Jalal AS, Baker NJ, Wu D.

[The effect of power converter on the design of a Linear Alternator for use with a Joule Cycle-Free Piston Engine.](#)

In: Electric Machines and Drives Conference (IEMDC). 2017, Miami, FL, USA: IEEE.

Copyright:

© 2017 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

DOI link to article:

<https://doi.org/10.1109/IEMDC.2017.8002218>

Date deposited:

29/08/2017

The effect of power converter on the design of a Linear Alternator for use with a Joule Cycle-Free Piston Engine

Aslan Sa. Jalal^{1,3}, Nick J. Baker¹ and Dawei Wu²

¹ School of Electrical and Electronic Engineering; ² School of Marine Science and Technology
Newcastle University, Newcastle Upon Tyne, NE1 7RU, UK

³ Mechatronics Engineering Dept., Al-Khwarizmi College of Engineering, Baghdad University, Baghdad, Iraq
a.jalal@ncl.ac.uk and nick.baker@ncl.ac.uk

Abstract—This paper describes the effect of alternative power conversion techniques on the performance of a Linear Alternator driven by a Joule Cycle-Free Piston Engine for electrical power generation. The design of a tubular Longitudinal Flux machine with axial magnets is performed using 2-D axisymmetric FEA modelling with transient solver to extract the rated power for three power conversion scenarios: Resistive Loading, Grid Interface, and Unity Power Factor Controlled Converter. The design study is carried out for a specific engine operating force and velocity, taking into consideration geometrical constraints for a compact system. Results are presented and discussed emphasizing the effect of the power conversion method on the idealized resultant machine physical and performance parameters.

Keywords— PM linear machines; Free Piston Engine; Joule Cycle; Renewable Energy; Hybrid Electric Vehicles; Electric Vehicles.

I. INTRODUCTION

The continued development of Hybrid Electric Vehicles has highlighted the global desire for more efficient drive systems to replace the conventional 100% fossil fuel engines in the automotive sector. Fully Electric Vehicles are energized by on-board batteries with associated limited range capabilities and long recharging time. This ‘range anxiety’ has introduced the need for an auxiliary power unit to improve system performance by on-board battery charging unit— known as a ‘range extender’. A potential range extender is the Linear Alternator (LA) driven by a Free Piston Engine (FPE). This electro-mechanical combination has benefits for both hybrid and pure electric vehicles [1-4], although it has not seen commercial success yet.

A number of groups worldwide have investigated the FPE and the LA. FPE with its few moving parts and crank-less operation has attractive features such as high thermal efficiency, ease of maintenance, reliability and suitability for small-scale application. An insight into the design and the operating characteristics of the engine has been presented for a two-stroke engine structure [5]. Petrol and diesel versions have

both received attention and been compared to engine performance of rotating engines [6, 7]. Most studies, summarized in [8], focused on increasing the engine’s efficiency, investigating its key parameters on performance and predicting the reduction of emissions. In this paper, however, an FPE operating on the Joule thermal Cycle, the Joule Cycle-Free Piston Engine (JC-FPE), is used to investigate the LA design. JC engines use the same mechanical structure as those in conventional FPEs, except that the combustion chamber is taken out of the expanding cylinder in order to achieve higher compression efficiency [9, 10].

Various linear machine topologies have been proposed as the electrical power take off in FPE applications, where high power densities, robustness and cost should all be taken into consideration. Permanent Magnet (PM) Flux Switching machines of single and three phase windings have been investigated for this application with their attractive construction [11, 12], where the magnets are sandwiched between stator teeth structure. This linear machine topology is preferable for long stroke applications, where the long translator can be a purely iron structure. In short stroke applications, where translator and stator are a similar size, effective use of magnets is challenging due to the effect of leakage flux between adjacent teeth. Transverse Flux machines have been also studied for this application [13]. This topology is known to have a high torque density in rotating machines [14] due to the normal interaction between its magnetic and electric loadings, which adds some flexibility to the designer and makes it attractive for linear applications such that both tubular [15] and flat [16] structures have been studied for this application. Even with its attractive torque (force) dense feature, transverse flux linear machines in different geometries were found to suffer from complex manufacturing and characterised by high inductance, resulting in a low power factor.

