



Quasi-flat linear PM generator optimization using simulated annealing algorithm for WEC in Indonesia

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Abstract

Linear permanent magnet generator (LPMG) is an essential component in recent wave energy converter (WEC) which exploits wave's heave motion. It could be classified into tubular-type, flat-tricore type, and quasi-flat type. In previous researches, these three models have been studied and designed for pico-scale WEC. Design optimization has further been conducted for flat-tricore LPMG, by using simulated annealing (SA) algorithm. It modified some parameters to minimize the resulted copper loss. This paper aims to optimize a quasi-flat LPMG design by applying SA algorithm. The algorithm would readjust the initial LPMG parts dimension. Then, the output of the optimized design would be analyzed and compared. The results showed that the optimization could reduce the copper loss by up to 73.64 % and increase the efficiency from 83.2 % to 95.57 %. For various load resistances, the optimized design also produces larger efficiency. However, the optimized design has a larger size and produces larger cogging force than the initial design.

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Keywords: Design optimization; copper loss; simulated annealing; quasi-flat LPMG.

1. Introduction

As the ocean wave provides relatively huge energy, several energy conversion methods have been developed. Considering the technique, one quite popular approach is by exploiting the heave motion of the ocean wave. Several models are utilizing this way, including Archimedes Wave Swing (AWS), SeaBeavI wave energy converter (WEC) and Aqua Buoy [1][2]. In recent WEC methods, the use of linear permanent magnet generators (LPMG) as mechanical to electrical converter is the key factor, hence it's design should be made as reliable and optimum as possible.

Basically, the LPMG could be classified based on its stator core shape. The first one, tubular-type has tubular shape, higher maximum flux density, and is able to produce low detent force [3][4]. The second model, flat-type LPMG, forms prism shape. It could be further formed into different cross-section shape: quasi-flat with rectangular prism and flat-tricore

with triangular prism. Compared to the first type of tubular LPMG, the flat-type LPMG could generate slightly higher output voltage and specific power for equal loads [5]. Furthermore, the previous investigation has found that the quasi-flat type produces slightly higher flux density as well as induced voltage than the flat-tricore LPMG [6]. The configurations of these types are shown in Figure 1 and Figure 2.

According to the placement site, there are three options: offshore, shoreline, and nearshore. The offshore location provides the highest input power, thus the generated electrical energy of this placement model is also the highest. However, it is also exposed to greater risk from environment conditions, such as weather, water salinity, and possible natural disaster. These factors give challenges to its building and maintenance. The shoreline and nearshore WECs, on the other hand, experience different conditions. They might produce less output power, but cheaper and easier in maintenance [7].

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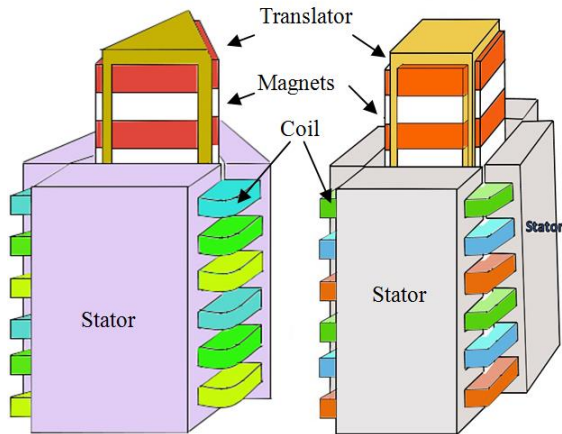


Figure 1. Flat-tricore type (left) and quasi-flat type (right) of LPMG

As one of the countries with promising wave energy resources, Indonesia could benefit from this source for electrical power generation. Previous researches have designed tubular and flat LPMGs for WEC in Indonesia [8][9]. The designs were built based on the offshore condition in south Java Ocean, Indonesia. Further research was also conducted to optimize the design of flat-tricore LPMG. The optimization was aimed to minimize resulted copper losses, by modifying the dimension of the generator parts. For this purpose, simulated annealing (SA) algorithm had been used [10]. The results showed that the utilization of the algorithm could reduce the copper loss and increase the electrical efficiency of the LPMG [10].

