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THE DESIGN, DIMENSIONING AND OPTIMIZATION OF A 1 KVA TUBULAR LINEAR ALTERNATOR

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ABSTRACT

In this study; basically the design of a 1KVA tubular linear alternator has been carried out for a free mechanical piston and internal combustion engine. In the conducted design, the conformity of the optimization data has been examined with finite elements method and the geometrical dimensionings of the designed alternator have been determined with a developed analytical calculation program. Because it is aimed to attain an alternator for usage in hybrid-electrical vehicles with this study; within this scope, the operational frequency and stroke status of internal combustion engine have been taken into consideration. In addition to the data of operational frequency and stroke status belonging to an internal combustion engine, the dimensions of a linear generator have been determined by using a circuit model equivalent to the generator. The physical shape of this generator is in tubular. Within the scope of the study; they have also been compared to the calculated analytical data, optimized dimension, weight, volume and cost values belonging to the alternator.

INTRODUCTION

Today; the increase in population, industrial developments and the decrease in the fossil fuels increase the need for energy day by day and therefore; new energy sources are seeked and the usage productivity of the existent resources have been oriented to increase. One of this orientation areas is the technology of hybrid electrical vehicles. Additional sub-systems producing energy are needed for the hybrid vehicles to provide high transportation range and usage comfort. The electricity is produced via regenerative braking system while a motor vehicle goes downhill or it brakes; in addition, the battery group could be continuously charged with the free piston system producing energy while driving. In addition to these applications, linear alternators are used in the suspension systems of the hybrid/electrical vehicles both for the minimization of the vibrations stemming from the road and the production of electricity. An internal combustion free piston motor could produce electricity with the help of a linear alternator when it is in forward-back (linear) motion cycle. Boldea (Boldea, 2013) has written a comprehensive book upon the existent and new linear machine topologies, their usage areas, advantages and disadvantages.

Atkinson *et al*. have conducted a design and application of a free piston linear alternator with the cylinder internal diameter of 36.5mm, maximum stroke length of 50mm and with the output power of 79V and 316W at full load in West Virginia University (Atkinson *et al*., 1999). Cawthorne has designed a linear brushless alternator with permanent magnet (Cawthorn, 1999). Rerkpreedapong *et al*. have designed moving iron alternator placed on the stroke and conducted the area analyses with the finite elements method (Rerkpreedapong *et al*., 1999)). Blarigan *et al*. have carried out the design and application of double piston linear alternator (whose fuel has nitrogen addition) with the power of 40KW (Blarigan *et al*., 1998, Blarigan, 2002). Arof *et al*. have analyzed the linear generator with permanent magnet via finite elements method (Arof *et al*., 2004). Abidin *et al*. have realized the application of the starting conditions of two-piston tubular linear alternator (Abidin *et al*., 2012). Wang and Howe have tried to determine convenient geometries with analytical equations for tubular linear machine with radial flux (Wang *et al*., 2004). Chen *et al*. (Chen *et al*., 2004) have compared the tubular linear alternator with longitudinal flux and axial magnet in terms of iron, loss of copper, productivity and power density depending on the change in the number of poles.

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Wang and Howe (Wang *et al*., 2005) have compared the use of soft magnetic materials with siliceous sheet (Transil 300) in tubular linear machines in terms of productivity, power factor, force, iron and loss of copper. Wang *et al*. have tried to estimate the knocking force with analytical equations for the purpose of decreasing the knocking force in tubular linear machines (Wang *et al*., 2005; (Wang *et al*., 2004)). Max has examined the differences between double and anti piston structures and has realized the linear alternator application for the double piston structure (Max, 2005). Pohl and Graf have conducted the dynamic analysis of a free piston linear alternator (Pohl *et al*., 2005). Ahmad *et al*. have tried to decrease the knocking force by using a special magnet structure in the tubular linear alternators (Ahmad *et al*., 2006). Faiz *et al*. have carried out the design and application of tubular induction alternator for free piston applications (Faiz *et al*., 2006). Nemecek and Vysoky have conducted the movement control of the free piston linear alternator under normal operation (Nemecek *et al*., 2006). Cosic has designed a tubular linear generator with transverse flux for usage in internal combustion engine and has applied it with crank and connecting rod mechanism (Cosic, 2010). Xu and Chang have designed a linear generator with bobbin movement for the free piston applications (Xu *et al*., 2010). Li and Chau have examined the force change of the linear magnetic teeth alternator under low and high speeds for free piston applications (Li *et al*., 2010). Razali *et al*. (Razali *et al*., 2010), Gieras *et al*. (Gieras *et al*, 2011) have worked on the flat type machines with permanent magnet. Zheng *et al*. (Zheng *et al*., 2011) have conducted the design of linear generator with different transverse flux for free piston applications and shown that they have lower knocking force and better productivity when compared to the existent machines with transverse flux. Kock *et al*. (Kock *et al*., 2013) have combined the linear alternator and the spring mechanism that could slow down the piston movement and carried out the design and application of flat type linear alternator in accordance with different fuels. Kosaka *et al*. (Kosaka *et al*., 2014), Goto *et al*. (Goto *et al*., 2014) have designed and applied free piston linear alternator with high productivity, short stroke and with the power of 10 KW and in which various fuels could be used. Zulkifli (Zulkifli, 2007) has integrated tubular alternator with internal combustion engine. The purpose of this study is to develop a free piston alternator producing additional energy for the rapidly developing hybrid vehicles. For this; tubular linear alternator has been designed with Matlab Gui based interface. The analyses have been carried out by accepting the most convenient 57.6 HZ and stroke length is 32.5 mm as the input parameter in the design of the mechanical system that could give the best productivity for 1KVA (Robinson, 2015). It has been seen that the geometric and equivalent circuit parameters belonging to the designed linear alternator are convenient for the free piston applications.