Therefore, the tubular PM Longitudinal Flux (LF) machine configuration is adopted in this work. Irrespective of magnet orientation, this topology has received much research interest over the years for this application [17-19]. Besides characterising this configuration by having high power (force) densities, the PMLF machine has a relatively simple construction with the total elimination of the end winding

Aslan Sa. Jalal would like to thank the Iraqi Ministry of Higher Education and Scientific Research (MOHESR) - University of Baghdad (UoB) for sponsoring this work under Grant number 63-10/2/2013.

effects often associated in tubular geometries. In this paper, the design study of a tubular PMLF machine with axial magnets is performed, using axisymmetric 2-D FEA modelling to extract the rated power for three power conversion scenarios: Resistive Loading (RL), Grid Interface (GI) and Unity Power Factor Controlled Converter (UPFCC). The authors have previously presented design optimization for a resistive load [20], and looked at the effect of slot cogging, ends effect and current loading on the LA force profile compared to that of a simple damper [21]. This paper looks at the effect of the power converter on the alternator design, which has not been covered in other literature for FPE application [22, 23].

II. DRIVING ENGINE DESCRIPTION AND DESIGN CONSTRAINTS

The linear Joule Cycle-Free Piston Engine (JC-FPE) has external combustion and works on the same thermodynamic Joule (Bryton) Cycle used in gas turbine engines [9, 21]. The engine provides a reciprocating linear motion to the load, which is rigidly connected to the piston via the connecting rod. In its most simple form, the load is a linear machine used for electrical power generation. In order for the engine to be able to function and to ensure compact system integration, there are some geometrical constraints and operational specifications imposed on the electrical machine. These are listed in table I for steady state operation of the engine under investigation.

III. DESCRIPTION OF MACHINE TOPOLOGY AND POWER CONVERSION METHODS

A. Linear Alternator

The LA adopted in this study is a PMLF machine composed of six stator slots, seven translator poles and a (1:1) ratio to engine stroke amplitude. Fig.1 shows a 3-D quarter cut view of the machine topology clarifying that the stator is short and equipped with three-phase winding of modular connection [12, 20]. The stator core back is constructed from a number of interlocked Soft Magnetic Composite (SMC) segments surrounding axially laminated teeth as shown in Fig.2. The translator consists of axially magnetized PMs of alternate polarity separated by SMC pole – pieces, shown protruding out of the stator in Fig.3. Translator components are mounted on a central nonmagnetic tube, with additional PTFE bearings

Fig.1: 3-D quarter cut view of the LA under investigation

acting on the external circumference.

As shown in Fig.1, seven poles are used during engine's stroke, and thus seven poles are modelled in this study

TABLE I. DRIVE ENGINE SPECIFICATIONS

Specification	Value	Unit
Peak force	≈ 800	N
Peak velocity	≈ 4.8	m/s
Moving mass	≤ 8.0	kg
Stroke Amplitude	120	mm

B. Power Extraction Methods

In order to make use of the electrical power generated within the LA during the continuous oscillating motion there should be a load to dump this power. In the literature [12, 18, 19, 23], the load was undefined and its impacts on the machine design and the resulting performance parameters therefore has not previously been considered. In this work the authors consider three possible scenarios to represent this load, Fig.4.

In all scenarios, the machines are designed to react the same engine force at peak speed corresponding to a fixed driving power. The resultant electrical power output will be a function of machine losses and the operating power factor, as

Fig.2: Stator structure showing laminated teeth and SMC core back

Fig.3: Translator structure showing PMs and SMC

governed by the three scenarios of Fig.4 and described below.

