Design, Development and Finite Element Magnetic Analysis of an Axial Flux PMLOM

Govindaraj Thangavel*, Debashis Chatterjee**, Ashoke K. Ganguli **

* Department of Electrical & Electronics Engineering, Muthayammal Engineering College,
Anna University, Chennai, India

** Department of Electrical Engineering, Jadavpur University, Kolkatta, India

Abstract— Several well-known analytical techniques exist for the force profile analysis of permanent-magnet linear oscillating motors (PMLOMs). These techniques, however, make significant simplifications in order to obtain the magnetic field distribution in the air gap. From the field distribution, the force profile can be found. These widely used techniques provide a reasonable approximation for force profile analysis, but fail to give really accurate results in the sense of the exact shape of the force profile caused by effects that due to simplification are not fully included. To obtain the exact shape for the force profile in these cases, the computationally expensive finite-element method (FEM) is often applied. In this from the resulting field distribution, the force profile is calculated by means of the Maxwell stress tensor. The objective of this paper is to determine the forces for aluminium mover embedded with Nd-Fe-B Rare Earth Permanent Magnet experimentally and analytically through FEMLAB6.2 WITH MATHWORKS software and develop a microcontroller based IGBT Inverter for its control. In this paper Development, Finite Element Analysis of Magnetic field distribution, performance , control and Testing of a New axial flux permanent magnet linear oscillating motor (PMLOM) along with a suitable speed and thrust control technique is described.

Keywords: Axial Flux Machine, Finite Element Analysis, Microcontroller based IGBT Inverter, Permanent Magnet Linear Oscillating Motor, Rare Earth Permanent Magnet

Nomenclature

PMLOM	Permanent Magnet Linear Oscillating Motors
FEM	Finite Element Method
IGBT	Insulated Gate Bipolar Transistor
SRM	Switched Reluctance Motor
A	Area of magnetic pole, m^2
Al	Aluminium Material
PM	N42 Permanent Magnet
AT	Total mmf of the exciting winding
AT_g	MMF required for the airgap
AT_i	MMF of iron parts
AT_A	MMF required for the attractive force
AT_R	MMF required for the repulsive force
aa' and bb'	Coil 1
cc' and dd'	Coil 2
F	Force between the Electromagnet and PM
B	Flux density
F_A	Attraction Force
F_R	Repulsion For
F_t	Total Force
dx	Distance the poles moved
H_c	Coercivity of the RE Permanent Magnet
L_m	Axial length of permanent magnet
l_g	Axial airgap length
P_m	Force per unit area
x	Displacement of the mover
L	Distance between stator 1 and Stator 2
H	Width of the Mover

