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***Corresponding author**

Aslan Sa. Jalal
aslan.jalal@coeng.uobaghdad.edu.iq

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Linear Generators: Comparison between Five – Phase and Three – Phase machines

Aslan Sa. Jalal*

Department of Electrical Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq

ABSTRACT

Linear electrical power generation is one of the methods to generate electrical power from linear moving forces with zero unwanted CO and NO emissions. Such power source can be harvested from linear moving systems such as oscillating engines (the so called free – piston engine), sea and ocean tides and waves. The linear generator is the major part responsible of generating the electrical power from the combined driving linear system and the generator as its load. Such electrical machines are found vastly in three – phase fashion. At first the linear generator in its five – phase mode is modelled, optimised and analysed. Then, the generator mass, cost and running features are investigated and compared with an existing three – phase machine. Few weak points have emerged in the selected five – phase machine models although better operational features have been harvested compared with the base three – phase linear generator model.

1.Introduction

A linear generator is one of the accompanying parts to free – piston engines (Ngwaka, Chen et al. 2022), wave – energy converter systems (Raju, McKee et al. 2022) and it even takes part in solar power technologies nowadays (Arslan and Akkaya Oy 2023). Free – piston engines have the ability to work with various fuels (Ngwaka, Chen et al. 2022) and therefore have variable driving forces and operational velocities (Wei, Zuo et al. 2024). The whole system can serve as an electrical power source for various applications (Balcombe, Rigby et al. 2015, Jia, Andrew et al. 2016). It has been emerged to comply with the global efforts focused towards reducing unwanted emissions resulting from fossil fuels usage, and in terms of the reinvention and the development of an adequate environment friendly power sources in the electrified transportation (Oprea, Szabó et al. 2013), one of the most important sectors in human life that requires large amount of power daily.

The heart of the drive-generation system is the linear generator which plays an important role in the electrical power generation. Thus, the research on the design of the machine has been explored by researchers for the purpose of improving the efficiency of the machine (Isfahani, H. Lesani et al. 2007, Lu and Ma 2011, Hu, Wei et al. 2017), introducing new designs (Boldea, Pucci et al. 2018, Lu and Mei 2018, Wang and Baker 2019), improving the whole system performance in terms of fuel consumption, operational control and overall efficiency (Ngwaka, Chen et al. 2022).

The design of the five – phase linear generator presented here is for the use with a free – piston engine. The characteristics and the dimensional constraints of the driving engine limiting the machine design and its constructional parameters are reported in (Wu and Roskilly 2014), and are also demonstrated in Table 1. The previous linear synchronous machine designed for integration with the engine was of three – phase modular windings, where each phase coils are positioned in consequent slots. It was designed in three possible scenarios based on the power extraction method (Jalal 2017, Jalal, Baker et al. 2017). In the current machine design the chosen power extraction method is the grid interface conversion method as shown in Figure 1. This power extraction scenario can ensure the usage of the machine generated power either in charging systems, or by injecting the generated power into a hybrid power system using a suitable inversion system.

Table 1: Driving engine dimensions and operational characteristics

Parameter (symbol)		Value (unit)
Dimensions	Stroke amplitude (x_L)	120 (mm)
	Maximum Outer diameter of engine cylinders	200 (mm)
Operational	Moving mass (m)	8 (kg)
	Driving force (F_{eng})	800 (N)
	Peak speed (v)	4.8 (m/s)
	Steady – state frequency (f_m)	12.5 (Hz)

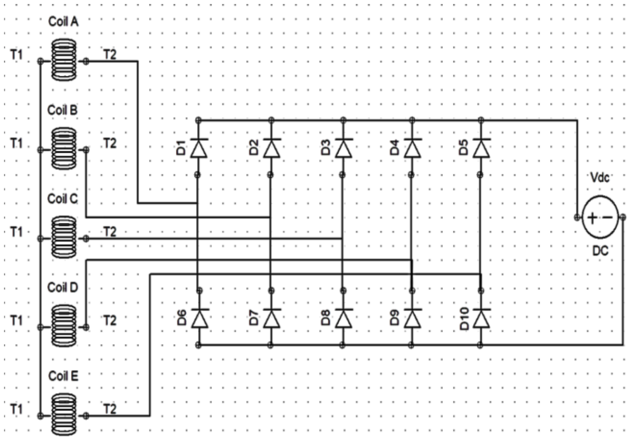


Figure 1: Linear generator power extraction circuit diagram

The purpose of proposing the five – phase design is to compare the resultant optimal machine model(s) with the existing design by considering the following criteria:

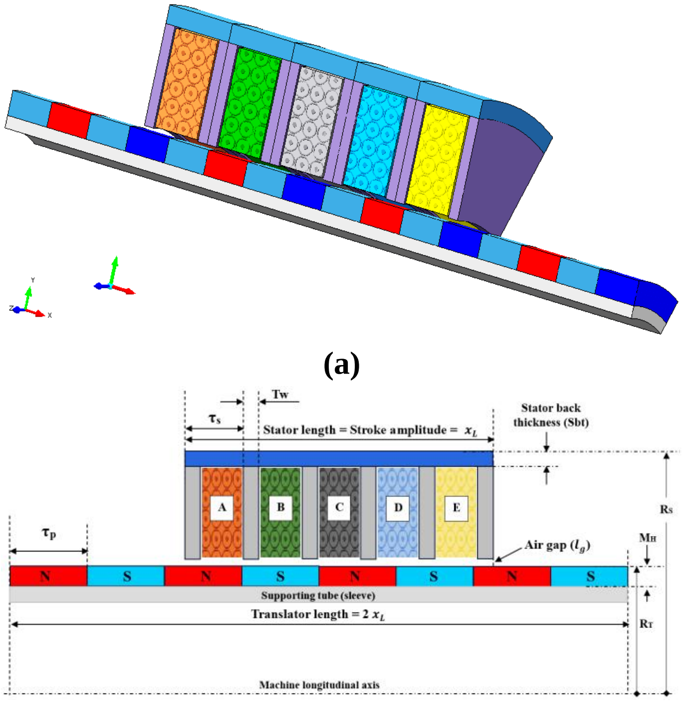
a- Machine cost.
b- Machine performance efficiency.
c- Machine power density.

The design of the machine was performed using the 2 – Dimensions Finite Elements Method (2DFEA) software. Specified performance parameters of the possible optimal designs are compared and the differences are highlighted in order to investigate the effect of important machine design parameters on its operational characteristics and the consequences on the whole system performance.

2. Linear generator model

2.1 Model structure

The linear generator model is shown in Figure 2. The machine geometry is tubular as can be seen in Figure (2 – a), and its longitudinal cut – through model is shown in Figure (2 – b).



(a)

(b)

Figure 2: (a) 3D view of the linear generator configuration; (b) Linear generator longitudinal cut – through model showing machine parameters

The machine has an outer stator with five – phases sandwiched between teeth made of non – oriented sheets of steel and the magnetic circuit closed from the top by rings made of Soft Magnetic Composite (SMC) material. Such material can guarantee the desired 3 – Dimensions (3D) flux distribution travelling at the circumferential direction of flux motion pattern within the stator core. Also, the SMC material has low magnetisation wattage loss compared to lamination sheets per unit mass. This feature has increased its use in various machine manufactured topologies nowadays.

The generator model has a mover (translator) of twice the length of the stator length. It consists of poles with a number satisfying five – phase machine operation. The magnets used in forming the mover poles are Neodymium Iron Boron Permanent Magnets (PMs) with strong axial magnetic orientation. PMs and pole faces are fixed at the top of the supporting tube which is hollow and made of stainless steel to assure the hardness of the mover structure. Pole faces are made of SMC material for the same requirements of 3D flux distribution at the mover core. The fixed and the variable parameters subjecting to optimisation are listed in Table 2, and the materials used for each part of the machine is also included in the table. Ranges used in optimising the variable parameters are included taking into consideration lamination thickness, and the mechanical tolerance of machining core back segments and PMs.

Table 2: Linear generator fixed and variable parameters and dimensions

Parameter type	**Parameter (symbol)**	**Value / range, unit**	**Material**
Fixed	Stator / translator (active length x_L)	120, mm	---
Fixed	Slots (N_s)	5	---
Fixed	Stator outer radius (R_S)	90, mm	---
Variable	Stator back thickness (Sbt)	(3 – 9), mm	AISI 1010 Steel (SMC)
Variable	Tooth width (T_W)	(2.88 – 11.88), mm	Non – oriented silicon steel lamination sheet (0.36mm) of grade M-1529 Ga
Fixed	Coil height / width	326 / 147.2, mm	Copper: 5.77e7 S/m
Fixed	**Air gap**	**1.5, mm**	**Air**
Fixed	Translator outer radius (R_T)	500, mm	---
Fixed	Poles (N_P)	4	---
Fixed	Pole pitch (τ_p)	30, mm	---
Variable	Pole height (M_H)	(6 – 11), mm	Neodymium Iron Boron: 28/23 – axially oriented
Variable	PM width (M_W)	(15 – 24), mm	
Variable	Pole face	$\tau_p - M_W$	AISI 1010 Steel (SMC)
Fixed	Supporting tube thickness	4, mm	Stainless steel

As stated before, the machine has a long translator and a short stator in order to achieve the full usage of the driving engine stroke. This structure adds the effect of cogging force at both machine ends, which is also termed detent force. Further, twice the cost of the machine translator parts would also be a penalty, especially in doubling the cost of the PMs.

