AC 2011-1731: PERMANENT MAGNET LINEAR ALTERNATOR MAGNETIC FIELD ANALYSIS

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Permanent Magnet Linear Alternator Magnetic Field Analysis

Abstract

Permanent magnet linear alternators are energy converting devices that have been under research and development for years. This type of alternators have advantages of high efficiency and no need of liner motion to rotation converting, when the driving force is in linear oscillation. Such applications can be found when ocean tide, solar power, and swing motions are used for generating electric power.

Magnetic field analysis is essential for electric machine designs. Results from the analysis provide the magnetic field distributions in a machine. Magnetic field analysis may help the designer to modify their design for getting a better product. Magnet field analysis may also be used for finding torque, force, power losses, and induced voltage, which are the primary parameters of electrical machine performance study.

This paper presents the magnet field analysis of a cylindrical permanent magnet linear alternator. This alternator has four permanent magnet rings mounted on a plunger (shaft), which oscillates linearly when the machine is working. The magnetic polarities (N pole or S pole) of the rings are in radial direction and the polarities alternate from one ring to the next on each side of the plunger. Two of the magnet rings are on each end of the plunger and a magnetic loop is formed by the permanent magnet rings, plunger, stator core, and the air gap between plunger and stator core. The stator core is an iron structure surrounding the plunger, magnet rings, and the stator winding. When the plunger is at one end position of its oscillation, one stator pole faces to an N pole of a magnet ring and the other stator pole faces to an S pole of another magnet ring. When the plunger moves to the other end position of its oscillation, the magnet ring polarities face to the stator poles are switched. Therefore, the magnetic flux in the loop changes its value and direction for each cycle of the plunger oscillation. The stator winding, which is a circular coil around the plunger and inside of the stator core, experiences the flux changes and generates AC power.

In this research, the magnetic filed study was conducted with Maxwell software, which is a product of ANSYS Company. The magnetic filed distributions for different positions of the plunger and different space gap between magnet rings were investigated. The results from the research are presented and discussed in this paper.

Introduction

In a cylindrical rotating alternating current (AC) generator, the magnets, which could be either permanent magnets or electrical magnets, are mounted on a rotor. When the rotor is rotating, these magnets create a rotating magnetic filed. The windings in stator slots cut the rotating magnetic field and produce induced voltages. Depending on the winding structure, the induced voltages can be either single phase or three-phase. When an electrical load is connected to the generator, the mechanical power used for driving the rotor is converted into electrical power and delivered to the load. Figure 1 shows a three-phase rotating AC generator[1]. Generators like this one have been used at most of the applications where an AC generator is needed, because majority of the power for driving generators are from a rotating machine, such as hydraulic turbine or a diesel engine.

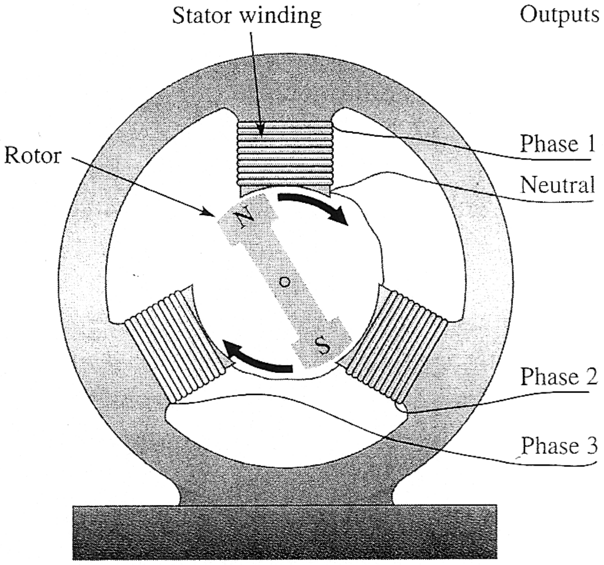

Figure 1. A three-phase AC generator

When the driving power is from a linear oscillating source, the linear moving force has to be converted to rotating torque before it can be used for driving a rotating generator. Such conversion involves extra mechanical parts and power losses. In an application like this, a linear alternator or generator could be more efficient, because no linear force to rotating torque conversion is needed. Linear alternators had been under research for many years [2,3,4,5]. When more and more research is conducted on renewable energy and green energy, linear alternators will get more attention, since some of the new energy sources come with oscillating force in small stroke. One of the examples is generating electrical power with ocean tide energy [6]. In this paper, operation of a linear alternator is reviewed and magnetic field study on this machine is presented.

