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***In: 2016 XXII International Conference on Electrical Machines (ICEM). 2016,
Lausanne, Switzerland: IEEE***

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DOI link to article:

<http://dx.doi.org/10.1109/ICELMACH.2016.7732868>

Date deposited:

07/12/2016

Optimization and Comparison of Linear Transverse Flux and Flux Switching Machines

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Abstract -- This paper investigates the design of alternative permanent magnet linear machines for use as the generator in a free piston engine. All of the machines are of a modulated pole structure with three dimensional flux flows. In transverse flux machines such as these, the current flows in a different plane to the flux path, eliminating the usual conflict between electric and magnetic loading. For a linear machine, the mass of magnets used is sensitive to whether the magnets are mounted on the stator or translator. Hence this paper compares transverse flux machines with translator mounted magnets and flux switching machines with stator mounted magnets. A three dimensional finite element analysis of each topology is run through an optimization routine in order to investigate the magnet usage, power factor and other performance criteria. It is concluded that flux switching machine is uncompetitive due to the 65% flux leakage even with improved tooth structure, moreover the transverse flux machine is shown to perform better overall, giving a better power factor, better efficiency and lower translator mass as a whole flux switching machine is not match for free piston engine applications.

Index Terms-- Free Piston Engine, Flux Switching, Linear Generator, Modulated Pole, Transverse flux

I. INTRODUCTION

FROM an electromagnetic perspective, linear machines operate in an identical manner to their rotary counterpart.

All electrical machine topologies can therefore be built in a linear form. From a mechanical perspective, however, when designing a linear machine the amplitude of oscillation is important. To achieve a constant active area over a full stroke length sets the relative length of the stator and translator components. One of these components can never be 100% utilized. For example, a linear machine with a peak to peak amplitude equal to the length of the stator must have a translator of twice this length to maintain the active area throughout the stroke. For a permanent magnet machine, topologies where the magnets are mounted on the translator can only ever achieve 50% utilization 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% utilized. Whether the magnets are translator or stator mounted is thus more important in linear machines than for rotary machines. Topologies which are considered to give poor performance in rotary machines may yet prove useful in linear applications.

This paper considers two topologies of modulated pole permanent magnet machine which are generally considered to give good torque per unit magnet mass – the transverse flux machine and a novel configuration of the flux switching machine.

The stator coil of both topologies produces a multi-pole field by modulating the field via a set of offset iron teeth,

hence the term modulated pole machine (MPM) [1]. This method of modulation means that every pole sees the entire coil magneto motive force (MMF). As the pole number rises, the stator tooth and rotor pole pitch falls, but the coil cross section remains unaltered. The electric loading expressed per unit of active length hence remains constant. The magnetic loading driven by the remanence of PMs will increase with pole number exponentially. As the torque is the product of volume, magnetic loading and electric loading, a high pole number leads directly to a high torque density within a given volume. This is not the case in a conventionally wound machine, where torque is independent of pole number, as a higher pole number results in a smaller coil and hence lower electric loading, or MMF.

Whilst a large torque density is possible with high pole numbers, perhaps exceeding 10Nm/kg, the high pole number results in a high electrical frequency. For this reason the MPM is generally considered well suited to torque dense, low speed applications. Force is derived from the interaction of the modulated field with permanent magnets. In a transverse flux machine, the magnets are mounted on the translator, whereas a flux switching machine has them mounted on the stator.

Both these machines have fully three dimensional flux paths which can only be analyzed using three dimensional finite element analysis. The bulk of this paper reports on numerical optimization results of three dimensional simulations of the two competing machines for the specification of a free piston engine.

II. BASIS OF COMPARISON

A. The Free Piston Engine

A free piston engine is an internal combustion engine where the reciprocating linear motion of the piston is coupled directly to a linear electrical machine. All rotary components, such as the crankshaft and connecting rods, are eliminated from the machine and it is hoped this has the potential to produce low mass, high efficiency generation devices. A number of alternative linear machines have been investigated for this application, including tubular permanent magnet [2,3] and transverse flux [4]. The 3.8 kW free piston engine presented in [5] is used to derive a specification upon which the machine topologies considered here can be evaluated. The relevant constraints are given in Table 1.

TABLE I
FREE PISTON ENGINE DESIGN CONSTRAINTS

Constraint	Value	unit
Power	3.8	kW
Peak force	1500	kN
Target Translator	6	kg

mass		
Translator diameter	80	Mm
Amplitude	152.4	Mm
Mean Speed	2.54	m/s

B. Optimization Routine

The optimization is carried out using commercially available 3D finite element analysis software MagNet with inbuilt optimization routine. The software has advanced and efficient algorithms to find optimal values for different design variables within the constraints specified. A transient solver was used on each permutation of topology over a single electric cycle moving at a constant linear speed of 2.54m/s.