In this paper, the copper loss optimization by using the simulated annealing algorithm would be applied to a quasi-flat LPMG. This LPMG would also be used as a component of a pico-scale WEC in south Java Ocean. Prior to the optimization, an initial unoptimized 1 kW quasi-flat LPMG design would be provided. After the optimization process, the output parameters of the optimized design would be analyzed and compared to the initial one.

II. Materials and Methods

A. Proposed quasi-flat LPMG

For comparison purposes, an initial unoptimized design would be presented first. In this case, a quasi-flat LPMG had been designed before, considering wave characteristics in south Java Ocean during

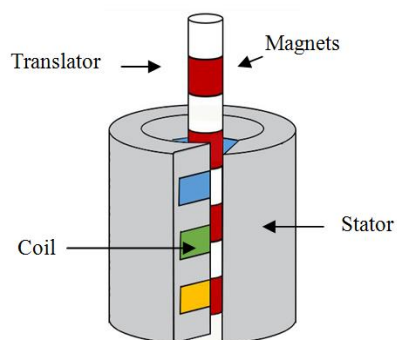


Figure 2. Tubular type LPMG

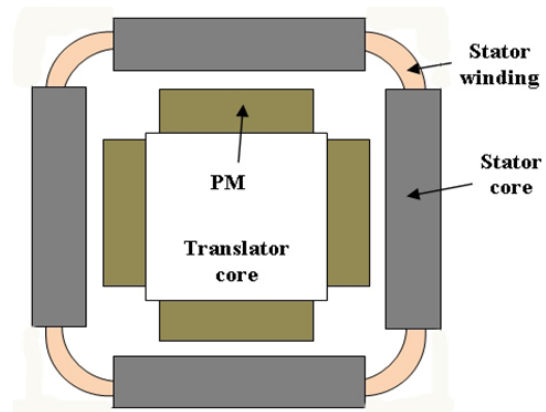


Figure 3. Upper view of proposed quasi-flat LPMG

certain periods [9]. The design has rectangular prism-shaped surface, as shown in Figure 3. The process and technique of designing this generator were based on [11]. The generator would be used for WEC with a floating buoy, where the scheme is shown in Figure 4.

The quasi-flat LPMG was composed of two main parts: translator and stator. The stator core was made of US steel type 2 core. To reduce power loss from eddy current, the stator was composed of stacks of lamination, with each lamination width of about 0.6 mm. Moreover, electrical output could be extracted from stator winding terminal, which used AWG 11 wire.

In translator, permanent magnets were placed in radial array. The magnets used NdFeB 35/N35, with residual flux density of 1.17 T and coercivity of 868,000 A/m. Meanwhile, the translator core was made of ferromagnetic carpenter silicon iron 1066 C. The use of ferromagnetic material in the translator core was meant to maximize the magnetic flux flowing to the stator. The path of the flowing magnetic flux in the radial array is shown in Figure 5.

The dimension of the generator parts were being calculated considering the expected output and wave characteristics in its location. The wave characteristics were previously analyzed based on the monthly average wave height data on that location from 2000 to 2010. However, only the wave height in July and August which were considered because the wave height in these periods was maximum.

According to the data, the average wave height used as the reference was 0.845 m, with wave period

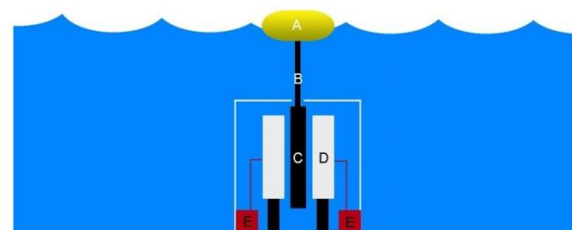


Figure 4. Placement scheme of LPMG in wave energy power plant: (A) floating buoy, (B) connector, (C) translator, (D) stator, (E) supporting part [10]

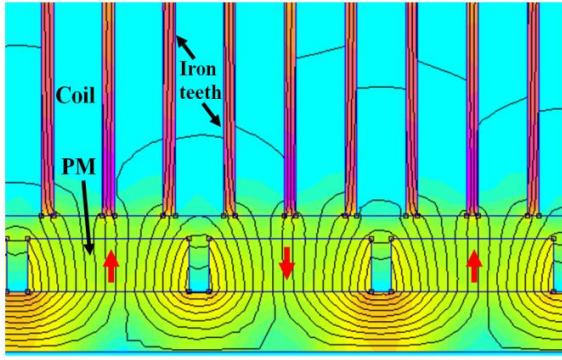


Figure 5. The flow of magnetic flux in radial permanent magnets array (red arrows show PMs' orientation)

was 5.61 s. The potential power which could be provided was then about 34.57 kW/mcl. Given these conditions, the size of the quasi-flat LPMG parts was then specified.

