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Design and Optimization of Tube Type Interior Permanent Magnets Generator for Free Piston Applications

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Abstract **– In this study a design and optimization of a generator to be used in free piston applications was made. In order to supply required initial force, an IPM (interior permanent magnets) cavity tube type linear generator was selected. By using analytical equations' basic dimensioning of generator was made. By using Ansys-Maxwell dimensioning, analysis and optimization of the generator was realized. Also, the effects of design basic variables (pole step ratio, cavity step ratio, inner diameter - outer diameter ratio, primary final length, air interval) on pinking force were examined by using parametric analyses. Among these variables, cavity step ratio, inner diameter - outer diameter ratio, primary final length were optimally determined by algorithm and sequential nonlinear programming. The two methods were compared in terms of pinking force calculation problem. Preliminary application of the linear generator was performed for free piston application.**

Keywords **– Linear generator, Genetic Algorithm, Sequential Nonlinear Programming, Optimization**

1. Introduction

It is predicted that replacement of vehicles with internal combustion engines by vehicles with electrical engines will occur simultaneously with the advancement of technology. But short driving distance and charging problems of electrical vehicles could be solved by additional energy transfer equipment. E.g. battery group is continuously charged with the system of free piston engine during driving by electrical engine.

Linear generators which have the ability to generate electric in stable and driving positions of electrical and hybrid vehicle technologies are the electromechanical machines which transforms linear movement to electric energy by electromagnetic induction. Although the first performed studies were over asynchronous engine, advancement in permanent magnet technologies speed up the studies about permanent magnet engine / generator. Boldea and Nasar [1-3] collected their researches about linear engine design into a book. Also; Boldea [4] wrote a comprehensive book about current and new linear machine technologies, usage fields, advantages and disadvantages. Arshad and others [5-7] examined the linear topologies which will be used at free piston applications. They compared in respect of yield, weight in motion, magnet type, power density and power factor. Chen and others [8] compared in respect to iron, copper loss, and yield and power density depending on pole number change of longitudinal current axial magnetic tube type linear generator for free piston applications. Wang and Howe [9] compared the usage of siliceous pillar (Transil 300) and soft magnetic materials (Samaloy 500-700) in respect to loss of yield, power factor, iron and copper in tube type linear machines. They showed that siliceous material display better performance and soft material enables in production. Wang and others [10-11] tried to estimate knocking force by analytic equitation in order to decrease the knocking force in tube type machines and recommended two techniques in order to remove the knocking force. Ahmad and others [12] carried out studies intended to decrease knocking force in tube type linear generators by using special magnet structure. Hlaing and Myint [13] designed tube type axial flux linear generator for using it in internal combustion engines and applied with crankshaft connection rod mechanism. Bianchi and others [14] compared tube type grooved and un-grooved embedded magnet (ipm) linear design. For maximum force/volume internal diameter external diameter

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ratio was 0.6 for grooved structure and 0.7 for un-grooved structure. Also, Bianchi and others [15], compared tube type surface insertion and embedded type magnet grooved two engines. Embedded type magnet engine's knocking and driving force is higher than surface inserted engine.

While primary coils were without energy interaction with poles and primary tooth is described as knocking force. The power of knocking force and period decreases the main power amplitude and spoils waveform. The knocking force changes depending on linear machine topology. In order to decrease the effects of the knocking force some methods are carried out.

