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A Comparison of Alternative Linear Machines for Use with A Direct Drive Free Piston Engine

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Abstract

In this paper the design of a linear electrical machine for use with a free-piston engine will be discussed. Three conventional permanent magnet machines are compared to a flux switching and modulated pole machine. Each of the topologies is optimised to give a specific force whilst adhering to a limit on the mass of the moving component. Using simple vector analysis, it is shown that machine power factor and efficiency are improved by optimising the machines with an objective function of minimising the MMF. Transient solver results are used to validate the static solver results and provide estimates on efficiency and operating power factor. This method of optimisation is shown to give modulated pole machines with relatively high power factors, which is a known limitation of this class of machine.

The modulated pole machine topology could be the best option among all five topologies as it has high efficiency and high power factor. The flux switching machine shows some potential benefits on magnet material use ratio compared with PMs, yet it is not compliant with mass constraint.

1 Introduction

From an electromechanical perspective, a linear machine operates in an identical manner to its rotary counterpart. All electrical machine topologies can therefore be built in a linear form. In conventional topologies, the translator (rotor) is made of laminated epoxy material with coils, the magnetic track is made of magnet (normally high-energy rare-earth magnet) fixed on the steel base. The translator contains coil windings, Hall sensor circuit board, temperature sensor and electronic interface. Identical to the rotating machine with central bearing to support the air gap, the linear machine needs a linear guideway to maintain the translator position in a magnetic field. As a rotating servo motor with encoder is required on the shaft in order to provide position feedback, the linear encoder is needed for position accuracy. The linear machines can be classified as flat, U shape and cylindrical types [1-3].

As for rotating brushless electrical machines the coil must be installed on the stator, for the linear counterpart the stator and translator position can be switched: either moving magnet track (no requirement for a coil manager system but it is necessary to bear the track mass) or moving coil (lighter moving mass ratio but need high flexible coil material and manager system).

In this paper a linear machine is designed for use with a free piston engine. The requirement for high force capacity, limited moving mass and integration within the engine has led the Authors to consider a variety of cylindrical translators placed within stationery stator mounted coils. This topology is anticipated to ensure both low magnet mass and easy coil arrangement.

In a free piston engine, the total mass of the translator and the peak force capability of the machine both influence the compression ratio, speed profile and hence performance of the engine. Five machine topologies are investigated in this paper: Permanent Magnet (PM) machine with Axial (PMA) [4], Radial (PMR) [4], Quasi-Halbach (PMH) [4-5] magnet array, Modulate Pole (MP) [6] machine and Flux Switching (FS) [7] machine. Four of these topologies have translator mounted magnets whereas the Flux Switching (FS) machine, has the magnets mounted on the stator.

The PMA, PMR and PMH (PMs) have the same stator structure, which are elsewhere classified as longitudinal flux machine or moving magnet machine.

The MP is inspired by the PMA with an identical translator structure but different stator and coil arrangement. Often referred to as a transverse flux machine, the coil is aligned to the oscillation direction and flux is actively modulated around the coil in three dimensions [6].

The FS is a further development of the MP, based on the hypothesis that by moving the magnets to the stator side, it may give better magnet utilisation by removing magnet material from the overhang area [7, 11].

When designing a linear machine the amplitude of oscillation is important, as to achieve a constant active area over a full stroke length sets the length of both the stator and translator. One of these components can never be 100% utilised. Consider a linear machine with a peak to peak amplitude equal to the length of the stator. In this case, the translator must be twice the length of the stator to maintain the active area. For a permanent magnet machine, topologies where the magnets are mounted on the translator will only ever achieve 50% utilisation in this scenario. In a rotary machine, however, the rotor is fully enclosed within the stator at all times, and so amplitude is of no concern and both components are 100% utilised. Whether the magnets are translator or stator mounted is thus more important in linear machines than for rotary machines. Topologies of FS which are considered to give poor performance in rotary machines may yet prove useful in linear applications with long amplitudes.

This paper compares the conventional PM structured machines to modulated pole and a flux switching topology with particular reference to linear applications. Optimisation is done with respect to reducing MMF requirements, as this is shown to help improve power factor, which is a known limitation of modulated pole machines.

