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Finite Element Analysis of the Direct Drive PMLOM

Govindaraj Thangavel

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1. Introduction

The **finite element method (FEM)** (its practical application often known as **finite element analysis** (FEA)) is a numerical technique for finding approximate solutions of partial differential equations (PDE) as well as integral equations. The solution approach is based either on eliminating the differential equation completely (steady state problems), or rendering the PDE into an approximating system of ordinary differential equations, which are then numerically integrated using standard techniques such as Euler's method, Runge-Kutta, etc. In solving partial differential equations, the primary challenge is to create an equation that approximates the equation to be studied, but is numerically stable, meaning that errors in the input and intermediate calculations do not accumulate and cause the resulting output to be meaningless. There are many ways of doing this, all with advantages and disadvantages. The finite element method is a good choice for solving partial differential equations over complicated domains (like cars and oil pipelines), when the domain changes (as during a solid state reaction with a moving boundary), when the desired precision varies over the entire domain, or when the solution lacks smoothness. For instance, in a frontal crash simulation it is possible to increase prediction accuracy in "important" areas like the front of the car and reduce it in its rear (thus reducing cost of the simulation). Another example would be in Numerical weather prediction, where it is more important to have accurate predictions over developing highly-nonlinear phenomena (such as tropical cyclones in the atmosphere, or eddies in the ocean) rather than relatively calm areas.

The finite difference method (FDM) is an alternative way of approximating solutions of PDEs. The differences between FEM and FDM are:

- The most attractive feature of the FEM is its ability to handle complicated geometries (and boundaries) with relative ease. While FDM in its basic form is restricted to handle

rectangular shapes and simple alterations thereof, the handling of geometries in FEM is theoretically straightforward.

- The most attractive feature of finite differences is that it can be very easy to implement.
- There are several ways one could consider the FDM a special case of the FEM approach. E.g., first order FEM is identical to FDM for Poisson's equation, if the problem is discretized by a regular rectangular mesh with each rectangle divided into two triangles.
- There are reasons to consider the mathematical foundation of the finite element approximation more sound, for instance, because the quality of the approximation between grid points is poor in FDM.
- The quality of a FEM approximation is often higher than in the corresponding FDM approach, but this is extremely problem-dependent and several examples to the contrary can be provided.

Generally, FEM is the method of choice in all types of analysis in structural mechanics (i.e. solving for deformation and stresses in solid bodies or dynamics of structures) while computational fluid dynamics (CFD) tends to use FDM or other methods like finite volume method (FVM). CFD problems usually require discretization of the problem into a large number of cells/gridpoints (millions and more), therefore cost of the solution favors simpler, lower order approximation within each cell. This is especially true for 'external flow' problems, like air flow around the car or airplane, or weather simulation.A variety of specializations under the umbrella of the mechanical engineering discipline (such as aeronautical, biomechanical, and automotive industries) commonly use integrated FEM in design and development of their products. Several modern FEM packages include specific components such as thermal, electromagnetic, fluid, and structural working environments. In a structural simulation, FEM helps tremendously in producing stiffness and strength visualizations and also in minimizing weight, materials, and costs.FEM allows detailed visualization of where structures bend or twist, and indicates the distribution of stresses and displacements. FEM software provides a wide range of simulation options for controlling the complexity of both modeling and analysis of a system. Similarly, the desired level of accuracy required and associated computational time requirements can be managed simultaneously to address most engineering applications. FEM allows entire designs to be constructed, refined, and optimized before the design is manufactured.

The 3-D finite element method (FEM) involves important computational methods. Many efforts have been undertaken in order to use 3-D FEM (FEMLAB6.2 WITH MATHWORKS). Analytical and Numerical Analysis have been developed for the analysis of the end zones of electrical machine.This paper presents different methodologies based on 3-D geometries using analytical solutions, This method has been implemented in conjunction with various geometry optimization techniques as it provides very fast solutions and has exhibited very good convergence with gradient free algorithms. 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.

Tradeoffs between accuracy, robustness, and speed are central issues in numerical analysis, and here they receive careful consideration. The principal purpose of the work is to evaluate the performances of the PMLOM models when implemented in the FEM analysis of electrical machines. The developed methods are applied in an in-house FEM code, specialized for the design and analysis of electrical machines. The FEM simulations and the analysis on axial flux PMLOM, and the numerical results are validated experimentally. The techniques developed for the calculation of integral parameters involve particular assumptions and simplifications and present specific advantages.