The length of the stator (L_s , in meter) could be calculated using the equation below,

$$L_s = \frac{P\sqrt{2}}{M_s B_m J W_s v} \quad (1)$$

Parameter P is expected output power (W), M_s is number of armature, B_m is air-gap flux density under magnets (T), J is current density (A/m), W_s is stator width (m), and v is rated translation speed (m/s). The L_s then determines the dimension of pole pitch (τ_p , in meter) and tooth pitch (τ_t , in meter). However, they are also determined by number of slot (s), pole (p), and phase (m).

$$\tau_p = \frac{L_s}{p} \quad (2)$$

$$\tau_t = \frac{\tau_p}{mq} \quad (3)$$

q is slot/pole/phase.

The size of the tooth pitch (τ_t) is then partitioned for slot width (b_s) and tooth width (b_t) –both are in meter by a certain proportion,

$$\tau_t = b_t + b_s \quad (4)$$

Meanwhile, the length of the permanent magnet (τ_m , in meter) is affected by magnetic flux comparison of C_m ,

$$\tau_m = C_m \tau_p \quad (5)$$

$$C_m = \frac{B_g}{B_m} \quad (6)$$

B_g is average flux density in air gap (T). The pole pitch (τ_p , in meter) then determines the thickness of stator yoke (Y_s) and translator yoke (Y_r) –both in meter, as follow,

$$Y_s = \frac{\tau_p B_g}{2B_{ys}} \quad (7)$$

$$Y_r = \frac{\tau_p B_g}{2B_{yr}} \quad (8)$$

B_{ys} and B_{yr} are the permissible flux density in stator core and rotor core (T) respectively.

The equivalent air gap width (g_{eq} , in meter) is based on initial air gap (g , in meter). It could be calculated by using the equation below,

$$g_{eq} = \frac{\tau_t(5g+b_s)}{\tau_t(5g+b_s)-b_s^2} g \quad (9)$$

The value g_{eq} and B_r (PM remanence, in tesla) then determine the thickness of the permanent magnet (h_m , in meter),

$$h_m = \frac{g_{eq}(B_r B_g)}{\mu_0 H_c [(B_r - B_g)]} \quad (10)$$

Finally, the number of stator coil turn is decided based on the expected induced voltage (E_{ph} , in volt),

$$E_{ph} = \frac{M_s N_{ph} B_m W_s v}{\sqrt{2}} \quad (11)$$

$$N_c = \frac{N_{ph}}{pq} \quad (12)$$

N_c and N_{ph} are winding turn/slot and winding turn/phase successively. For R_w is typical wire resistance (Ω/m) and L_c is coil length (m), the phase resistance is,

$$R_{ph} = R_w L_c N_{ph} \quad (13)$$

The output real power of the generator (P_{out} , in watt) could be calculated based on the load resistance,

$$P_{out} = i_{ph}^2 R_L \quad (14)$$

Meanwhile, the copper power loss of the generator (P_{loss} , in watt) is,

$$P_{loss} = i_{ph}^2 R_{ph} \quad (15)$$

i_{ph} is phase current (A), R_L and R_{ph} are the load winding resistance (Ω) and phase winding resistance (Ω) successively. The complete design and its parameters' symbol is shown in Figure 6.

B. Simulated annealing (SA) algorithm

In an optimization process, there are basically several ways to solve a problem. One of them is by using stochastic approach. In this way, optimal solution is searched by trials and error in several iterations. Furthermore, this approach could be divided into heuristic and metaheuristic. The latter approach includes tradeoff and randomization during trial and error process. The randomization is useful so that the search is for global optimal rather than local optimal, thus the result would be more accurate.

Many nature events inspire the building of metaheuristic optimization algorithms. Among them, there is simulated annealing (SA), composed by Kickpatrick et al. in 1983. This method uses a single agent or solution which goes along a search space in a piecewise style [12][13].

