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Electrical Machine Design for use in an External Combustion Free Piston Engine

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Abstract

The work is focused on investigating the performance of a linear alternator for use with external combustion – free piston engine. This family of engine can be powered either from renewable sources, scavenging waste energy from other sources of heat, or bespoke combined heat and power plants. Finite element analysis optimisation techniques followed by development of a Matlab/Simulink model were used to investigate the effects of electrical machine inductance and the combined electromagnetic loading of the machine on the resulting force. Cogging force is showed to have the most effect on the resultant force fluctuation, whereas machine inductance has showed its effect at loads exceeding (76 %) of machine rating besides reshaping the resulting force profile. The model also accounts for machine loading and total efficiency variation over mechanical cycle. This enables the system designer to investigate the effect of actual machine model thrust force on the engine performance rather than assuming the electrical machine behaves as a simple damper.

1 Introduction

Free Piston Engine (FPE) was invented some 200 years ago but control technology at that time prevented it from prevalence. FPE has no crank-shaft mechanism which dramatically reduces friction loss and increase thermal efficiency of the engine. The flexible compression ratio brought along with no crank-shaft mechanism allows high efficient operation of engine even for partial loads. Since 1990s, the researches on FPE have been revived due to the advancement on control and electrical engineering technologies. FPE could use all sort of different renewable fuels, which makes it an attractive alternative to reduce emissions from engines. With the use of Linear Alternator (LA) as a direct drive, the system could be applied as range extender on Electric Vehicles (EVs), scaled up to work as main engines on board ships, or used as portable battery chargers. The potential of seamless integration of FPE and LA will lead to a compact engine-generator with versatile capability.

At late 90's, the “more electric engine” concept based free piston engine was described, aimed at increasing engine

efficiency and reducing exhaust emissions [1]. Since that time, more intense investigations have been carried out to describe the dynamic performance and the force profile of possible linear loads including linear machines as load devices to free piston engines [1, 2].

Few significant works found in the literature have been identified in predicting the performance of the combined system. Li et.al [3] have investigated the performance of a two stroke FPE for electrical power generation. FEA, Matlab/Simulink and Chemkin simulation tools have been used to model the LA dynamically, piston dynamic and cylinder kinetic process respectively. FPE dynamic performance description was aimed in this work.

Hung and Lim [4] have presented a work on a similar system to the previous system, except that they integrate the three models using Fortran programming language to solve the system dynamics numerically. Effects of reciprocating mass, spark timing and spring stiffness have also been investigated and optimised for high engine performance.

Feng et.al [5] have reported a detailed simulation model of a single cylinder loaded by a linear alternator and a linear motor acting as the rebounding device. Extensive efforts have been presented in this work accounting for piston frictional loss, rebounding force profile parameters and control for increasing cylinder power output.

In all these works, thrust force of the linear alternator has been simulated as a damping force to the driving force. In other words, the LA reacting force was always assumed to vary linearly with system velocity. This is by assuming that the effect of machine inductance is treated by using series compensation. The assumption is applicable in reality for constant speed operating machines. However, with the variable velocity operation of the system and consequent variation in EMFs induced amplitudes and electrical frequency, applicability of series compensation diminish due to practical complexity. In addition to the machine inductance, investigation on combined effects of the electromagnetic forces of the machine at no and load conditions have not been yet introduced. Furthermore, influence of machine core and copper losses have not been considered in different works. All these influences and reacting forces need to be added to any LA model in order to account for their effects on the integrated system efficiency.

Figure (1): Schematic diagram of EC-FPE [7]

In this paper, a complete model of a three phase LA machine is presented. The machine is for use with an External Combustion (EC)-FPE [7] shown in fig.1. The machine is axially magnetised with tubular geometry and designed using FEA for a specific design force and velocity of the engine [6]. Machine cogging and reluctance forces are modelled using empirical equation and based on slot/pole number combination [8]. Total machine input, output and loss powers, and the corresponding forces are also included in that model from which total efficiency can be estimated. As a contribution to the exiting work, combined effects of electromagnetic forces and losses have never been considered before in the found literature. Moreover, the effects of machine inductance and electrical loading on its reacting force have not been highlighted earlier which is one of the merits in the operation of the integrated system.