- In embedded type machines 0.4 could be taken as design start [16]. Also; it should be watched out that, magnetic flux density in the final teeth does not reach saturation.
- Knocking force decreases, due to increasing the air space decreases the gravitation between magnet and groove tooth. But the decrease of air space magnetic flux density also decreases the resultant force which was generated by machine. So, changing the air space is not preferred. For that reason studies were carried out for decreasing knocking force in different methods.
- Semi closed slots decrease knocking force compared to open slot structure slots significantly [17]. This configuration increases effective resultant force. But satisfaction effect of slot tooth should be considered.
- One of the parameters effects knocking force in embedded magnet type engines change of primer size. Short primer types which have radial and axial machine structures have higher knocking force compared to long primer types. The increase of effective prime length for short and long primer types increased the knocking force [18].
- Change of pole length also changes knocking force. Optimum pole length/pole step ratio which will give minimum knocking force varies according to linear machine configurations. This method applications is selected 0.63 for embedded magnet generators [19].
- Another method for reducing knocking force is pole sliding. It means to make magnets closer each other as their multiple ratios. Applying this method in axial and radial type machines significantly decreases knocking force. E.g. it could be reduced approximately 65 % in embedded type linear engines [20].
- One of the methods to reduce the knocking force is to place the magnets or slots sloping to axial [18]. Although magnet or slot slope show the same effect in application slot slope make the production difficult in this type of engines. Generally configuring magnets in sloping type is preferred. Its cost increases the production costs due to requiring special manufacturing magnet.
- Centered coils are commonly used in respect of manufacturing than distributed coils. But, due to pole number and slot number changes of the knocking force and the amplitude frequency in this type of coils, it should be selected carefully. For that reason pole could be selected as 3/2, 3/4, 9/8, 9/10, 15/14, 15/16, 21/20, 21/22. When Traditional 8/12 (pole/groove) structure engines transformed into 9/10 structure in the same conditions, knocking force almost disappears and driving force increases about 23% [21]. But arrangement of coils and slots asymmetrically cause noise and vibration by generating magnetic force in tree-phase machines. In practice 6/4, 6/8, 12/10, 12/14, 18/16, 18/20, 24/22, 24/26 are selected mostly. Pole/slot should be determined by considering coil factor, harmonic effect and knocking coefficient [22-25]. Although the machine designs with this combination (18-slot and 16-pole, 27-slot and 24-pole, 9-slot and 10-pole, etc.) have all the advantages of fractional slot permanent magnet machines, they result in a large number of undesirable harmonics. To reduce the undesirable harmonics significantly by the use of even number of pole-pairs, the number of slots is doubled to 18, and the stator windings are separated into two 3-phase sets [26].

Due to the advantages provided by tube geometry effects on teeth, total knocking force could be calculated by FEM. Gruber and others [27] analyzed knocking force by using genetic algorithm and FEM in modular structure linear engine. Chen and others [28] designed axial flux embedded magnet 12 groove/11 poles combination generators (hoop type) for free piston application. Wang and others [29] designed quasi-Halbach magnet aligned 9 groove/10 poles linear generator for free piston application. Zheng and others [30]; examined axial flux and embedded magnet generator in different pole numbers for free piston application. But, although there were classic structured (embedded disc type) magnet engine studies, there wasn't a generator study. Besides, there was no study about consecutive non-linear programming technique application for linear generator problem. In this study, the main sizing of embedded type axial flux disc shape magnet generator was done by using analytic equitation. Sizing, analyzing and optimization of generator Ansys-Maxwell was realized. Also, the effects of design of essential factors (pole pitch ratio, groove pitch ratio, internal diameter-outer diameter ratio, primer end length, air space) over knocking force was examined by parametric analyzes. The primer end length, air space and internal diameter outer diameter ratio were determined optimum by consecutive non-linear technique and genetic algorithm.

2. Axial Magnetic Tube Type Linear Generator Design

The design of traditional rotary engine or generators starts with force expression. But, linear machines are characterized by force. For that reason, the force expression is calculated by equitation 1:

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

Here, force expression is proportioned with P yield expression is proportioned η and rated speed is proportioned with v. f_x Power density (over 10000 – 15000 N/m^2 , 30000 N/m^2 water cooled) effective air space of generator is calculated by equation 2:

$$A_{air} \approx \frac{F_x}{f_x} \tag{2}$$

The power expression of traditional rotary engine or generators are proportioned with machine diameter square and packed length multiply (D^2L). In linear generator, the main size of the generator could be calculated with effective air space.

$$D = \frac{A_{air}}{\pi L_p} \tag{3}$$

In respect to understandability design, rz and xyz plane views should be given for tube type generator. (Figure 1.)