The computer magnetic field study of this research was conducted as a graduate student project. Through this project, the involving graduate students not only leaned how to use the Maxwell software for creating an electrical machine geometry, adding permanent magnet and current to the machine, and interpreting the calculation results, but also got an in-depth understanding on the linear alternator operation and design as well as what the machine may do in utilizing renewable energy.

Principle of Linear Alternator

Figure 2 is a cross section view of a single-slot single-phase cylindrical permanent magnet linear alternator. This alternator has two parts: a stator and a plunger. The stator consists of a stator core, made of silicon-iron, and a circular stator winding embedded inside of the stator core. The plunger is a piece of silicon-iron tube with four permanent magnet rings mounted on it.

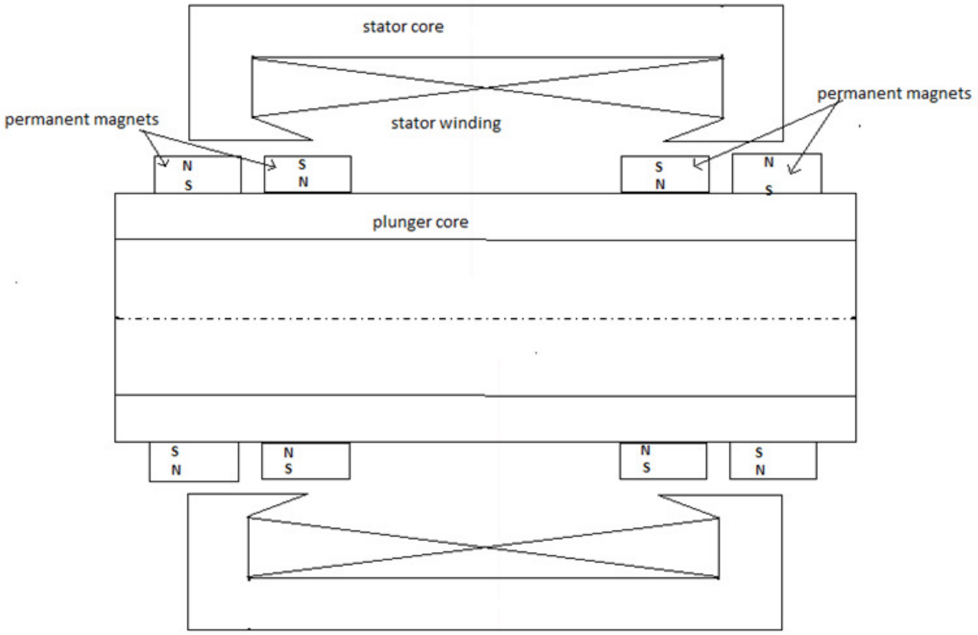

Figure 2. A linear permanent magnet alternator

This permanent magnet linear alternator's magnetic flux loop, the dash line path labeled with ABCDEF, and dimension symbols are shown in Figure 3. When the linear alternator is in operation, its plunger reciprocates with the stroke length:

$$l_{stroke} = \tau_m \qquad (1)$$

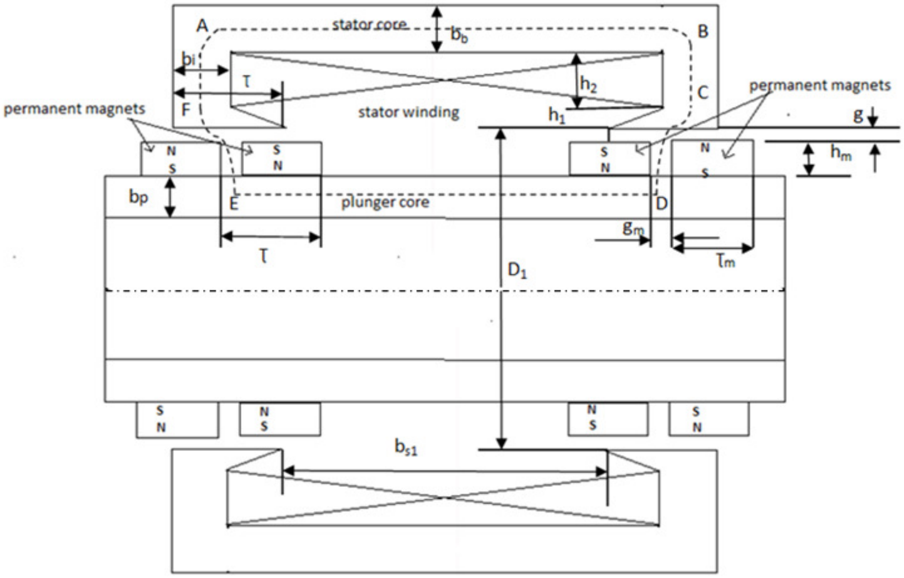

Figure 3. Linear alternator’s flux loop and dimension symbols

At one end of the plunger reciprocation, a stator pole surface covers one permanent magnet ring and the space, labeled as g_m, between the pair of magnet rings at the same end of the plunger, as shown in Figure 5. When the plunger moves to the other end of plunger reciprocation, this stator pole surface covers the space g_m and the magnet ring at the other side of the space, as shown in Figure 9. Hence, the magnetic flux ϕ in the magnetic flux loop of Figure 3 should vary almost linearly with the position of the plunger, as shown in Figure 4. The induced voltage of the linear alternator depends on the plunger moving speed. If the plunger moves sinusoidally, a sinusoidal voltage will be induced in the stator winding.

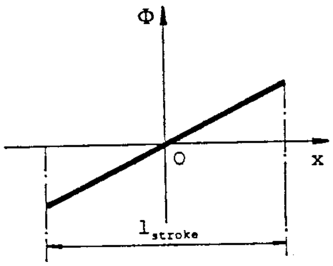

Figure 4. Flux versus plunger position

Electromagnetic Field Analysis Methods and Maxwell Software

Two very useful laws for electromagnetic filed analysis are Ampere's law and the law of continuity of flux. Suppose there are n parts in a magnetic loop, then by the Ampere's law:

$$WI = \sum_{i=1}^{n} H_i l_i \tag{2}$$

and continuity of flux requires that:

$$\phi_1 = \phi_2 = \phi_3 = \ldots = \phi_n \tag{3}$$

In these two equations:

W = turns of winding
I = current in the winding, Ampere
H = field intensity, Ampere/meter
l = length of a magnetic loop section, meter
ϕ = flux, Weber

Other two equations used for electromagnetic field analysis are:

$$B_i = \frac{\phi_i}{A_i} \tag{4}$$

$$B_i = \mu_i H_i \tag{5}$$

where:

B = flux density, Tesla
A = cross section area of flux loop, square meter
μ = permeability of the magnetic loop material

With equation (2) – (5), many electromagnetic filed problems could be solved with magnetic circuit method. However, since the results obtained from these analyses are based on some assumptions, such as the flux distribution is the same at everywhere of each loop section, they more or less have some errors.

Following the development of computer hardware and software, electromagnetic field numerical analysis has been used for more and more applications. One of the numerical analysis methods is finite element analysis, which uses Maxwell equations and boundary conditions for finding magnetic flux and flux density in a magnetic filed [7]. Furthermore, magnetic forces or torques related to the magnetic filed can be calculated from the finite element analysis results.