LINEAR motors are finding increasing applications in different specific areas like high-speed transport, electric hammers, looms, reciprocating pumps, heart pumps etc. [1]-[7]. 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 Permanent Magnet Linear Oscillating Motors (PMLOMs) are one of the derivatives of the linear motors in the low power applications having the advantages of higher efficiency. They can be supplied with dc or ac voltages [4]-[7] of which, the dc motors are having better efficiency due to the absence of the core losses.

The motor designed and analyzed in this paper finds the suitability of application in the loads having low frequency and short stroke requirements. 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 [6], [9] executed which assumes the machine inductance to be constant for simplicity of the model although different other works [4], [7]and [8] dynamically estimate the inductance through FEM and field analysis and control[10-15] for getting correct results. 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

The construction of the prototype PMLOM is shown in Fig.1 below. 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.
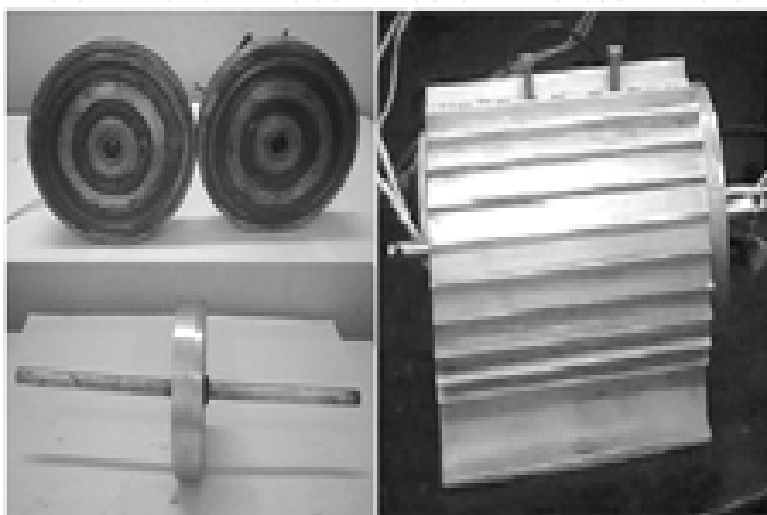
Figure 1. Construction details of the developed PMLOM (i) Stators to be mounted on both sides of the mover and (ii) the mover (iii) the PMLOM machine
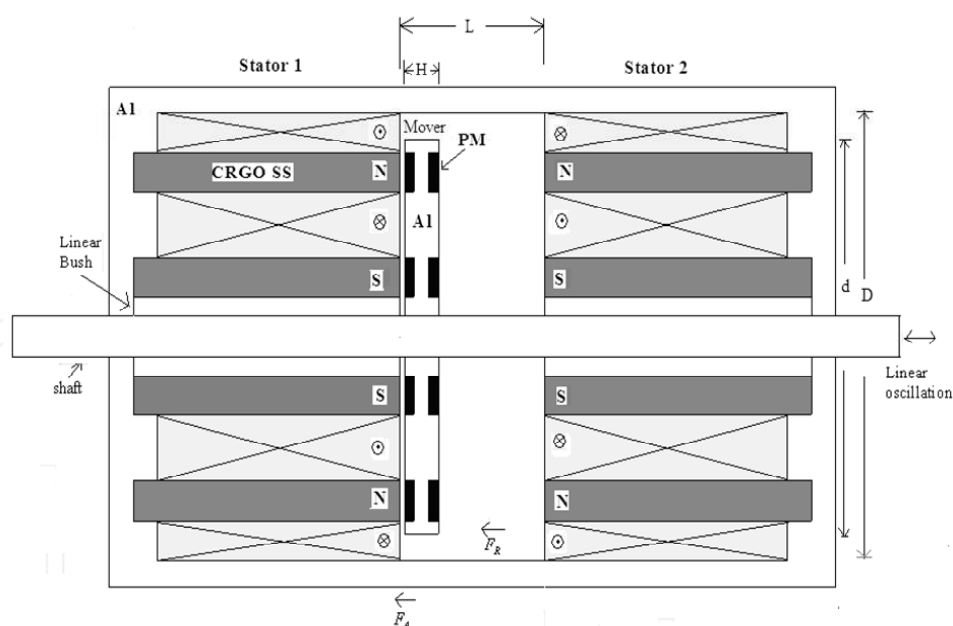
Al – Aluminium material   PM-N42 Permanent Magnet

Attraction Force F_A and Repulsion Force F_R

Coil 1 – aa′ and bb′   Coil 2 – cc′ and dd′

Figure 2. Dimensional details of the developed PMLOM

3. 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-1.