Simulations were repeated with two objective functions: minimizing electric loading and minimizing magnetic mass.

The single objective optimization tends to make machines which are compliant but high in stator mass. Optimized designs produced by the software can then be manually tuned to give a more sensible overall design.

In this work, it is assumed the active length is equal to peak to peak oscillation amplitude. Section V removes this restriction in an attempt to generalize the results.

III. THE TRANSVERSE FLUX MACHINE

A. Machine Topology

The Transverse Flux Machine (TFM) is often proposed for torque dense applications such as that required for electric vehicles [6,7]. In a linear form it has been studied for wave energy [8] and the free piston engine [9,10]. The flux path is three dimensional, precluding the use of a simple laminated structure. Rotary topologies have been presented which use soft magnetic composites [10], laminations [11], or a combination [1]. The advantage of having no competition between space requirements of flux carrying teeth and space occupied by windings is well documented in the literature [12].

Fig 1 TFM flux schematic diagram

Fig 1 shows a single phase of a linear TFM with axially magnetized permanent magnets on the translator. Within the translator magnetic flux travels axially from the magnet into the pole pieces (1), radially across the air gap and into the stator tooth (2). In the stator core back, flux travel is axial and circumferential around the outer edge of the coil (3) to align with the next translator pole piece. The path is

completed by radially returning down a stator tooth (4), across the air gap into the translator pole piece. Flux in the translator pole piece and the stator piece is three dimensional, so it is here assumed that the entire structure is made of soft magnetic composite. All the components can be pressed directly making a tubular structure easy to assemble.

Linear versions of the TFM have received attention for some years, usually with a flat cross section and inherent 50% magnet usage, e.g. [4] where a peak force of 1.5kN has been reported by an estimated 10kg of translator mass. Magnet utilization and translator mass is improved more recently with static optimization of a single phase flat version of this design with a peak force of 700N using 13A/mm² modulated through square teeth and a machine mass of 8.38kg being reported [12]. Authors there developed their own algorithms to drive a reduced reliance on FEA software – recent developments in available software and computing power effectively mean users no longer need to develop their own such methods.

It has been shown elsewhere that the shape and angular sweep of the stator teeth can have a major effect on torque ripple and back emf profile [13]. In the present study, two alternative tooth shapes are compared: rectangular tooth and the trapezoidal tooth. As shown in Fig 2, the trapezoidal tooth introduces an additional variable, root thickness.

Rectangular tooth

Trapezoidal tooth

Fig 2 Different tooth structures

In rotating machines, electric frequency is the product of pole number and mechanical frequency. In linear machines, frequency is a function of oscillation amplitude and mechanical frequency. Fixing the number of poles means comparing machines of the same electrical frequency.

For a fixed active length of 152.4mm, translator diameter of 80mm and an air gap of 1mm, the variation in force capability with pole number of an initial TFM machine design is shown in Fig 3. Force is seen to increase linearly at low pole numbers, but leakage between teeth dilutes the effect at high pole numbers. For this active length, five pole pairs is shown to be beyond the linear region, but below the constant force region where leakage completely offsets the improvements associated with pole number increase. Five pole pairs are used in the constant active length part of this paper

Fig 3 Variation of force with pole pairs for a fixed active length

B. Optimization Constraints and Results

Fig 4 TFM dimensions definition

The parameters for the TFM are defined in Fig 4 and optimized design results are given in Table 2, with detailed parameter values given in Table 4. Design (a) corresponds to minimizing electric loading and design (b) to minimizing magnet mass. Both are compliant with the specification, and the designer has a straight choice between a low magnet mass 88% efficient design with power factor of just 0.17 (b), or a more sensible 96% efficient machine with power factor 0.67 using 85% more magnet (a). In this instance, optimizing for minimum electric loading gives a better looking design.

TABLE II
TFM RESULTS

Tooth shape	Rectangular		Trapezoidal		unit
	A	B	C	D	
Objective	Electric loading	Magnet mass	Electric loading	Magnet mass	
MMF	2135	5894	1850	5894	A
Magnet mass	2.28	1.23	2.24	1.21	kg
Translator mass	5.29	5.76	5.72	5.68	kg
Stator mass	15.65	28.49	20.79	26.88	kg
Copper Loss	117.8	325.2	89.3	325.5	W
Iron Loss	39.9	125.4	35.1	107.1	W
Efficiency	95.9	88.2	96.7	88.6	%
Power factor	0.67	0.17	0.70	0.20	

Repeating the optimization for trapezoidal teeth, Table 2 shows the modified tooth can give only a slight increase in efficiency and improvement in the power factor to 0.7 for the low electric loading design (design c). The total mass of magnet in this design is 2.24kg. The low magnet mass trapezoidal machine (design d) shows a similar minor improvement in performance, but is still dogged by a power

factor of 0.2. In practical situations, this is likely to exclude it from being taken forward. Design (c) is hence selected as the baseline machine design against which improvements can be measured.

