Design of A Double-sided Permanent Magnet Linear Generator for Laboratory Scale Ocean Wave Energy Converter

Addy Wahyudie
United Arab Emirates University

Tri Bagus Susilo
United Arab Emirates University

Mohammed Jama
Abu Dhabi University

Bisni Fahad Mon
United Arab Emirates University

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Addy Wahyudie*, Tri B. Susilo, M. Jama, Bisni F. Mon, H. Shaaref
Electrical Engineering Department
United Arab Emirates University (UAEU)
Alain, Abu Dhabi, United Arab Emirates
*Email: addy.w@uaeu.ac.ae

***Abstract*—Design of a laboratory scale wave energy converter (WEC) system based on planar double-sided permanent magnet linear generator (PMLG) is considered in this paper. The detail procedure in designing the PMLG is reported including analytical work and experimental testing. The main objective is to create a simple and easy procedure in the design and optimize the detailed parameters to achieve the aimed output voltage with the constraint of physical designs. The PMLG is incorporated with sensors, linear actuators, springs, and data monitoring devices to create a WEC system and conduct the experimental testing. The test is conducted to show the performance of the design procedure by comparing the output voltage between the design and measurement. The result shows that the output voltages are close. Additionally, another experiment is performed to check the conversion efficiency of the machine.**

I. Introduction

Ocean waves energy is a huge potential renewable energy resource due to its high energy density, which is about 2−3 kW [1], [2]. The accessible power from ocean wave globally can reach up to 0.5 TW [3]. The works on how to harness this resources are tremendously important,including how to design an efficient and low-cost generator. One of the most famous techniques to exploit ocean wave power is power-take-off (PTO) mechanism, which utilize permanent magnet linear generator (PMLG). Various designs of PMLG have been suggested such as tubular [4], [5] and planar [6], [7] PMLGs.

In the process of designing PMLG, there are several steps that can be considered. Initially, analytical work should be performed in order to set main parameters or goals such as the wanted maximum dimension and output power [8], [9], [10]. Next step is the simulation or computational work for the distribution of magnetic field on the designed PMLG. It provides the designer to optimize several parameters such as magnet size, number of coils, air gap, etc [5], [11]. Finally, experimental work should be considered to see how close is the design and actual result [10].

In this work, a planar PMLG with a double-sided permanent magnet was designed and experimentally tested in laboratory scale. The planar double-sided structure is selected due to its simplicity of the design and low cost in production. The main purpose of the design is to obtain the structural parameters and material properties of the PMLG to match the desired peak value of electromotive force (EMF) voltage with the designed constraints.

II. Design and Setup

PMLG is the core of WEC devices because it is the one that enable the ocean wave power harnessing. Figure 1 shows the proposed structure of the planar double-sided PMLG. It consists of two arrays of permanent magnets with coils between the slabs. Each magnet bar is attached to a steel module to hold The coils are insulated with epoxy resin to reduce the leakage currents. The pack of coils move linearly on the track that is connected to the slider rail. In a real application the slider is connected to floater to provide extra damping force. The constraint in the proposed design is the peak stroke. It affect the working section length to be short; the length of the coils' pack is less than magnets array.

A. Design of the PMLG

In this part, we emphasize the design process on the practical and handy aspects so that the designer will be convenient to comply. The goal was to create a simple tool, such as

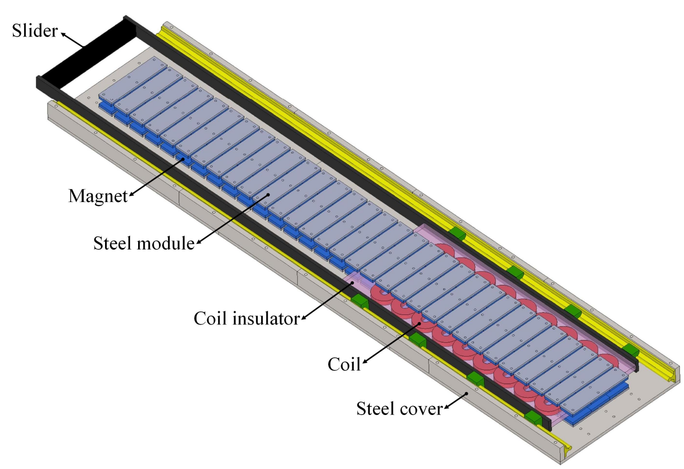

Fig. 1. General design of the planar double-sided PMLG structure.