1. INTRODUCTION

The PMLOM can perform precision oscillation task without exceeding the given limit on allowable average power dissipation. The use of new powerful permanent magnet materials such as Neodymium-Iron-Boron alloys can greatly improve the performance of electrical machines. Also its performance parameters, such as the force, current etc. are experimentally assessed. Interior permanent magnet motors are widely applied to the industry because of many advantages. Also the characteristics of magnetic materials are important to the performance and efficiency of electrical devices. Linear motors are finding increasing applications in different specific areas like high-speed transport, electric hammers, looms, reciprocating pumps, heart pumps etc.(G.Kang*, et a.l,*2001; N.Sadowski, et al,1996; B. Tomczuk, and M. Sobol.,2003; D. G. Taylor and N. Chayopitak. 2006; Kou Baoquan *et al.* 2009). They are also well suited for manufacturing automation applications. Therefore, design of energy efficient and high force to weight ratio motors and its performance assessment has become a research topic for quite a few years. The PMLOMs are one of the derivatives of the linear motors in the low power applications having the advantages of higher efficiency and high force to weight ratio. They can be supplied with dc or ac voltages. (G.Kang*, et a.l,*2001; N.Sadowski, et al,1996; B. Tomczuk, and M. Sobol.,2003; Kou Baoquan *et al.* 2009; D. G. Holmes,*et al*,2009)of which, the dc motors are having better efficiency due to the absence of core losses. The motor designed in this paper finds the suitability of application in the loads having low frequency and short stroke length. One such application is the heart pump, where frequency of oscillation is to be adjusted between 0.5 to 1.5 Hz, with the requirement of variable thrust depending on the condition of the heart under treatment. For analysis of such motors the main task is to determine the essential equivalent circuit parameters, which are its resistances and inductances. The resistances, for the machine, though vary with operating conditions due to temperature, do not affect much on its performance assessment. However, the inductances for these machines are mover position dependent and mostly affect the machine performance. Therefore, determination of these parameters is essentially required for analyzing the machine model. There are several works e.g. (S.Vaez-Zadeh, and A. Isfahani. 2006;B. Tomczuk and M. Sobol.2003) which assumes the machine inductance to be constant for simplicity of the model although different other works e.g. (G.Kang*, et a.l,*2001; N.Sadowski, et al,1996; D. G. Taylor and N. Chayopitak. 2006; Iakovos St. Manolas,et al, 2009) dynamically estimate the inductance through FEM and field analysis for getting correct results. In (Kou Baoquan *et al.* 2009) a low power tubular linear motor is developed for space usage where an equivalent circuit model is developed for the machine to analyze its characteristics. In (Ge Baoming, et al, 2009) the development of Linear is realized with higher primary poles which can result in complex switching topology for speed control . Also in (Iakovos St. Manolas,et al, 2009,) FEM based analysis and estimation of parameters are shown for a SRM. Design, Development, control and FEM analysis of PMLOM is discussed in (Govindaraj T, et al, 2009a, b, c, d, e, and f). In this paper, a novel axial flux linear machine of different configuration is designed and developed with Ne-Fe-B N42 permanent magnet in the mover so that the force to weight ratio is improved.

In this paper, the machine under consideration is an axial flux machine and the mover is having a non-magnetic structure, which is aluminium. Also the rare earth permanent magnets used in the mover are having a relative permeability nearly equal to unity and therefore the magnetic circuit under consideration will be unsaturated due to major presence of air in the flux path. Hence, consideration of constant inductance is quite errorless for such kind of machines, which also conforms to the experimental data shown later. Finally the machine is analyzed with the help of the field equations and solved for forces and resultant flux densities through FEMLAB6.2 WITH MATHWORKS backed by suitable experimental results. A controller using PIC16F877A microcontroller has been developed for its speed and thrust control for successful implementation in the proposed application.

2. MACHINE CONSTRUCTION

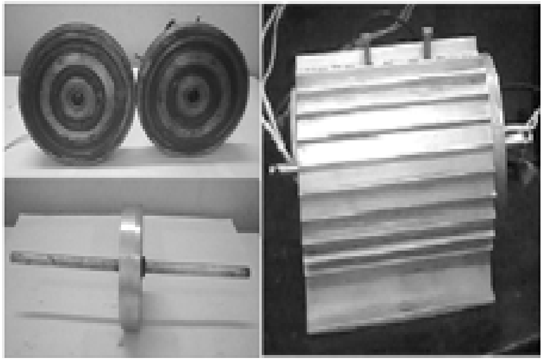

Fig.1. Construction details of the developed PMLOM (i) Stators to be mounted on both sides of the mover and (ii) the mover (iii) the PMLOM machine.

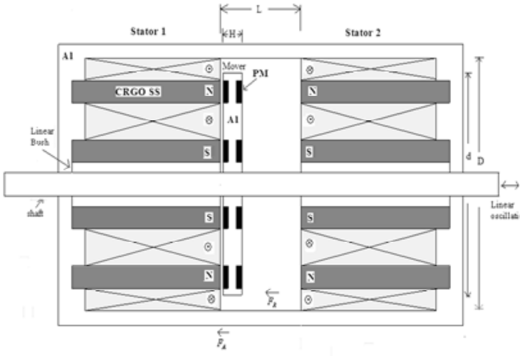

Fig.2. Dimensional details of the developed PMLOM

The construction of the prototype PMLOM is shown in Fig.1.Also the dimensional details of the motor are shown in Fig.2.There are two concentric coils on the surface of the stators connected in such polarities that the fluxes for both the coils aid each other to form the poles in the iron parts. The formation of the N and the S poles of the electromagnet of the stator are shown in the Fig.2.