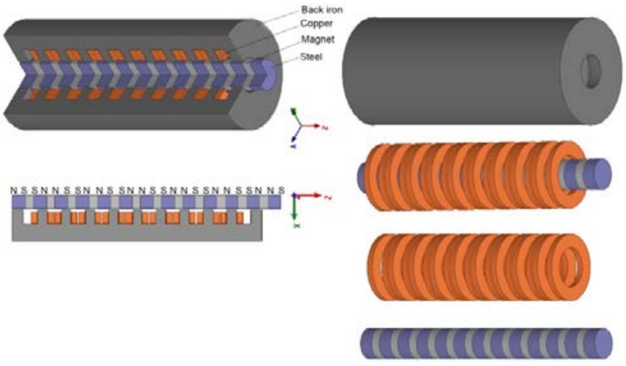

Figure 1. View of designed generator in rx and xyz planes

As it is shown in figure 1., L_p was given as primer length, D was given as the diameter expression until the primer tooth. Synchronics is calculated with equation 4 in Permanent magnet generators.

$$v = 2fT_{op} \tag{4}$$

Here; T_{op} was give as pole pitch and f was given as frequency. Pole pitch is the distance of N-S pole to the other pole and N_p pole number, primer length L_p is calculated by equitation 5.

$$L_p = T_{op} N_p \tag{5}$$

As it is shown in figure 1., the basic variables and equations were given as alpha, beta and gamma:

$$alfa = \frac{Tom}{Top} \tag{6}$$

$$beta = \frac{Bw}{Tos} \tag{7}$$

$$gama = \frac{D}{D_e} \tag{8}$$

As it is shown in figure 1., theta primer was given as end teeth pitch. Working distance of linear generator is expressed as stroke length. Due to being back and forth movement, the total stroke length is $2L_{str}$. So total seconder length is calculated by equation 9.

$$L_s = L_p + 2L_{str} \tag{9}$$

Primer teeth pitch;

$$T_w = T_{os} - B_w \tag{10}$$

Groove pitch (Bw), teeth pitch (Tw) ratio effects electrical and magnetic charge. As long as this ratio increases, electrical charge increased against magnetic charge decreasing due to stray fluxes. Groove pitch in these criteria and taking teeth pitch equal is enough for design start. The power of electric machines is a function of electrical charge and magnetic charge. For this reason, the electrical and magnetic loading of the machines to be designed can be selected within a certain range, so that the designed machine can be made suitable for the temperature. Also, air space magnetic flux density causes increasing over efficiency and tension. But, due to the un-linearity characteristic of core material some acceptance is required for primer and seconder in flux densities:

- Primer teeth magnetic flux density <1.8 T
- Yoke magnetic flux density 1.3 – 1.5 T
- Magnetic charge 0.35 – 0.8 T
- J Flux density is taken 1,5-5 A/ mm2 normal machines, 5-15A/mm2 is taken for water cooled machines

3. Finite Elements Solution of Designed Generator With Ansys-Maxwell

There are some commercial CAD based analyzes software developed for magnetic studies. While the capacities of this software vary, the methodology and usage purpose are generally common [29]. In this field, Ansys-Maxwell is commonly used in solution of engineering problems. It is preferred due to its communication ability, having rotary engine/generator design tools, ability to provide different solutions and using the finite elements in order to make these solutions.

Free piston applications are characterized as high speed against wave or suspension applications. So, it should be smaller than the other generators which are used in wave and suspension systems in order to obtain the same output power. Sizing values of tube type generator's reference geometry were given in figure 1.

Table 1. Tube type generator's reference geometry

Geometric Parameters	Values	Stator (primer) Steel Material – Rotor (secondary) Steel Material	M43_24G - Steel1020
Pole pitch(m)-Top(m)	0.03	Permanent Magnet Material	NdFe35
Slot pitch(m)-Tos(m)	0.033	Pole/Slot	10/9
Stator(primer) inner diameter-D(m)	0.038	Alfa	0.5
Air gap-g(m)	0.002	Beta	0.55
Slot width-Bw(m)	0.01833	Gama	0.15
Slot height-Hw(m)	0.02033	Teta	0.01

It is difficult to calculate analytically due to stress is occurred in medium primer gears besides gravitation at end and top points of core tooth. For that reason in order to calculate knocking force numerically, the finite elements method is preferred.

