

Linear flux reversal PM oscillo-machine with effective flux concentration

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Abstract Linear motion oscillo - machines – as motors or generators are suitable for compressors and, respectively, as electric generators for small residential (or space) or vehicular electric energy production.

The present paper introduces a novel configuration with PM mover flux concentration capable of high thrust density while retaining high efficiency and good power factor (6 N/cm², $\eta = 0.9$, $\cos(\phi) = 0.78$). Conceptual design and FEA provides encouraging results. Experimental work is planned for the near future.

Keyword: linear oscillo-machines, generator, flux reversal

I. INTRODUCTION

Linear permanent magnet PM oscillo-machines have been proposed as linear single phase alternator and oscillo-machines. Potential prime users for linear alternators are free piston Stirling engines and linear internal combustion engines for automotive application. Linear piston compressors for refrigeration are potential loads for linear oscillo-machines. Most linear oscillo-machines work connected to the commercial energy system (at 50 - 60Hz).

Among the existing versions of the linear PM oscillo-machines those with PM-mover [1-3], coil mover [4-5], iron mover [6-9] are predominant [Fig. 1].

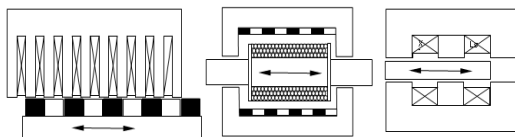


Fig. 1. Oscillo machines a) PM mover b) coil mover c) iron mover

Having a cylindrical shape, existing PM mover and coil mover configurations are not easy to manufacture from laminations and do not allow in general PM Flux concentration

The iron mover flux reversal machine with stator PMs [1], in contrast, is easy to manufacture, provides good efficiency but at moderate thrust density (1-2N/cm²), Fig. (2). Again, the difficulty in PM – flux concentration due to high fringing is the

main obstacle to produce higher thrust density but maintain high efficiency and good power factor.

In an effort to circumvent this difficult, the present paper introduces a novel configuration of linear flux reversal (LFRM) oscillo-machine with efficient PM flux concentration.

The novel configuration is first introduced and a conceptual design methodology is presented related to a case study. FEA is then used to calculate more exactly the thrust for various current and mover positions. The efficiency and power factor are treated through thrust/watt of losses and IX_s/E rates as speed independent indexes.

II. PROPOSED CONFIGURATION AND OPERATION PRINCIPLES

The configuration proposed here, Fig.2, is made of two longitudinal-lamination stator cores which accommodate 4 identical coils which may be connected in series or series – parallel to (from) a single phase AC power grid.

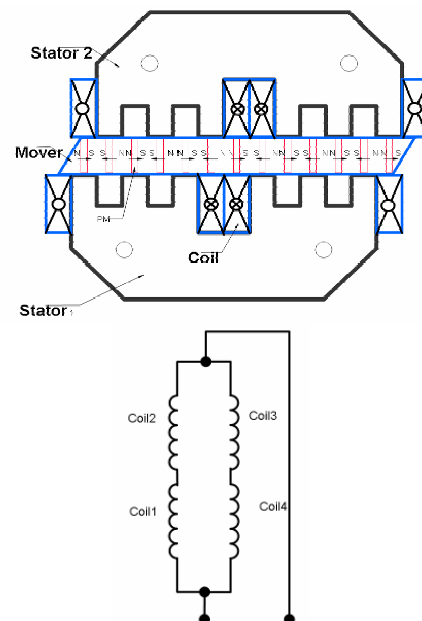


Fig. 2. Cross section of the LFRM cross section and winding configuration

The PM mover is also made of a longitudinal laminations with flux barriers filled with permanent magnets of alternating polarity. The stator poles have

smaller poles and inter-poles where τ_{PM} is equal to the PM placement pitch on the mover, Fig. 4. The big slots in the stator which hosts the coils have an opening equal to $2 \cdot \tau_{PM}$

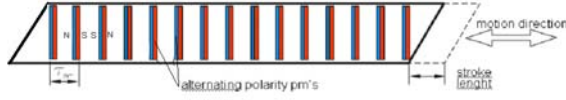


Fig. 3. Mover PM placement

The two stator slots are shifted by τ_{PM} along the direction of motion. The ideal excursion length from extreme left to extreme right is equal to τ_{PM} . As long as mover height h_r is larger than τ_{PM} flux concentration takes place. The higher h_r / τ_{PM} , the larger the PM flux concentration effect.