2. DESIGN OF PMLOM

PMLOM is the equivalent of an unrolled rotational permanent-magnet motor. The field distribution is now not only confined to the interior of the machine, but extended to all the space surrounding the machine. The air-gap field distribution is of prime importance for determining the force on the machine. Consequently, extra components in the force profile of the PMLOM are introduced due to this nonperiodicity and nonconfined field distribution in comparison with a rotational motor that need to be taken into account. Depending on the prerequisites of the application for which a PMLOM is to be designed, it is important during the design to get a good prediction of the force profile of the PMLOM.Many techniques are available to determine the magnetic field distribution in the air gap of such devices. All are based on Maxwell's equations. The equations, however, cannot be solved analytically for most practical geometries. Assumptions and simplification are made to obtain an approximate solution of the field distribution in the air gap.

The design of electrical machines is both a science and an art. A science, because it follows established and universally accepted physical and Mathematical principles which have been verified by the experimental methods and an art in that the knowledge of these principles is often insufficient to produce a correct and economic design. This can be achieved by correct decisions based upon judgment and intuition and through understanding of the subject. The design of electrical machines at the first onset requires the choice of principal constructional scheme appropriate to the desired machine performance and types of construction of its basic machine parts. Calculations are made whereby the main dimensions of active parts of machine ,winding details and other parameters are determined. The overall design process, right from specification requirements to the determination of machine dimensions and other items of information required for the manufacture is considered as a single engineering problem. Other important design parameters are the pole number, magnet thickness, conductor size, number of turns and material types. On the other hand, every design has its particular constraints and they differ with the type of application. Generally, one tries to obtain the maximum force/torque for a given motor diameter at a given speed. Mostly for small machines, the number of poles is limited due to the reduced space available for the windings. Nevertheless, the most restricting limitation for the number of poles is the motor operating speed. If the speed is high, a large number of poles will bring about an increase in the frequency, which directly leads to higher stator core losses and higher converter losses. The volume, thickness, shape and type of the permanent magnets also affect both the performance and the cost of the machine. By decreasing the permanent magnet width, linkage and leakage fluxes are both decreased though not proportionally. Magnet protection must also be considered as a constraint together with the dimensional machine parameters. The derivation of the basic equations for quantities such as Attraction Force, Repulsion Force, Current, voltage, Power, and inductance which are valid for PMLOMs is included in this section. The differences of the sizing equations of the machines are emphasized. The specification of PMLOM are load weight, stroke length and maximum speed. The first step in design is to determine the attraction force and repulsion force required by the motor for the given specifications for which it is necessary to calculate Ampere turns of the stator winding and the H_C of PM to provide the required force. Then the various dimensions of stator and mover are decided.

2.1. *The proposed specifications for the Design of PMLOM*

The following specifications are used for design of the proposed PMLOM.

Table 1. Specification of proposed PMLOM

Input voltage	75V A.C.
Input current	3.0 A
Rated Frequency	0-5 Hz
Stroke length	10 – 20 mm
Maximum speed	500 mm/sec
Load	20 Newton

3. DETERMINATION OF THE TOTAL FORCE

3.1. *Determination of the Attraction Force*

Considering the Electromagnet and permanent magnet system in the Fig. 1 and Fig. 2, The magnetic force between the electromagnet and permanent magnet poles can be found and in the following manner.

This work done is equal to the change of energy stored in magnetic field.