The classical description of static magnetic fields are provided by Maxwell's equations

$$\nabla \times H = J \tag{1}$$

$$\nabla \cdot B = 0 \tag{2}$$

Where H is magnetic field intensity, B is magnetic flux density and J is the current density of the magnetic field.

Subject to a constitutive relationship between B and H for each material:

$$B = \mu H \tag{3}$$

Where μ denotes material permeability. Boundary conditions that must be satisfied at the interface between two materials having finite conductivities are,

$$\hat{n} \times \left(H_1 - H_2 \right) = 0 \tag{4}$$

$$\hat{n} \cdot \left(B_1 - B_2 \right) = 0 \tag{5}$$

Since the divergence of the curl of any vector must always be zero, it follows from (2) that there exists a so-called magnetic vector potential A such that,

$$B = \nabla \times A \tag{6}$$

Substituting (3) and (6) into (1) and taking a curl on both sides yields

$$\nabla \times \left(\frac{1}{\mu} \nabla \times A \right) = J \tag{7}$$

If

$$J = J\hat{z} \tag{8}$$

Then,

$$A = A\hat{z} \tag{9}$$

Thus, (7) reduces to,

$$-\nabla \cdot \left(\frac{1}{\mu} \nabla A \right) = J \tag{10}$$

The above equation (10) may be written in the expanded form as,

$$\frac{\partial}{\partial x}\left(\frac{1}{\mu}\frac{\partial A}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{1}{\mu}\frac{\partial A}{\partial y}\right) = -J \qquad (11)$$

This equation (11) represents the *scalar Poisson equation*.

