A novel concept of a Transverse Flux Linear Free-Piston Generator

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Abstract This paper investigates the electrical machine, which is one of the important parts in the Free Piston Energy Converter (FPEC). In the previous work it was found that one of the best candidate suitable for the FPEC is a Transverse Flux Machine (TFM) due to the very tough requirements on the electrical machine such as a low weight of the translator (movable part in the machine).This paper presents a new concept of a linear TFM in which strong emphasis has been put to achieve a design that is simple to manufacture. Different types of the magnet configurations on the translator have been investigated. It has been found that the buried magnet design suffers from a very high leakage to the nearby poles and is thus not suitable for this type of machine. Another configuration, which has been investigated, is the surface mounted magnet configuration. Analytical models for this configuration have been established. It has been found that the tough requirements, 4kN from a 6kg movable mass, can be achieved at the required speed, specific power and efficiency.

Keywords: FPEC, TFM

1. Introduction

Recent increase in oil price have put the environmental friendly cars in a big focus. Many car manufacturers have in their development program some alternative solutions to the conventional car. As the price of oil, will probably continue to increase, these types of cars will be even more interesting in the future.

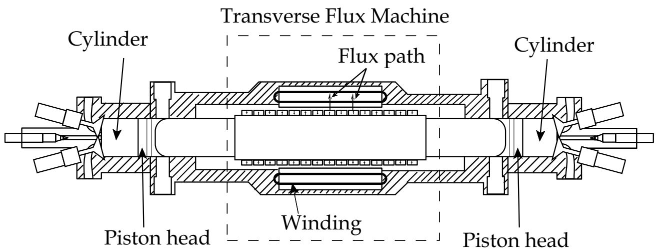

Fig. 1. Schematic view of the FPEC.

The Free Piston Energy Converter (FPEC) is formed by the integration of a linear (free-piston) combustion engine with a linear electrical machine. The piston is no longer guided by the crankshaft, as in the conventional Internal Combustion Engine (ICE), which introduce another degree of freedom in the control of the combustion volume. Therefore the FPEC is perfectly suitable for HCCI (Homogenous Charge Compression Ignition).

One possible solution is shown in figure 1. Because of its nature the FPEC is well suited for the Series Hybrid Electric Vehicles. It allows a reduction of fuel consumption and may thereby decreases environmental pollution. This technology may be seen as the first step toward a more sustainable development of environmental friendly vehicles. The FPEC is also suitable multi fuel application which makes it even more interesting for the future.

2. Electrical machine

In previous work [1] different types of electrical machines for the FPEC application have been investigated. It was found that the appropriate machine for this application that could meet the requirement was the PM machine. Furthermore, due to the tough requirements on the specific weight and the force density, the Transversal Flux Machine (TFM) was the most promising one. The type of machine suggested in [1] was a novel TFM design with flux concentration and low flux leakage. Unfortunately, the prototype built showed weakness in mechanical stiffness and robustness.

Due to the high forces during the combustion process, the stress on the movable part (translator) is high. In order to limit the impact of the high forces during a combustion cycle a tubular cross section of the translator was suggested. In this way the forces that act on the translator will be more equally distributed along the surface and will have a minimum mechanical impact on the translator.

Although the previous machine investigated had a good electrical performance, the idea of the flux concentration design applied to the tubular construction did not give the desirable performance. Thus a new type of electrical machine is proposed, and it will be presented in more detail in this paper.

The concept of the new TFM has taken into consideration not only the electromagnetical performance but also the manufacturing process of the machine. By simply taking the lamination of a conventional asynchronous or synchronous machine and concentric windings the stator is not more complicated to manufacture than in conventional synchronous/asynchronous machines. Usually, for large synchronous machines, in order to achieve better cooling, pressure fingers are put between stack of stator laminations. This feature is also shared by the new TFM design, not only because of the better cooling achievement but also because it is inherent of the working principle of the TFM. By shifting the magnets on the translator, phase shift can be achieved for the different phases.