Work done = $F\ dx$

Change in energy stored in magnetic field
= energy density × change in volume

$$= \frac{1}{2}\frac{B^2}{\mu_0} \times A\ dx \quad = \frac{1}{2}\frac{B^2}{\mu_0} A\ dx \tag{1}$$

$$\therefore\ F\ dx = \frac{1}{2}\frac{B^2}{\mu_0} A\ dx\,, F = \frac{1}{2}\frac{B^2}{\mu_0} A \qquad Nw \tag{2}$$

Hence from above, Force per unit area

$$P_m = \frac{1}{2}\frac{B^2}{\mu_0} \qquad N/m^2 \tag{3}$$

The flux density in the airgap, B depends upon the mmf of the exciting winding and the permanent magnet. A portion of this mmf is required for the airgap and the rest for the iron parts of the magnetic circuit.

$$AT = AT_g + AT_i \tag{4}$$

Now,

$$B = \frac{\mu_0 AT_g}{l_g}, \tag{5}$$

$\therefore$ From eqn. (2), The Force

$$F = \frac{1}{2}\left(\frac{\mu_0\left(AT_g\right)}{l_g}\right)^2 \frac{A}{\mu_0} = \frac{1}{2}\mu_0\left(\frac{AT_g}{l_g}\right)^2 A \quad Nw \tag{6}$$

If there is no saturation in the iron parts, the mmf required for them is small and therefore

$$AT = AT_g \tag{7}$$

This gives :

$$F_A = \frac{1}{2}\mu_0\left(\frac{AT_A}{l_g}\right)^2 A \qquad Nw \tag{8}$$

when the polarities are opposite, the MMFs of primary coil and secondary PM assist each other, but when the polarity is the same, the MMfs of primary coil and secondary PM oppose each other. In these machines B can be increased to 1 tesla without saturating the core, in which case the force density becomes $4\times10^5\ N/m^2$ .This force is sufficient for the good performance of the PMLOM. Permanent magnets, as an MMF source, yield a high airgap flux density and simplify the power supply system.

3.2. Determination of Repulsion Force

Now, considering the repulsion force, The fluxes in the airgap are predominately radial. Qualitatively we now have a force of repulsion between the coil and the permanent magnets.

$$F_R = \frac{1}{2}\mu_0\left(\frac{AT_R}{x}\right)^2 A \quad Nw \tag{9}$$

3.3. Total Force

$$F_t = F_A + F_R \tag{10}$$

4. SIMULATION AND EXPERIMENTAL RESULTS

The proposed scheme is simulated under FEMLAB6.2 WITH MATHWORKS environment, which provides a finite element analysis. The machine specification used for both simulation and experiment is given in Table-2.

Table 2. PMLOM Design Parameters

Rated Input Voltage	75V
Rated input power	175 watts
Stroke length	10 mm
Outer Diameter (Stator)	100 mm
Stator core type	CRGO SS
Thickness of lamination	0.27 mm
Stator length	60 mm
Number of turns in Coil aa’,cc’	950
Number of turns in Coil bb’,dd’	475
Coil resistance	17.5 Ohms
Slot depth	30 mm
Permanent Magnet Type	Rare Earth N42,
Permanent Magnet Length	2 mm
Coercivity	925000 A/m
Remanence	1.3 T
Outer diameter (Mover)	45 mm
Shaft diameter	8 mm
Coil Inductance	0.18 Henry

Fig.3 shows the mesh configuration, Fig. 4 and Fig. 5 show the corresponding flux plotting of the machine for different input frequencies of the machine. Fig.6 shows Finite element Magnetic flux plotting at upper and lower part of the airgap while mover oscillates within stator. The control block diagram along with the power circuit is shown in Fig.7. In this experimental set-up the thrust control is provided with the help of phase controlled ac supply which can vary the input voltage. The frequency control is provided with the help of a low cost and commercially available microcontroller PIC16F877A. The set-up is reliable and provides a scope for portability to any remote place. Fig. 8 shows the plot of the input voltage and current of the machine at 5 Hz. From which the assumption of constant inductance for the machine can be well validated.