DESIGN AND DIMENSIONING

If the stator of a machine is split in half and pressed, double-sided flat machine stator is attained. If the linear secondary (rotor) is placed between the separated stator, bilateral movable linear machine is attained. If one of the stator parts are taken out of the system, uni-lateral movable linear machine is attained. If the motionless part is rolled again around an axle in parallel to the direction of area movement, a completely different cylindrical structure is formed and the magnetic area is ensured to move along the occurring primary split. These machines are called as tubular machines. Tubular structure is preferred due to the fact that it has less stray flux when compared to the flat structure and it has higher electromagnetic force (emf) (Ansys Maxwell Files; Schmülling *et al*., 2010). In addition; there will be very little force on the bearings and their life cycle will increase due to their other advantages and the balance in the high forces (normally) withdrawing between the armatures (the total of the normal forces is equal to zero) (Schmülling *et al*., 2010). In addition; other advantages could be said as high impulse force, having perfect servo-characteristics due to not seeing the final impact (final winding impact) in the flat linear generators, easy construction, termination of the need for the usage of movement transformation mechanisms, decrease in the mechanical losses and increase in reliability. It is desired that the forces in linear generators are not asymmetrical. For this reason; single-sided flat type is not preferred (Chen *et al*., 2004; Ribeiro *et al*., 2010). While the magnetic flux density between the air ranges of tubular structured generators is in fixed value, the magnetic flux density changes due to the fact that the air way length in the 4-corner structure is higher. When compared to the tubular type generator, iron and copper losses are more in 4-corner structure. For this reason; their productivity is lower (Oprea *et al*., 2011). In addition; tubular machines are separated depending on the flux direction (radial, axial, halbach). The windings in boreless structure are ordered through the ferromagnetic materials in the shape of an empty cylinder. In the structure with bore, they are placed in the bores inside the primary.

Linear generators with permanent magnet are used due to their high force density and high productivity in the free mechanical piston systems. Linear generators show varieties such as radial flux, embedded, halbach ordered or longitudinal-transverse flux. Generators with radial flux are widely used due to having low knocking force. In this study; the design of a tubular generator with 4 poles and 1 KVA power has been considered.

Some magnitudes in the generators with radial flux show differences for linear machine. The magnitude of the torque and knocking torque in the radial flux generator is given as force and knocking force in linear generator. The design is commenced with the expression of the force in the traditional rotating engines or generators. However; because the linear machines are characterized with force, the calculation will be commenced with the expression of force given in Eq. 1:

$$F_x = \frac{P}{\eta v} \tag{1}$$

Here; F_x is proportional to the expression of force; P is proportional to the power, η is proportional to the productivity and v is proportional to the nominal speed. F_x is the force density or common voltage (10000–15000 N/m^2).

The main dimension of the generator could be calculated with the efficient air range in linear generator.

$$D = \frac{A_{air}}{\pi L_p} \tag{2}$$

Here; L_p expresses the primary length and D expresses the diameter up to the primary threads. The synchronous speed is calculated with the Eq. 3 in the generators with permanent magnet.

$$v = 2fT_{op} \tag{3}$$

Here; T_{op} is given as the pole step and f is given as the frequency. Pole step is the distance of N-S pole to the other pole. Primary length L_p could be defined with Eq. 4:

$$L_p = T_{op} N_p \tag{4}$$

D ve D_e is value;

$$D = 2H_s + 2L_m + 2g \tag{5}$$

$$D_e = D + 2H_w + 2H_p \tag{6}$$

Conducting design in analytical way and conducting solution with the finite elements provide shorter time in 2-D design and easiness in solution. The operating distance of the linear generator is expressed as the stroke length. Due to the forward-back movement, total stroke length is $2L_{str}$. Therefore; total secondary length will be calculated with Eq. 7:

$$L_s = L_p + 2L_{str} \tag{7}$$

Primary thread width;

$$T_w = T_{os} - B_w \tag{8}$$

b_{tson} Thickness of thread in the last parts to decrease the knocking force in the right and left sides of the primary core:

$$b_{tson} \approx 0.52T_{op} \tag{9}$$

Approximately; The ratio of the bore width (B_w) to the thread width (T_w) affects the electrical and magnetic loading. As this ratio increases, the electrical loading increases despite the decrease in the magnetic loading due to the stray flux. This ratio is selected between 1.6 and 2 for maximum force (Giacometti *et al*., 2014). The equality of the bore width and thread width is sufficient for the commencement of the design under these criteria. Slot width;

$$B_w = T_w \tag{10}$$

In Figure 3, on condition that it is open bore; while H_{p0} is given as the height of the bore clearance, H_{p1} is given as the maximum height of bore thrust, Bw0 is given as semi-open bore width, B_{s1} is given as the upper width in radial flux machines, they are taken as equal to the sub-width (B_w) in the linear machines. Hs is given as the winding height.