The mover consists of aluminium structure embedded with rare earth permanent magnets with the polarities as shown. The force developed will be attractive on one side and simultaneously repulsive on the other side. These two forces act in the same direction to enhance the total force on the mover, assisting the linear oscillation of the mover cyclically.
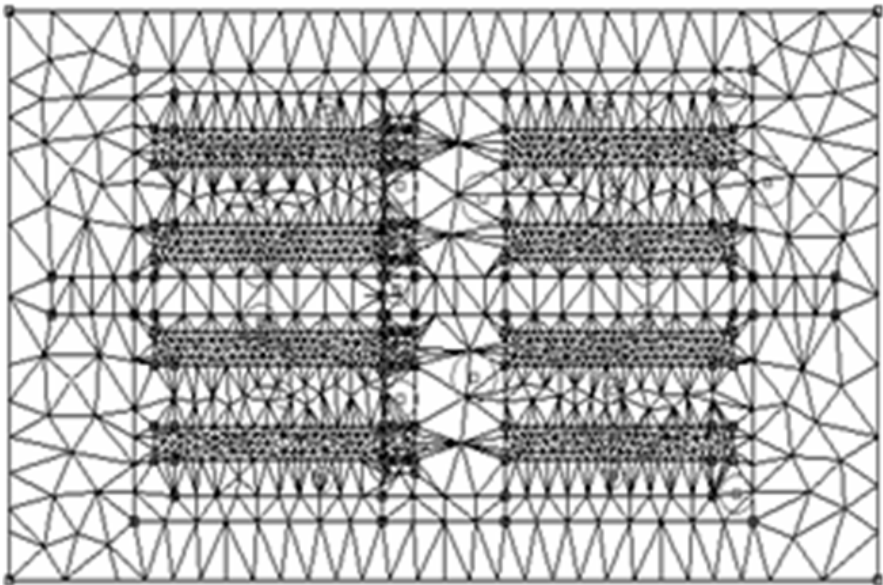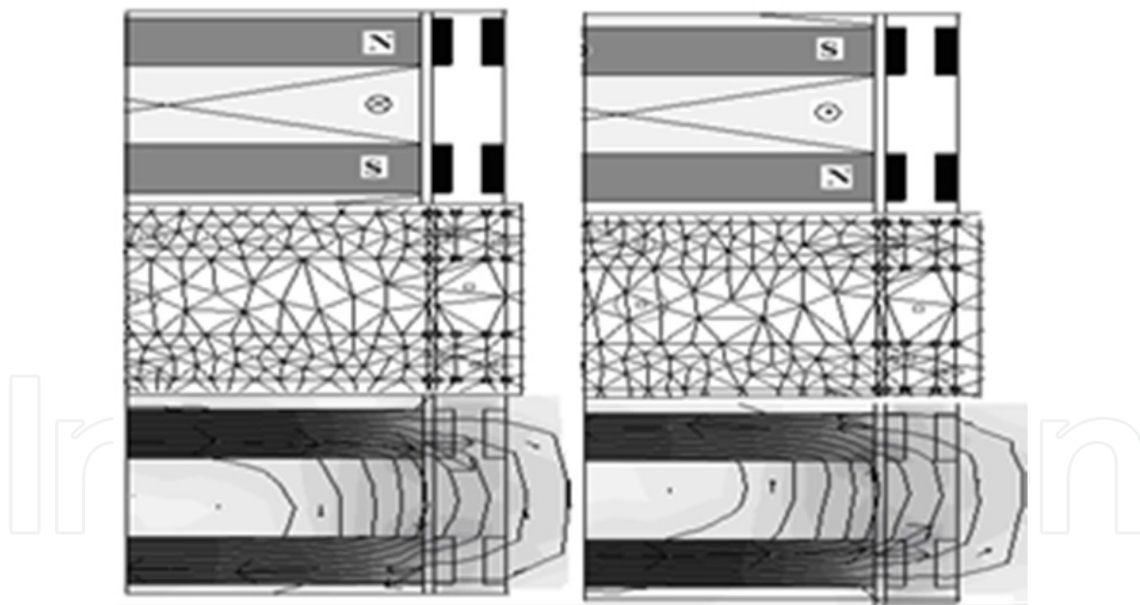