It is worth mentioning that if a short translator and a long stator are used, although these dimensions are useful in overcoming cogging force at the machine ends due to mover shortening, yet inactive coils during machine operation would result in producing extra copper loss and hence a lower machine efficiency (Korbekandi, Baker et al. 2019).

2.2 Pole / Slot combination formula

The number of stator slots ($\mathrm{N_S}$) and mover poles ($\mathrm{N_P}$), also termed (pole / slot) combination, that can give the desired number of machine phases can be obtained using the following formula:

$$\mathrm{N_S} = \frac{\mathrm{N_P}}{q}\left(\frac{N_{ph}[1\pm k]}{1\pm N_{ph}k}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

Where:

q: number of slots per pole per phase, (q =1) in this design.

$K = 0, \pm 1, \pm 2, \ldots \pm n; with\ n: an\ integer)$.

N_{ph}: Number of phases.

3. Optimisation procedure

The optimisation procedure has been performed manually in a similar manner to the one followed in optimising the base three – phase generator model in a previous work (Jalal 2017). It started by setting low values for the PM dimensions set on the mover while optimising the stator optimisable parameters for maximum power production. Then, the mover parameters were optimised in order to achieve the desired target force. Sample of the PMs set of dimension optimisation results are clarified in Figure 3.

3.1 Chosen models and mass comparison

The optimisation results show that the PMs dimensions are the most effective parameters on the power production. Furthermore, there are more than one set of dimensions that can achieve the desired design force. The difference in the magnets' set of dimensions leads to differences in the overall machine performance parameters, as well as differences in the overall cost of the resulting machine.

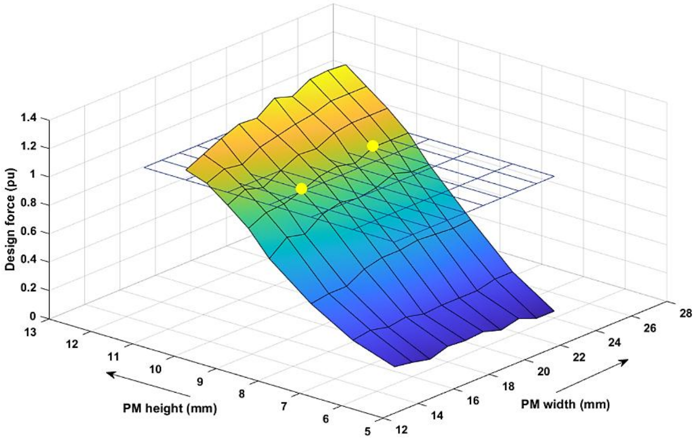


Figure 3: The effect of increasing PM dimensions on the resultant per unit force production

Two models are picked from the results in order to compare their performance parameters, as well as to compare the cost of the most effective parts of the machine with those of the base model. The chosen models are marked with yellow circles on the graph in Figure 3.

The comparison with the base model is divided into two parts. The first part includes the comparison of the main machines' dimensions and their major parts masses. For comparison fairness, the air gap in these designs and the outer dimensions are kept the same from the start of optimisation procedure for all machines. Table 3 lists the comparison between the picked models (A & B) and the base design. Figure 4 shows a comparison between the machines' masses.

Both models (A & B) share the same stator mass, which is cheaper by (~ 29.1 %) than that of the base model. The mover of model A is cheaper than that of the base model by (~ 21.26 %) and is also cheaper compared to the mover of model B which is heavier. Nevertheless, the cost of PMs of model A is the highest compared to that of base model and model B which are cheaper by (~ 10.67 %) and (~ 13.7 %) respectively.