$$H_w = H_{pw} - H_{p1} + H_{p0} \tag{11}$$

In Figure 1; simplified 2-D image of the attained 4-pole tubular linear generator is given in rz plane:

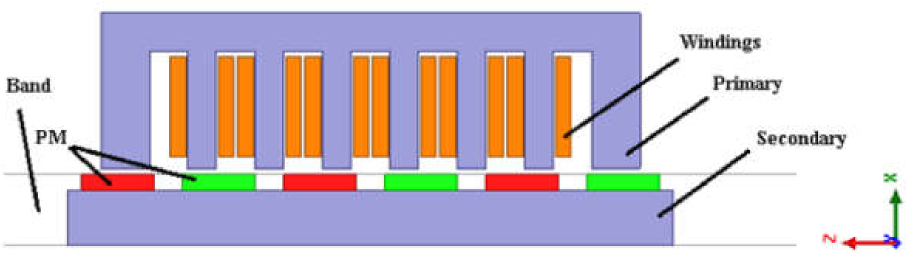

Figure 1. Image of tubular linear generator in rz plane

Stray flux is calculated with Eq. 12 on condition that Φ_g is the air gap magnetic flux and Φ_m is the magnetic flux resource:

$$k = \frac{\Phi_m}{\Phi_g} = 1 + 2\frac{R_g}{R_{ms}} + 4\frac{R_g}{R_{mm}} \tag{12}$$

If the equivalent model of Figure 1 is extracted, the equivalent circuit model in Figure 2 is attained as Rg air gap reluctance, Rp primary reluctance, Rmm Magnets and Rms magnet secondary reluctance and Rt primary thread reluctance. Rg is given in Eq. 13, Rms is given in Eq. 14 and Rmm is given in Eq. 15 (Chen *et al*., 2014).

$$R_g = \frac{L}{A\mu_o} = \frac{g}{\mu_o T_m \pi (D-2g)} \tag{13}$$

$$R_{ms} = \frac{g + \pi g}{\mu_o g \pi (D-2g)} \tag{14}$$

$$R_{mm} = \frac{(T_{op} - T_m) + \pi g}{\mu_o g \pi (D-2g)} \tag{15}$$

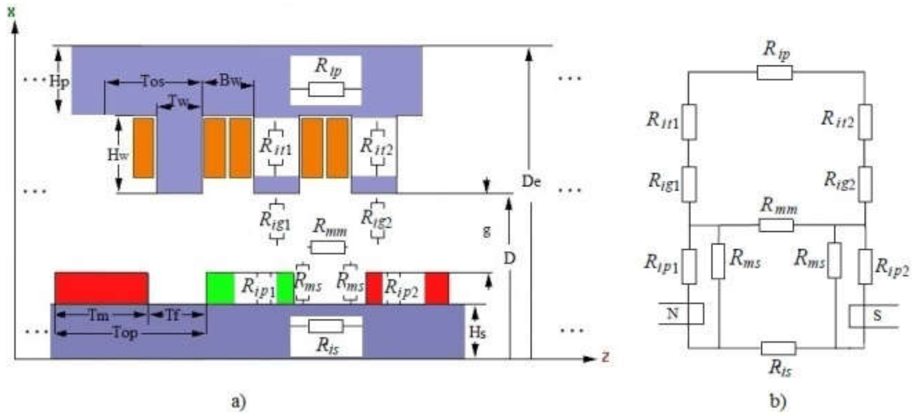

Figure 2. a) Extraction of reluctance model b) Magnetic equivalent circuit model

Generally the electrical machines modeled with approximate magnetic circuit saving time for the researchers from the complex reluctance calculations are seen rather than the fully magnetic circuit model. Some reluctance values in the magnetic circuits modeled with approximate magnetic circuit are neglected and the calculations are made in this way. Because the primary and secondary materials are ferromagnetic ones (permeability is between μ_r 1000-10,000), the reluctance values in the stator and rotor may be neglected. The reluctance values of ferromagnetic materials are not included in the magnetic circuit. In this way; the magnetic circuit is modeled with the reluctance value in the air gap. The neglected magnetic flux is shown in Equation 16:

$$\phi_i = \frac{2F_{PM}}{R} = \frac{2H_C L_m}{(R_{i1p} + R_{i1g} + R_{i2p} + R_{i2g})} \tag{16}$$

Purpose Functions and Optimization

Although currently used FEM-based software items include the analytical calculation equations belonging to the traditional machines, there are no design modules on the linear machine design. For this reason; Matlab-based iterative design and optimization software has been developed for tubular alternator used in free piston applications. The analytical results attained from Matlab Gui within the direction of the developed Matlab interface, optimization modules and input data given in Table 1 are given in Figure 3.

Table 1. Input Data for the Dimensioning of the Generator

	Value	Unit
Frequency	57.6	Hz
Stroke Length	0.0325	m
Force Density	2	N/cm^2
Magnet Thickness	0.005	m
Air Gap	0.002	m
Current Density	3	A/mm^2
Induced Voltage	55	V
Primer Yoke Flux Density	1.8	T
Working Temperature	80	C^o
Slot/Pole	6/4	-
Fill Factor	0.7	-
Approximate Cost of Copper	30	Tl
Approximate Cost of Magnet	250	Tl
Approximate Cost of Steel	10	Tl

Input data have been formed by taking into consideration the stroke length, frequency and power value given for the mechanical system having maximum productivity for 1KW [29]. Common tension is taken as 2N/cm^2 for such kinds of alternators. The selection of this value as high will significantly decrease the alternator dimensions; but it also causes to heat problem. The dimensional data of tubular generator to be used in the mechanical system has been calculated with Matlab Gui (Figure 3).

