen the same current density for all machines so that the copper loading difference can be regarded as the copper loss difference as well. As shown in equation (2) the force capacity is due to the product of copper loading and no load flux loading, where no load flux loading comparison of machines is based on the flux linkage value for a unit length of one coil turn.

The optimization was carried out using commercially available finite element software using an evolutionary based solver [12]. Randomly generated geometries from a range of user defined variables are assessed against an objective function. The algorithm narrows the geometric search window to identify an optimum, solution. The objective was here defined as minimum the magnet mass. Constraints were translator mass no more than 6Kg and force on translator should be no less than 1500N. Table2 shown below gives a summary of machine constants based on free piston engine aspect and user self-defined aspect as well as the optimization objective and constraints.

Optimization used static finite element analysis force on the translator with the MMF waveform aligned with the no load EMF waveform to maintain peak force – i.e. current added in the q axis.

Table 2

Free piston constant	Stroke 152.4mm, pole pitch 30.48mm
Self-defined constant	Air gap 1mm, shaft radius 40mm, peak current density 7A/mm ²
Objective	Minimum magnet mass
Constraints	Translator mass ≤ 6Kg, force ≥ 1500N

III. TOPOLOGY STUDY

The stroke length, translator mass and peak force are as defined in Table 1, set primarily by the target engine. The remaining constants are shown in Table 2 and discussed below. They were set with consideration to both copper loading and no load flux loading aspects.

The peak current density is set at 7A/mm². For a fixed speed machine this would correspond to 5A/mm² RMS, but in a linear machine where the translator is stationary twice

every cycle the equivalent current is less. This value has been selected assuming only air cooling.

Secondly, the coil fill factor for each slot is defined at 50% and the conductor cross sectional area is defined as 1mm^2 . In this case the copper loss is directly proportional to the copper loading and the copper loading difference is only relevant to the active coil volume.

Thirdly the translator inner radius is defined at 40mm with no limit on the stator outer radius.

The air gap length is defined at 1mm, fixed by mechanical constraints. The air gap length dictates the coil inductance and hence operating power factor of the generator. This has not been considered in this research. The air gap length also influences the static flux leakage, which shows particularly in the flux switching machine discussed later.

The pole pair number is defined at 5, which means the pole pitch is 30.48mm and the machine stator width is at 1:1 ratio to the stroke length, the reason for this constraint is also for the comparison fairness.

The remaining dimensions are all regarded as variables which can be optimized to lower the magnet mass.

A. Surface Mounted

1) Topology

Fig. 1 SM overview

Fig. 2 SM with axial magnet

Fig. 3 SM with radial magnet

Fig. 4 SM with Halbach magnet

The three magnet orientations for the SM machine are shown in Fig.2 - Fig.5. They have been proposed elsewhere for this application [2]-[5] and use a fractional-slot-per-pole modular permanent-magnet-machine topology with three-phase, 9-slot/10-pole combination. They all have a modular stator winding in which the coils of each phase are disposed adjacent to each other. The translator magnets are mounted to form an axial array, a radial array or a Quasi-Halbach array. These three different magnet arrays show their pros and cons on the copper loading and flux loading, which are shown in the results section. One feature here for the SM with Quasi-Halbach magnet array is a very high force to

translator mass ratio because of this magnet array enhances the flux linkage towards the stator side whilst minimizing the translator core back depth and the translator mass.

Fig. 3 -Fig. 5 also show the flux path for a single phase. The principle of the flux path for SMs is that the magnet driven flux linkage around the coil changes according to the translator's position. The winding distribution means the current flow is orthogonal to the motion direction. The distributed winding means the three phases are contained within a single stator body.

2) Constraints

The constraints for all the SMs are as given above.

3) Results of optimisation

The results of the optimization are shown in Table 3. The force is the average value during one electrical cycle, whereas copper loading and no load flux loading are the peak values.

Table 3

Data/machine	Axial	Radial	Halbach
Force(N)	1516	1513	1526
Magnet mass(Kg)	0.93	0.79	0.82
Translator mass(Kg)	4.80	4.00	2.85
Machine mass(Kg)	15.85	19.29	16.28
Copper loading(Am)	2042	2404	2060
No load flux loading(μWb)	3.48	3.43	3.47

The Halbach array is shown to have the lightest translator mass and use small amount of magnet material. In Fig. 6 the data has been normalized to the Halbach array. For all categories, the higher the per-unit number is, the better the machine performance is. To achieve this, the inverse copper loading is used.

Fig. 5 SMs' comparison

The data is presented in this way to allow greater understanding of machine performance. The machine force capacity is a synthetic action between copper loading and no loading flux loading, where copper loading is a function of both current density and coil volume. No load flux loading is a measure of the magnetic circuit, the effectiveness of using the magnet. Without observing them together with the force, the comparison would lack comprehensiveness. The flux loading/ magnet mass can directly show the magnet use rate. As current density is fixed, 1/copper loading indirectly show the machine efficiency based on the copper loss.