(a)
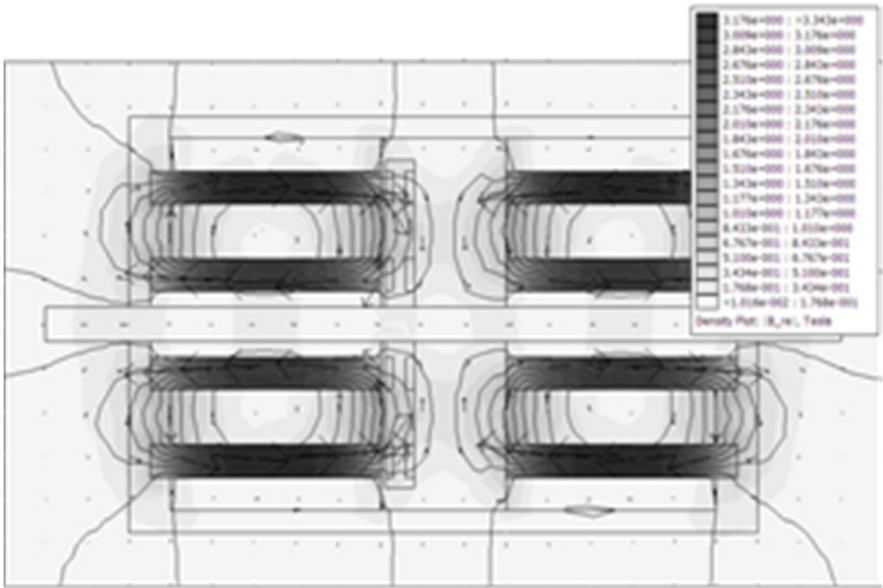
(b)
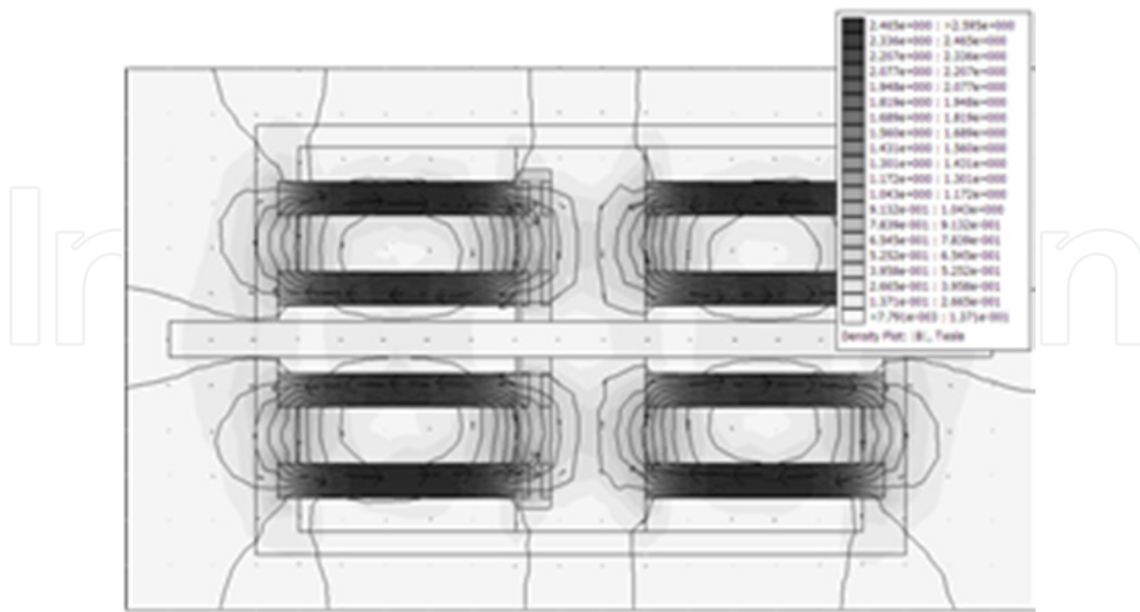
(c)

(d)

Figure 3. (a) Finite element mesh of PMLOM while mover is oscillating with in Stator 1. (b) Magnetic flux plotting of PMLOM while mover is oscillating with in Stator 1, at 1 Hz, 4Amps, (c) Magnetic flux plotting of PMLOM while mover is oscillating with in Stator 1, at 0 Hz. (d) Finite element Magnetic flux plotting at upper and lower part of the airgap while mover oscillates within stator 1. Now Mover is attracted to the Stator 1

Rated Input Voltage	70V
Rated input power	200 watts
Stroke length	10 mm
Outer Diameter (Stator)	85 mm
Stator core type	CRGO Silicon Steel
Thickness of lamination	0.27 mm
Stator length	60 mm
Number of turns in Coil aa',cc'	800
Number of turns in Coil bb',dd'	400
Coil resistance	17.8 ohms
Slot depth	45 mm
Permanent Magnet Type	Rare Earth N42, Nd-Fe-B
Permanent Magnet Length	2 mm
Coercivity	925000 A/m
Remanence	1.3 T
Outer diameter (Mover)	65 mm
Shaft diameter	8 mm
Coil Inductance	0.18 Henry