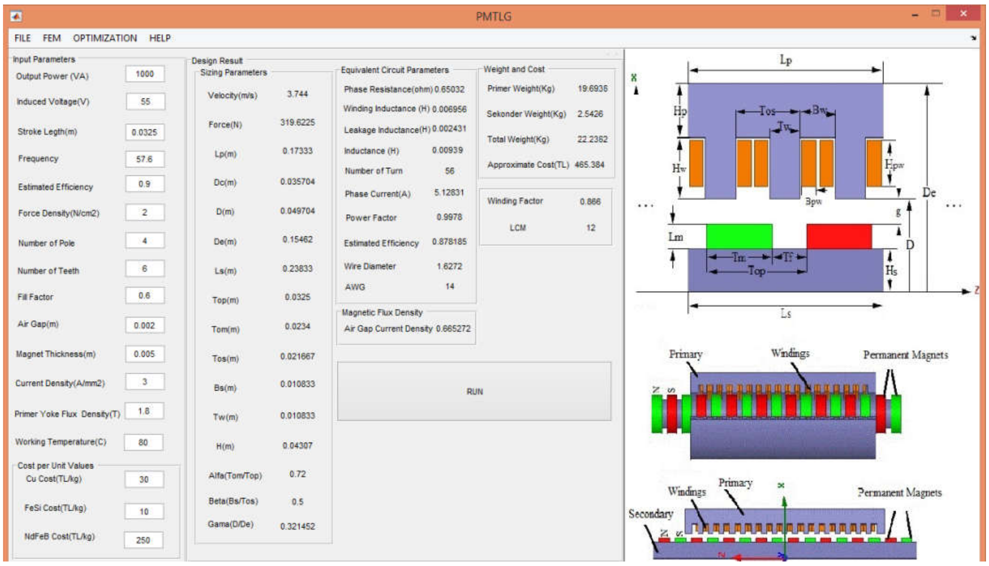

Figure 3. Matlab Gui interface and optimization modules

Both analytical design has been conducted and iteratively most convenient design results have been tried to be reached with the developed algorithm (Figure 4). The value calculated in each iteration made within the algorithm and the value desired in starting design parameters have been compared and the winding parameters in the stator are changed and in accordance with this, design dimension values are re-calculated. The common parameters used in this study are respectively the current density, productivity, weight, cost and volume. These variables have been defined among the purpose functions in many different configurations.