2 Free-piston Engine

In this paper the target free-piston engine [8] with the mechanical constraints is shown in the following Table1:

Stroke	152.4mm
Translator mass	≤ 6Kg
Operation	Two-stroke
Nominal compression ratio	15:1
Average Speed	2.54m/s
Boost force	1500N

Table 1 Mechanical constraints

3 Optimisation strategy

When designed for a free piston engine, there are two electrical machine parameters limited by the mechanical requirement: the required electrical force and the translator mass limit [9].

$$\mathrm{Fe} = C_f D \left\{ \frac{2p_0 L}{\pi m} \left\{ \frac{\varepsilon(\varepsilon^{\Upsilon-1}-1)}{(\Upsilon-1)(\varepsilon-1)} \right\} \right\}^{\frac{1}{2}} + K_f \pi D b p_0 \left\{ 1 + \frac{\varepsilon(\varepsilon^{\Upsilon-1}-1)}{(\Upsilon-1)(\varepsilon-1)} \right\} \quad (1)$$

Eq. 1[9] relates the output force, Fe, to, C_f the viscous friction force coefficient, K_f the static friction force coefficient, D the cylinder bore, b the ring width, p_0 the ambient pressure, L the effective stroke, m the translator mass, ε the compression ratio and ϒ the adiabatic exponent . For a free piston engine design in completion, the electrical force and moving part mass will directly influence the compression ratio (stroke) and speed profile (acceleration). The other parameters can be regarded as constants.

In this paper the electrical machine magnetic flux flow is based on the finite element method software MagNet, thus simple equations can be used for analysing machine electrical force. From the electrical machine aspect, for a linear machine with cylindrical structure the electrical force can be simplified as below in Eq. 2 [10]

$$\mathrm{F_e} = (1/\sqrt{2}) A B_{gmax} l_c r \int_0^{2\pi} sin(\theta + \Psi)\, sin\theta d\theta \quad (2)$$

Where A is the peak total current for each phase as machine electric loading in Ampere, B_{gmax} is the air gap flux density which is defined as machine magnetic loading in µWb /mm^2, l_c is the effective coil length in mm, r is the machine translator radius in mm, Ψ is the phase angle which is 0^0 to achieve maximum magnetic force of a machine (in this paper Ψ is always 0^0 as main magneto-motive force is at 90 degree to the armature current providing the magneto-motive force). To simplify the equation further it can be written as following in Eq. 3

$$\text{Force} = \text{machine constant} \times \text{electric loading} \times \text{magnetic loading} \times \text{translator surface area} \quad (3)$$

For the simpler comparison among five topologies the equation can be unified into Eq. 4 below, where flux loading is in µWb/mm unit.

$$\text{Force} = \text{constant} \times \text{MMF} \times \text{flux loading} \times \text{coil length} \quad (4)$$

In Eq. 4 MMF is the electric loading which is a product of peak current density and effective the slot area in static solver (or phase current times coil turns in transient solver), flux loading is the main flux loading (no load flux loading) per unit length of coil. The coil length is one phase coil length for each turn as in static force analysis each effective slot can be regarded as consisting of a single solid turn. In PMs (Axial, Radial, Halbach) each effective slot coil length is the mean circumferences of the stator torus' shape coil. In MP the coil length is the active stator length. A transient solution is used to check static solution accuracy, machine EMF and Power factor. Windings assume a 1 mm^2 conductor cross section with 50% fill factor.

The authors have previously shown using static analysis [11] that the Flux Switching machine has strong potential in this application but can only match the performance of other machines if a smaller air gap is permitted. The optimisation strategy in this paper is to minimise the slot MMF whilst meeting the force requirement without exceeding the mass limit. This optimisation objective is selected for three reasons:

1. Maximise the machine force capacity, reduce Copper loss and increase the error-tolerance which may be caused by simulation inaccuracy (namely higher force can be achieved in practice by merely increasing the current density of the machine);

2. To avoid thermal overloading and reduce demagnetization risk;

3. To improve machine power factor, as deduced from Eq. 5, Eq. 6 and Fig. 1 below.

$$\mathrm{I}_q X_q = \frac{MMF}{n} \omega_s \frac{n^2}{R} = \frac{MMF \times n \times \omega_s}{R} \quad (5)$$

$$EMF_{rms} = \frac{2\pi}{\sqrt{2}} n \hat{\phi} f K_w \quad (6)$$

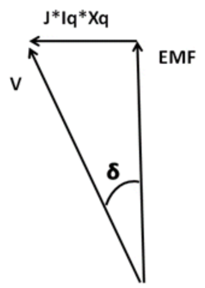

Fig. 1 Simplified phasor diagram

Where I_q is equal to the armature current, n is the coil turns number, ω_s is the synchronous speed, R is the air gap reluctance, $\hat{\phi}$ is the peak air gap flux density, f is the electric frequency and K_w is the winding factor. When the armature current is in phase with EMF (I_d=0, phase angle =0) as in Fig. 1, the load angle is equal to the power factor angle, as there is no terminal voltage restriction considered in this paper (ignoring field weakening), the EMF and I_qX_q share the same "n" so only MMF influences the vector of I_qX_q and thus the load angle and power factor angle.