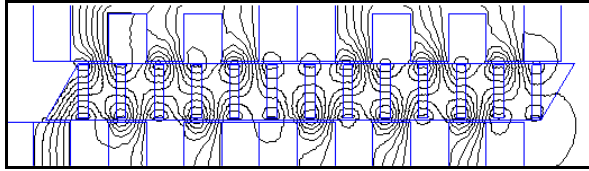


Fig. 4. Flux concentration effect

All PMs are participating all the time to reverse the PM flux in the coils when the mover moves from extreme left to extreme right position. In Fig 4 it can be observed concentration effect of the two opposite magnets.

This complete use of all PMS all the time offsets the rather large imminent fringing flux present in any variable reluctance PM topology, and makes the configuration unique.

III. CONCEPTUAL DESIGN OF THE LINEAR FLUX REVERSAL OSCILLO-MACHINE

Specifications for the prototype are:

Power:	1 kW (motoring);
Excursion length:	$\tau_{PM}=12\text{mm}$;
Frequency f_1 :	$f_1=60\text{Hz}$;
Supply voltage	$V_1: 120\text{V}$;
Average speed:	$u_s = 2\tau_{PM}f_1 = 1.44$

m/s;

The conceptual design is based on the following main relationships:

The developed thrust is:

$$F_x = 4 \frac{2}{\tau_{PM}} (\phi_{PM})_{coil\ max} \frac{1}{\sqrt{2}} (n_c I_n) K_{end} \quad (1)$$

where:

$(\phi_{PM})_{coil\ max}$ is the maximum flux in a coil;

n_c the number of conductors in a coil;

I_n the rated current;

The maximum flux in a coil is:

$$(\phi_{PM})_{coil\ max} = 2.5 B_{gPM} l_{stack} \quad (2)$$

Considering harmonic motion:

$$x = X_m \sin(\omega t) \quad (3)$$

The linear speed is:

$$u = \frac{dx}{dt} = X_m \omega_1 \cos(\omega_1 t) \quad (4)$$

And quasi-linear flux variation in the coils with position:

$$\Psi_{PM} = \Psi_{coil\ max} \left(1 - \frac{2x}{\tau_p}\right) \quad (5)$$

will produce a sinusoidal emf E per coil:

$$E(t) = -n_c \frac{d\Psi_{PM}}{dx} \frac{dx}{dt} = \Psi_{PMm} \frac{2}{\tau_p} \omega_1 X_m \cos(\omega_1 t) \quad (6)$$

Now if the phase current is in phase with emf maximum thrust is obtained.

The thrust is:

$$F_x = \frac{d(\phi_{PM})}{dx} i \sqrt{2} \cos(\omega_1 t) \quad (7)$$

The average linear speed is

$$u_{av} = 2 X_m f_1; f_1 = \frac{\omega_1}{2\pi} \quad (8)$$

In this particular (ideal) case the current is in phase with the linear speed and if: $\omega_1 = \sqrt{K/m}$, with:

K - mechanical springs (flexures) rigity (N/m);
 m - mover total mass;

Then the machine works at resonance and yield good performance. In order to precisely calibrate the springs these can be build from flexures bearings, (Fig. 5) which can be easily selected to obtain the desired rigidity.



Fig. 5. Flexures bearings

The various phase relations are shown in Fig. 6.