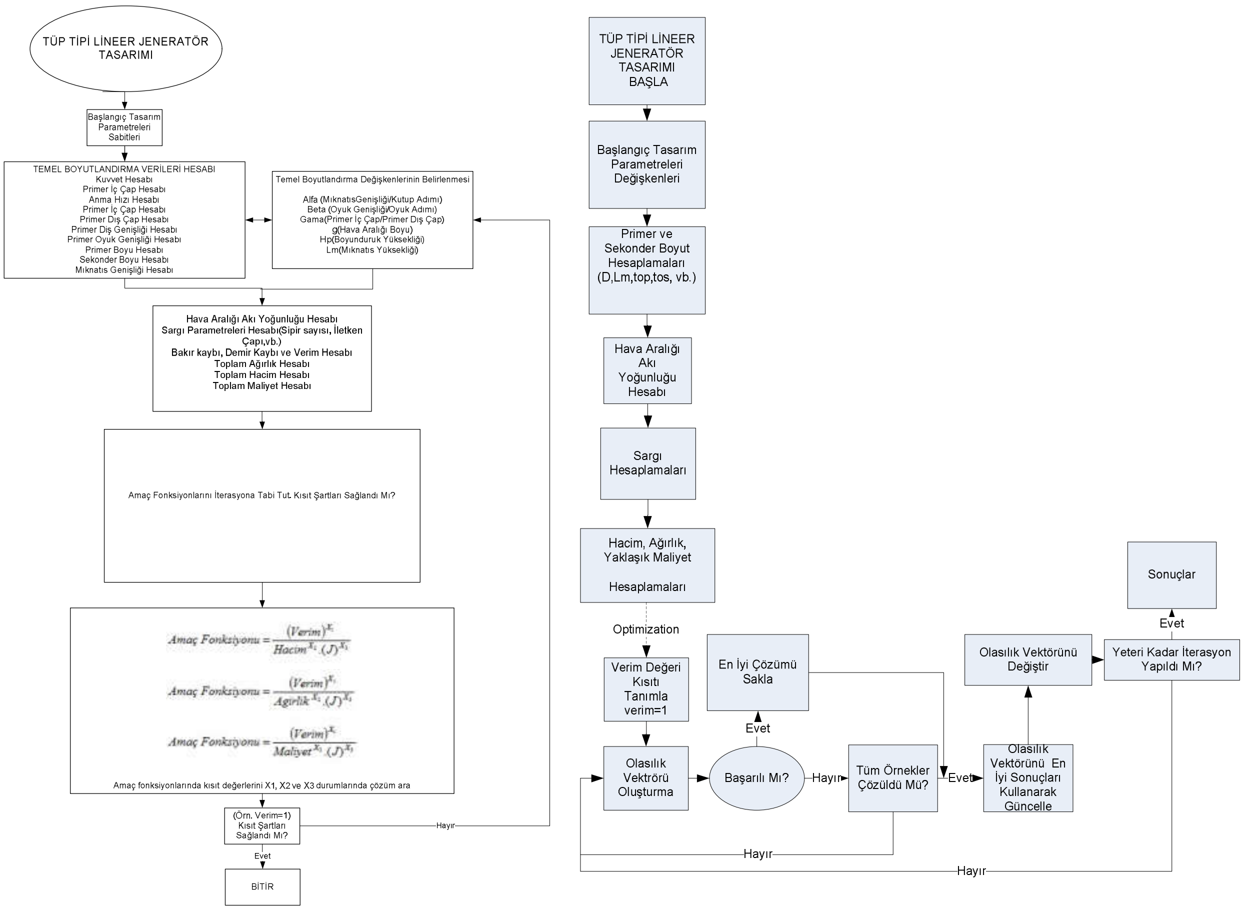

Figure 4. Solution algorithm for the tubular linear generator and the flow diagram of Analytical-SEY optimization

Primary M700 steel density has been 7700 *kg/m³*, secondary 1020 steel density has been 7872 *kg/m³*, NdFeB 35 magnet density has been 7400 *kg/m³* and copper density has been 8933 *kg/m³*. The weight and cost functions used in the algorithm developed in this study have been respectively defined in Eq. 17-19:

$$\text{Purpose function 1} = \frac{(\text{Efficiency})^{X_1}}{Volume^{X_2}.(J)^{X_3}} = \frac{\left(\dfrac{3E_f I_f}{F_x v}\right)^{X_1}}{(V_{sp}+V_{ss}+V_m+V_{cu})^{X_2}.(J)^{X_3}} \tag{17}$$

$$\text{Purpose function 2} = \frac{(Efficiency)^{X_1}}{\text{Weight}^{X_2}.(J)^{X_3}} = \frac{\left(\dfrac{3E_f I_f}{F_x v}\right)^{X_1}}{(V_m\rho_m+(V_{sp}\rho_{fep}+V_{ss}\rho_{fes})+V_{cu}\rho_{cu})^{X_2}.(J)^{X_3}} \tag{18}$$

$$\text{Purpose function 3} = \frac{(Efficiency)^{X_1}}{Cost^{X_2}.(J)^{X_3}} = \frac{\left(\dfrac{3E_f I_f}{F_x v}\right)^{X_1}}{(V_m\rho_m P_{cm/kg}+(V_{sp}\rho_{fep}+V_{ss}\rho_{fes})P_{cfe/kg}+V_{cu}\rho_{cu}P_{ccu/kg})^{X_2}.(J)^{X_3}} \tag{19}$$

The defined three different optimizations have been examined under four different conditions. The conditions for the optimization purpose function could be explained as follows:

1st Condition X_1=1, X_2=X_3=0 focuses on separately increasing the performance in purpose functions, in other words, the productivity value.

2nd Condition X_1=0, X_2=X_3=1 focuses on decreasing the volume, weight and cost to minimum level in purpose functions.

3rd Condition X_1= X_2=0, X_3=1 focuses on decreasing the current density to increase the performance.

4th Condition X_1=X_2= X_3=1 focuses on increasing the general performance.

The cost has been calculated on the geometry given in Figure 4 while conducting cost calculation. The manufacturing costs have not been included in the calculations. The use of round or rectangular sectioned copper will form results different in terms of costs. In addition; the manufacturing costs, sheet cutting (laser cutting, teleresion etc.) and workmanship have not been included in the manufacturing costs due to having different costs.

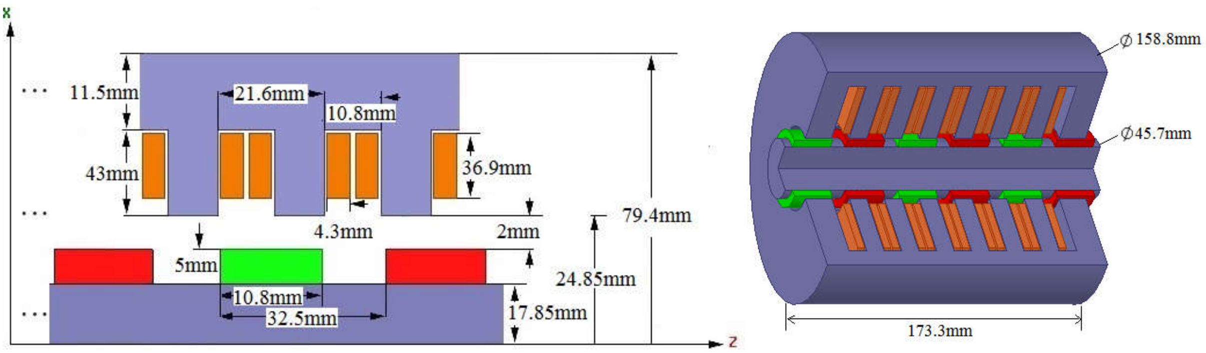

Figure 5. Tubular generator for sizing data

Optimization Results and Finite Elements Analysis

The generator dimensioning values calculated in response to the dimensioning parameters in Table 1 have been examined under three different conditions after the process of iterative optimization. Design 1 given in Table 2 has been maximized for the purpose function 1 and productivity has been maximized for 2.