Apart from the aforementioned optimisation objective and constraints, there are three constants being set by the designer: firstly the stator active length is equal to the oscillation length with 5 electric poles; secondly the air gap is fixed at 1 mm; lastly the translator inner radius is 40 mm. Table2 lists the optimisation routine used for all five topologies.

Machine topologies	PMs	MP	FS
Objective	Minimising the slots MMF		
Constraints	1. Electrical force ≥ 1500N 2. Translator mass ≤ 6Kg		
Constants	1. oscillation length = 152.4mm 2. Electrical circle = 5 3. Air gap = 1mm 4. Translator inner radius = 40mm 5. Coil cross section area = 1mm^2		
Variables	1. Translator steel sizes 2. Magnet sizes 3. Stator slot and tooth sizes 4. Current density		

Table 2 Optimisation routine

4 Machine Topologies

4.1 Conventional PM machines

Fig. 2, Fig. 3 and Fig. 4 give one-phase sectional topologies for the conventional PM machines [4]. Their magnetic flux paths at the same position are analogous. The stators use a fractional slot-per-pole modular permanent-magnet-machine topology with three phase 9-slot/10-pole combination [12]. They all have a modular stator winding in which the coils of each phase are disposed adjacent to each other. However, different magnet orientations distinguish them and the resulting characteristics are discussed in the results section.

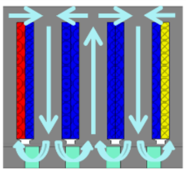
Fig. 2 PMA

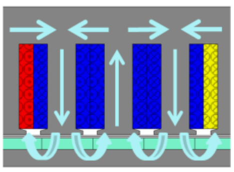
Fig. 3 PMR

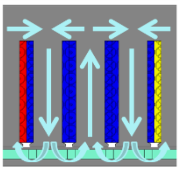
Fig. 4 PMH

4.2 Modulated Pole Machine

Fig. 5 gives the schematics of the MP machine [6] flux path in two extreme positons. The translator has axially magnetised permanent magnets separated by iron pole pieces, similar to the PM translator with axial magnet array – the PMA. The difference is that 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 arrows visually illustrate the flux concentration from the inner radius of coupled magnets on the translator part. At the peak mutual flux position (left) the flux is concentrated in the pole piece and flows into the stator teeth, where it encompasses the coil and returns to the translator by an adjacent tooth. At the 0 mutual flux position (right) the flux is shorted by the stator tooth, the equivalent flux encompasses the coil is 0.

The MP is expected to inherit the advantages from PM axial and can further reduce the winding usage and is known to perform well in high force density applications.

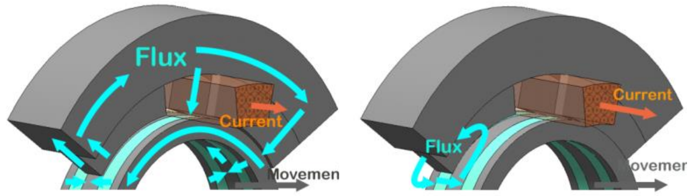

Fig. 5 Two extreme magnetic flux schematics of MP

4.3 Flux Switching Machine

A linear Flux Switching machine has the magnets located within the same toothed structure as the coil. Interaction with a moving iron translator manipulates the flux to oscillate around the coil in order to induce an emf. Fig. 6 gives schematics of a linear FS machine [7, 11] flux path in two extreme positions. Compared to the MP the FS has only one magnet energized in the outwards radial direction mounted on a single phase stator. The translator consists of isolated iron pole pieces which align to each stator pole. When the translator is at the left position the flux is through the tooth adjacent to the coil on the left and returns from the separated tooth on the right edge, the equivalent flux path has encircled the coil which the flux linkage is at maximum value. When the translator is at the right position the flux is shorted by the two teeth on the same side of the coil, which gives zero flux linkage.

The FS is a derivative from MP which is expected to keep the MP working characteristics and further save the magnet material usage by moving the magnets to the stator and eliminating them from inactive the unenclosed part of the translator.