To validate the optimization strategy and results, the saturation level for both current density and no load flux loading can be checked. Fig. 7 - Fig. 8 show the machine force for increased magnet mass and current density for Halbach array machine. It shows the optimized machine is not saturated implies an effective use if current and magnet to achieve the force.

Fig. 6 Force versus magnet volume

Fig. 7 Force versus current density

4) Discussion

From the saturation condition check in Fig. 7 - Fig. 8, the optimization of the machine can be regarded as successful as both copper loading and no load flux loading are within acceptable level. From Fig. 6 it can be seen that the SM with Halbach magnet array offers the best performance at no load flux loading and force to translator mass ratio, SM with axial magnet array offers the best performance at force to machine mass ratio and 1/copper loading, the radial magnet array offer the best performance at flux loading to magnet mass ratio. However the Halbach one compared with the other two offers the best average performance on all comparison standards.

The Halbach magnet array is selected as the best configuration from all the three candidate machines. In the following sections, only the Halbach surface mounted machine is taken forward for comparison. Throughout this paper, per unit values are normalized to the Halbach array values.

B. Modulated Pole

1) Topology

Fig. 8 MPM overview

Fig. 9 MPM front view

Fig. 10 MPM left view

Fig. 11 MPM right view

The modulate pole machine shown in Fig. 9 has axially magnetized permanent magnets mounted on the translator, separated by iron pole pieces, which act as flux concentrators. The stator consists of three separate phases, each with a set of iron teeth surrounding the copper coil. Each phase covers 120 mechanical degrees around the circumference of the translator.

The flux path of the MPM is shown in Fig. 10 - Fig. 12, where the arrows visually illustrate the flux concentration from the inner radius of coupled magnets on the translator part. Flux is distributed in the pole pieces and flows into the stator teeth, where it encompasses the coil and returns to the translator by an adjacent tooth. A general flux loop around the coil has been formed. Current flow is parallel to the direction of motion and flux flow is fully three dimensional. The flux path is explained more fully elsewhere [13]

Fig. 9 shows the translator when the flux linkage is at the minimum value, the q axis. When the translator position is changed the flux linkage would be enhanced and reversed until it is aligned with the next pole. As a result the flux linkage is formed as a sine waveform. The force optimization is conducted in the q axis.

2) Constraints

As shown in Fig. 9, the MPM stator consists of three separate phases, which require a physical space to prevent mutual fluxes. In this paper the influence of this parameter has not been analyzed, instead the gap has been fixed at 5 degrees.

3) Results of optimisation

The results of the MPM are used to compare with the SM with Halbach magnet array. Table 4 below gives the target optimized results for both SM with Halbach and MPM.

Table 4		
Data/ machine	Halbach	MPM
Force(N)	1526	1570
Magnet mass(Kg)	0.82	1.20
Translator mass(Kg)	2.85	4.94
Machine mass(Kg)	16.28	32.79
Copper loading(Am)	2060	441
No load flux loading(μ Wb)	3.47	10.10

One feature in MPM is the copper loading is only about 21% of that in SM with Halbach whereas the no load flux loading is about 3 times larger. Furthermore as the optimization strategy used in this paper fixes the active diameter, the machine size is similar for all machines. The

MPM has less coil area while more steel area on the stator as a result the machine weight is about double that of the SM (Halbach). This feature decreases the copper loss significantly, however high coil mutual inductance produced from translator magnet may cause low power factor when the machine is in generator mode, influencing the high cost of power electronics converter.

Fig. 12 Comparison between the SM with Halbach and the MPM

Fig. 13 visually shows the comparison (PU value) between SM (Halbach) and MPM based on the same data ratio from previous section, which shows the MPM has superior advantage on both magnet use rate and low copper loss. In static solution, MPM offers much better performance on machine running cost (high no load flux loading and low copper loading) but higher machine built materials cost (more iron materials on both translator and stator). The no load flux loading and copper loading saturation conditions which used to validate the optimization strategy be feasible are shown in Fig. 14 - Fig. 15 below.

Fig.13 Force versus magnet volume

Fig.14 Force versus current density

4) Discussion

There is a compromise problem between high no load flux loading machine or high copper loading machine. High copper loading causes high copper loss meanwhile high no load flux loading cause lower power factor which is explained elsewhere[14]. Comparing the ratio of no load flux loading to magnet mass shows the MPM gives about double magnet use rate compared with the SM (Halbach). This can be regarded as the consequence of more iron material used in MPM.

Lower copper loading in the MPM will produce less heat than that in the SMs for the same force. However, the large amount of iron offers an improved thermal route, so the

MPM could have higher current density without improving the cooling method. This can be used to further optimize the MPM machine in terms of magnet reduction.