1) *Resistive Loading (RL)*: Resistive Loading assumes lighting, an electrical heating or an effective internal resistance of a battery charging system loading the LA, see Fig.4a. Simple resistors can effectively replace such loads without affecting the resulting machine performance. This method has been used in a previous work [20] to demonstrate the design methodology using 2-D FEA modelling, and to explain how the machine was found to give the best PM utilisation when the magnets have axial magnetization. The prototype for the model designed using this method was shown in Fig.2 and Fig.3.

2) *Grid Interface (GI)*: The Grid Interface scenario assumes power is injected into the referenced LV side of the UK power grid, see Fig.4b. It assumes a 5% voltage drop in each uncontrolled conversion unit representing internal losses, and an ideal DC link voltage.

3) *Unity Power Factor Controlled Converter (UPFCC)*: The Unity Power Factor Controlled Converter of Fig.4c, assumes a fully controlled current density equals that resulted from the previous (GI) loading method. The Controlled Converter forces the machine to operate at UPF, i.e. the current is controlled to be in phase with the back emf and the load absorbs all the real power generated by the alternator [23]. In fixed speed, rotary applications, this could be achieved by using a tuning capacitor to offset the phase synchronous inductance's inductive reactance. In a linear machine, varying electrical frequency means varying reactance and advanced control techniques, with the associated cost and losses, are required. This can be thought of as the penalty of compensating phase inductance effects in variable speed direct driven machines in order to convert the variable frequency generated power to a constant frequency useful power [24, 25].

IV. DESIGN OBJECTIVES, VARIABLES AND OPTIMIZATION RESULTS

The goal of any electrical machine design is a multi-objective task, especially when coupled to a thermodynamic system and power converter. Finding a satisfactory design

Fig.4: Power conversion methods (a) Resistive Loading; (b) Grid Interface; (c) Unity Power Factor Controlled Converter

solution that optimises against all desired objectives is challenging due to the multi physics nature of the system. The following sections define the objectives and variables used in this work to investigate the resultant LA dimensional parameters and performance when operating under one of the predefined three loading conditions.

A. Objectives

The design study is constrained by both geometrical and performance specifications of the JC-FPE given in table I. Thus, the design procedure followed in here gives priority to the geometrical dimensions of the machine as a first objective, then it looks at the resultant machine force capability, as the second objective. Both objectives are entirely coupled by the design variables and have mutual effects on the resultant machine performance. Therefore, investigating the variables that have an influence on both objectives must be performed first, then the effect of the remaining independent variables can be studied. This saves computational time, selecting design variables one by one and avoid solving models of the undesired variable changes.

B. Design Variables

Based on the power conversion (loading) methods proposed, three individual models were established and manually optimized to achieve the objectives in order to perform the design study. Since the loading condition is the only variation between these scenarios, a unified model can be used to define the variables for design purposes. This is done using 2-D axisymmetric FEA modelling supported by the transient solver in *Magnet* (a commercially available software). For the topology shown in Fig.1 a unified base model comprising a single slot/pole geometry is shown in Fig.5, defining the design variables investigated in all models. All models ignore the ends effect, use the same magnet and iron core materials, the same translator radius (R_T) and the same air gap length (A_g) as constrained by the mechanical tolerances, stiffness and mover radial forces.

Fig.5: Single slot / pole of the machine showing design variables

C. Optimisation Results

Starting from initial analytical design [26, 27] and with the variable influencing both design objectives, optimisation started with the stator radius (R_s). Optimising the ratio (R_T/R_s) was previously investigated to obtain the optimal value of electromagnetic loadings for a given stator diameter [22, 23] and unconstrained pole pitch (τ_p). Optimization results of stator diameter, shown in Fig.6, depict that the balanced electromagnetic loading condition is guaranteed at almost the same value in both RL and GI models, whereas this condition

Fig.6: Effect of stator radius increase on force capability

Fig.7: Effect of magnet's dimensions on the machine force capability (a) M_H effect; and (b) M_W effect.

was not satisfied for the UPFCC model. Extra electrical loading can be achieved due to the increased coil area and fixed current density in the latter case. Therefore, enforced by the design objective, the stator diameter in the UPFCC model is selected to be equal to that used in the other two models.