2 System description

In a conventional Internal Combustion Engine (ICE), heat energy is injected into the combustion chamber by igniting the working fluid, which is a mixture of fuel and air, and must be replaced during each cycle for continuous expelling combustion products from the cylinder. In an EC – FPE shown in fig.1, however, the working fluid is re-circulated in a closed system. Heat is added and removed to the fluid using heat exchangers. The working fluid does not contain fuel and can now be any inert gas and the source of heat is independent of the working fluid. Any source of heat, such as solar energy or waste heat from another process can be used.

In the linear version of an EC engine just like an ICE, the LA is coupled directly to the moving piston, giving the machine designer freedom to look at engine configurations which can fit into limited space envelopes. With the fact that the engine has no rotating components, inertia cannot be used to smooth out force ripple of either the electric machine or the thermodynamic process. The two processes are therefore interdependent and both must be considered during the design phase.

2.1 Force equation

The force balance equation of the system shown in fig.1 is given as:

$$\sum F - a \cdot M_{mov} = 0$$

or,

$$\bar{F}_{exp} + \bar{F}_{LA} + \bar{F}_{com} = a \cdot M_{mov} \quad (1)$$

The R.H.T term ($a \cdot M_{mov}$) represents the acceleration multiplied by total translator moving mass obeying Newton's

second law of motion. The L.H.T. consists of three parts. The first part ($\bar{F}_{exp}$) is the driving force (s) which is generated in the expanding cylinder of double – acting pistons operation [7] shown on the left of the system in fig.1. Similar structure is found on the right side of the system, where this cylinder represents a compressor producing the reacting force ($\bar{F}_{com}$). The third term is the LA reacting force ($\bar{F}_{LA}$), which is shown in the middle of the system. It worth mentioning that system frictional loss, in general, vary linearly with system speed. Friction loss is composed of system linear bearings loss and piston – cylinder loss, and due to the direct coupling of LA translator with pistons via the connecting rod, this loss has low values and in steady – state analysis it can be assumed constant [1, 5].

3 Linear Alternator reacting force components

The linear machine has the geometry and construction as shown in fig.2. As mentioned before, machine parameters have been optimised using FEA modelling in order to minimise the PM cost with maximum utilisation for a specific design force and velocity, [6]. The LA reacting force can be subdivided as follows:

$$\bar{F}_{LA} = \bar{F}_{cog} + \bar{F}_{AR} + \bar{F}_{cu\ loss} + \bar{F}_{iron\ loss} + \bar{F}_{PMec} + \bar{F}_{ele} \quad (2)$$

The term ($\bar{F}_{cog}$) is the inherent cogging force in PM machines due to the variation in reluctance seen by magnets due to stator teeth. It is periodic with periodicity (R_c) depending on the number of stator slots and translator poles, [8, 9].

Figure (2): 3D view schematic diagram of LA [6]

The variation of cogging force over one translator pole as a function of mover position (x) is given as:

$$\bar{F}_{cog}(x) = \hat{F}_{cm} \cdot \sin\left(\frac{\pi}{\tau_{pp}} R_c \cdot x \pm \vartheta_c\right) \quad (3)$$

$$\text{with} \quad R_c = \frac{LCM(S, T_p)}{T_p} = S \quad (4)$$

Where ($\hat{F}_{cm}$) is the peak of cogging force and the symbols (S , T_p , τ_{pp}) are the number of slots, number of translator poles and translator pole pitch, respectively. The ($\pm$) sign in phase shift (ϑ_c) holds for oscillating motion of the translator, and

the phase shift represents the shift from position corresponds to peak cogging force of total moving translator with respect to the stationary stator, where: $0 \leq \vartheta_c \leq 180$. (LCM) stands for Least Common Multiple between stator slot number and translator pole number.

The term ($\bar{F}_{AR}$) represents the armature reaction force of amplitude ($\hat{F}_r$) and is due to machine current loading. It varies with current loading and mover position with repetition cycles equal to the number of machine phases (m) over translator pole. In general, the armature reaction force is in phase with the travelling stator MMF, and is given as:

$$\bar{F}_{AR}(x) = \hat{F}_r \cdot \sin\left(\frac{m \cdot \pi \cdot x}{\tau_{pp}}\right) \quad (5)$$

Fig.3 shows the variation of typical linear alternator cogging and armature reaction forces over one electrical cycle.

Figure (3): Variation of cogging and armature reaction forces over electrical cycle (FEA)

With useful air-gap flux of peak ($\hat{\Phi}$) varies sinusoidally with pole position [10] at a speed (u , m/s), and for coil of (N) turns per phase, instantaneous induced EMF ($\bar{E}_a$) can be expressed as follows:

$$\bar{E}_a = -N \cdot \omega \cdot \hat{\Phi} \cdot \cos(\omega x) \cdot u \quad (6)$$

Where: $\omega = 2\pi f_e$; and f_e is the electrical frequency.