3.1. Consecutive non-linear programing (SNLP)

This optimizer assumes spread of optimization variables in a continuous space. In SNLP optimizer variables could take any value between the allowed restrictions and numerical precision limits of simulator and it updates optimizer values to current optimal values. SNLP optimizer assumes that the noise is not important and forms a reaction surface by using Taylor serial prediction (zooming) which comes from FEA simulation results obtained from previous solutions. The reaction surface is in the local environment the most accurate.

Response surface is used in order to determine gradients and calculate the next step direction and distance in optimization loop. Response surface works as a deputy for FEA simulation by speeding up the problem and decreasing FEA simulation number. Convergence realizes as long as much more FEA solution is formed and surface response prediction develops (Figure 2.). This optimizer includes many advantages in comparison to semi-Newton and texture seeking optimizers [31]. SNLP optimizer gives more idea about optimization problem by revealing faster optimization process. One of the other advantages is requiring cost derivatives which could be estimated by keeping SNLP optimizer against cost uncertainty (noise).

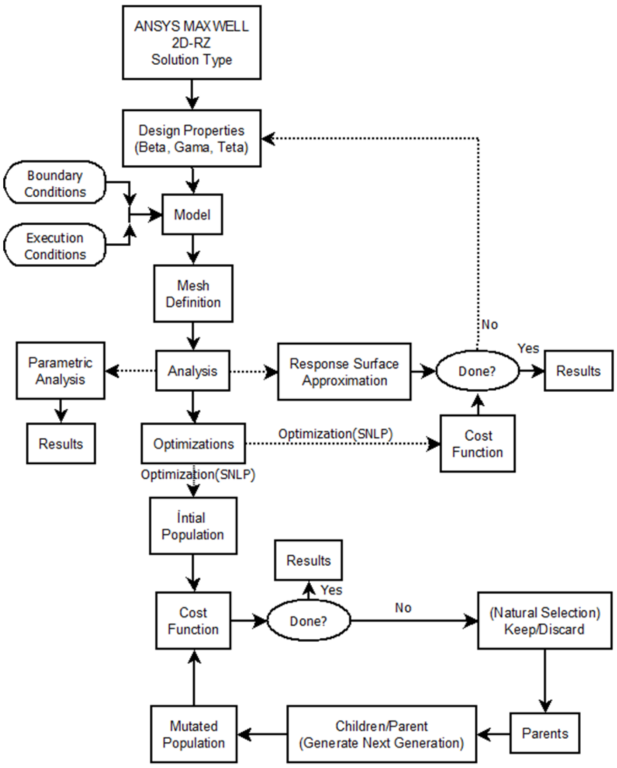

Figure 2. Solution algorithm for (Including parametric and optimization process) linear generator analyze.

As seen in figure 2., 2D-rz plane was selected for tube type linear generator in Ansys-Maxwell. Because, modeling three dimensional models up to two dimensions provides time and analysis ease [32]. Solver type (transient) and solution plane (2D-rz) are selected. Surface conditions and manager conditions are selected. Mesh definition is too important according to the analysis. In time dependent solutions, dense mesh definitions to moving field section will increase the accuracy of force calculation. The period of movement is as groove pitch. For that reason analysis of basic variables is realized in constant groove pitch. Primer teeth magnetic flux density was determined in air space by Magnetostatic analysis. Then transient analysis was selected for optimization methods. Knocking force was calculated depending on time or position in transient analysis. Variables - limits and target conditions were given in table 2. for two optimization methods.

Table 2. Variables- limits and target conditions

Variables	Limits	Target	Function
Beta	0.4-0.6	$F_{pk-pk}=0$	Min
Gama	0.1-0.2		
Teta(m)	0-0.025		

3.2. Parametric analysis and optimization with Ansys-Maxwell

Magnetic flux density is seen according to the change of basic variables (Alpha, Beta, Gamma and Theta).