ANSYS Corporation's Maxwell software is used in this linear alternator electromagnetic filed study. Maxwell is premier electromagnetic field simulation software for engineers tasked with designing and analyzing 3-D and 2-D electromagnetic and electromechanical devices such as motors, actuators, transformers, sensors and coils. Maxwell uses the accurate finite element method to solve static, frequency-domain and time-varying electromagnetic and electric fields. A key benefit of Maxwell is its automated solution process where users are only required to specify geometry, material properties and the desired output. From this point, Maxwell will automatically generate an appropriate, efficient and accurate mesh for solving the problem. This proven automatic adaptive meshing process removes complexity from the analysis process and allows engineers to benefit from a highly-efficient, easy-to-use design flow [8].

Magnetic Field Analysis and Results

The no-load (stator current = 0) electromagnetic field of the permanent magnet linear alternator in Figure 3 was investigated with Maxwell software. The calculation results show the distributions of the flux and provide guidance for future improvement of the alternator. The results also tell how the magnet field is affected by the spaces between the two permanent magnet rings at each side of the plunger. This effect is very difficult to be investigated by magnetic circuit method discussed in the last section. The initial width of this space (g_m) was 0.2 inch. Then it was changed to 0.15 inch and 0.25 inch. The magnetic field for each of the space width and several plunger positions were calculated with Maxwell software.

The dimensions of the alternator used in the study are:

τ_m = 1.0 in; h_1 = 0.2 in; h_2 = 2.0 in; g = 0.03 in; h_m = 0.4 in; b_i = 0.8 in;
b_b = 0.8 in; b_p = 0.8 in; b_{S1} = 3.5 in; D_1 = 16 in, and $\tau = \tau_m + g_m$.

Both stator core and plunger materials are silicon-iron and the permanent magnets are NdFe35.

Figure 5 to 9 show the linear alternator's flux distribution for different plunger positions, which change from left to right with a 0.25 inch interval (one-fourth of a stroke). In these figures, g_m =0.2 in. These results prove the mutual magnetic flux, which is the flux loops around stator winding, does change linearly with the plunger position as shown in Figure 4. The mutual flux has maximum value but opposite direction, when the plunger is at two end positions of reciprocation (Figure 5 and 9). It is 0, when the plunger is at the middle position of reciprocation (Figure 7).