For a fixed stator magnetic circuit in all models, optimization results of magnet height and width (M_H , M_W) are shown in Fig.7 (a, b), illustrating how the performance improves with the increase of both. This is expected since the useful air gap flux is increased until the magnetic circuit starts to saturate. In the GI model saturation starts much earlier at ($M_H = 8\text{mm}$) compared with other models. In all models the dimensions of the magnet are limited by the desired performance objective in addition to the limitation imposed by magnetic saturation. Hence dimensions are selected based on force capability. Increased magnet dimensions have corresponding increased cost and moving mass.

The final optimizable design variables are the Tooth Width (T_w) and the Stator Core Back Height (SCBH), and the results are illustrated for one value in 2-D view as shown in Fig.8, and illustrated in 3-D view as in Fig.9 for the selected range of these design variables. Optimization results for these machine dimensions appear not to have been considered elsewhere, e.g. [19, 22, 23], despite having notable influence on the resulting force capability of the range (12%, 20% and 25%) in the RL, GI and UPFCC design models respectively. Also, it can be

Fig.8: The effect of power converter on the machine force capability and variation due to changes in (a) Teeth Width; and (b) Stator Core Back Height

seen that the trend of each surface change is different, highlighting the importance of considering the power conversion scenario at the design stage.

For instance, the effect of changing tooth width for fixed slot and core-back height dimensions can be explained by

Fig.9: The effect of teeth width and stator core back height variation on machine force capability (a) Resistive Loading; (b) Grid Interface; and (c) Unity Power Factor Controlled Converter

Fig.10: Configurations of the three selected machine designs (a) Resistive Load design; (b) Grid Interface design; and (c) Unity Power Factor Controlled Converter design

examining this effect on the magnetic circuit reluctance, knowing that the reluctance increases linearly with flux path length, and inversely with the cross-sectional area and permeability. Decreasing tooth width increases the electrical loading, due to the increased coil area. On the other hand, and for a fixed stator diameter, this will result in decreasing the machine magnetic loading. The hypothesis is reversed as tooth width is increased, and the optimal value is selected as a balance between the coupled electromagnetic loadings. Final selected dimensions are highlighted in the graphs considering manufacturing feasibility, although other dimensions can be selected with attention to machine losses when thinner dimensions are considered. Selected machines configurations are shown in Fig.10.

V. COMPARISON AND DISCUSSION ON THE PERFORMANCE OF SELECTED MODELS

Dimensional parameters and performance characteristics for the three machines are listed in tables II and III respectively. In comparison with RL design model, the GI model has almost the same translator and overall machine mass, however, there is an extra cost of 12.6% increase in

magnet material, an 8.4% increase in stator core mass and a 7.5% reduction in copper mass. High current loading is responsible for a 220 % increase in copper loss, giving reduction in LA efficiency and power densities and requiring external cooling. Current density in the RL design version is such that the LA could be naturally-cooled. The GI design also shows the highest rated force ripple compared with other design models, and will be explained at the end of this section.

The UPFCC design model offer savings of 65.5% and 30.5% with respect to PMs and stator core material versus an extra 22% copper mass. Also, it has the highest power densities and the lightest translator mass compared with other designs.

TABLE II. SELECTED MACHINES DIMENSIONAL PARAMETERS AND WEIGHTS

Object (unit)	Power Conversion scenario		
	RL	GI	UPFCC
Stator outer diameter (mm)	180		
Air gap (mm)	1.5		
Translator outer diameter	103		
Stator back thickness (mm)	4	4.5	3
Tooth width (mm)	7.7		5.6
Coil turns	120	112	146
PM height, width (mm)	12, 8	12, 9	5, 5.5
Copper mass (kg)	9.34	8.64	11.38
Stator mass (kg)	16.45	16.35	16.74
PM mass (kg)	1.59	1.79	0.5
Two stroke Translator mass(kg)	8.38	8.41	5.09