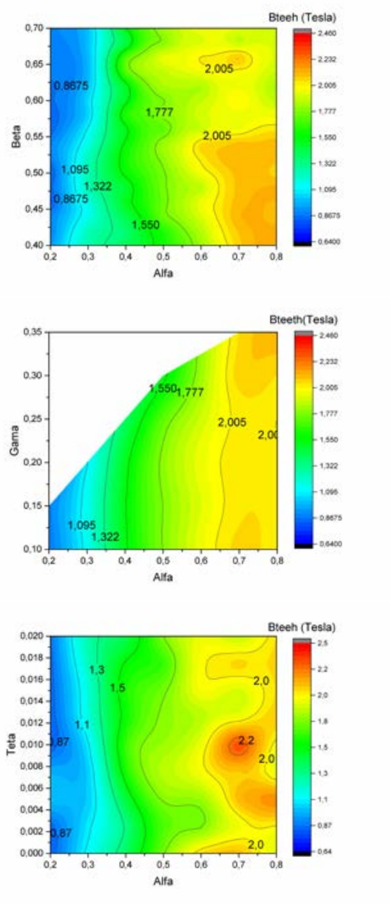

Figure 3. Maximum magnetic flux density along with primer

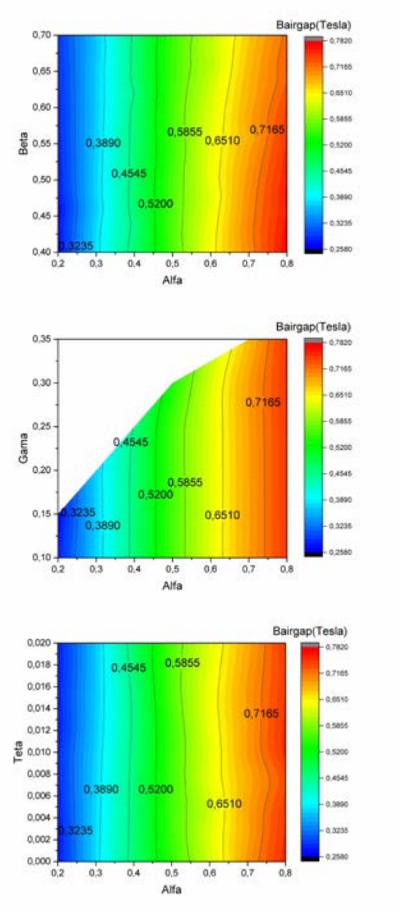

Figure 4. Along with air space effective magnetic flux value

As the magnetic flux density in the primary core material approaches the saturation value, it is inevitable that the contour lines depart from the linearity as seen in figure 3. But, alpha value effects directly stroke the length for stable magnet width. For that reason frequency of generated tension will change against rated speed. For that reason alpha value was taken as 0.5. Based on this value, finite elements are optimized with constant genetic algorithm and SNLP to find minimum knocking force.

Ansys-Maxwell offers the tools for simulating the cogging force, flux linkage and the back EMF performance characteristics. In order to calculate the cogging force in the transient analysis, the speed must be at the slot pitch value. The current and the voltage values through each phase of the generator are defined as 0s. The mover mesh must be optimized to a smaller size in order to achieve the most accurate results. The stop-time and the time-step are defined for the Transient Setup. The cogging force for the generator is shown in figure 5. which is compared with the GA and SNLP cogging forces.

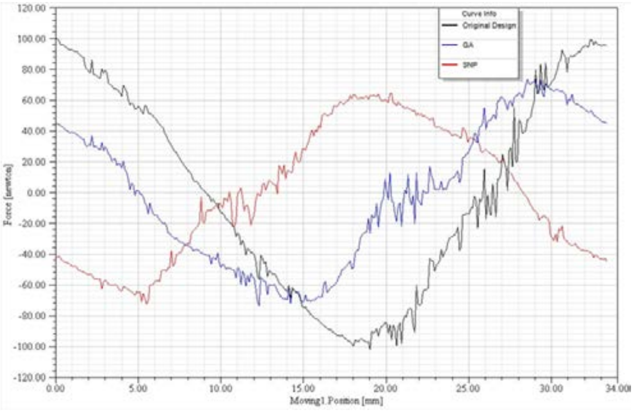

Figure 5. Comparison of cogging forces

Comparison of flux linkage in Phase A is shown in figure 6. GA and SNLP results are little more than the original design result for flux linkage.