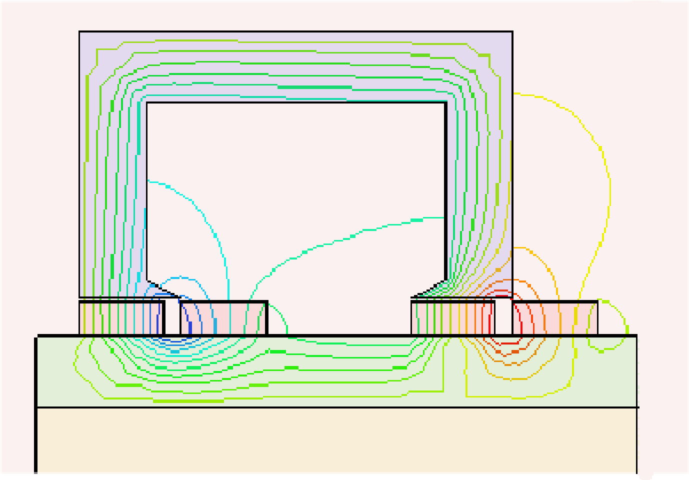

Figure 5. Magnetic field for plunger at left end point

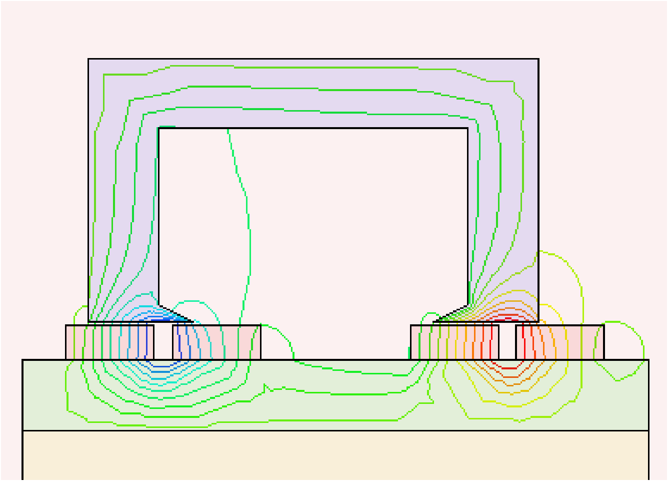

Figure 6. Magnetic field for plunger moving 0.25 inch to right

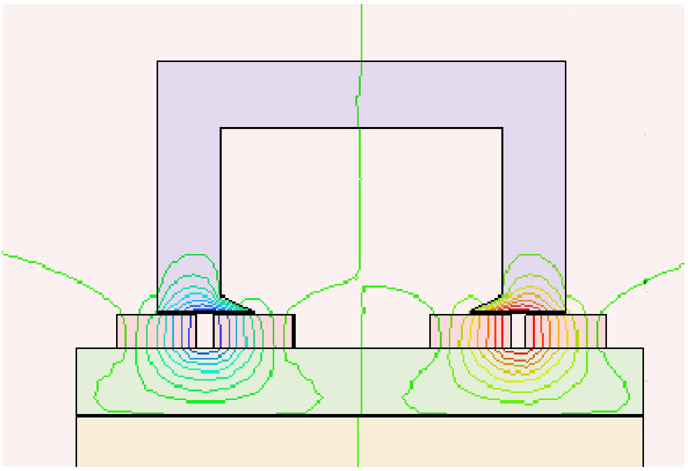

Figure 7. Magnetic field for plunger moving 0.50 inch to right

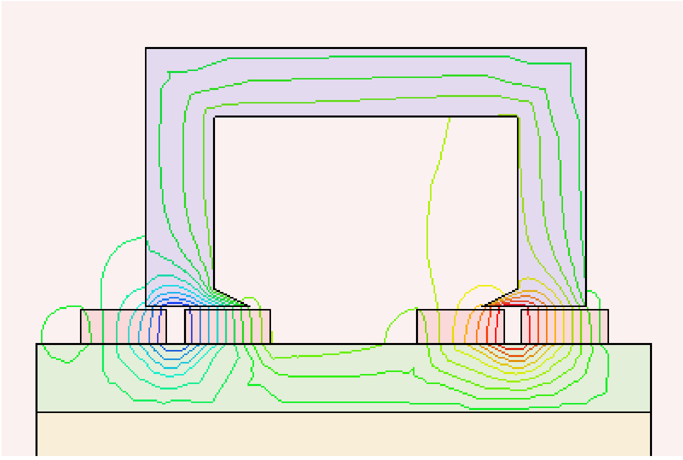

Figure 8. Magnetic field for plunger moving 0.75 inch to right

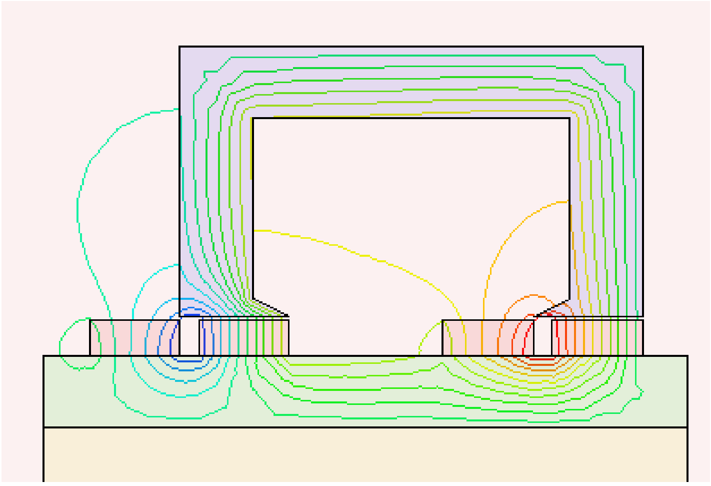

Figure 9. Magnetic field for plunger at right end position

Figure 10 and 11 show the magnetic filed when the plunger was at left end position, but g_m was changed to 0.15 inch and 0.25 inch. Comparing to Figure 5 where g_m was 0.20, the space between the two magnet rings was decreased 0.05 inch or 25% in Figure 10 and increased 0.05 inch or 25% in Figure 11. However, both the mutual flux and leakage flux, which is the flux that does not loop around the staotr winding, have no significant change when g_m value was modified.

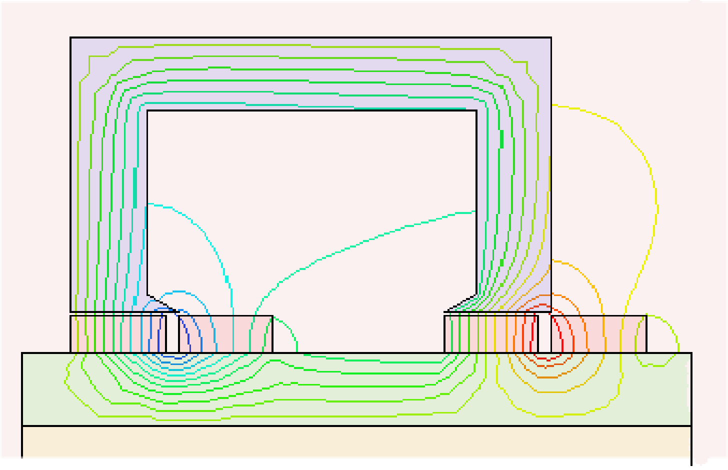