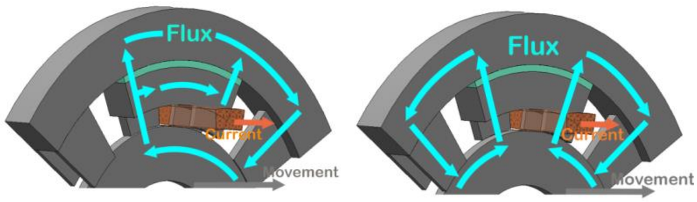

Fig. 6 Two extreme magnetic flux schematics of FS

5 Optimisation Results

The optimisation is processed in software OptiNet by following the optimisation routine in Table2. OptiNet is an automated design optimization option to MagNet, it uses advanced and efficient algorithms to find optimal values for different design variables within the constraints specified.

5.1 Conventional PM machines

The dimensions of the initial design of the three PM topologies together with the optimised results are listed in Table 3 (minimised MMF with two constraints being full filled), Fig. 7 below visually illustrates the PMH parameters specification as an example for PMs.

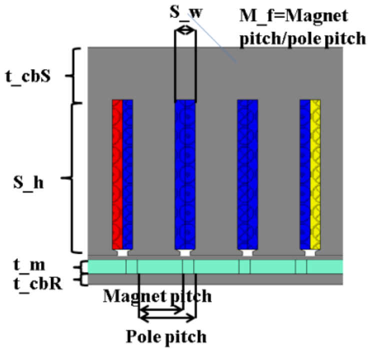

Fig. 7 PMH schematic with parameters' specification

Where magnet factor (m_f) is the ratio of magnet pitch to pole pitch; t_cbR and t_cbS indicate the core back depth for the translator and the stator, in PM with axial magnet array the core back depth of translator is separated by the magnet pieces which depend on the magnet factor so there is no data on t_cbR; t_m is the magnet depth however in axial magnet array topology t_m is equal to the translator height; J is the current density; slot height (s_h)and slot width (s_w) indicate the stator slot size (indirectly indicate the tooth size). Objective 1 (ob_1) minimising the MMF, constraint 1 (co_1) force requirement and constraint 2 translator mass limit (co_2) are as listed in Table3.

PMA										
ID	m_f	t_cbR	t_m	J	s_h	s_w	t_cbS	Ob_1	Co_1	Co_2
unit		mm						A	N	Kg
0	.2	-	7.2	7	35.5	10	4	7452	1570	4.80
97	.35	-	8.1	5	43.5	6.4	5.9	3924	1510	5.43
PMR										
0	.1	4.2	1.6	6.8	46	7.5	15.4	7038	1670	3.83
76	0	5.1	3.4	5.9	25	8.5	11	3756	1509	5.70
PMH										
0	.1	3.2	1.3	7	43.5	8.5	4.36	7764	1659	2.85
72	.2	2.8	3.9	5.2	40	5.5	14	3432	1501	4.38

Table 3 Optimisation results of PMs

All three topologies are seen to be compliant with the required specification, and the optimisation routine has successfully reduced the MMF requirement by approximately 50% in all cases. Overall translator mass has increased during the optimisation, but still remains below the 6kg limit.

5.2 Modulated Pole Machine

Table4 below presents the optimisation results of MP and Fig. 8 gives visual specifications of MP's dimension.

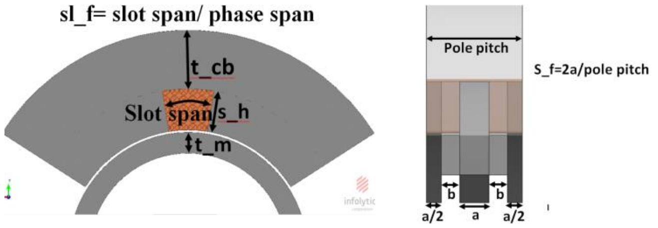

Fig. 8 MP dimension specifications

Where slot factor (sl_f) indicates the slot span angle to one phase mechanical angle ratio; J is the current density; stator factor (s_f) is the interval pitch between the interlaced stator teeth to pole pitch ratio; t_m is the translator height which is equal to both the magnet height and translator core back width; translator factor (t_f) is the magnet depth span to pole pitch ratio, s_h is the slot height; t_cb is the core back depth of the stator. The objective and constraints are the same with the PMs. The optimisation routine has reduced the MMF required to fulfil the force requirement by 31%.