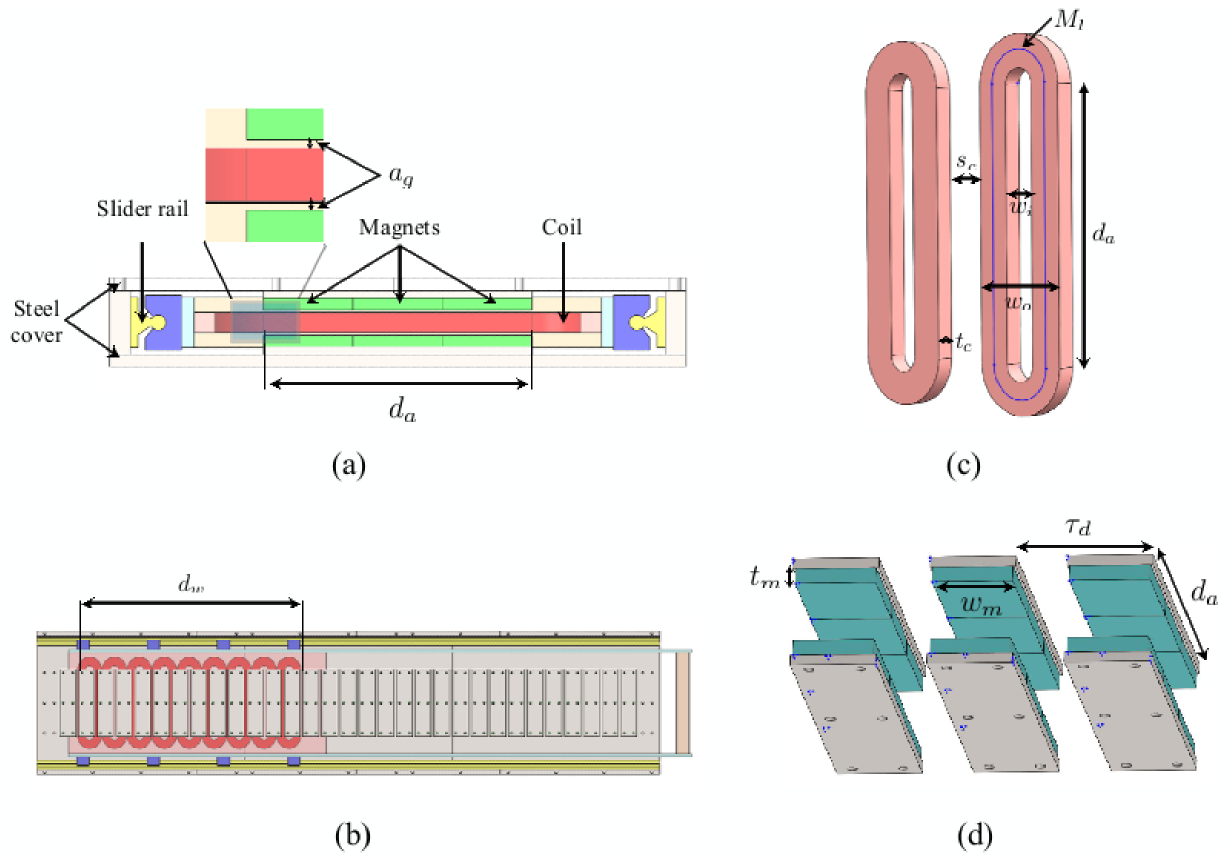

Fig. 2. Arrangement of the PMLG from top (a) and side views (b). The coil (c) and magnet (d) parameters.

a spreahsheet table, to help the designer to configure and determine the parameters with specific constraints and targets.