Figure 10. Magnetic field for plunger at right end position and 0.15 inch space between two magnets

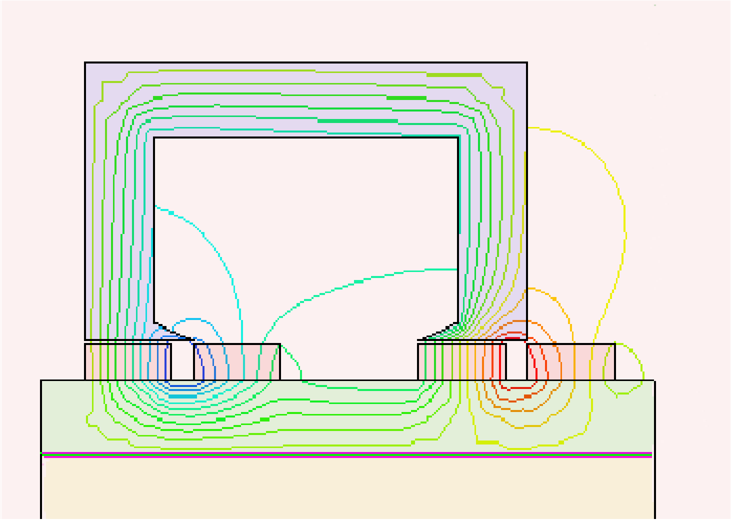

Figure 11. Magnetic field for plunger at right end position and 0.25 inch space between two magnets

Conclusions

The linear alternator's no-load magnetic field was calculated for different plunger positions and different values of the space between two magnet rings. Although only the flux line distribution is presented in this paper, the flux value at any point of the linear alternator has been found. The calculated results demonstrate the mutual flux varies linearly with the plunger position and the space between two magnet rings has very little effect to the mutual flux and leakage flux.

The students involving in this research have learned applying electromagnetic theory in magnetic field analysis and using Maxwell software in 2-D and 3D magnetic filed simulations. They also have an in-depth understanding on the permanent magnet linear alternator operation and design.

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