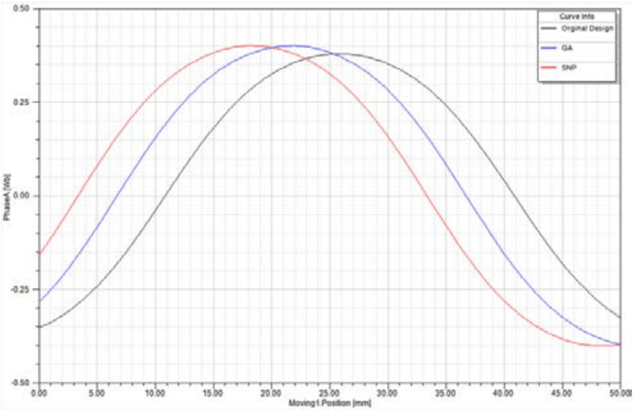

Figure 6. Comparison of flux linkage in Phase A in constant speed

Comparsion of optimaziton methods and geometric parameters were given in Table 3.:

Table 3. Optimization results

Geometric Parameters	Original Design	SNLP	GA
Bw(m)	0.01833	0.01357	0.01383
Hw(m)	0.02033	0.019138	0.016673
Beta	0.55	0.407335	0.4149
Gama	0.15	0.172517	0.1714
Teta	0.01	0.025	0.01825
Mover Weight(kg)	2.5963	2.5963	2.5963
Total Weight(kg)	27.697	22.940(-%17.17)	22.931(-%17.2)
Cogging Force(N)	65.75	41.96(-%36.18)	45.16(-%31.31)

Speed profile of free-piston application is in sinusoidal form. Speed and position variations are given in figure 7.:

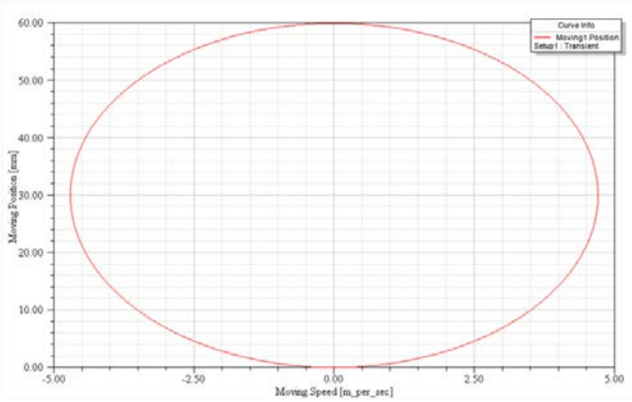

Figure 7. Changing the speed position by using GA model in FEM

Different conditions can be analyzed by creating circuit structures with the help of the circuit editor program running under Ansys-Maxwell program. Phase windings created in Maxwell should be imported into this sub-program. Thus, the moving speed and time-dependent phase inductances calculated in Maxwell and the induced voltage can be used directly in electrical circuit. Current values are calculated according to the circuit structures designed in Editor.

Current values obtained from electric circuits are sent again to Maxwell program and these values become phase currents for machine model. In this way, the dynamic analysis of the generator is performed. By adding external equivalent circuit model in figure 8., resistive load analysis of the generator is performed.