For both the SMs and MPM machines, the magnets are mounted to the translator, resulting in only half the magnets being used at any time, with the other half not in the stator as shown in Fig. 2. To tackle this, the flux switching machine [11] will be discussed in the next section.

C. Flux switching

1) Topology

Fig. 15 FS overview

Fig. 16 FS front view

Fig. 17 FS left view

Fig. 18 FS right view

The FS machine has only one magnet energized in outwards radial direction mounted on a single phase stator. The translator consists of isolated iron pole pieces which align to each stator pole which is shown in Fig. 16. A rotating machine applied a similar structure in [11].

The flux path of the FS is given in Fig. 17 - Fig. 19 and shows there is no magnet attached on the translator instead the magnet and coils are both attached to the stator. The translator is a purely iron structure, meaning all magnets are in the active part of the machine at all times. The disadvantage here is about the flux leakage (green arrows in Fig. 17- Fig. 18) at the maximum no load flux linkage position (as shown in Fig. 18) which would make the individual magnet use rate lower. The challenge in optimization is to exploit the amount of magnet saved by being mounted on the stator versus the flux leakage resulting from the less effective magnetic circuit.

The red and blue of arrows show the flux linkage and flux leakage paths separately, the arrows shown in Fig. 17 - Fig. 19 are only half of the idea flux paths, another half are symmetric to the coil area and have an opposite variation. As the translator moves the ratio of flux flow in the two paths are changed so that the variation of the total coil flux linkage is formed.

2) Constraints

Two extra variables have been added to the optimization protocol:

Firstly, the air gap of FS has been set as a variable and allowed to be less than 1mm. the leakage in this topology is particularly sensitive to the size of the air gap and it proved hard to meet the target force with this air gap. At this stage, the reduced air gap is a penalty for the performance advantages shown later. It is anticipated that changing the aspect ratio of the machine may allow for a 1mm air gap in future work.

Secondly, the mass constraint on the translator forces the back iron to be quite small. The translator hence saturates easily under a current loading of $7A/mm^2$ and 50% fill factor as shown below in Fig. 20. To keep the current density unchanged, the fill factor has been set as a variable in this machine to reduce the MMF and avoid saturation.

Fig. 19 Force capacity versus current density in the FS

3) Results of optimisation

Table 5 below gives the target optimized results for both MPM and FS.

Table 5

Data/ machine	MPM	FS (0.5mm air gap at 0.25 fill factor)
Force(N)	1570	1502
Magnet mass(Kg)	1.20	1.67
Translator mass(Kg)	4.94	5.77
Machine mass(Kg)	32.79	61.18
Copper loading(Am)	441	276
No load flux loading (μWb)	10.10	16.70

The FS has a greater number of variables than the other machines meaning the optimization accuracy for a reasonable computation time is considerably lower. The results show that: the no load flux loading/ magnet mass ratio is higher than the MPM, however the machine weight is about double of the MPM (quadruple of SMs). Fig. 20 gives a comparison between MPM and FS based on the 6 comparison protocols mentioned before:

Fig. 20 Comparison between the MPM and the FS

4) Discussion

The FS machine has the potential for better magnet utilization than the MPM, although the overall mass is greater. Also, the air gap length has been reduced to 0.5mm compared to the other machines. It is predicted that with better optimization and mass reduction alterations to the design the FS can reach much higher performance.

D. Comparison

To make a clear comparison among all 5 machines, Fig. 21 gives a summary of the machines' performance on the 6 criteria: Force capacity, no load flux loading, force/translator mass, force/ machine mass, no load flux loading/magnet mass and 1/ copper loading. All data are shown in PU values regard the MPM's value as 1 unit.

Fig. 21 All machines comparison

MPM and FS can have much higher flux loading and magnet use rate compare with SMs and a much lower copper loss, the drawback being the use of more iron materials in the machine. FS can be a good substitution to MPM to improve the magnet use rate further more. Lower copper loading with higher magnet loading is the biggest characteristic of the FS.

IV. CONCLUSION

This paper was focused on the novel machine topology design for the use with free piton engine based on the static solution analysis. Comparing with conventional distributed

winding linear machine the SMs had already showed the superior performance according to elsewhere [3]-[6], then an alternative machine (MPM) had been compared which showed a lower copper loss performance as well as better magnet saving strategy. Finally, a FS has been shown to potentially reduce the magnet requirement even more. Although both MPM and FS showed an advantage at copper loss and magnet use rate, more iron was needed hence the machine mass is bigger. The FS machine could only reach the required force by reducing the air gap to 0.5mm, as compared to 1mm for other machines in the study. The play off between translator mass and back iron saturation is also a difficulty for this machine.

Future study on this research will be focused on the dynamic solution to include iron loss, with control strategies and experimental data comparison. It is anticipated that more detailed design of the FS machine will yield a saving in mass.

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VI. BIOGRAPHIES

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