Table 3: Base model and selected models dimensional and masses comparison

Object (unit)	3 – phase model Base design	5 – phase selected models	
		Model A	Model B
Stator outer dimeter (mm)	180		
Stator back thickness (mm)	4.5	5	
Tooth width (mm)	7.7	8.28	
Coil turns	112 (modular)	200 (single coil)	
Air gap (mm)	**1.5**		
Mover outer diameter (mm)	103	99.8	
PM height / width (mm)	12 / 9	9.5 / 22	10 / 18
Copper mass (kg)	8.64	6.79	
Stator mass (kg)	16.35	11.59	
PM mass (kg)	1.79	1.981	1.71
Mover mass (kg)	8.41	7.907	8.202
Full machine mass (kg)	24.76	19.497	19.792

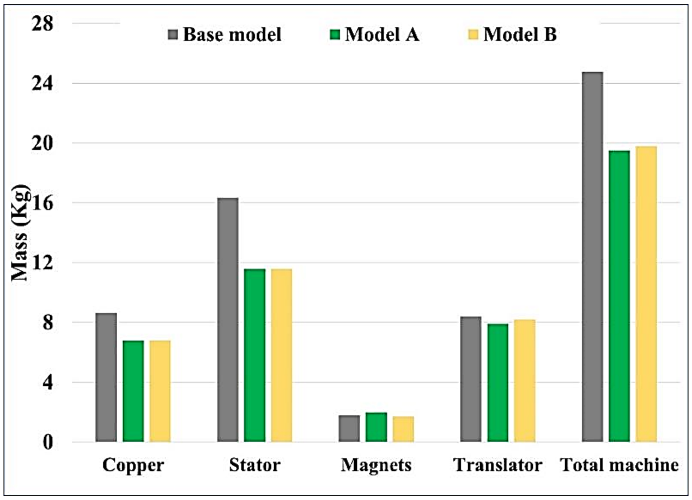


Figure 4: Mass comparison of effective machine parts

3.2 Performance parameters comparison

The second part of the comparison includes the performance parameters comparison between the selected models and the base model as clarified in Table 4. It can be seen that the current ripple of the DC bus link is higher compared to that of the base model, and Figure 5 shows the charging current (Idc) for the selected models enclosed by one electrical cycle during the translator motion.

Table 4: Base model and selected model performance parameters comparison

Parameter (symbol, unit)	3 – phase model Base design	5 – phase selected models	
		Model A	Model B
Copper loss (W)	165	142	153
Iron loss (W)	11.5	11.89	11.51
Sleeve and PMs eddy currents loss (W)	108	48	36
Conductor diameter (mm)	1	1.68	
Maximum current density (J, A/mm^2)	9.15	6.6	6.83
Electromagnetic reacting force (F_g, N)	802	798	799
Output power (kW)	3.33	3.64	3.78
Efficiency (%)	92	94.75	94.97
Power density (kW/mm^3)	1.09	1.19	1.238
Power mass density (W/kg)	162.2	234.1	240.9
% Force ripple to rated	15.17	60.18	58.53
% Current ripple to rated	9.42	13.01	10.18

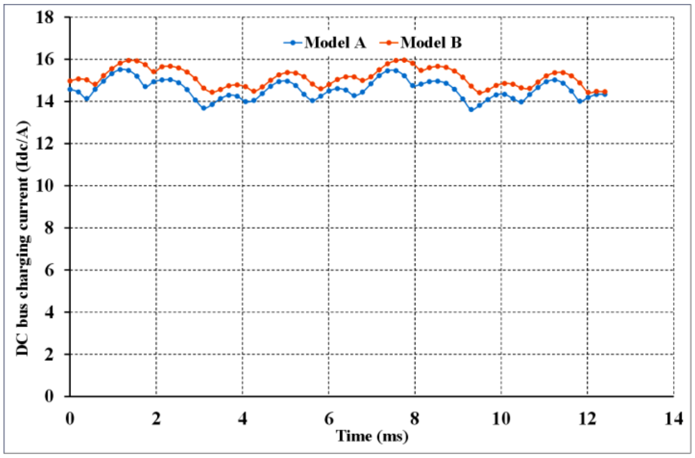


Figure 5: DC bus link charging current (Idc) over one electrical cycle

Although current ripple is not affecting the machine output power as the current variation can be handled by the DC bus filter capacitor, yet if the current fluctuation is not filtered its consequences on the engine operation is not predicted elsewhere and must be considered by the engine's operation experts and designers. This due to the fact that current ripple results in an undesired fluctuation in the machine reacting force to the driving engine force which must handle it. The effect of the current fluctuation can be noticed clearly in the reacting force ripple which is high in five – phase machines compared to the three – phase base machine model.

4. Discussion

From the results reported in Table 4 one can note that both five – phase machine models (A & B) are better in performance than the base three – phase machine model.

The losses in general are lower, power production capabilities are higher resulting in higher efficiencies. In addition to these advantages, coils current density in both designs is low and this is very helpful and cheaper in considering electrical machine design with air – cooled (normal cooling) windings. The power densities in both their volumetric and mass representations are higher in the five – phase machine models compared to those of the three – phase machine base model. An extra (~ 13.57 %) of watts per unit volume, and an extra (~ 48.5 %) watts per unit mass are generated by the five – phase machine compared to the power of the three – phase machine.