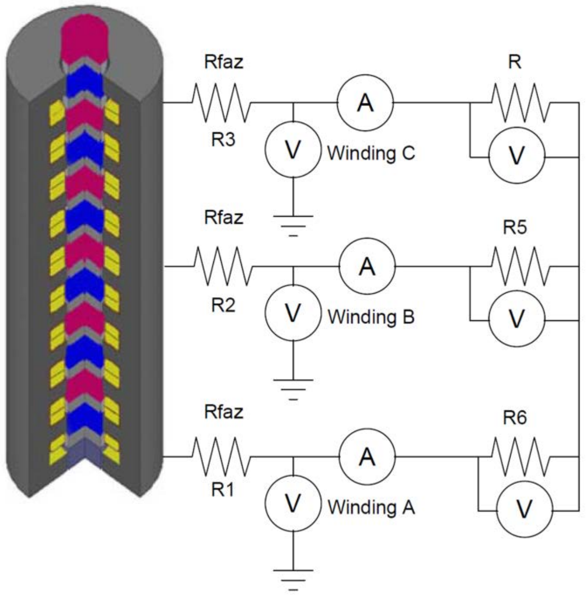

Figure 8. External equivalent circuit using GA model in FEM

Voltages induced in generator at the nominal speed are given in figure 9. The voltage alternates between positive and negative sequence depending on the velocity.

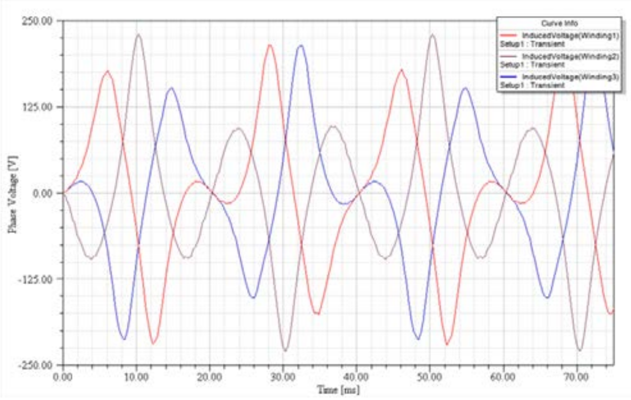

Figure 9.Three-phase induced voltage calculated using GA model in FEM

Three-phase current calculated in generator at the nominal speed are given in figure 10. Losses in generator at the nominal speed are given in figure 11.

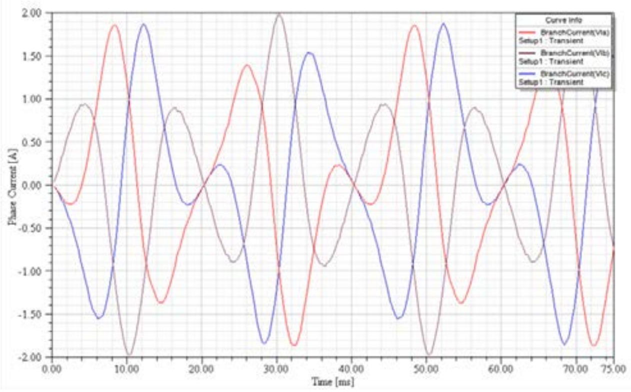

Figure 10. Three-phase current calculated using GA model in FEM

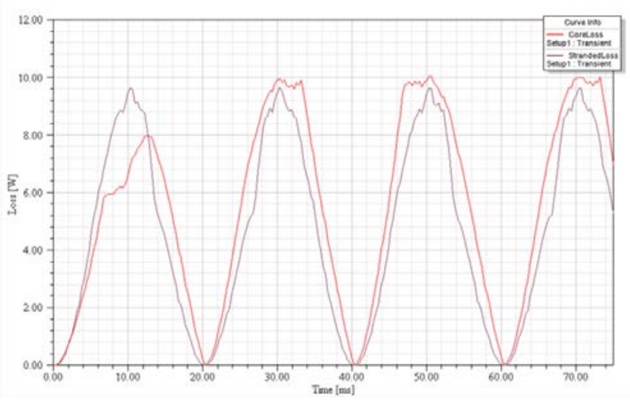

Figure 11. Loss with using GA model in FEM

4. Conclusion

Tube type linear generator is designed for free-piston applications. By using the finite element method whose design is performed, impact force of the generator is tried to be decreased by GA and SNLP. GA and SNLP give close results to the minimum impact force function. Without making any changes on the movement, total weight and impact force of the generator are reduced significantly.

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