There are two types of parameters to be considered: basic parameters, which are based on design constraints and are determined at the beginning, and derived parameters, which are calculated from the formulas derived from the basic parameters. The parameters are separated into three groups: general design, coil design, and permanent magnet design.

In the group of general design, the basic parameters are maximum stroke (d_s), number of coils (N_c), active length (d_a), working section length (d_w) and maximum linear velocity (v_l). On the other hand, the derived parameters are number of active poles each side (N_a), pole pitch (τ_p), and total poles per side (N_p), which can be calculated using the following formulations.

$$N_a = \frac{N_c}{\beta} \tag{1}$$

$$\tau_p = \beta \cdot \frac{d_w}{N_c} \tag{2}$$

$$N_p = 1 + \left(\frac{d_w + d_s}{\tau_p}\right) \tag{3}$$

where β is a constant coefficient with a value less than one (we selected $\beta = 0.75$).

Furthermore, in the group of coil design, the basic parameters are inner width (w_i), thickness (t_c), and gap (s_c) of the coil, as shown in Fig. 2c. The derived parameters are outer width of the coil (w_o), mean pitch (m_p), pitch factor (K_p), spread factor (K_s), coil spread (c_s), number of turns per coil (N_t), and mean length per turn (M_l).

determined by the following equations.

$$w_o = \left(\frac{\tau_p \cdot N_a}{N_c}\right) - s_c. \tag{4}$$

$$m_p = \frac{(w_o + w_i)}{2} \frac{\pi}{\tau_p}. \tag{5}$$

$$K_p = \cos\left(\frac{\pi - m_p}{2}\right). \tag{6}$$

$$K_s = \frac{\sin(c_s/2)}{c_s/2} \tag{7}$$

$$c_s = \frac{(w_o - w_i)}{2} \frac{\pi}{\tau_p}. \tag{8}$$

$$N_t = \frac{w_a \cdot t_c \cdot K_f}{A_w} \tag{9}$$

where K_f is the fill factor of the coil's wire, w_a is defined as

$$w_a = \frac{w_o - w_i}{2}, \quad (10)$$

and A_w is the area of the wire

$$M_l = 2 \cdot d_a + \pi \cdot \frac{w_o + w_i}{2} \quad (11)$$

At final, we discuss the parameters for the permanent magnet design. Figure. 2d shows its basic parameters, such as thickness of the magnet(t_m), width of the magnet(w_m), and the air-gap distance (a_g). The derived parameter is the magnetic field in the air-gap (B_g) that is determined as

$$B_g = \frac{\Phi}{A} \cdot H_w \quad (12)$$

where

$$H_w = \frac{4}{\pi} \sin\left(\frac{\pi \cdot r_m}{2}\right), \quad (13)$$

A is the surface area of the magnet, and Φ is the magnetic flux that is calculated using reluctance model as reported in [12].

Those parameters are used to determine the electromotive force (EMF) voltage as mentioned below

$$V_p = N \cdot V_c \quad (14)$$

where N is the number of coils per phase, and V_c is defined as

$$V_c = N_c \cdot V_t \cdot K_s \cdot K_p \cdot \eta_e \quad (15)$$

with V_c and V_t are the maximum EMF voltage each coil and each coil turn, respectively. The V_t is calculated using the following equation

$$V_t = 2 \cdot B_g \cdot v_l \cdot d_a, \quad (16)$$

and η_e is the end effect adjustment factor and is formulated as

$$\eta_e = \left(1 - \frac{\tau_p}{4 \cdot d_a}\right) \quad (17)$$

Utilizing those parameters $1-17$, a handy spreadsheet table can be yielded to help a PMLG designer to find optimum parameters for the design iteratively.

B. Lab Test Setup

Final stage of the PMLG design is experimental test. We managed to construct a Lab scale setup for the WEC experiment as shown in Fig. 3. It was constructed to perform various researches related to WEC in a droughty condition. The left part in Fig. 3 shows the cad design of the WEC setup in minimum and maximum stroke conditions. It was also designed with a steel pod to ease the transportation of the setup. The middle part is the realization from the cad. It comprises the PMLG itself, sensors, data monitoring device, and wave emulator. The right part shows the closed-up of the springs and coils. The machine assembly has minimum and maximum heights of 2.35 m and 3.45 m, respectively.