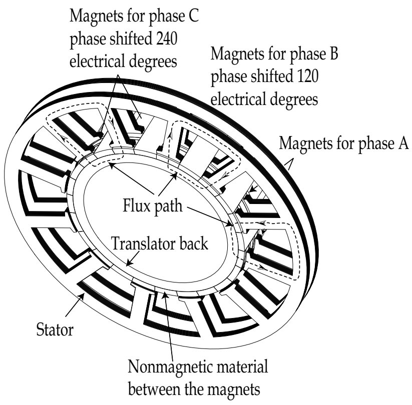

Fig. 2. Layout of the new TFM design

3. Winding and magnet arrangement

The design of the new TFM machine can be achieved in several different ways. From the stator point of view the winding can be arranged by winding around a stack of teeth (local winding) or, it can be wound as in conventional machines where the winding is wound around the complete length of the machine (global winding). Figure 3 shows one possible arrangement of the local winding together with the Hallbach arrangement of the translator magnets.

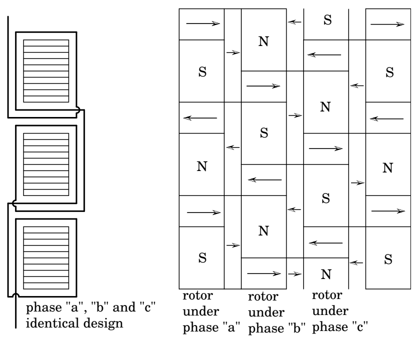

Fig. 3. Local winding design with mixed phases and hallbach magnet orientation

The local winding arrangement has some drawbacks compared with the global winding. The total voltage induced in the winding will be same for both winding arrangements. This is because the parts that are contributing to the voltage are only those in the axial direction, the rest of the winding will not contribute to the voltage. However the losses will be higher because the length of the winding in the local winding arrangement will increase and thereby the resistance of the winding. Furthermore the local winding arrangement will, from the construction point of view, be more difficult to achieve. Thus only the global winding will be discussed in this paper.

Three different magnet arrangement are thought to be suitable in the design of the translator.

- Buried magnet design
- Surface magnet design
- Hallbach magnet design

The first two will be discussed and analyzed in this paper, the hallbach magnet design has still to be investigated.

3.1 Buried magnet design. The buried magnet design did not turn out to be an appropriate alternative for this type of machine. This is because the alternative poles on the translator will short circuit each other and thus negligible flux will enter the stator.

An interesting feature of TFM machines is that the power rating of the machine can be increased by simply increasing the number of poles. However, if the length of the machine is kept constant, increasing the pole number will mean decreasing the pole length.

In this case, the length of the machine is kept constant and the pole length of the machine has been adopted to achieve a certain power. Mechanical constraints have been taken into consideration as well.

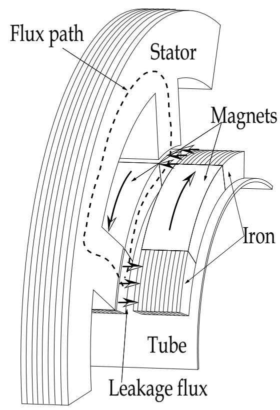

Fig. 4. Axial leakage flux for the buried magnet design.

As can be seen from figure 4 the space between the two neighboring poles is of high importance. Assuming the iron is ideal the ratio between the air gap reluctance and the reluctance of the space between the poles will determine how much flux will enter the stator. By increasing the space between the poles one can improve this ratio. However, the active area of the magnet is then decreased, because of the constant pole length, which also means a loss in the thrust force.

Therefore the buried magnet design is omitted and the further analysis is based on the surface magnet design.

4. Machine performance

Two different configurations of the novel TFM design have been investigated. In figure 5 cross sections of the

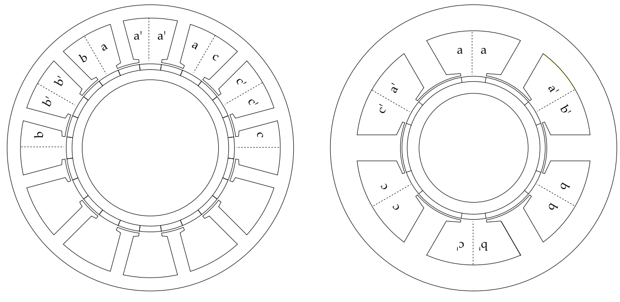

Fig. 5. Axial cross section of new TFM machine with a) $Q_s = 12$ and b) $Q_s = 6$

two layouts are shown.

According to equation (8) the translator tube thickness is inversely proportional to the number of slots. As the weight of the translator is a critical requirement, the higher number of slots is desirable. However, a higher number of slots results in more magnet parts, which implies more difficulties in the manufacturing process.