Design 3 and 4 minimize the generator volume for the purpose function 1. Again; Design 5 and 6 provide maximization for the increase of general performance depending on the productivity, volume and current density for the purpose function 1. The attained results are given in Table 2. Generator main dimensioning data as a result of the analytical calculation are given in Table 2: The attained data, the increase or decrease in percentage in terms of weight, cost and productivity when compared to the first design data are shown in Table 3. The decrease in the movable weight is among the properties seeked in free piston applications.

As it is known; the acceleration of the moving part will increase as the movable weight decreases under a fixed force. The most convenient situation in which total weight and movable weight decrease and an increase in productivity is observed is seen as Design 2 (Table 3). The analysis of the first design and Design 2 has been carried out with the finite elements method.

Table 2. Generator main dimensioning output data and optimization results

	First Design Analytic	Design1 X1=1, X2=0, X3=0, Analytic	Design2 X1=1, X2=0, X3=0, FEM	Design3 X1=0, X2=1, X3=0, Analytic	Design4 X1=0, X2=1, X3=0, FEM	Design5 X1=1, X2=1, X3=1, Analytic	Design6 X1=1, X2=1, X3=1, FEM	Unit
Primer inner diameter, D	0.0497	0.0497	0.0497	0.0497	0.0497	0.0497	0.0497	m
Primer length, Lp	0.1733	0.1733	0.1733	0.1733	0.1733	0.1733	0.1733	m
Secondary length, Ls	0.23833	0.23833	0.23833	0.23833	0.23833	0.23833	0.23833	m
Primer slot step, Tos	0.02167	0.02167	0.02167	0.02167	0.02167	0.02167	0.02167	m
Secondary pole step Top	0.0325	0.0325	0.0325	0.0325	0.0325	0.0325	0.0325	m
Primer slot height, Hw	0.04307	0.03102	0.04074	0.03403	0.034	0.03347	0.04752	m
Primer yoke height, Hp	0.01152	0.01499	0.01147	0.01369	0.01369	0.01402	0.00827	m
Magnet height, Lm	0.005	0.00725	0.0065	0.0085	0.0085	0.009	0.003	m
Magnet width, Tom	0.0234	0.0234	0.02691	0.01404	0.01404	0.01638	0.01404	M
Number of turn	56	46	58	49	48	48	69	
Alfa (Tom/Top)	0.72	0.72	0.828	0.432	0.432	0.504	0.432	
Beta (Bs/Tos)	0.5	0.575	0.55	0.55	0.55	0.55	0.55	
Gama (D/De)	0.31281	0.3507	0.3224	0.34244	0.342	0.343	0.3081	
Sekonder weight	2.5426	2.557	2.43	1.99	1.99	2.052	2.52	Kg
Total weight	22.23	18.012	20.51	18.21	18.21	18.2	21.89	kg
Approximate cost	465.38	468.89	514.84	402.75	402.75	435.15	384.92	TL
Efficiency	0.87	0.892	0.928	0.88	0.728	0.889	0.8241	

Table 3. The assessment of the design data

	First Design	Design1 Analytic %	Design2 FEM %	Design3 Analytic %	Design 4 FEM %	Design5 Analytic %	Design6 FEM %
Sekonder weight	2.5426	0,566	-4,428	-21,73	-21,73	-19,29	-0,88
Total weight	22.23	-18,97	-7,73	-18,08	-18,08	-18,12	-1,52
Approximate cost	465.38	0,75	10,62	-13,45	-13,45	-6,49	-17,28
Efficiency	0.87	2,52	6,66	1,14	-16,32	2,18	-5,27

The motion mechanism of the free piston shows a sinusoidal speed profile. For this reason; the operating profile of the tubular linear alternator modeled in Ansys-Maxwell 2D rz plane in nominal speed is shown with Figure 6:

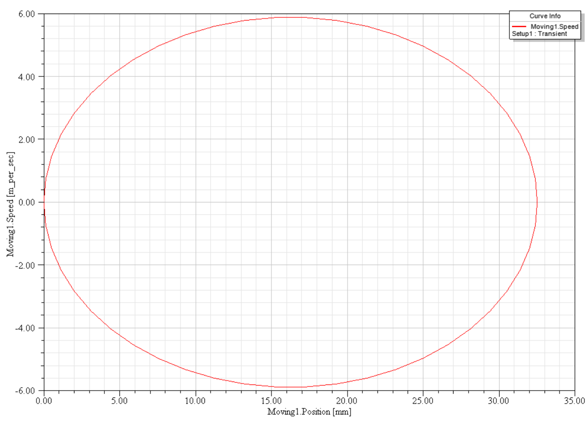

Figure 6. Speed-Position change

The speed profile result given in Figure 6 and the waveform of the tension induced in the windings for the first design and Design 2 are given with Figure 7:

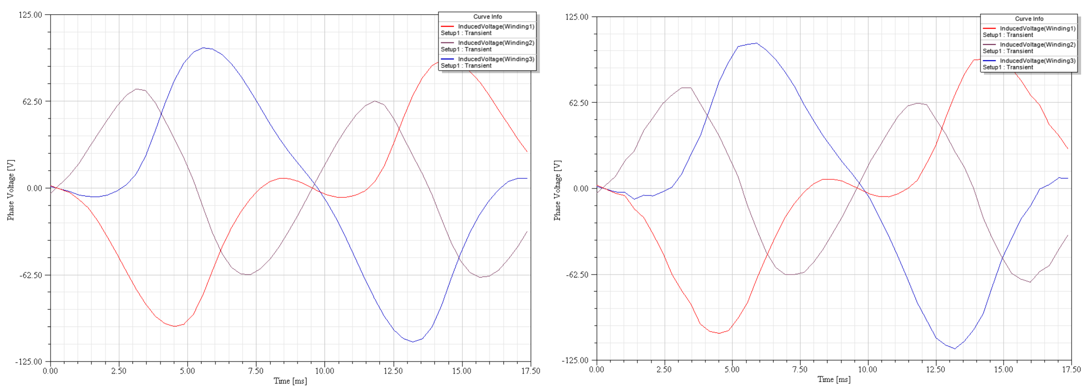

Figure 7. The voltage induced in the windings

The speed profile result given in Figure 6 and the waveform of the current passing from the phase windings for the first design and Design 2 are given with Figure 8:

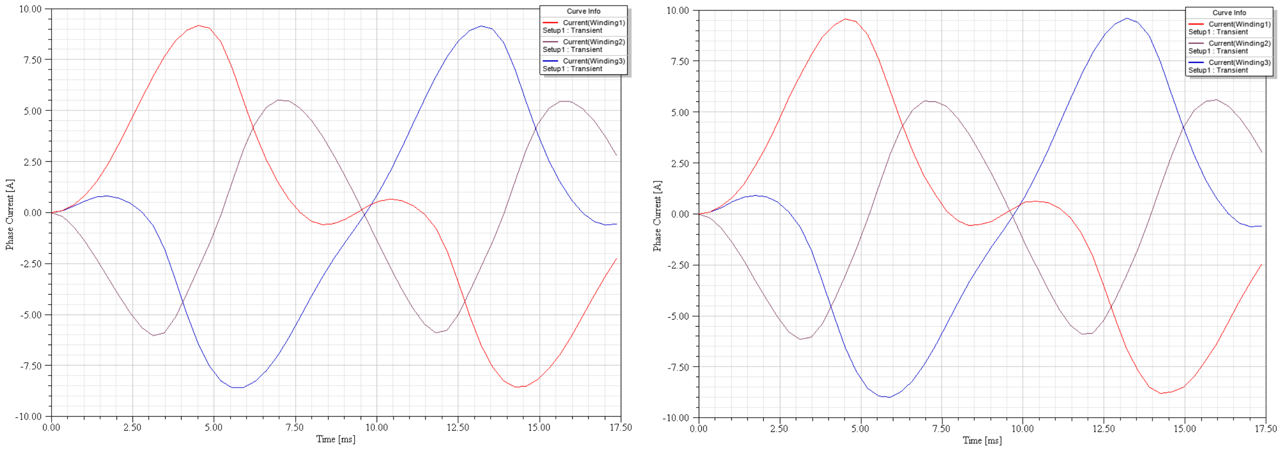

Figure 8. Phase currents

Flux linkages due to the PMs for Phase A,B and C of both the designed generators are compared in Fig. 9.

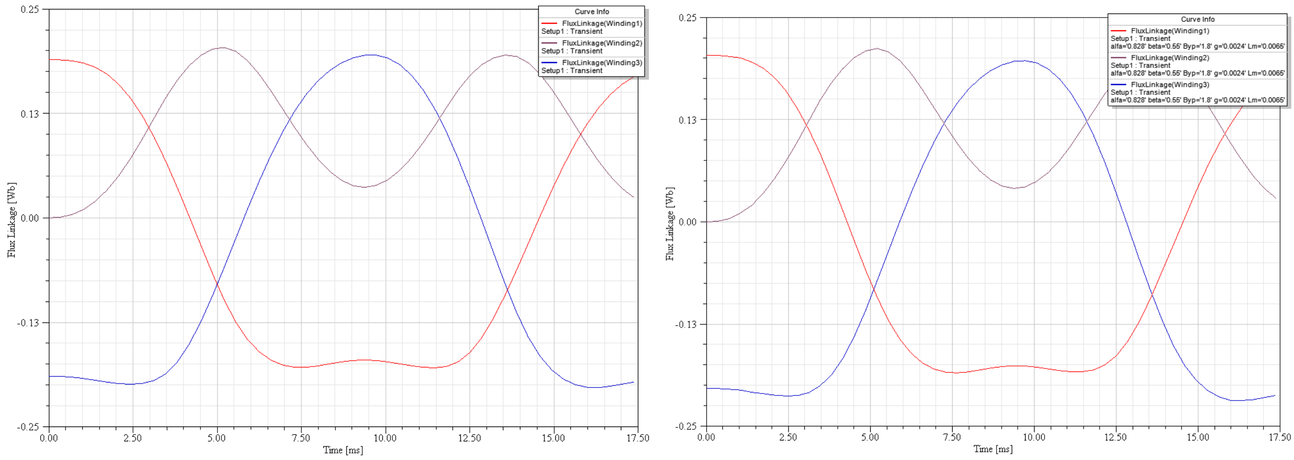

Figure 9. Comparison of flux linkage (a) First design. (b) Optimized design

The speed profile result given in Figure 6 and the output force change for the first design and Design 2 are given with Figure 10:

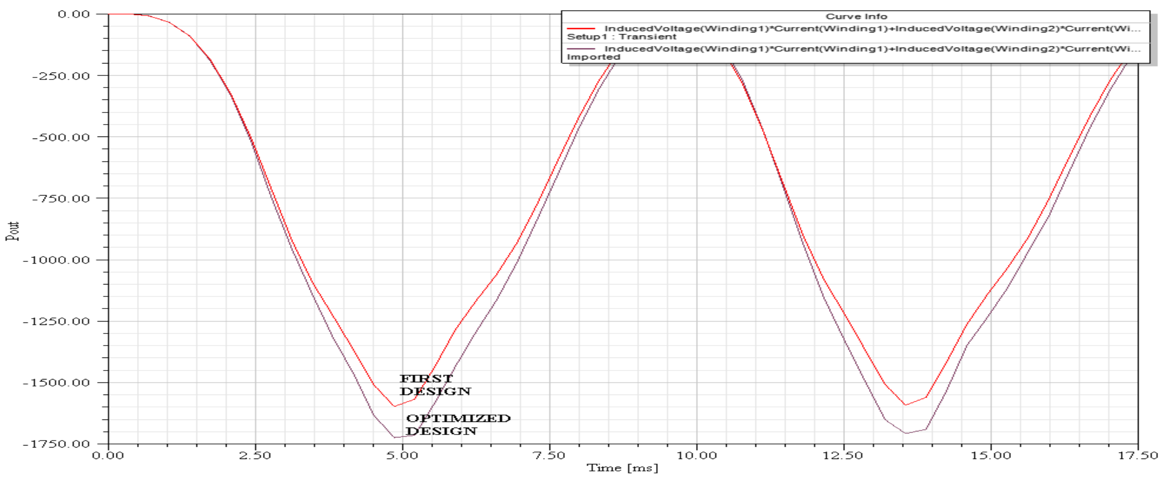

Figure 10. Output force change

The tension induced in the windings is in direct proportion to the flux density in the air gap. In addition; it is obligatory to know the magnitude of the magnetic flux density in the core thread to be able to prevent the magnetic saturation possible to occur in the threads of the core.

Line has been defined alongside the air gap and primary core threads. The air gap flux density change alongside the defined line and the magnitude of the magnetic flux density in the threads could be seen (Figure 11).

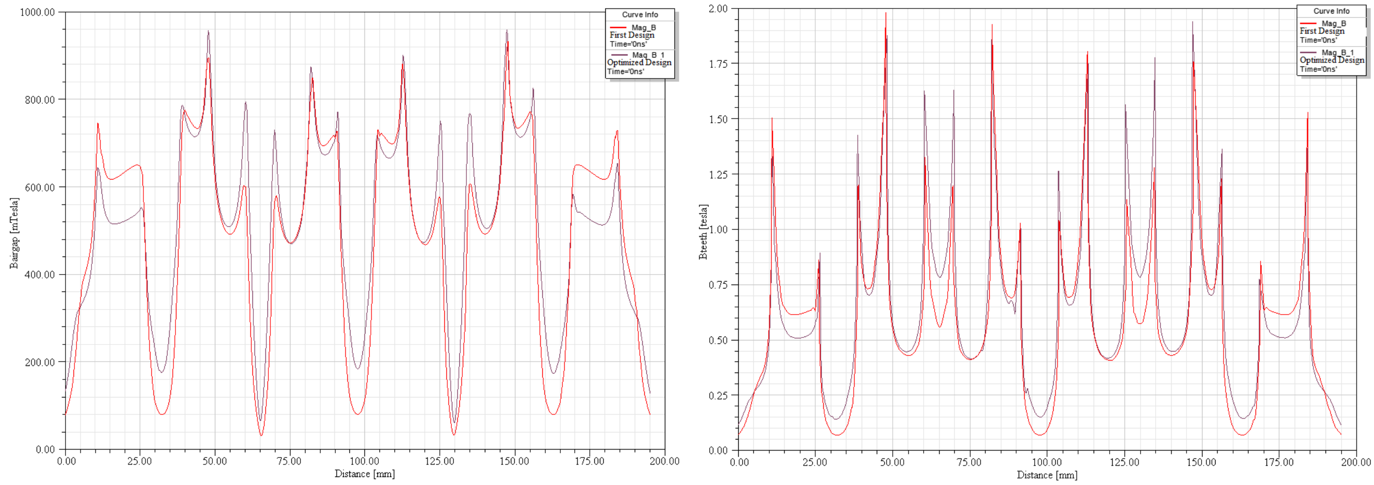

Figure 11. The air gap flux density and the thread flux density change

Conclusion

In this study; tubular linear alternator has been designed for the free piston applications and design software has been developed. Three different purpose functions have been defined for usage in this software and all these purpose functions have been examined under four separate conditions. Purpose function 1has been used for the optimization success test. The attained analytical results have been used to form two dimensional analysis model of the alternator in finite elements environment. The results of the analytical and finite elements analyses have been submitted in the study. The calculation results of the program developed with the conducted analysis results are in conformity with too little error margins. Matlab-based iterative design and optimization software has been developed for the linear alternators frequently used in the areas in which the production of electricity is currently needed from the linear movement. The purpose functions defined in the study could also be used within its own solution domain and also in the solutions of other generator dimension optimization problems. In addition; the approximate cost of the alternator could be calculated thanks to the cost function used in the software. The attained results have shown that Design-2 has better values in terms of weight and productivity when compared to other designs.

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