In this scenario, the amplitude of oscillation is equal to the active length of the stator, and so at any one time only 50% of the magnets are being utilized. Focusing on the low electric loading design, in order to improve magnet utilization a topology where the magnets are moved to the translator is next considered and compared to design (c).

IV. THE FLUX SWITCHING MACHINE

A. Machine Topology

Fig 5 FSM flux schematic diagram

A Linear Flux Switching Machine (FSM) 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 5. Linear FSMs have been proposed in Super conducting form for wave energy [14] and linear transportation [15,16]. They are particularly attractive in applications where the stroke is long, as the moving translator consists of a pure iron structure [17]. Other authors have considered topologies where the current moves perpendicular to the physical motion, in both flat [18] and tubular configurations [19].

In all reported configurations, the coil slot width and magnet height share the same orientation and together make up the stator pole pitch. There is hence a play off between the magnetic and electric loading. The topology proposed here has the current flowing parallel to the direction of motion and hence imitates the three dimensional flux path of the transverse flux machine where there is no competition between space requirements of flux carrying component and armature windings. The stator mounted magnets are radially magnetized and the flux path is modulated by the interaction of a set of offset translator teeth and straight stator teeth.

Fig 6 Flux paths in the FSM

The two flux paths, corresponding to the translator teeth aligning with alternate stator teeth, are shown in Fig 6. The flux is gathered circumferentially on the upper and lower surfaces of the magnet, before being channeled radially down stator teeth. There is an inherent leakage path circumferentially across adjacent teeth - also shown in Fig 6. The topology was first previously introduced by the authors [20] and is effectively a linear version of the Flux Switching Modulated Pole Machine which was shown in [21] to offer a lower component count and simplified rotor at the expense of an 18% reduction in rated torque per unit magnet mass.

B. Optimization Constraints and Results

Fig 7 FSM dimensions definition

The parameters for the FSM are defined in Fig 7. It was found that no rectangular tooth design was compliant with all aspects of the specification. Previous work by the authors found reducing the air gap length from 1 mm to 0.5 mm is one way of overcoming this problem [20]. As this limit is set by anticipated tolerances, this reduction is unlikely to be acceptable outside of the laboratory. If, however, the 6kg mass constraint on the translator is lifted, the routine for optimizing for minimal magnet mass could produce a design that was able to meet the remaining specification. The translator mass constraint is a performance variable for the thermodynamic behavior of the free piston engine and not a fixed constraint. Increased translator mass adversely affects the engine frequency and hence output power and engine power density [4]. The system will likely still operate,

however.

TABLE III
FSM RESULTS

Tooth shape	Rectangular		Trapezoidal		
	E	F	G	H	
Objective	Electric loading	Magnet mass	Electric loading	Magnetic mass	unit
MMF	6506	4305	4868	3675	A
Magnet mass	8.6	3.1	10.5	2.5	kg
Translator mass	8.2	22.2	6.3	16.4	kg
Stator mass	92.1	91.2	111.7	103.1	kg
Copper Loss	359	238	269	203	W
Iron Loss	43	66	55	98	W
Efficiency	87.7	92.0	91.5	92.1	%
Power factor	0.2	0.3	0.2	0.4	

The FSM designs corresponding to the two optimization criteria are shown in table 3. Other design parameters are given in table 4. The minimum magnet mass design (f) resulted in a machine with a high MMF and low power factor (0.29). The efficiency of 92% was encouraging but the magnet mass of 3.1kg implied that the advantage of having the magnets on the stator was offset by the leakage in this machine. Further, the translator mass to achieve this was 22kg.

Performance is primarily being limited by the leakage flux, which is shown over an electric cycle in Fig 8 for topology f. The graphs show flux linking a single phase coil, plus leakage flux, calculated as linkage cutting dummy coils inserted on each leakage path. In the direct axis position, 0mm, 26% of the magnet driven flux is following the main flux path and 74% is split between the two leakage paths.

Fig 8 Leakage within the FSM

Optimization of the trapezoidal tooth version of the FSM, gives an improved design with 35% of magnet driven flux following the main path and 65% split between the two leakage paths. Changing the tooth to a trapezoidal profile therefore has a remarkable effect on leakage and performance, much more so than for the TFM. Even so, FSM designs using trapezoidal teeth were still unable to produce machines of sufficiently high force until the translator mass constraint was removed. Table 3 shows the trapezoidal tooth FSM results with no translator mass constraint for an objective function of minimum magnet mass (design h) and minimum electric loading (design g). Other mechanical parameters are given in Table 4.