The force for a linear TFM according to [1] is given by

$$F = \hat{B}_{\delta 1} \cdot \hat{S} \cdot k_w \cdot \frac{A_{active}}{2} \tag{1}$$

where k_w is the winding factor, $\hat{B}_{\delta 1}$ is the peak fundamental value of the flux density in the air gap, A_{active} is the active area in the air gap and the $\hat{S}$ is the current loading for the machine. In a TFM machine the current loading is given by equation [1]

$$\hat{S} = \frac{\sqrt{2} \cdot N_s \cdot I}{2 \cdot \tau_p} \tag{2}$$

and the fundamental value of the flux density is given by [1]

$$\hat{B}_{\delta 1} = \frac{4}{\pi} B_m \cdot \sin(\alpha) \tag{3}$$

Neglecting flux fringing the flux density in the air gap, produced by the magnets, can be calculated as follows.

$$B_m = B_{r,m} \cdot \left(\frac{1}{1 + \mu_r \cdot \frac{\delta_e}{l_m}} \right) \tag{4}$$

where $B_{r,m}$ is the remanent flux density of the magnets and is chosen to be 1.1T at 100 °C, δ_e is the equivalent length of the air gap and l_m is the thickness of the magnet. The relative permeability of the magnets is 1.05 and the equivalent length of the air gap is calculated by multiplying the real air gap length by a factor of 1.5 to account for iron saturation.

The voltage on the DC of the inverter is chosen to be $U_{DC} = 350$V and the maximum phase voltage possible can be calculated as [2]

$$U_{phase} = \frac{\sqrt{2}}{\pi} \cdot U_{DC} \tag{5}$$

The no load induced EMF is given by the following equation

$$E_{phase} = \omega \cdot N_s \cdot \Phi_{stack} \tag{6}$$

where Φ_{stack} is the total flux and is given by

$$\Phi_{stack} = \frac{1}{\sqrt{2}} \cdot \frac{2}{\pi} \cdot \hat{B}_{\delta 1} \cdot \tau_s \cdot \omega_m \cdot N_{stack} \cdot \frac{Q_s}{3} \tag{7}$$

The thickness of the translator back is calculated as follows

$$h_{rr} = \frac{\hat{B}_{\delta 1} \cdot 4 \cdot R_{touter}}{B_{rr} \cdot Q_s} \tag{8}$$

where B_{rr} is the flux density in the translator back and is assumed to be 1.8T.

The total inductance in the machine is the sum of the main inductance and the leakage inductance. Furthermore the leakage inductance can be divide into four different inductances.

The main inductance is calculated according to:

$$L_m = \frac{2}{\pi} \cdot \tau_s \cdot \omega_m \cdot N_{stack} \cdot \frac{Q_s}{3} \cdot N_s^2 \cdot \frac{4\pi}{\left(\delta_e + \frac{l_m}{\mu_m}\right)} \tag{9}$$

The slot leakage inductance is calculated by the following equation

$$L_{slot} = 2 \cdot \mu_0 \cdot \lambda \cdot \omega_m \cdot N_{stack} \cdot \frac{Q_s}{3} \cdot N_s^2 \tag{10}$$

where λ is the specific permeance coefficient of the slot opening and can be calculated for the chosen slot shape according to [3] as follows

$$\lambda = \frac{h_1}{3b_{ss}} + \frac{h_{ti}}{b_{ss}} + \frac{h_{tt}}{b_{so}} + \frac{h_{ts}}{b_{ss} - b_{so}} \cdot \ln\left(\frac{b_{ss}}{b_{so}}\right) \tag{11}$$

where h_1 is the distance for the winding in the slot and can be calculated as follows

$$h_1 = h_{ss} - h_{tt} - h_{ts} - h_{ti} \tag{12}$$

The end leakage inductance is given by

$$L_{end} = \lambda_{end} \cdot l_{end} \cdot 2 \cdot \frac{Q_s}{3} \cdot 4\pi \cdot N_s^2 \tag{13}$$

where l_{end} is the length of the end winding and λ_{end} specific permeance coefficient [3] and can be calculated as follows

$$\lambda_{end} = \frac{k_a}{0.3 + \tau} \tag{14}$$

where τ is the pole pitch and k_a is an empirical value in the range 0.15-0.20 [3]