The algorithm has a similar concept with annealing process of solid material. It is a physical process where a solid material is heated up to its melting state. After that, the material would be chilled down slowly until reaching a certain low temperature, with sometimes crystallization occurs to the material. In optimization problem, probable solution is represented by the solid material's state. Meanwhile, the values of the objective function are represented by the energy of states. In this case, the optimal solution corresponds to the lowest energy state.

Table 1.
LPMG optimization setting using SA algorithm

Parameters	Symbol	Value
Initial temperature	T0	324 (°C)
Reduction rate	alpha	0.99
Maximum iteration	i	100
Number of sub-iteration		20
Variables		
stator width (m)	Ws	30<Ws<100 (mm)
slot width (m)	bs	3<bs<20 (mm)
slot height (m)	hs	30<hs<300 (mm)
Constraint		
electromotive force (V)	Eph	≤ 150 (V)

In finding the optimum solution, the SA algorithm exploits iterations. In each iteration, current solution is randomly updated to a new solution. The algorithm would compare the updated solution in each iteration to the previous one. If a new solution is better according to the objective, it would replace the old one and would become the new solution for the next iterations. Nevertheless, the probability of random uniform number that is generated from the iteration process might be smaller than predetermined function value. In this case, the new solutions would be treated as a better solution to replace the prior solution. This repeated process would run until the last iteration.

This algorithm has had wide applications in power system. It helps to solve economic load dispatch problems in power generation by minimizing generation cost function, even penalty terms are included [14]. It could also guide to optimum distribution network reconfiguration with power loss considerations. The mechanism of this algorithm could avoid the search process being fell into local optimal, and thus the solution of this method is most likely the global optimal. On the other hand, this algorithm requires quite longer computation time than some other metaheuristic algorithms.

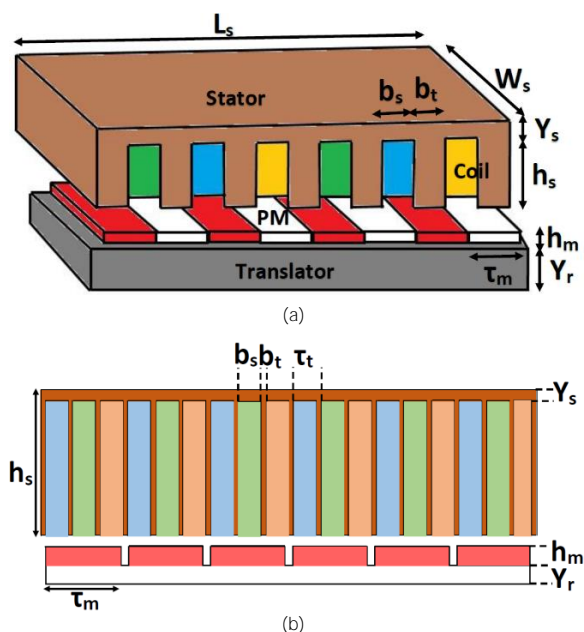


Figure 6. Design of the LPMG: (a) 3-dimension, (b) front view

In this research, the SA algorithm would be used to find the optimum dimension of the quasi-flat LPMG design which produce minimum copper loss, as stressed in the objective function below,

$$F_{Objective} = \min(P_{loss}) \quad (16)$$

To achieve this objective, the dimension of stator width (W_s), slot height (h_s), and slot width (b_s) were modified. However, the dimension of the remaining LPMG parts would be affected and would be readjusted later based on those three.

Among the three variables, the first is affecting the induced voltage. Meanwhile, the other two affect the coil length, which corresponds to its resistance. Combination of these components would determine the resulted copper loss, and the algorithm is expected to adjust these variables in order to minimize the copper loss.

After setting those variables, the resulted copper loss would be calculated. At the end of this process, the minimum copper loss would be obtained, and the other parts' dimensions were re-calculated based on the optimized parameters. Finally, the output values of the resulted generator would be presented and compared. The optimization flowchart is presented in Figure 7, while the optimization settings are shown in Table 1.