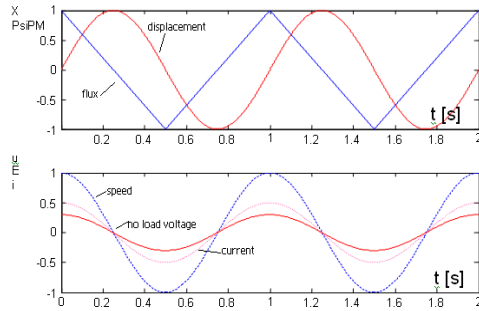


Fig. 6. Phase relationship for max (ideal) thrust/current operation a) displacement x and PM flux (ideal case) b) mover speed u, back emf E, current i,

The final results are:

TABEL I
MAIN DIMENSIONS AND PERFORMANCES

Stack length	l _{stack}	100mm
Number of coils	n _c	76
Rated coil current	I _n	6.298A
Terminal current	2I _n	12.6
Coil resistance	R _s	0.4107Ω
Coil inductance	L _s	0.01792H
Efficiency	η	0.938
Power factor	cos(φ)	0.706
Stator core weight	G _{stator}	9.7036kg

Where:

$(\phi_{PM})_{coil\ max}$ is the maximum flux in a coil;

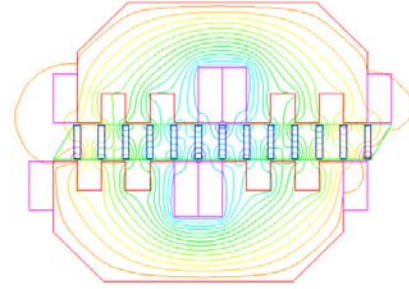
n_c number of coils;

I_n the rated current;

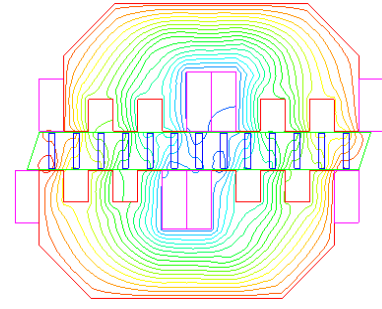
Based on this preliminary geometry rather detailed 2D-FEM calculations have been performed to validate the conceptual design.

IV. FEM ANALYSIS

For the geometry of the 1 kW machine, designed in paragraph 3, using PMs made of NeFeB and usual machinery silicon steel laminations, the PM flux distribution for the extreme left position was investigated and it is shown in Fig. 5. Flux reversal is visible.



a)



b)

Fig. 7. Flux path for extreme left (no load) a) and middle position (rated current) b)

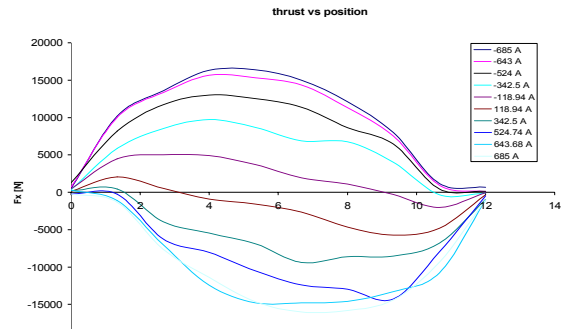


Fig. 8. Total thrust for various currents

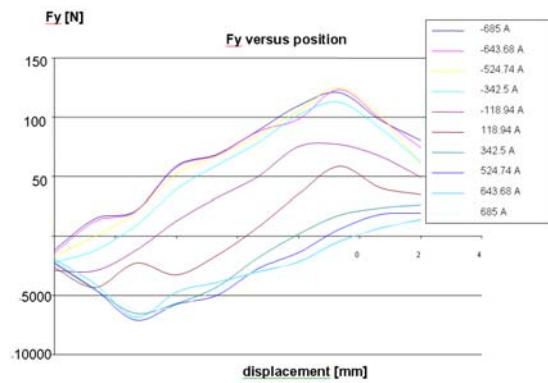


Fig. 9. Normal force (per one stator) for various currents

It is clearly that the emf (and thrust) coefficient $K_E=K_F$ decreases from center to extreme mover positions. $K_F(x) = \frac{Fx}{i} = K_E(x)$ is dependent on current due to magnetic saturation, Fig 8.