The PMLG was designed with rated power at 1.2 kW based on 1 m/s of v_l and 1 m of maximum stroke. Neodymium iron boron (NdFeB) magnet bars were used to construct the magnet slabs. The grade of the magnet is N45. Figure 4 shows the array of permanent magnets. The coils, as shown in Fig. 3, made of copper wire with 317 per coil with resistance of around 4/3 Ω. The machine yields peak EMF voltage per phase up to 233 V. The detail parameters are tabulated in Table 2.

TABLE I
LIST OF THE PMLG PARAMETERS.

Variable	Symbol	Value	Unit
General Design Parameters			
Maximum stroke	d_s	1	m
Working section length	d_w	0.7	m
Maximum linear velocity	v_l	1	m/s
Magnet Parameters			
Variable	**Symbol**	**Value**	**Unit**
Magnet Bgap	B_g	0.67	T
Magnet Brem	B_r	1.3	T
Air gap distance	a_g	$25{\cdot}10^{-4}$	m
Pole pitch	τ_p	58.5	mm
Magnet thickness per side	t_m	$9{\cdot}10^{-3}$	m/s
Active poles per side	N_a	12	-
Total poles per side	N_p	30	-
Coil Parameters			
Variable	**Symbol**	**Value**	**Unit**
Active length	d_a	0.21	m
Wire diameter	w_d	$1{\cdot}10^{-3}$	m
Coil turns	N_t	317	-
Coil outer width	w_c	$76{\cdot}10^{-3}$	m
Coil inner width	w_i	$32{\cdot}10^{-3}$	m
Coil thickness	t_c	$15{\cdot}10^{-3}$	m
Space between coils	s_c	$2{\cdot}10^{-3}$	m
Coil peak EMF	V_c	78	V
Coil spread	c_s	1.18	rad
Coil surface area	A_s	$26{\cdot}10^{-3}$	m^2
Spread factor	K_s	0.94	-
Pitch factor	K_p	0.99	-
mean pitch	m_p	2.9	rad
Fill factor	K_f	0.755	-
Mean length turn	M_l	0.526	m
Eng effect adjustment	η_e	0.93	-
Number of coils per phase	N	3	-
Number of coils	N_c	9	-
EMF peak per turn	V_t	0.28	V
EMF peak per phase	V_p	233	V

Several sensors are mounted to the setup, such as SP1-50 linear potentiometer as position sensor to measure the movement of the translator, 600 Richmond S-beam 2500 N load cell to quantify damping force on the springs, LEM LF 205-S/SP3 current transducer to measure the flowing current, LEM LV 205-1000 voltage transducer to measure the generated voltage, and K-type thermocouple to measure the coil's temperature. All data from the sensors are monitored by data acquisition system using cRIO-9073 National Instruments (NI) controller with multi analog and digital inputs.

In order to simulate ocean wave in the system, we set a wave emulator system using a 3Φ 415 V AKM65P Kollmorgen servo motor as linear actuator, a Thomson T90 driver to drive the actuator, and springs to represent damping force of wave hydrodynamic. The actuator driver is connected to a software that provide wave profiles commands to the system.