Using the per phase equivalent circuit diagram shown in fig.4, assuming balanced variable resistive load, the alternator phase currents can be obtained from:

$$\bar{E}_a = I_a(R_L + R_a) + L \frac{dI_a}{dt} \quad (7)$$

Figure (4): Per phase equivalent circuit of a linear alternator

Hence, alternator copper loss can be determined by knowing phase currents and phase resistances (R_a, R_b and R_c), and the total instantaneous force representing copper loss may be expressed as:

$$\bar{F}_{cu\ loss} = (I_a^2 \cdot R_a + I_b^2 \cdot R_b + I_c^2 \cdot R_c)/u \quad (8)$$

Machine iron loss varies with the electrical frequency and therefore velocity. Its components are the hysteresis (P_h) and eddy currents (P_e) losses of the LA core material. Hence, the subsequent force may be expressed as:

$$\bar{F}_{iron\ loss} = (P_h + P_e)/u \quad (9)$$

Eddy currents loss in the magnets has been segregated from those in the core material and the corresponding force can be retrieved as:

$$\bar{F}_{PMec} = (P_{PMec})/u \quad (10)$$

Machine output power and the corresponding force ($\bar{F}_{ele}$) can be explained as given in (11) with the machine efficiency obtained using (12).

$$\bar{F}_{ele} = (I_a^2 \cdot R_L + I_b^2 \cdot R_L + I_c^2 \cdot R_L)/u \quad (11)$$

$$\% \eta = \frac{\text{output}}{\text{input}} = \frac{F_{ele}}{F_{PPE}} \times 100\% \quad (12)$$

3.1 FEA and SIMULINK machine models

Useful design constraints and optimal machine parameters are listed in Table 1. The table also includes data obtained from analysing the optimal machine model using FEA model with maximum engine speed. These data include per phase equivalent circuit parameters, peaks of cogging and armature reaction forces ($\hat{F}_{cm}$ and $\hat{F}_r$), iron loss components and PM eddy current loss data.

Parameter, symbol(unit)	Value
Stroke amplitude, (mm)	120
Rated power output, kW	≤ 3.35
Phases, m	3
Slots, S	6
Turns per phase, N	40
Poles, T_p	7
Translator pole pitch, τ_{pp} (mm)	17.1428
Per phase resistance, R_{ph} (Ω)	0.0461
Per phase inductance, mH	2.834
Resistive loading, R_L (Ω)	$2 \leq R_L \leq 12$
Peak air-gap flux, $\hat{\Phi}$ (mWb)	≈ 3.1
Peak cogging force, $\hat{F}_{cm}$ (N) With no end effects	≈ 15
Peak cogging force, $\hat{F}_{cm}$ (N) With end effects	≈ 100
Peak armature reaction force, $\hat{F}_r$ (N)	≈ 5
Iron loss, P_h, P_e (W)	20, 5
PM eddy current loss, P_{PMec} (W)	37.5

Table 1: Optimised LA useful parameter and dimensions

4 Simulation results

The LA SIMULINK model shown in fig.5 is investigated against the engine's velocity profile shown in fig.6 in open loop feedforward manner. The variation of alternator phase EMFs, currents and power dumped by load resistance, at peak load condition, are shown in fig.7. Phase EMFs and currents show amplitudes imbalance over the entire mechanical cycle with variable (f_e) operation. The output power shows smooth profile, similar to the velocity profile, variation over the mechanical cycle which is, when reflected to engine, will be smooth reacting force and varies as velocity profile.

Figure (5): Three phase LA Simulink model based velocity profile of EC-FPE

Figure (6): Velocity profile variation over one mechanical cycle of EC- FPE

On the other hand, when comparing the LA force from a damper, normally used to represent the LA force [3-5], with the force results of both FEA and Simulink models a difference in resulting force sketches appears clearly as shown in fig.8. First of all, the force fluctuation, identified with both simulation tools, is obvious and its origins are from the combined effect of cogging and armature reaction forces superimposed on the load power force profile.

Secondly, the effect of machine inductance is notable in adding forces reflecting the stored energy in phase inductance. This is due to the variable speed operation of the system, including the LA, which pushes the energy stored in the inductance to continuously being stored and released over

the mechanical cycle. The resultant total LA force is close to flatten shape, with fluctuation, and this will have an impact on the thermodynamic performance of the engine.