Model B as compared to model A, is cheaper in cost with its lowest PMs mass, and is better in performance with its low current ripple, low force ripple and its higher efficiency.

Figure 6 shows one electrical cycle of the reacting electromagnetic force of both models (A & B) against mover displacement. Both machines force trends show high ripple (high force fluctuation). This is one of the issues of short stator / long mover machines where a detent force reduction technique would be a must. High electromagnetic force ripple must be handled by the driving engine, and it leads to continuous deceleration and acceleration to the driving engine (Jalal 2017). It also adds complexity to the operation of the driving engine fuel and motion control system.

One electrical cycle of the air gap flux distribution of both models A and B is shown in Figure 7 during the mover displacement and loading conditions (charging condition). The imbalance in the fluxes cannot be disregarded and further modification and improvement are mandatory to the design.

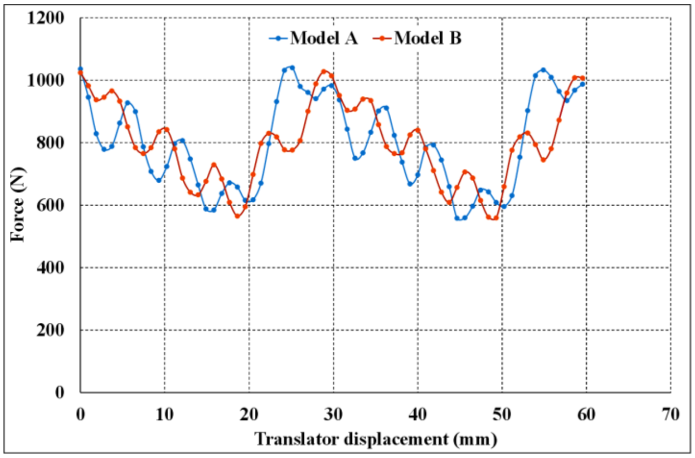


Figure 6: Linear generator electromagnetic force against translator displacement

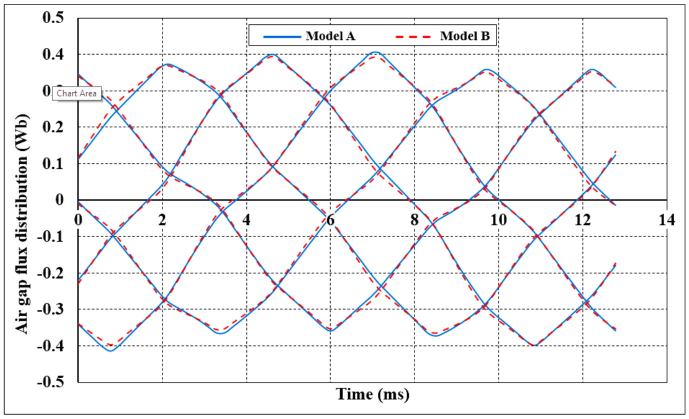


Figure 7: One electrical cycle of the air gap flux distribution against translator displacement

Nevertheless, the five – phase generator models as compared to the three – phase generator base model had showed cheaper machine parts, better performance efficiency and higher power density as clarified in Table 5.

Table 5: Machines comparison criteria

Criterion	3 – phase model Base design	5 – phase selected models	
		Model A	Model B
Cost	Higher	Lower	Lower
Performance efficiency	Lower	Higher	Higher
Power density	Lower	Higher	Higher

Conclusions

The design of five – phase linear generator for use with linear engines has been presented. More than one design of the machine configuration can achieve the design target force from the driving engine under consideration. The models chosen for comparison with a base model showed a cheaper machines' parts and a lower total machines' mass. However, although one of the models had showed a lower moving mass compared to the base model, the cost of PMs is high. Nevertheless, the machine model has a lighter mover which is better for driving engine operation and electrical loading variation of the linear generator like high ripples in the charging current.

From electrical machine design prospective, the five – phase machines showed better electrical performance compared to the three – phase model. The lower losses, higher efficiencies and the higher power densities figures are good performance parameters to evaluate a machine design. However, there still high charging current fluctuation, and imbalance in the flux distribution within the air gap of the five – phase machine for both models (A & B). This must be examined for better flux distribution within the machine core to minimise the high force ripple of the machine, minimise charging current fluctuation and make the five – phase flux distribution in the machine parts into a more balance pattern. Extra machine modelling with structure variation and with distributed windings is required to be explored in a future work to improve the operational parameters of the five – phase machine.

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