The minimum magnet mass design (h) has 2.53kg of magnet – as compared to 2.24kg in the baseline TFM design

(c). Both the power factor and efficiency of this machine are well below that of the baseline design

V. RESULTS AND DISCUSSION

Fig. 9 Trapezoidal teeth results summary Designs c and d are transverse flux, e and f are flux switching, c and g are designs optimized for electric loading, d and h minimum magnet mass.

The summarized results of all machines with trapezoidal teeth are shown in Fig 9. Against the initial specification, where active length is equal to peak to peak oscillation amplitude, the FSM cannot save magnet mass compared to either of the TFM designs. The FSM with the lowest magnet mass performs poorly in all other metrics. The ‘best’ all round design (c) is that with the second lowest magnet mass and is the TFM optimized for low electric loading – as this allows for a high power factor and a good efficiency. In reality, if power factor is a concern then this low loaded TFM must be used – and this work shows using the objective function of minimizing electric loading is a good tool for lifting the power factor.

Design (c) was subjected to a mass reduction design stage, by reducing stator diameter and S_{cb} (Fig 4) to give a final design of translator mass 5.7kg and stator mass of 8.9kg. The combined machine mass of 14.6kg for a three phase machine compares favorably with that reported in the literature eg [12].

VI. CONCLUSION AND FUTURE WORK

Two types of modulated pole linear electrical machine have been compared: the transverse flux and flux switching machine. Each has been optimized using commercially available software against the specification for a free piston engine. The transverse flux machine is shown to be best optimized machine for minimum electric loading for all round good performance, whereas the flux switching machine must be optimized for minimum magnet mass to be competitive.

A trapezoidal tooth shape in the direction of motion was investigated and was found to have little effect on the transverse flux machine but significantly improve the performance of the flux switching machine.

The best all round machine in terms of magnet mass, power factor, and efficiency was found to be the transverse flux machine when optimized for minimum electric loading with trapezoidal tooth structure. An alternative TFM was proposed with half the magnet mass, but leakage was found to limit performance. Due to the prohibitively large translator mass of the flux switching machine, only the transverse flux machine was fully compliant with the translator mass restriction imposed by the free piston engine.

For the future work a transverse flux machine based on this work has been designed and a laboratory prototype is being assembled. For stator assemble simplification concern the designer decided to combined the three phase separated stator into a single component, whilst to shorten the end winding the designer decided to apply single tooth winding instead of torus winding as shown below in Fig 10. To consider the feature of fully 3D flux flows the designer further decided to form a assemble strategy as shown in Fig 11 below: the translator steel is composed of soft magnetic component powder (SMC) to sustain reciprocating flux; the tooth is made of laminated steel layers; two different teeth are connected through a laminated core back component which is laminated in a perpendicular plane; the whole components are assembled on the solid non-magnetic housing. By this mean the 3D flux flows path can be formed meanwhile the cost on SMC material can be minimized. Fig 12 shows a 3D printed stator component being used to assess alternative coil configurations.

Fig. 10 Stator components simplification process

Fig. 11 Machine assemble strategy

Fig. 12 Plastic mock-up of combined phase stator

VII. APPENDIX

TABLE IV
DETAILED PARAMETERS FOR ALL TOPOLOGIES

	S_cb mm	S_sh mm	S_sa °	S_r	T_h mm
a	23.5	16.5	18.4	0.61	8.3
b	24.5	29.5	25.3	0.7	8.9
c	28.4	16.5	13.8	0.57	8.9
d	26.5	28.5	26.5	0.55	8.8
	T_r	E_l A	M_m Kg	T_m Kg	Fe N
a	0.56	2135	(2.28)	5.29	1500
b	0.78	(5894)	1.23	5.76	1500
c	0.6	1850	(2.24)	5.72	1500
d	0.78	(5894)	1.21	5.68	1500
	M_d mm	M_uc mm	M_dc mm	S_sh mm	S_sa °
e	16.4	34	37	49	11.5
f	6.1	45	33	18	13.0
g	21	48	32	35	13.8
h	5.1	44	40	22	11.5
	S_ta °	S_r	T_h mm	T_r	T_ir mm
e	21.2	0.83	29	0.71	(40)
f	17.0	0.62	48	0.65	73
g	22.8	0.85	24	0.69	(40)
h	18.63	0.88	41	0.63	63
	E_l A	M_m Kg	T_m Kg	Fe N	
e	6506	8.56	8.22	1290	
f	4305	3.1	22.17	1500	
g	4868	10.47	6.3	1500	
h	3675	2.53	16.37	1500	

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