Figure (7): Variation over one mechanical cycle of (a) LA induced EMFs, (b) Phase currents and (c) load power

Figure (8): LA electromagnetic force ($\bar{F}_{LA}$) variation with EC-FPE velocity profile

However, fig.9 shows that LA force profile follows the velocity profile at loads lower than the peak load. This linear variation changes as the load exceeds ($\approx 76\%$) of the machine rating and results in the close to flatten shape force profile.

Above that point of loading, the effective load resistance starts to take part in increasing the time constant of the series phase circuit. This time constant increase will cause a fast decay of inductance voltage across phase resistors accompanied by a rise in rate of change of phase current with time (dI_{ph}/dt). As a consequence to the rise in change of phase current with time, higher energy will be stored in phase inductance which will be supplied by the engine to the machine as an extra force, as clarified by arrows in fig.8. Such force profile shape will have an effect on engine behaviour when compared with a damping force. The result

will be unpredictable on the interconnected processes. The most important parameter for consistency between the electric machine and engine models is the engine compression ratio, as any change in this parameter would affect the stroke amplitude and the total system dynamic stability.

Figure (9): Variation of LA electromagnetic force ($\bar{F}_{LA}$) with load over one mechanical cycle

The effect of current loading on LA resultant electromagnetic force and copper loss, both averaged over one electrical cycle, is shown in fig.10. It is obvious that the force capability increases with current loading until reaching peak level the machine designed for. Any further current increase would result in increasing the copper losses of the machine, PM demagnetisation and consequently reduction of the resulting force. This relationship has been described by other research groups [4] to be linear, and the fact is linearity starts to decline at current loading of almost (60%) of rated current till reaching peak loading and then further slow declination that starts due to increased machine losses and magnetic circuit limitations.

Figure (10): Variation of LA electromagnetic force and copper loss with current loading

Fig.11 shows the variation of per unit instantaneous LA dynamic efficiency over mechanical cycle. One important conclusion from efficiency graphs need to be discussed here. It can be noticed that the efficiency has high values over wide span of entire mechanical cycle. For instance, an average

efficiency rounding about (0.86 pu) can be noticed from (76% current loading) efficiency graph. This indicated that the LA works at high efficiency values from mechanical view of point. On the other hand and from the machine design (electrical) view of point, the machine is working at an electrical efficiency according to its current loading, i.e. in this case it works with electrical efficiency of only (0.76 pu). This point will be left here and reviewed at the end of an ongoing study on this system.

Figure (11): Variation of LA efficiency over entire mechanical cycle at different current loadings

Another important point to discuss here is the use of different current loadings to show the influence of cogging and armature reaction forces on efficiency fluctuation. A large effect on efficiency sketches can be noticed at low current loadings with instants showing efficiency values higher than unity.

Figure (12): Effect of cogging force amplitude on LA efficiency over entire mechanical cycle at low current loadings

This indicates that the combined effect of these forces have minute contribution in helping the engine to drive the LA translator which in practice would be some newtons. This contribution increases as the amplitude of cogging force increase due to LA end effects and size of the machine. The influence of cogging force amplitude, without and with end effects, on machine efficiency at low current loading is emphasised as illustrated in fig.12. In both cases force fluctuation will have, as mentioned earlier, an unpredictable impact on engine compression ratio and consequent variation in stroke amplitude and the interconnected dynamic system.

At the last, but not least, cogging force amplitude effect on average LA efficiency on entire mechanical cycle against current loading up to rated is demonstrated in fig.13. LA efficiency increases with increasing current loading when machine end effects are not taken into consideration, while efficiency experience decrease with current loading increase with account for machine end effects. Also, higher efficiency value at peak electrical loading can be noticed with the fact that the resulting electromagnetic force of the LA suffer from large amplitude fluctuations.

Figure (10): Variation of LA electromagnetic force and copper loss with current loading

5 Conclusions

This work has presented a simple model of a linear alternator for use with an external combustion free piston engine. It is shown that the assumptions of the electric machine acting like a pure damper is an oversimplification. The model account for electrical machine electromagnetic forces, which showed critical impacts on shaping LA force profile. With regard to machine efficiency prediction, future simulation of this type of engines should include a full model accounting for the electromagnetic forces in the alternator, engine driving force (expanding force) and reacting force (compression force) all arranged to work in a closed loop form. A simple model has been presented in this which describes the forces for a linear machine designed specifically for this application.

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