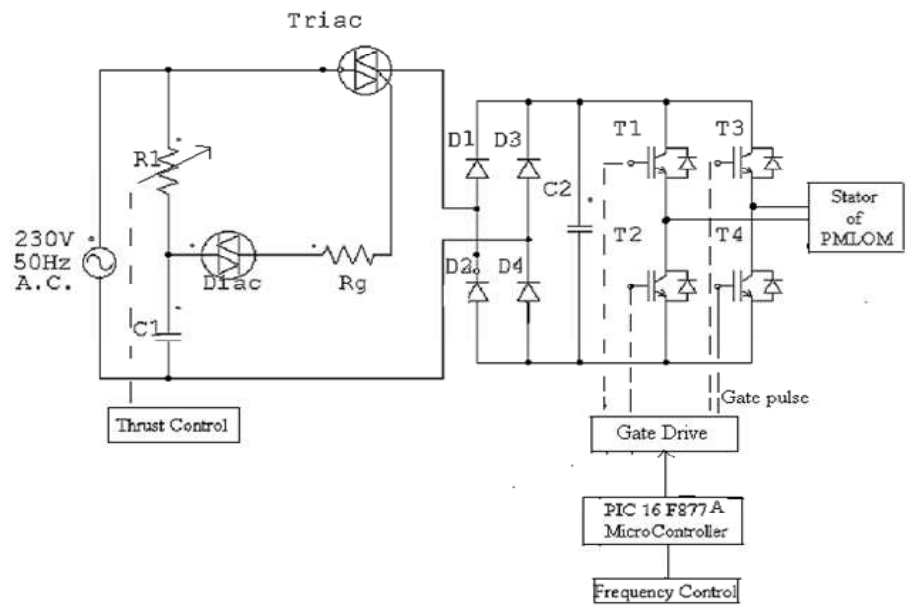**Table 1.** PMLOM Design Parameters

Figure 4. Power Circuit of PMLOM

Figure 3(a), shows the FEM mesh configuration for the PMLOM Prototype. Figure 3(b) shows the Magnetic flux plotting of PMLOM while mover is oscillating within Stator 1, at 1 Hz, 4Amps.Figure 3(c) is the corresponding flux plotting of the machine while mover is oscillating within Stator 1, at 0 Hz. Figure 3(d) illustrates the finite element analysis of the PMLOM at the axial airgap. Thus, the geometries of the mover and stator have been

accurately discretized with fine meshes. Symmetry was exploited to reduce the problem domain to half of the axial cross section of the overall motor.

The halved longitudinal cross section of the motor has created the calculation area, with Dirichlet boundary conditions (Fig. 3(d)). Thus, the magnetic field has been analyzed. For the calculations, material linearity of the NdFeB permanent magnet (μ_r =1.048) was supposed. Its coercive force was assumed to be H_c = 925 KA/m and the magnetization vector direction were adopted for the calculations. Very small air gaps compared with the main motor dimensions between permanent magnets and ferromagnetic rings were neglected due to very small magnetic permeability of the permanent magnets, it is acceptable.

The finite-element mesh (Fig. 3(d)) is dense in the air gap between stator cylinder sleeve and the mover. The fine mesh is also used near the edges of ferromagnetic parts where the magnetic field is expected to vary rapidly (Fig. 3(d)). In order to predict the integral parameters of the PMLOM, it is necessary to analyze the magnetic field distribution in the stator and mover. Obviously, it is possible to optimize the construction by making changes in the stator and mover geometries. The improvements of the structure result from knowledge of the magnetic field distribution. The presented results have been obtained for one variant of the motor construction.

The control block diagram along with the experimental set-up power electronic control circuit is shown in Fig.4. Here 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. 5 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. 6 shows the characteristics plot of input power, voltage and force as a function of current for the machine taken at a frequency of 1Hz. Figure 7 shows Force at different axial airgap length. Force observed by measurement is compared with the theoretical Force value and shown in fig. 8.
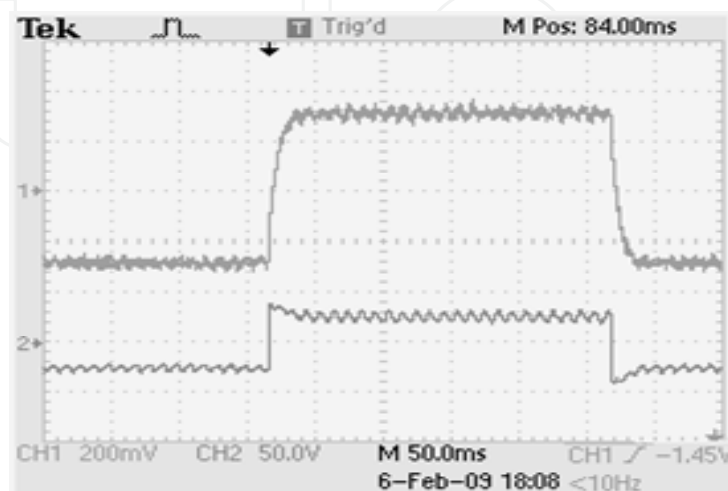
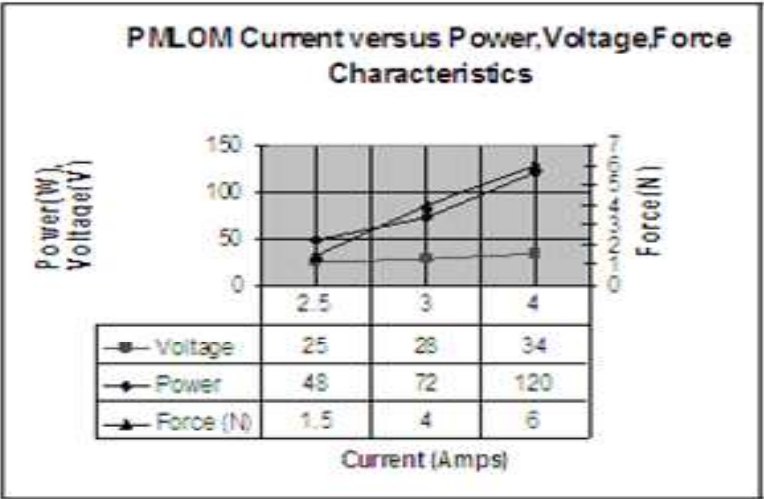**Figure 5.** Current waveform of PMLOM taken from Tektronix make Storage Oscilloscope