ID	sl_f	J	s_f	t_m	t_f	s_h	t_cb	Ob_1	Co_1	Co_2
unit				mm		mm		A	N	Kg
0	0.13	7	0.3	9	0.25	27.5	28.5	3213	1386	5.82
89	0.21	5	0.3	8.75	0.5	18.5	40.5	2296	1503	5.59

Table 4 Optimisation results of MP

After the optimisation the force requirement has been fulfilled, meanwhile MMF usage dropped to 70% of that in the original topology and the translator mass is still within the 6 kg limit.

5.3 Flux Switching Machine

The optimisation results for FS are as follows in Table5 and its dimension specifications are shown in Fig. 9 below.

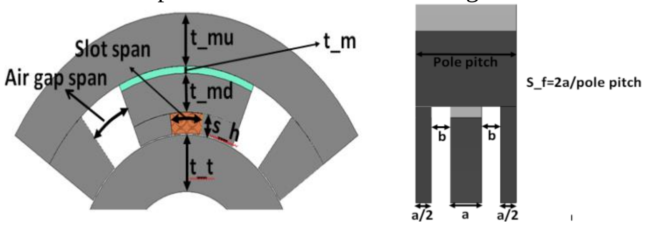

Fig. 9 FS dimension specifications

Where t_m is the magnet depth; t_md and t_mu are the core back depth beneath and above the magnet; s_h is the slot height; sl_f is the ratio of slot span angle to the one phase mechanical angle; a_f is the ratio of air gap span angle between two stator teeth on one side of the coil to the angle of one phase mechanical angle subtract the slot span angle; t_t is the translator height; s_f indicate the same meaning of that in MP; t_f means the translator pieces' thickness. Same objective and constraints are applied in the FS's optimisation.

ID	t_m	t_md	t_mu	s_h	s_f	a_f	t_t	sl_f	t_f	J	Ob_1	Co_1	Co_2
unit	mm						mm				A	N	Kg
0	14	20	20	20	.1	.45	20	.2	.8	7	1995	525	5.86
179	16	37	34	49	.1	.41	29	.17	.71	7	6506	1291	8.22

Table 5 FS optimisation results

Observing from Table5 the optimal result shows that for FS with the applied optimisation routine neither of the two constraints from Table2 (translator mass, output force) can be full filled, if the translator mass must be limited at 6 Kg the force can only reach 525N. In previous work, the airgap of the FS machine was reduced to combat this [11]. In reality, this is unlikely to be acceptable to manufacturers. Here, a further optimisation routine is taken to explore if the FS can save magnet material usage at the expense of a heavier translator mass. The new optimisation removes the translator mass limit and also changes the objective Ob_1 to minimising the magnet usage. All other requirements are left unchanged. The new optimisation results are as followed Table6 where s_ indicates the shaft radius.

ID	t_m	t_md	t_mu	s_h	s_f	a_f	t_t	s_	sl_f	t_f	J	Ob_1	Co_1
unit	mm						mm					Kg	N
0	14	20	20	20	.1	.45	20	40	.2	.8	7	5.18	525
96	6.1	33	45	18	.13	.34	48	73	.38	.65	7	3.10	1508

Table 6 FS optimisation results with new routine

The result shows that not only has the force increased to the required value, but also 40% magnet material has been saved. This has been achieved by increasing the shaft radius and thus increasing the size and active mass of machine significantly.

6 Full results and comparisons

6.1 Static Results

Topologies	PM			MP	FS	
	PMA	PMR	PMH		Meet mass requirement	Meet force requirement
MMF A	3924	3762	3432	2296	1995	4305
Force N	1511	1509	1501	1500	525	1508
Translator mass Kg	5.43	5.72	4.38	5.60	5.86	22.17
Magnet mass Kg	1.86	2.24	2.52	2.75	5.18	3.10
Total mass Kg	23.28	19.06	23.38	35.02	42.96	52.58

Table 7 Results directly extracted from MagNet

Detailed results are required to compare the two versions of the FS machine with the four other topologies. The data above in Table7 are extracted from the optimisation results in the MagNet with static solver.