Fig. 9 shows resultant total force at varying axial airgap length as the mover of PMLOM oscillates within two stators. Fig. 10 shows the characteristics plot of input power, voltage and force as a function of current for the machine taken at a frequency of 1Hz. The comparison of force measured versus the theoretically calculated force at an axial airgap length of 7 mm and current at 2.5 amps is shown in Fig. 11.Efficiency versus Load (per unit) characteristics is plotted as shown in Fig. 12.At rated Voltage, Load was varied up to 1 p.u. and efficiency remained almost constant with slight fall as the winding resistance being not appreciable. Core loss remained almost negligible at frequencies below 5 Hz. Improvement in power factor as the Load varied up to 1 p.u.Power Factor versus Load(p.u.) characteristics is shown in Fig.13.

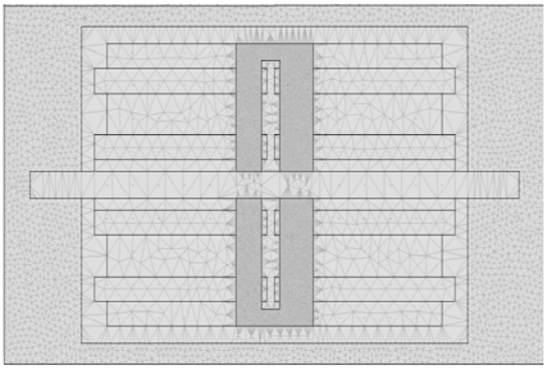

Fig.3. Finite element mesh of PMLOM while mover is oscillating at the centre, 5 Hz,3.5A

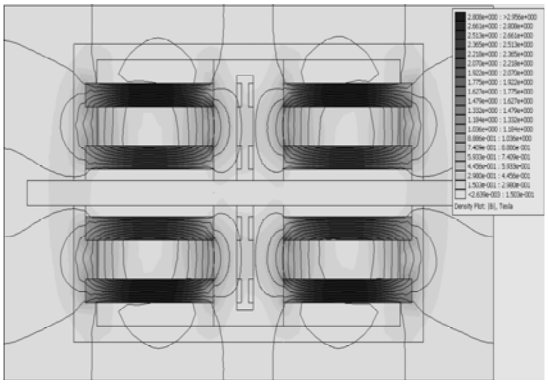

Fig.4. Magnetic flux plotting of PMLOM while mover is oscillating at the centre of both stators at 5 Hz, 3.5Amps

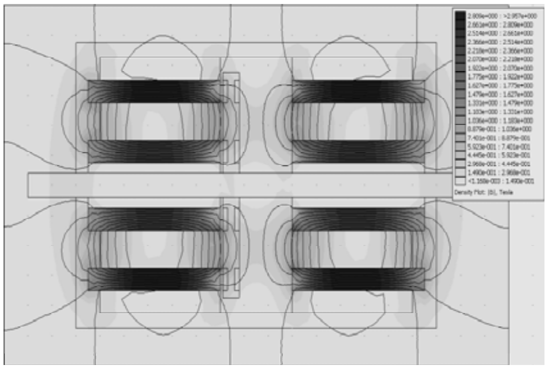

Fig.5. Magnetic flux plotting of PMLOM while mover is oscillating near stator 1 at 5 Hz, 3.5Amps

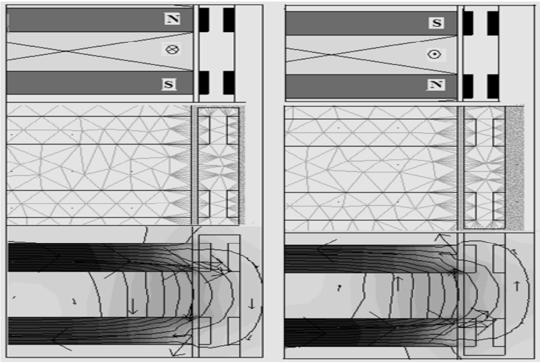

Fig.6. Finite element Magnetic flux plotting at upper and lower part of the airgap while mover oscillates within stator 1