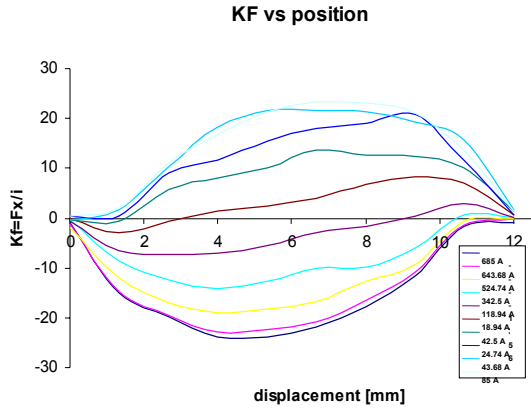


Fig. 10. Thrust coefficient, K_F (N/A), curves.

Curve fitting may be exercised to express $K_F(x, i)$. Design operation on land $K_f(x, i)$ has to be used to account for magnetic saturation properly.

It is clear that for sinusoidal motion the current will be basically sinusoidal and in phase with speed, for maximum thrust per current (E in phase with I). From the family of thrust/position/current we extract the thrust versus position, for sinusoidal current, Fig 9. It is evident that the average thrust is above 700 N, the design target. Consequently, the FEM validates the conceptual design in its critical performance index.

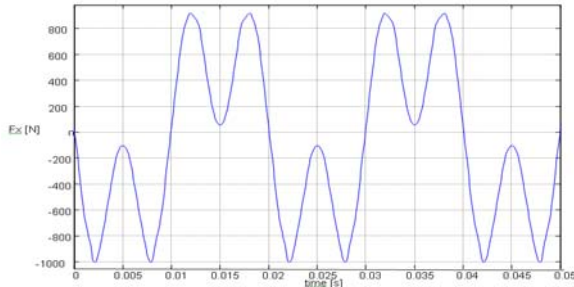


Fig. 9. Thrust for sinusoidal current supply

The PM flux in the coils for various mover positions shows some departure from the linear (ideal) distribution. This is more evident in the $d\Psi_{PM}/dx$ curve, Fig. 6a.

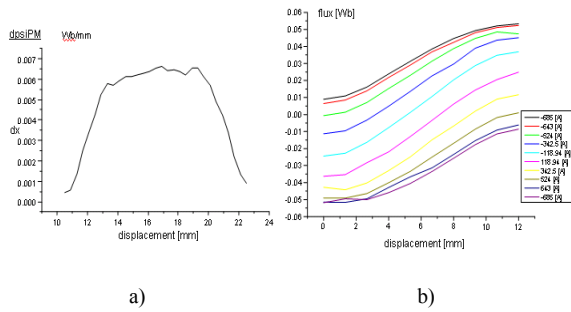


Fig. 10. $d\Psi_{PM}/dx$ curve and flux variation for different values of current

We may calculate the armature reaction flux and machine inductance L_s from the flux variation in the coils:

$$L_s(x, i) \approx \frac{\Psi(i + \Delta i, x) - \Psi(i, x)}{\Delta i} \quad (9)$$

The variation of the L_s with position indicates a low reluctance thrust component while saturation influence seems to be notable, Fig 10.

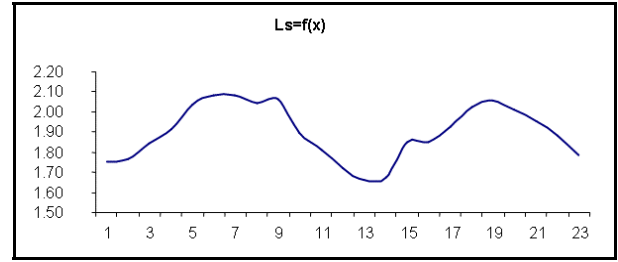


Fig. 11. Inductance versus position for maximum current

Analytical approximations for the thrust coefficient K_F and and inductance can be obtained, to be used in eventual transient or steady state analysis.

The flux density at the airgap under one stator versus position for extreme left position Fig 11 evidentiates the flux concentration high level (the maximum PM flux density is 1.2T).