The air gap leakage inductance and the leakage inductance between the stacks may be calculated as follows

$$L_l = \sigma_l \cdot L_m \tag{15}$$

where the coefficient σ_l can be derived for the air gap leakage and for leakage between the stacks respectively

$$\sigma_{lgap} = \frac{3}{4} \cdot \frac{\frac{l_m}{\mu_{rm}} + \delta_e}{\left(\frac{1}{2} \cdot l_\delta + \frac{3}{8} \cdot \tau_s\right) \cdot 0.9} \tag{16}$$

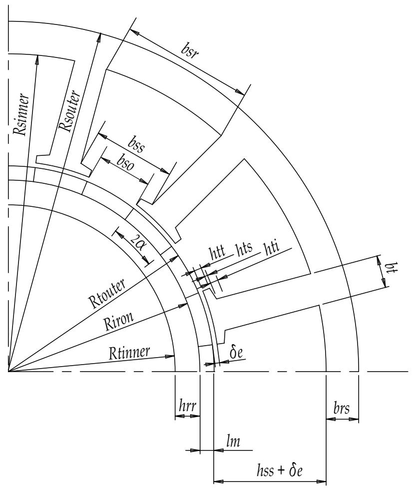

Fig. 6. Machine parameters

$$\sigma_{lstack} = \frac{3}{2} \cdot \frac{\frac{l_m}{\mu_{rm}} + \delta_e}{h_1 + \frac{1}{4} \cdot (b_{sr} + b_{ss})} \quad (17)$$

The copper and the iron losses are calculated respectively [3] as

$$P_{cu} = 3 \cdot R \cdot I_a^2 \quad (18)$$

$$P_{fe} = 0.078 \cdot W_f \cdot f \cdot (100 + f) \cdot \hat{B}_{fe}^2 \cdot G_{fes} \cdot 10^{-3} \quad (19)$$

where f is the frequency, $\hat{B}_{fe}$ is the peak flux density in the iron and the G_{fes} is the weight of iron. W_f is the loss factor, which depends on the thickness of the iron lamination and is 2.7 for 0.35 mm thick iron sheet.

5. Power factor

The output power from an electrical machine is given by

$$P = 3 \cdot U_a \cdot I_a \cdot \cos\phi \quad (20)$$

The TFM machines are known for their high force/torque density but the price for that must be payed by a low power factor [4] i.e. the last factor in the equation (20) is low.

The problem with the low power factor is discussed in [4]. The representation of the TFM with the phasor diagram is essentially identical to that of a conventional synchronous machine. If the voltage drop across the winding resistance is neglected, a simple phasor diagram is obtained. Basically the power factor can be improved during the design procedure [1] or by controlling the current so that it comes closer in phase with the terminal voltage i.e. by introducing the d-current component in the current vector.

If the later method is used, an analysis, of possible improvements of $\cos\phi$, can be made by looking at the ratio between the voltage drop across reactance and induced EMF IX/EMF. It was shown that if the ratio is high e.g. 2 or higher introducing the d current does not improve the power factor. However if the ratio is close to unity or lower then the power factor can be increased.

In the machine presented here, from the analytical calculation, the ratio between the induced EMF and the voltage drop across reactance was find to be close to unity. For a surface mounted magnets the d-axis reactance and the q-axis reactance are equal. According to discussion above the power factor can therefore be improved by placing the current between the induced voltage and the terminal voltage according to figure 7 below.

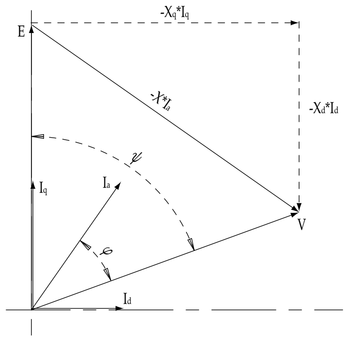

Fig. 7. Phasor diagram

Table 1. Analytical results

Parameter	Value
Translator weight	5.8kg
Power factor	0.79
Force developed	4.1kN
Efficiency	94%
Pole number	19
Magnet height	3.8mm
Translator back	6.8mm

6. Conclusions

In this paper a new linear TFM machine has been presented. An analytical model for a surface magnet design has been developed. By using the equations developed the calculated force was found to be 4.1kN and movable mass of the translator 5.8kg.

The 2D model has been used to develop analytical expressions and some empirical factors have been used in order to predict leakage in the 3rd dimension. Analysis of the hallbach oriented magnets is still to be performed together with a verification of the analytical model with a 3D FEM simulation.

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