Topologies	PM			MP	FS	
	PMA	PMR	PMH		Meet mass requirement	Meet force requirement
Constant N/(A*Wb)	288	306	302	300	162	270
MMF A	3924	3762	3432	2296	1995	4305
Flux loading µWb/mm	4.79	4.68	5.36	14.34	10.63	8.52
Coil length per turn mm	277	278	270	152.4	152.4	152.4
Force N	1511	1509	1501	1500	525	1508
Translator mass Kg	5.43	5.72	4.38	5.60	5.86	22.17
Magnet mass Kg	1.86	2.24	2.52	2.75	5.18	3.10
Total mass Kg	23.28	19.06	23.38	35.02	42.96	52.58
Flux loading/ magnet mass µWb/(mm*Kg)	2.58	2.09	2.13	5.21	1.81	2.75

Table 8 Data matching Eq.4

Table8 list the results, where the first five rows correspond to variables in the simplified force equation defined in Eq. 4. To achieve the same electrical force MP requires the minimum MMF then comes to PMs and last to FS.

Flux loading / magnet mass is the flux loading (no load) produced by unit magnet material which indicates the magnet use ratio. MP shows a big advantage on this parameter compared to all other candidates. Due to this, less MMF is required to achieve the design force.

From above, the MP takes advantages on low electrical loading and high magnetic loading / unit magnet material mass, however the total mass (main from stator) is about 50% more than PMs.

MMF produced armature flux can cause saturation, although the optimisation routine to minimise MMF makes this unlikely. By comparing the machine constant values PMs and MP show similar armature flux condition (not saturated).

As for the FS, due to the translator mass constraints, the force requirement cannot be met by this topology. As long as this constraint is removed the required force can be reached with better magnet use ratio compared with PMs, but still less than that of PM. Due to the large translator mass (nearly 4 times the limit given in Table 2), it can be concluded that the FS is not fit for the target free-piston engine.

6.2 Transient Results

In transient solution only PMs and MP will be discussed, more machine characters can be extracted like EMF, terminal voltage, power factor, EMF harmonic, copper loss and iron loss based on the static optimal topologies.

Fig. 10 below is the EMF harmonic analysis. It shows that PMA takes advantage on the EMF harmonic at THD 1.5%. MP shows the worst among all four topologies with 21% THD. This is the biggest disadvantage of PM discussed in this paper.

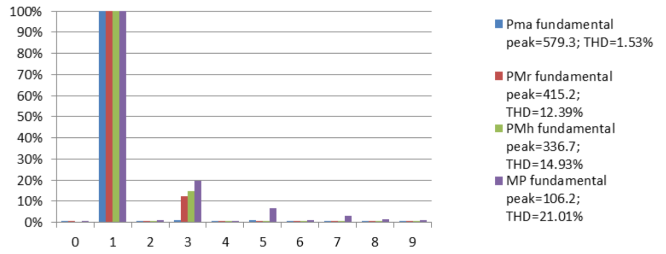

Fig. 10 PMA, PMR, PMH and MP Harmonic analysis

With the coil cross section at 1 mm^2 Table 9 below gives the machine loss, efficiency and power factor profiles, MP shows advantage on the machine total efficiency (the copper loss of MP includes the return windings). Furthermore PMR and MP have higher power factor than the other 2 topologies.

Designing a modulated pole machine with a high power factor is a direct result of the decision to optimise based on a low MMF requirement. Using this optimisation routine hence removes one of the traditional barriers to this type of machine topology. The modulated pole machine gives the highest efficiency by quite some margin, again directly resulting from the low MMF design.

Topologies	PM			MP
	PMA	PMR	PMH	
Current density peak A/mm^2	4.7	5.9	5.2	5
Copper loss W	150	178	142	90
Iron loss W	77	33	59	13
Efficiency %	94	94.5	94.7	97.3
Power factor	0.53	0.67	0.55	0.66

Table 9 Efficiency profile

7. Conclusions

In this paper three conventional permanent magnet topologies have been compared to a modulated pole and flux switching machine for use in a free piston engine.

The optimisation process is based on the engine constraints and machine working phasor vector analysis, the machine performance criteria are extracted from the electric force equation. The optimisation routine focused on meeting a specific force requirement, whilst minimising MMF and staying within a 6kg moving mass constraint.

Both the static and transient solver simulation results have been analysed, the static results show conformation to the transient results which validate the static solver accuracy.

Based on the static and transient results, the flux switching machine has been excluded from this free-piston engine application due to the large moving mass required. The modulated pole machine shows superior performance because of its high flux loading per unit magnet mass magnet allowing a low electric loading giving high efficiency and a relatively high power factor for this class of machine. However, higher stator mass, higher magnet mass and higher harmonic content compared to the conventional topologies could offset these advantages.

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