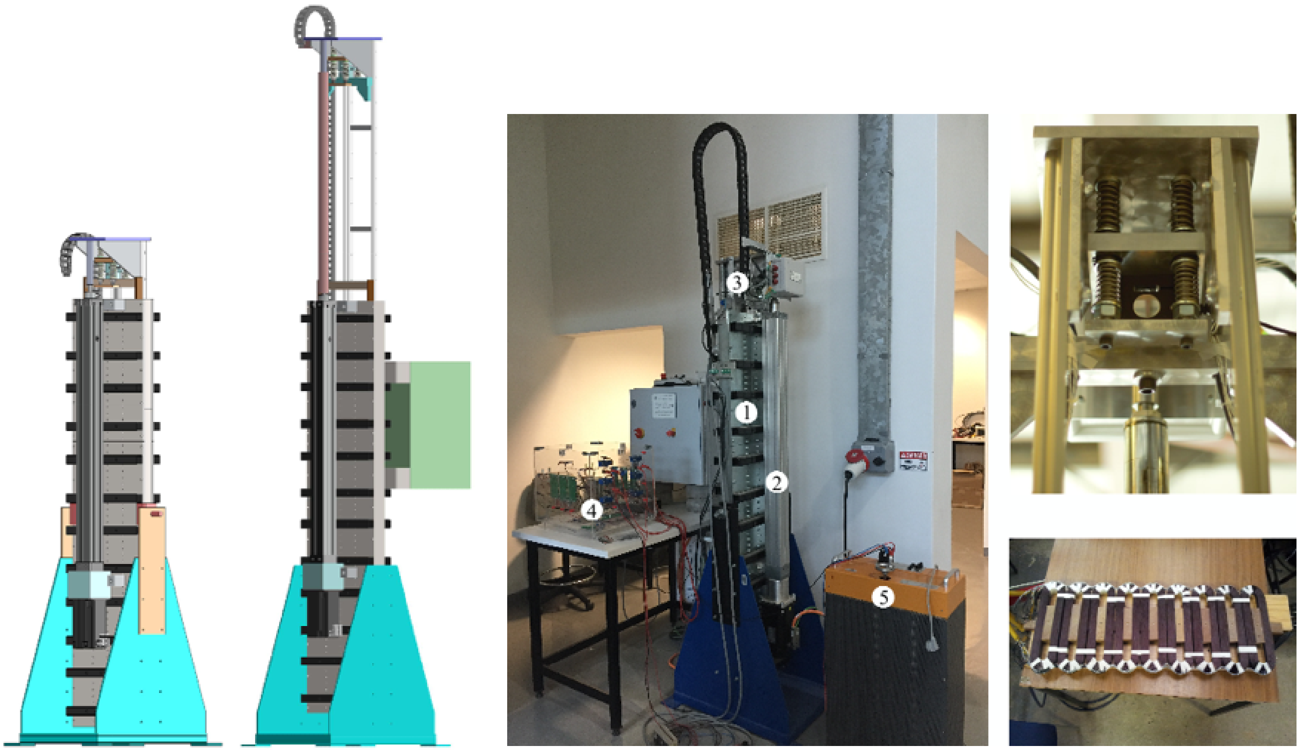

Fig. 3. WEC experimental setup. Left: setup cad designs. Middle: setup realization, which consists of the PMLG (1), linear actuator (2), springs (3), sensors and data acquisition (4), and three-phase load (5). Bottom right: the arrangement of coils before lamination. Top right: adjustable springs.

Fig. 4. Array of N45-grade NdFeB magnets placed on the steel sheet.

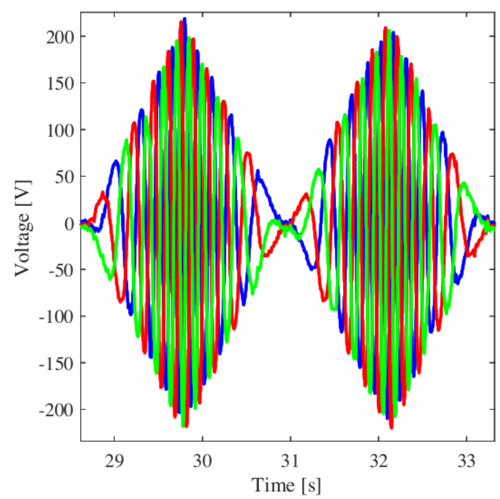

Fig. 5. 3Φ EMF voltage of the experiments under zero load condition.

III. Experimental Tests

The experimental testing is conducted with two scenarios: load-free and loaded tests. The first test is aimed to see the performance of the design procedure by comparing EMF value of designed and measured. The results shows that under open circuit scheme, the designed peak value of EMF voltage, 233 V, is close to the value resulted from the machine, which is 221 V as shown in Figure 5. The machine was given a monochromatic wave spectrum with velocity of 1 m/s and 1 m maximum stroke.