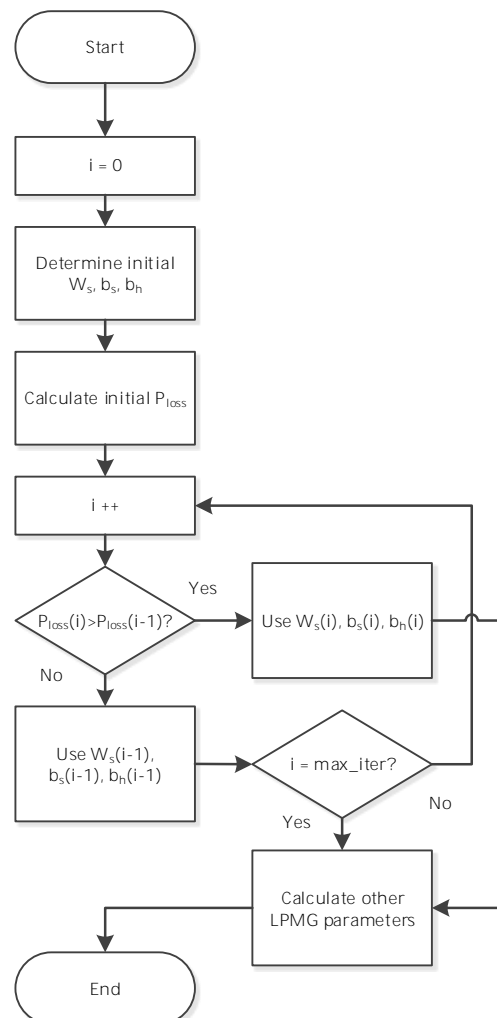


Figure 7. Flow chart of the optimization using SA algorithm

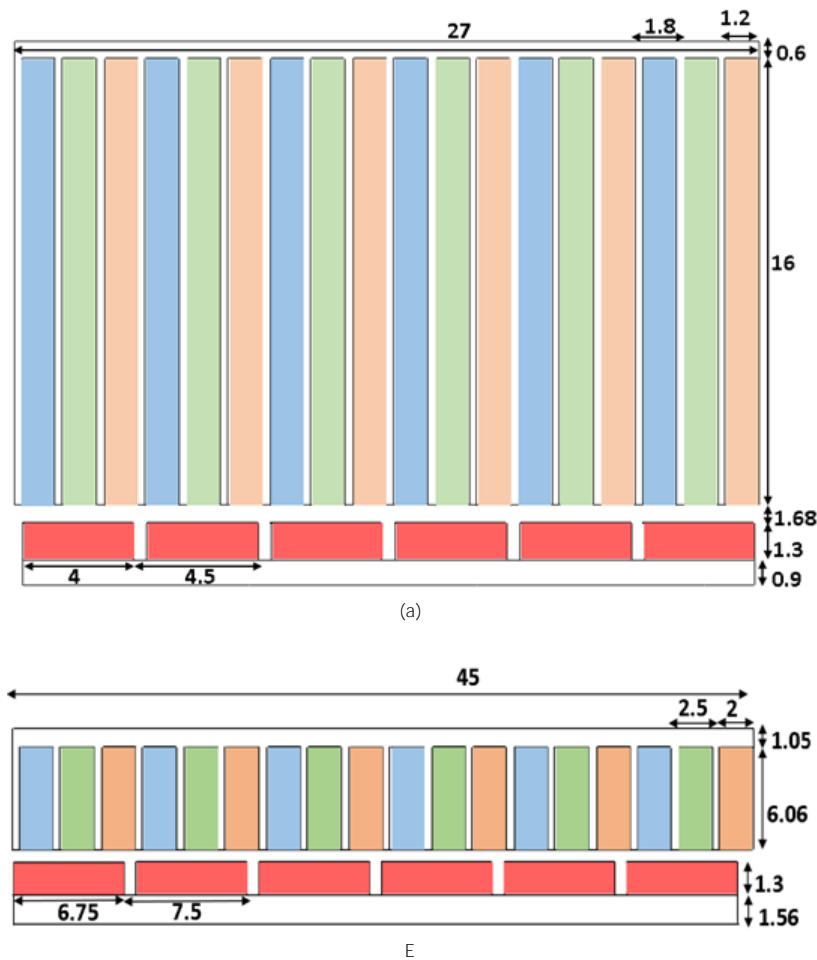


Figure 8. Detailed design of (a) initial design, and (b) optimized design of LPMG (all dimensions are stated in cm)

III. Results and Discussions

A. Resulted design of quasi-flat LPMG

The resulted initial and optimized dimensions of the quasi-flat LPMG design are shown in Table 2. It could be seen that, except the slot height and the air gap width, most of the optimized LPMG parts have larger dimension than the corresponding initial design parts.