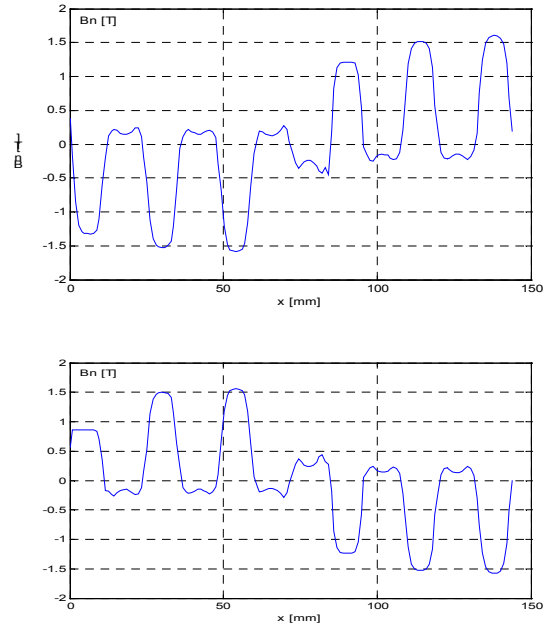


Fig. 12. PM airgap flux density at extreme left position and extreme right position

The armature reaction influence is given by:

$$K_{\cos(\varphi)} = \frac{X_s I}{E} \quad (I \text{ in phase with } E) \quad (0.1)$$

It is evident that with smaller $K_{\cos(\phi)}$ the larger power factor as the armature reaction is smaller .

$$\cos(\phi_1) = \frac{E + R_s I}{\sqrt{(E + R_s I)^2 + X_s I^2}} \quad (10)$$

$$\cos(\phi_1) \approx \frac{E}{\sqrt{E^2 + (X_s I)^2}} = \frac{1}{\sqrt{1 - K_{\cos(\phi_1)}^2}} \quad (11)$$

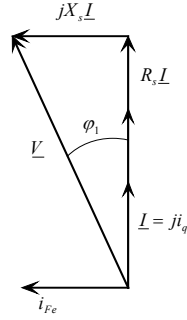


Fig. 13. Phasor diagram For E and I in phase

The coefficient $K_{\cos(\phi)}$ is very useful to calculate the resultant maximum flux density in the airgap and thus becomes a key factor for the magnetic circuit of the machine:

$$B_{\max} = B_{PM} \sqrt{1 + K_{\cos(\phi)}} \quad (12)$$

V COGGING FORCE

At zero current there is a cogging force acting on the mover due to the interaction between the PMs and the stator cores, Fig 12. This force is zero in the middle position and it is characteristic to a mechanical spring. If it were a linear characteristic spring it would have helped the mechanical flexures placed to store the energy at travel ends. Unfortunately towards the ends of travel the cogging force drops and thus it may bring some instabilities in the oscillatory motion, unless the mechanical flexures are designed to overcome this.

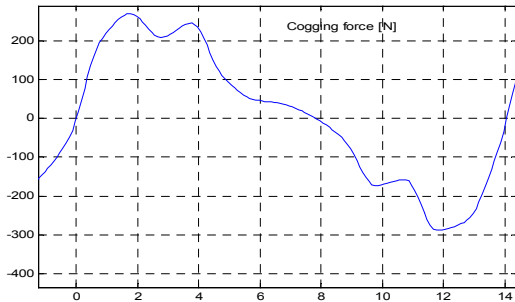


Fig. 14. Cogging force (for 1m stack length)

VI. DINAMIC SIMULATION OF THE LFRM

The derived oscillo-machine have been utilized for a nonlinear system state model.

a) Electrical Circuit Equation

The electrical circuit equation for the LFRM is:

$$V = Ri + \frac{d(Li)}{dt} + \frac{d\lambda_m}{dt} \quad (13)$$

For the LFRM motor, the self inductance is can be considered to be independent of the mover position, and the above equation becomes:

$$V = Ri + L_1 \frac{di}{dt} + e_m \quad (14)$$

where $e_m = \frac{d\phi_{PM}}{dt}$ is the induced *emf* in the coil

due to the permanent magnet, and $v = dx/dt$ is the mechanical speed.