TABLE III. SELECTED MACHINES PERFORMANCE CHARACTERISTICS COMPARISON

Parameter (unit)	Power Conversion scenario		
	RL	GI	UPFCC
Copper loss (W)	75	165	231
Hysteresis and Eddy currents losses (W)	13, 2.6	9.5, 2.0	23, 12
Total iron loss (W)	15.6	11.5	35
PM Eddy currents loss (W)	136	108	159
Maximum current density (J, A/mm ²)	5.8	9.15	
On load peak-to-peak force ripple as a percentage to rated force	1.77%	15.17%	3.1%
Power output (kW)	3.63	3.33	3.73
Power factor	0.7	0.71	1.0
Efficiency (p.u.)	0.94	0.92	0.9
Reacting force (N)	815	802	866
Power density (kW/mm ³)	1189	1075	1223
Power mass density (W/kg)	176	160	193

Fig.11: Cogging force variation over half electrical cycle for the three selected design models

Fig.12: Force fluctuation at rated load over one electrical cycle and possible power conversion methods.

However, the significant increase in copper loss, of order three compared to that of RL design, resulted in a notable efficiency reduction.

The variation of the inherited cogging force at no – load is shown in Fig.11 for half an electrical cycle. The UPFCC design has the lowest cogging, due to the low PM material mass in this design version. Rated load force ripple over one electrical cycle is shown in Fig.12, and is significantly higher in the GI design version. This can be explained with the aid of the circuit diagram shown in Fig.13. Assuming identical phase quantities and parameters, the instantaneous current (I) circulating in the loop shown in Fig. 13 may be expressed as follows:

$$I = \frac{[V_a(\omega t) - V_b(\omega t - 2\pi/3) + 2L \frac{dI}{dt}] - [V_{DC} + 2V_{drop}]}{2R_{ph}}, (A) \quad (1)$$

Where

$V_a(\omega t)$: Phase (a) induced emf, (V).

$V_b(\omega t - 2\pi/3)$: Phase (b) induced emf, (V).

L, R_{ph} : phase inductance and resistance, (H, Ω).

And V_{drop} : diodes on state voltage drop, (V).

Fig. 13: Grid Interface circuit diagram clarifying current path at one instant of three phase system operation.

Fig. 14: Instantaneous variation of phase and line voltage quantities per turn over one electrical cycle.

Equation (1) clarifies that the instantaneous circulating current is a measure of induced phase voltages difference, i.e. the line voltage (V_{ab}), supported by the energy stored (released) in the uncompensated phase inductance of both phases, and is limited by the DC link voltage and partly by converter and phase resistance volts drops. This can be noticed from the variation of phase voltages in all designs, and a line voltage in the GI design, as shown in Fig.14. Therefore, in the GI design, the higher on load force ripple is due to the high instantaneous current flow which is also responsible of the high resulting current density in the design. It should be appreciated that although the same current density is used in the third scenario design, yet the compensation of phase inductance by the controlled converter had the advantage of reducing the force ripple to almost (1:5) of that in the GI design. Thus, controlling the current flowing from the alternator would help in minimizing the on load force ripple, but with negative impacts on the other performance parameters of the machine.

Furthermore, if a cogging force reduction technique is applied [28, 29], it should be assessed not only at no – load conditions, but also and most importantly at rated loads with consideration to the power conversion method and the load variation margins.

VI. CONCLUSIONS

In this paper, the effect of three power conversion scenarios on the design of a tubular LF linear alternator with axial PMs have been presented. Design objectives, variables and design method results have been demonstrated which clearly highlight the effect of power conversion method on the resultant machine dimensional parameters and performance characteristics. It also showed how to order the design objectives priorities as well as how the design variables are entirely interconnected. It demonstrated the effect of machine current loading in varying the force ripple which means that the variation of load margins must also be taken into consideration when investigating a cogging force reduction technique.