Among the three independent variables, the dimension of the slot height in the optimized design is the only part that decreases. However, due to its huge reduction, the space volume which the stator coils could fill also reduces significantly. As shown in Table 2, the number of turn then decreases by half. This condition at first leads to decrease of the induced voltage.

To maintain the output after this winding turn reduction, the magnetic flux flowing to the winding was adjusted. In this case, the size of the permanent magnet should normally be increased. From the table, it could be seen that the length of the optimized permanent magnets increases, while the thickness is constant. It then results in an increase of the magnet's mass and volume.

B. Electrical and mechanical properties

The output parameters of both designs are shown in Table 3. From the table, it could be seen that the induced voltage is constant during the optimization. The reduction of the turn number is compensated by increase of the PM dimensions. On the other hand, the decrease in turn number also reduces the coil length, which directly proportional to the coil resistance. By reducing it, the coil resistance drops so does the copper loss.

It is shown that the optimization could reduce up to 73.64 % of the copper loss. This decrease is caused by shortening of the stator coil length, which then reduces its resistance value. Consequently, the electrical efficiency increases from 83.2 % to 95.6 %, considering equal input power. Meanwhile, other parameters including the induced voltage and the line current are relatively constant.

On the other hand, the optimization also increases the overall mass and volume of the LPMG, as shown in Figure 8. According to the previous Table 2, the weight of the generator increases after the optimization process. Besides, the optimization also increases the resulted cogging force of the LPMG, due to stronger interaction between the larger permanent magnets and the ferromagnetic yoke.

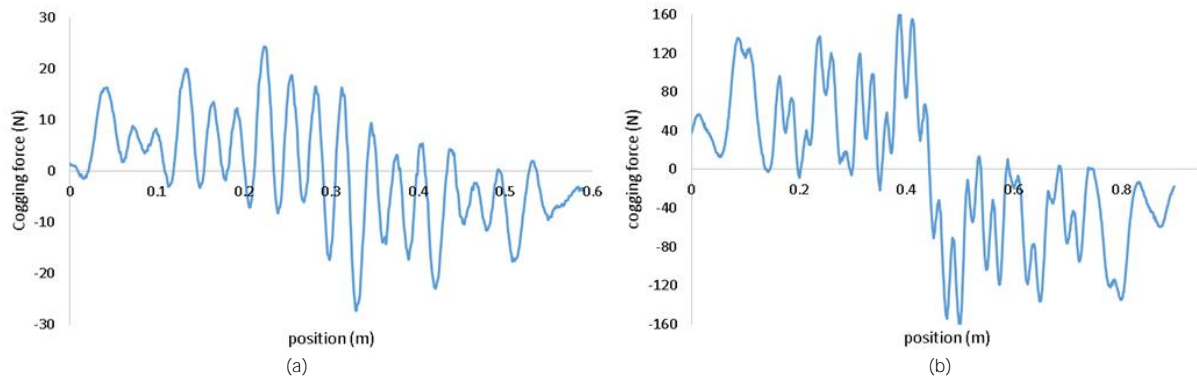


Figure 9. Cogging force of (a) initial design, (b) optimized design

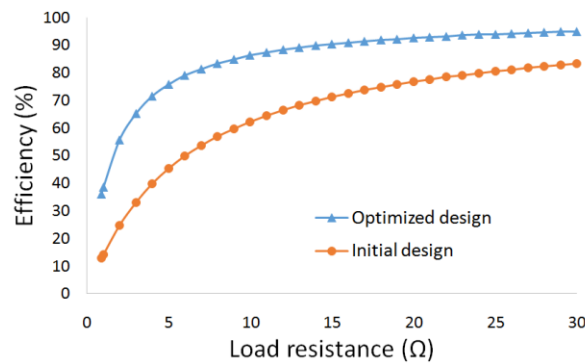


Figure 10. Output electrical efficiency of both initial and optimized design

Table 2.
Detailed dimensions and parameters of initial and optimized design of the LPMG