b) Mechanical Equations

By Newton's law, we have

$$F - F_{load} = m \frac{dv}{dt} \quad (15)$$

Where: m is the mover mass,

$F = K_F i$ is the electromagnetic force produced by the current in the coil, K_F is the electromagnetic force constant, and

$$F_{load} = Kx + Bv \quad (16)$$

is the load force due to the spring and damper. K is the spring constant and B is the friction constant.

c) State Equations

When the electrical and mechanical equations expressed in the form of state equations, we obtain:

$$\frac{di}{dt} = -\frac{R}{L}i - \frac{K_E}{L}v + \frac{1}{L}V \quad (17)$$

$$\frac{dv}{dt} = \frac{K_F}{m}i - \frac{K}{m}x - \frac{B}{m}v \quad (0.2)$$

These equations can be solved together with initial conditions:

$$i(0) = i_0, \quad v(0) = v_0, \quad x(0) = x_0$$

The simulation were performed in Ansoft Simplorer.

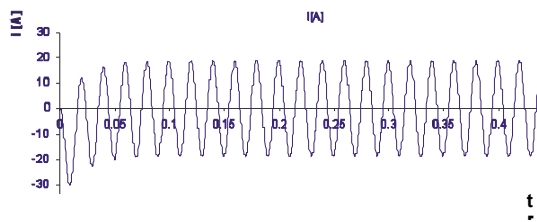
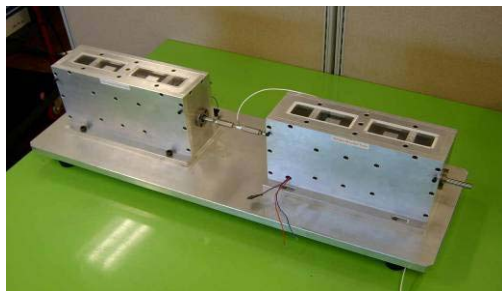
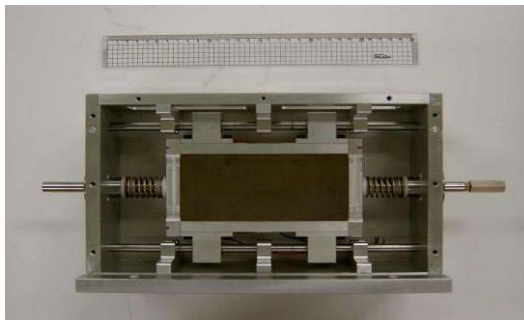


Fig. 15. Current transients from dynamic simulation

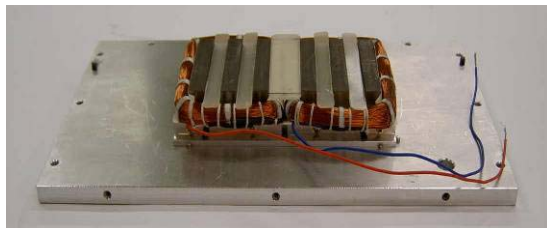
It can be seen that the oscillo-machine shows quick synchronization.



a)



b)



c)

Fig. 16. a) Back to back action prototype b) mover assembly c) stator with coils

VII. DISCUSSION AND CONCLUSION

A novel linear reversal PM machine characterized by mover PM flux concentration has been proposed and proven by FEM capable of 1 kW, 50 Hz, power delivery (generator) at 6N/cm² of thrust for a calculated electrical efficiency of 0.938. and a power factor about 0.7.

The calculated copper losses are 65W which translated into more than 10N/W of losses. The total

active weight of the machine is 13.64 Kg (44N/Kg). And the mover weight is about 2.3 Kg. The efficiency is high for an average speed of 1.44 m/s, and this explains why the weight is not so small. The weight may be further reduced, for lower efficiency. Design optimization may also bring some improvements.

The theoretical results are notably better than for most existing linear PM machines.

Experiments should follow to back up these preliminary results.

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