Amongst the three designs, the machine designed for unity power factor operation showed the highest power densities, the lightest translator mass, the lowest requirement for PM material and gave the highest electrical power output. The GI version had the largest force ripple and the RL version gave the best efficiency.

The intended use of the electrical power generated from a system composed of a linear alternator driven by any free piston engine type is of importance on overall system cost, efficiency and dynamic performance. A machine prototype has been constructed to validate the findings for the design model with the highest overall machine efficiency.

REFERENCES

- [1] W. R. Cawthorne, P. Famouri, C. Jingdong, N. N. Clark, T. I. McDaniel, R. J. Atkinson, S. Nandkumar, C. M. Atkinson, and S. Petreanu, "Development of a linear alternator-engine for hybrid electric vehicle applications," *IEEE Transactions on Vehicular Technology*, vol. 48, no. 6, pp. 1797-1802, 1999.
- [2] W. Cawthorne, P. Famouri, and N. Clark, "Integrated design of linear alternator/engine system for HEV auxiliary power unit." pp. 267-274, 2001.
- [3] F. Rinderknecht, "A highly efficient energy converter for a hybrid vehicle concept - focused on the linear generator of the next generation." pp. 1-7, 2013.
- [4] S. Schneider, F. Rinderknecht, and H. E. Friedrich, "Design of future concepts and variants of The Free Piston Linear Generator." pp. 1-8, 2014.
- [5] R. Mikalsen, and A. P. Roskilly, "The design and simulation of a two-stroke free-piston compression ignition engine for electrical powergeneration," *Applied Thermal Engineering*, vol. 28, no. 5-6, pp. 589-600, April, 2008.
- [6] R. Mikalsen, and A. P. Roskilly, "Performance simulation of a spark ignited free-piston engine generator," *Applied Thermal Engineering*, vol. 28, no. 14-15, pp. 1726-1733, 10//, 2008.
- [7] R. Mikalsen, and A. P. Roskilly, "A computational study of free-piston diesel engine combustion," *Applied Energy*, vol. 86, pp. 1137-1143, 2009.
- [8] M. R. Hanipah, R. Mikalsen, and A. P. Roskilly, "Recent commercial free-piston engine developments for automotive applications," *Applied Thermal Engineering*, vol. 75, pp. 493-503, 2015.
- [9] R. W. Moss, A. P. Roskilly, and S. K. Nanda, "Reciprocating Joule-cycle engine for domestic CHP systems," *Applied Energy*, vol. 80, no. 2, pp. 169-185, 2005.
- [10] D. Wu, and A. P. Roskilly, "Design and Parametric Analysis of Linear Joule-cycle Engine with Out-of-cylinder Combustion," *Energy Procedia*, vol. 61, pp. 1111-1114, 2014.