Variables and symbols	Initial	Optimized
Stator width, W_s	50 (mm)	100 (mm)
Stator surface, A_s	13,500 (mm ²)	44,900 (mm ²)
Stator length, L_s	270 (mm)	450 (mm)
Pole-pitch, τ_p	45 (mm)	75 (mm)
Tooth-pitch, τ_t	15 (mm)	25 (mm)
Slot width, b_s	12 (mm)	20 (mm)
Tooth width, b_t	3 (mm)	5 (mm)
Carter coefficient, K_c	3.36	4.98
Equivalent air gap, g_{eq}	16.8 (mm)	14.9 (mm)
PM thickness, h_m	13 (mm)	13 (mm)
PM length, τ_m	40 (mm)	67.5 (mm)
Stator yoke thickness, Y_s	6 (mm)	10.5 (mm)
Translator yoke thickness, Y_r	9 (mm)	15.6 (mm)
Number of turns/slot, N_c	276 turns	138 turns
Number of turn/phase, N_{ph}	1,656 turns	828 turns
Space between PM, s_{PM}	5 (mm)	7.5 (mm)
Slot height, h_s	160 (mm)	60.6 (mm)
Average coil length, L_c	890 (mm)	590 (mm)
PM mass, m_{PM}	4.617 (kg)	15.570 (kg)
Translator mass, m_{trans}	1.878 (kg)	5.144 (kg)
Moving part mass, m_{mov}	6.495 (kg)	20.714 (kg)
Stator mass, m_{stat}	50.534 (kg)	74.169 (kg)
Total mass, m_{tot}	57.029 (kg)	94.883 (kg)

This emerged effect could produce vibration, disturb the motion of the translator, and then resulted in some noises [15]. The comparison of the cogging force from both designs over a translation period is shown in Figure 9. Nevertheless, as opposed to a better electrical output, the optimized design suffers more mechanical loss compared to the initial one.

The output characteristics of both designs in loaded condition were also analyzed. The efficiency of both designs for various load resistances is shown in Figure 10. It could be seen that the optimized design produces larger efficiency for various load compared to the initial design. Moreover, the efficiency has been increased as the resistance increased up to a certain values. At the certain load resistance value, the efficiency is getting stable even if the resistance increases.

If those optimization results are compared with those from the flat-tricore type LPMG [10], the quasi-flat type produces larger output power as well as efficiency for equal input power. However, the flat-quasi type has larger size and weight. In fact, it is understandable that with fewer side number, the flat-tricore design is relatively slimmer and thinner, thus becomes lighter.

In the next research, the electrical and mechanical properties of the generator are better be considered altogether during the optimization process. The weight and material cost of the generator should also be optimized or at least the possible increase should be considerably limited.

Table 3.
Output parameters of initial and optimized design of LPMG

Electrical parameters and symbols	Initial design	Optimized design
Coil resistance, R _{ph}	6.1 (Ω)	1.6 (Ω)
Coil inductance, L _{ph}	2.40 (mH)	1.5 (mH)
Emf (rms), E _{ph}	110 (V)	110 (V)
Line current, i _{ph}	3.03 (A)	3.033 (A)
Electrical frequency, f	9.37 (Hz)	5.64 (Hz)
Output power, W	832 (W)	955.8 (W)
Copper power loss, P _{loss}	168 (W)	44.2 (W)
Efficiency, η G	83.2 (%)	95.6 (%)

IV. Conclusion

Design optimization of the quasi-flat LPMG has been conducted by using simulated annealing (SA) algorithm. The optimization was applied in previously designed LPMG, which was proposed for wave energy converter (WEC) in south Java Ocean, Indonesia. It was aimed to minimize the copper loss in stator winding by modifying stator width, slot width, and slot height. The results showed that the optimized design could reduce 73.64 % of power loss and increase electrical efficiency from 83.2 % to 95.6 %. The efficiency of the optimized design was also larger than the initial design for various load resistances. However, design optimization has increased the size of the generator, as well as the weight of the overall WEC.

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Declarations

Author contribution

B. Azhari is the main contributor of this paper. All authors read and approved the final paper.

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Conflict of interest

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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