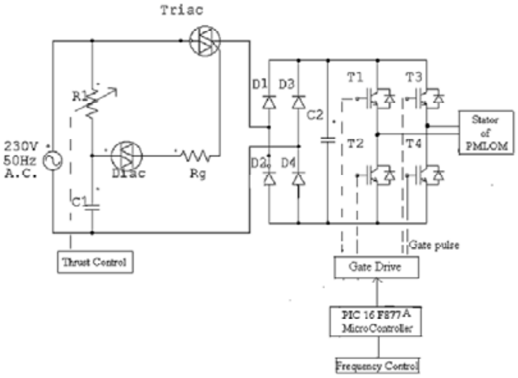

Fig.7. Power Circuit of PMLOM

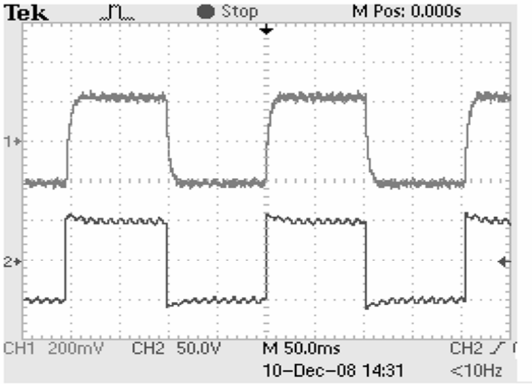

Fig.8. Current waveform of PMLOM taken from Tektronix make Storage oscilloscope.

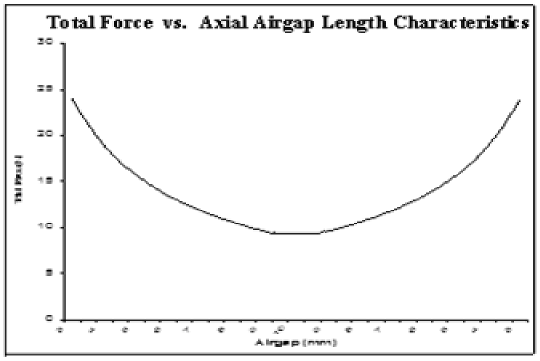

Fig.9. Total Force versus Axial Airgap length resultant of oscillating Mover of PMLOM

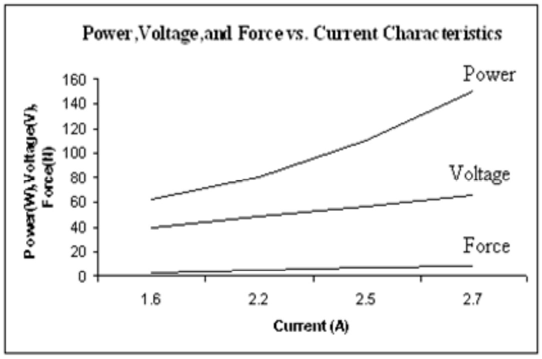

Fig.10. Power(W).Voltage(V),Force(N) versus Coil Current measured Characteristics of PMLOM

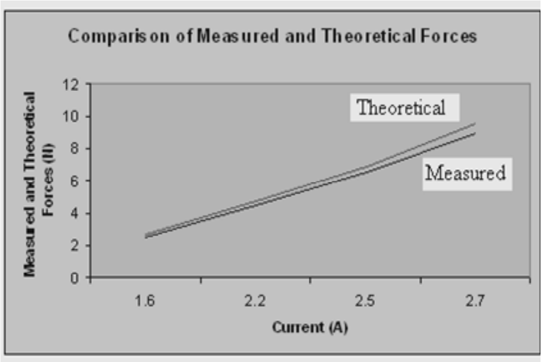

Fig.11. Comparison of Force measured versus Theoretically calculated Force at an axial airgap length of 7 mm and Current at 2.5 Amp