- [11] P. Zheng, Y. Sui, C. D. Tong, J. G. Bai, B. Yu, and F. Lin, "A novel single-phase flux-switching permanent magnet linear generator used for free-piston Stirling engine," *Journal of Applied Physics*, vol. 115, no. 17, pp. 17E711, 2014.
- [12] W. Jiabin, W. Weiya, K. Atallah, and D. Howe, "Design Considerations for Tubular Flux-Switching Permanent Magnet Machines," *Magnetics, IEEE Transactions on*, vol. 44, no. 11, pp. 4026-4032, 2008.
- [13] J. Wang, and N. J. Baker, "A comparison of alternative linear machines for use with a direct drive free piston engine." pp. 1-6, 2016.
- [14] K. Lu, and W. Wu, "High Torque Density Transverse Flux Machine Without the Need to Use SMC Material for 3-D Flux Paths," *IEEE Transactions on Magnetics*, vol. 51, no. 3, pp. 1-4, 2015.
- [15] W. M. Arshad, P. Thelin, T. Backstrom, and C. Sadarangani, "Use of transverse-flux machines in a free-piston generator," *IEEE Transactions on Industry Applications*, vol. 40, no. 4, pp. 1092-1100, 2004.
- [16] Z. Ping, T. Chengde, C. Gang, L. Ranran, S. Yi, S. Wei, and C. Shukang, "Research on the Magnetic Characteristic of a Novel Transverse-Flux PM Linear Machine Used for Free-Piston Energy Converter," *Magnetics, IEEE Transactions on*, vol. 47, no. 5, pp. 1082-1085, 2011.
- [17] J. Wang, and D. Howe, "Design optimization of radially magnetized, iron-cored, tubular permanent-magnet machines and drive systems," *IEEE Transactions on Magnetics*, vol. 40, no. 5, pp. 3262-3277, 2004.
- [18] J. Wang, D. Howe, and G. W. Jewell, "Analysis and design optimization of an improved axially magnetized tubular permanent-magnet machine," *IEEE Transactions on Energy Conversion*, vol. 19, no. 2, pp. 289-295, 2004.
- [19] Z. Ping, T. Chengde, B. Jingang, Y. Bin, S. Yi, and S. Wei, "Electromagnetic Design and Control Strategy of an Axially Magnetized Permanent-Magnet Linear Alternator for Free-Piston Stirling Engines," *Industry Applications, IEEE Transactions on*, vol. 48, no. 6, pp. 2230-2239, 2012.
- [20] A. S. Jalal, N. J. Baker, and D. Wu, "Design of tubular moving magnet linear alternator for use with an external combustion - free piston engine," in 8th International Conference on Power Electronics, Machines and Drives (PEMD), Glasgow, UK, 2016, pp. 6.-6.
- [21] A. S. Jalal, N. J. Baker, and D. Wu, "Electrical Machine Design for use in an External Combustion Free Piston Engine," in International Conference on Renewable Power Generation (RPG), London, UK, 2016.
- [22] J. Wang, M. West, D. Howe, H. Z. D. La Parra, and W. M. Arshad, "Design and Experimental Verification of a Linear Permanent Magnet Generator for a Free-Piston Energy Converter," *Energy Conversion, IEEE Transactions on*, vol. 22, no. 2, pp. 299-306, 2007.
- [23] Z. Ping, T. Chengde, Z. Jing, Y. Bin, L. Lin, B. Jingang, and Z. Lu, "Investigation of a 7-pole/6-slot Halbach-magnetized permanent-magnet linear alternator used for free-piston stirling engines," *Journal of Applied Physics*, vol. 111, no. 7, pp. 07E711, 2012.
- [24] A. H. Rajaei, M. Mohamadian, and A. Yazdian, "Carrier-based PWM and space vector modulation of three single phase PFC rectifier as generator-side converter of PM WECS." pp. 1-8.
- [25] E. Sunan, F. Kucuk, H. Goto, H. J. Guo, and O. Ichinokura, "Three-Phase Full-Bridge Converter Controlled Permanent Magnet Reluctance Generator for Small-Scale Wind Energy Conversion Systems," *IEEE Transactions on Energy Conversion*, vol. 29, no. 3, pp. 585-593, 2014.
- [26] I. Boldea, and S. A. Nasar, *Linear electric actuators and generators*: Cambridge University press, 1997.
- [27] J. Wang, and D. Howe, "Analysis of axially magnetised, iron-cored, tubular permanent magnet machines," *IEE Proceedings - Electric Power Applications*, vol. 151, no. 2, pp. 144-150, 2004.
- [28] A. Souissi, I. Abdennadher, and A. Masmoudi, "An approach to reduce the cogging force in tubular linear PM synchronous machines." pp. 1-7, Tenth International Conference on Ecological Vehicles and Renewable Energies (EVER), 2015.
- [29] Q. Wang, and J. Wang, "Assessment of cogging-force-reduction techniques applied to fractional-slot linear permanent magnet motors equipped with non-overlapping windings," *IET Electric Power Applications*, vol. 10, no. 8, pp. 697-705, 2016.