In case of loaded system scenario in which a 3Φ 20Ω resistive load is connected to the WEC setup, Fig. 6 shows the mechanical quantities of the system. The displacement and velocity profiles of the translator are displayed in Fig. 6a and b, respectively, measured by the position sensor. The peak stroke almost reached 1 m and the peak velocity was 0.5 m/s.

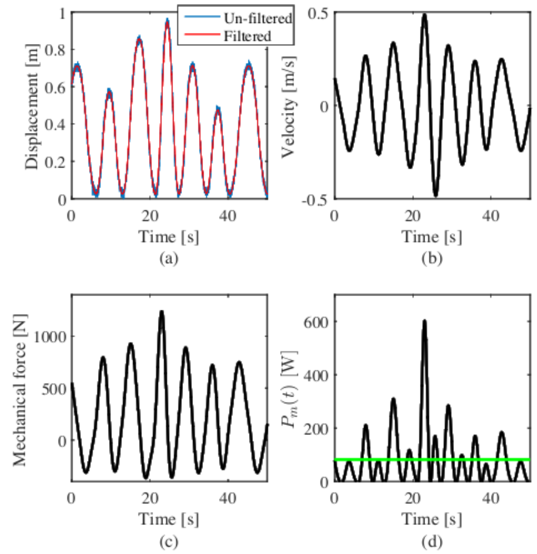

Fig. 6. Mechanical quantities of the loaded scenario: (a) displacement, (b) velocity, (c) F_m , and (d) P_m with its average values (green line).

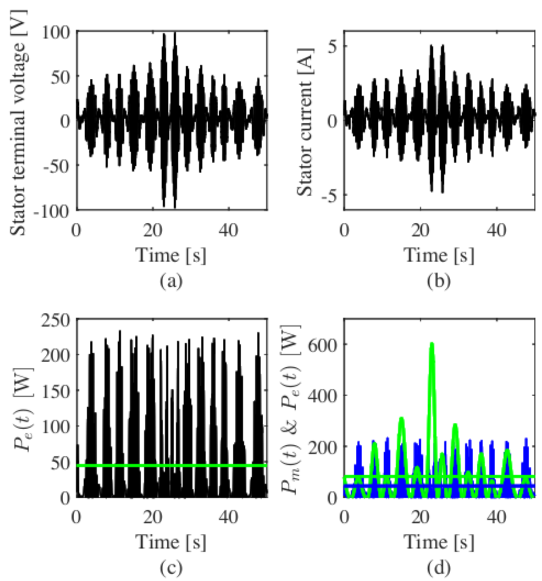

Fig. 7. Electrical quantities of the loaded scenario: (a) $u_s(t)$, (b) $i_s(t)$, (c) P_e with its average value (green line), and (d) P_e and P_m with its average values (blue and green lines, repectively).

Figure 6c shows the corresponding force measured by the load cells and reached up to about 1240 N. Figure 6d displays the mechanical power (P_m) with average value of 83 W and peak value of 600 W. This quantity is calculated from the following equation

$$P_m(t) = F_m(t) \cdot v_l(t) \tag{18}$$

where $F_m(t)$ is the mechanical force. The electrical quantities from the loaded experiment are shown in Fig. 7. Figure 7a and b show the stator terminal voltage (u_s) and current (i_s), respectively. The peak voltage reached 100 V while the maximum current is about 5 A. The average electrical power (P_e) is about 44.7 W shown in Fig. 7c. The P_e is formulated as

$$P_e(t) = 3 \cdot u_s(t) \cdot i_s(t) \tag{19}$$

Figure 7d shows the comparison between P_e and P_m. The conversion efficiency is found to be around 54%.

IV. Conclusion

A procedure in designing a planar double-sided PMLG for WEC application has been presented, which included analytical and experimental works. The PMLG was integrated with other devices such as sensors, linear actuator, springs and data acquisition devices to construct a Lab scale WEC system. We did two scenarios for the experimental test, with and without load. The first scenario provided the good meet between design and experiment in term of EMF voltage. The second scenario gave the information of machine efficiency, which is aroung 54%.

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