Figure 6. Measured Coil current versus Power((W).Voltage(V),Force(N) Characteristics of PMLOM
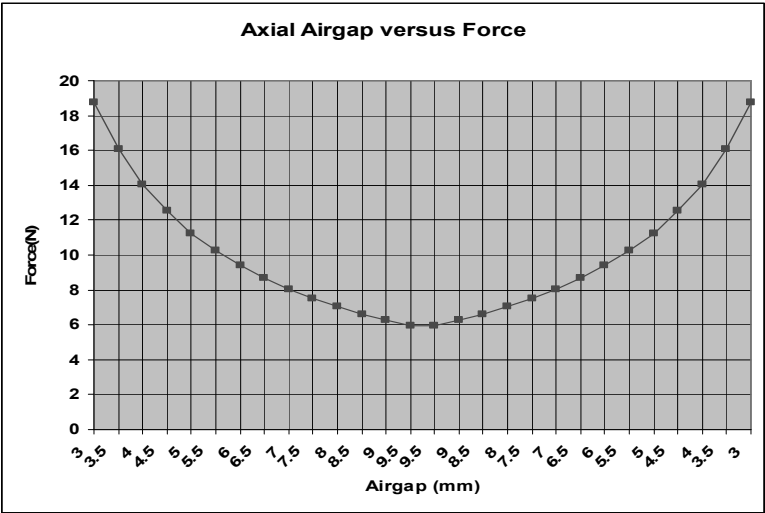

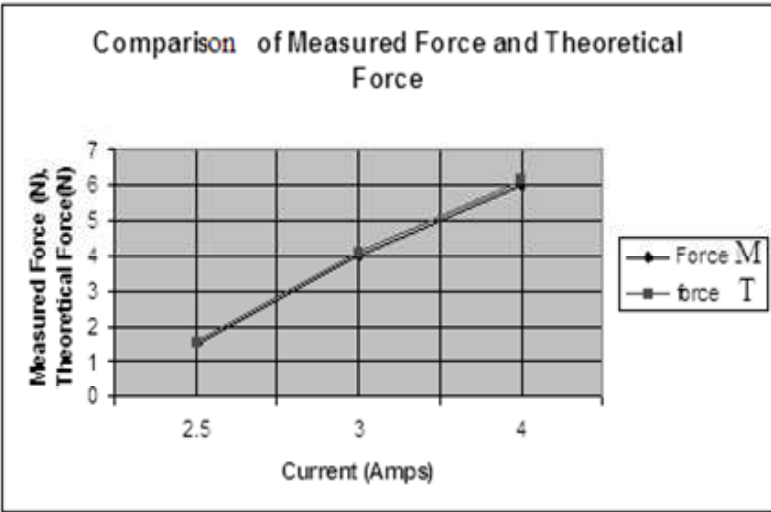**Figure 7.** Axial Airgap Length versus Force

Figure 8. Comparison of measured Force Versus Theoretical Force

4. Conclusions

A simple control method along with the development of an 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.

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