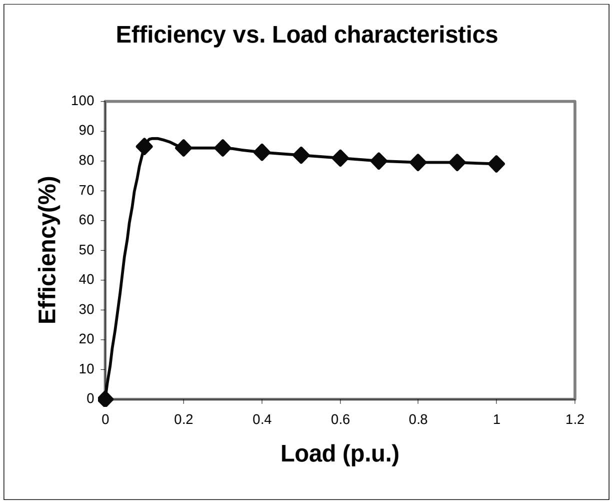

Fig.12. Efficiency (%) versus Load(p.u.) characteristics of PMLOM

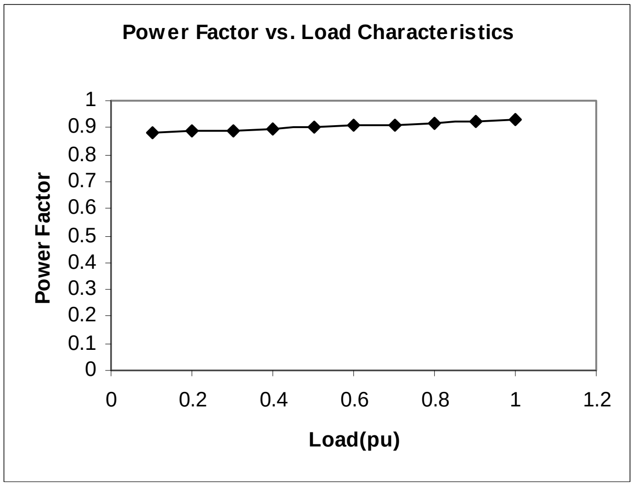

Fig.13. Power Factor versus Load(p.u) Characteristics of PMLOM

5. Conclusion

Design and development and simple control method of an new axial flux PMLOM suitable for low frequency and short stroke application is presented. Analytical solution to the forces and determination method of the integral parameters of a PMLOM are shown. Finite element method with FEMLAB6.2 WITH MATHWORKS is used for the field analysis of the different values of the exciting current and for variable mover position. Computer simulations for the magnetic field distribution, forces are given. To obtain experimentally the field distribution and its integral parameters, a physical model of the motor together with its electronic controller system has been developed and tested. The Prototype has been operated in the oscillatory mode with small loads at low frequency up to 5 Hz. The theoretically calculated results are compared with the measured ones and found a good conformity.

6. REFERENCES

[1] Ge Baoming, Aníbal T. de Almeida, and Fernando J. T. E.Ferreira (2009). Design of Transverse Flux Linear Switched Reluctance Motor. IEEE Trans. Magn. 45:113-119.

[2] Govindaraj Thangavel, Debashis Chatterjee, and Ashoke K. Ganguli,(2009a).A Permanent Magnet Linear Oscillating Motor for Short Strokes. in Proc.Int .Conf. Electrical Energy Systems & Power Electronics in Emerging Economies- ICEESPEEE 09, SRM University, India, Apl. 16-18, pp. 351- 355

[3] Govindaraj Thangavel, Debashis Chatterjee, and Ashoke K. Ganguli, (2009b). Development, Finite Element Analysis and Electronic Controlled Axial Flux Permanent Magnet Linear Oscillating Motor direct drive suitable for short Strokes. in Proc. Int. Conf. Control, Automation, Communication and Energy Conservation - INCACEC 2009, Kongu Engineering College, India, Jun.4–6, pp. 479–483.

[4] Govindaraj Thangavel, Debashis Chatterjee, and Ashoke K. Ganguli, (2009c).FE Magnetic Field Analysis Simulation Models based Design, Development, Control and Testing of An Axial Flux Permanent Magnet Linear Oscillating Motor. in Proc. Int. Conf. Electrical and Electronics Engineering, ICEEE2009,Int. Association of Engineers, World Congress on Engineering 2009 vol 1, London, United Kingdom, July 1-3,

[5] Govindaraj Thangavel, Debashis Chatterjee, and Ashoke K. Ganguli, (2009d). Development, Analysis and Control of an Axial Flux Permanent Magnet Linear Oscillating Motor suitable for Short Strokes. in Proc. 2009 IEEE Int.Sym. on Industrial Electronics,IEEE ISIE 2009, Seoul Olympic Parktel, Seoul, Korea, July 5-8, , 29-34.

[6] Govindaraj Thangavel, Debashis Chatterjee, and Ashoke K. Ganguli, (2009e). Development, Control and Testing of a New Axial Flux Permanent Magnet Linear Oscillating Motor using FE Magnetic Field Analysis Simulation Models. In Proc. 2009 Int. Conf. on Mechanical and Electronics Engineering, ICMEE2009,Int. Association of Computer Science and Information Technology, IACSIT, Chennai, India, July 24-26, pp 191 – 195

[7] Govindaraj Thangavel, Debashis Chatterjee, and Ashoke K. Ganguli, (2010f). FEA Simulation Models based Development and Control of An Axial Flux PMLOM," J. of Modelling and Simulation of Systems, Vol.1, Iss.1, pp.74-80,

[8] Holmes, D.G., Lipo, T. A., McGrath, B. P., and Kong, W.Y. (2009). Optimized Design of Stationary Frame Three phase AC Current Regulators. IEEE Trans.Power Electronics, 24, pp 2417-2426

[9] Iakovos St. Manolas, Antonios G. Kladas, and Stefanos N. Manias (2009). Finite-Element-Based Estimator for High-Performance Switched Reluctance Machine Drives. IEEE Trans. Magn. 45:1266-1269.

[10] Kang, G., Hong, J., and Kim, G. (2001). Design and analysis of slotless-type permanent-magnet linear brushless motor by using equivalent magnetizing current. IEEE. Ind. Appl. 37:1241–1247.

[11] Kou Baoquan, Li Liyi, and Zhang Chengming (2009). Analysis and Optimization of Thrust Characteristics of Tubular Linear Electromagnetic Launcher for Space-Use. IEEE Trans. Magn. 45:250-255.

[12] Sadowski, N.,Carlson, R., Beckert, A. M., and Bastos,J. P. A. (1996). Dynamic modeling of a newly designed linear actuator using 3D edge elements analysis. IEEE Trans. Magn. 32: 1633–1636.

[13] Taylor, D. G., and Chayopitak,N. (2006). Time-optimal position control of electric motors with steady-state temperature constraints. Proc.IEEE Int. Symp. Industrial Electronics Montreal, QC, Canada. 3142–3146.

[14] Tomczuk, B., and Sobol, M. (2003). Influence of the supply voltage on the dynamics of the one-phase tubular motor with reversal motion. Proc. 39th Int. Symp. Electrical Machines—SME'2003. Gdansk/Jurata, Poland.417–426.

[15] Vaez-Zadeh, S., and Isfahani,A.(2006). Multi-objective design optimization of air-core linear permanent-magnet synchronous motors for improved thrust and low magnet consumption, J. IEEE Magn. 42:446–452.

AUTHORS PROFILE

Govindaraj Thangavel was born in Tiruppur, India, in 1964. He received the B.E. degree from Coimbatore Institute of Technology, M.E. degree from PSG College of Technology and Ph.D. (Thesis Submitted) pursuing from Jadavpur University, Kolkatta, India in 1987, 1993 and 2009 respectively.

Since July 2009 he has been Professor and Head of the department of Electrical and Electronics Engineering, Muthayammal Engineering College affiliated to Anna University, Chennai, India. His Current research interests includes Permanent magnet machines ,Axial flux Linear oscillating Motor , Advanced Embedded power electronics controllers and finite element analysis of special electrical machines.

He is a Member of Institution of Engineers India and Chartered Engineer (India) since 1999.Member of International Association of Computer Science and Information. Technology (**IACSIT**). Member of International Association of Engineers(**IAENG**), Member of Indian Society for Technical Education. He has published Six research papers in International Journals and conferences. Organized twelve National / International Conferences. Convener for the National Symposium PWRSPARK'09 and National Conference ITEES'10.