Stator Tooth Shape Optimization of a Permanent Magnet Linear Generator for Harvesting Oceanic Wave Energy

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Among various types of generators used for converting oceanic wave energy into electricity, the permanent magnet linear generator (PMLG) has attracted a lot of attention because of its various advantages, such as structural simplicity and high efficiency. Its performance, however, depends greatly on the proper design of stator tooth and translator pole shapes. This paper proposes a multi-objective graphical optimization method using the genetic algorithm to determine the stator tooth shape of a PMLG. To observe the effectiveness of the proposed method, a PMLG has been designed and the proposed method has been applied to optimize the stator tooth shape. The analysis is done by using the finite element method. The simulation results show that the optimizing the stator tooth shape can not only increase the power density, but also minimize the electromagnetic force ripples of the PMLG. Therefore, the proposed method offers an excellent design solution by selecting proper geometric dimensions considering electromagnetic constraints.

***Index Terms*— Linear generator, Oceanic wave energy conversion, Optimization, Stator teeth**

I. Introduction

THE OCEANIC wave energy (OWE) has attracted a lot of attention worldwide because of its distinguishing features than other renewable energy resources (RERs). The OWE is more concentrated, persistent, and predictable than the other RERs. It is estimated that the global wave energy production is around 2000 TWh every year [1]. One of the key advantages of the permanent magnet linear generator (PMLG) for OWE extraction is that it has the ability of harnessing the vertical movement of the incident sea wave directly [2]. However, it has been observed that the shape of permanent magnets (PMs), magnetic pole shoes (MPSs), and stator and translator cores could greatly affect the performance of PMLGs, such as the power density, efficiency, and cogging force [3]. As reported in [3], the power density of a PMLG can increase by 20% by optimizing the stator core shape. To improve the performance and minimize the cogging forces of a PMLG, various PM shapes has been studied in [2]. The end effect force has been minimized by the bulged stator length optimization of a tubular PMLG for the direct-driver OWE conversion system [4]. A novel double sided flat superconducting magnetic flat linear generator has been presented in [5]. Most research papers focus on the optimization of harvesting OWE [6], [7] and some other parameters [1], [8], but the shape optimization of PMLG is rarely found [3].

In this paper, the stator tooth shape of a PMLG has been optimized in multi steps by using the genetic algorithm (GA) to achieve two major goals: generating more electricity or achieving higher power density, and minimizing the electromagnetic force ripples. The simulation results show that the selection of proper slope, curvature, and size of the stator teeth by the proposed method can effectively increase the power density and reduce the electromagnetic force ripples of the PMLG.

II. Stator Tooth Shape Optimization

It is simulated that, the modification of the stator teeth can increase the power density of a PMLG because of increasing the teeth surface area for adequate magnetic flux linkage. Farther analyses have shown that optimizing the stator tooth shape can also improve the performance of a PMLG. In this paper, the stator tooth shape optimization has been carried out in three steps: (1) select proper PM and stator tooth thickness, (2) determine the dimensitons of *a* and *b*, and (3) find the optimum curvature, as sketched in Fig. 1. The slope of the pole tooth had been selected before the proper curvature was selected. The pole teeth curvatures have been shown in Fig. 2.

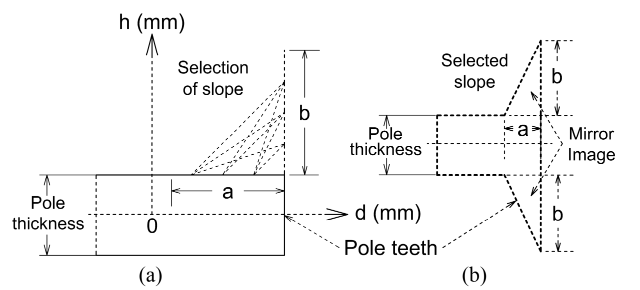

Fig. 1. (a) Selection of points and pole teeth slope. (b) Selected points a and b.

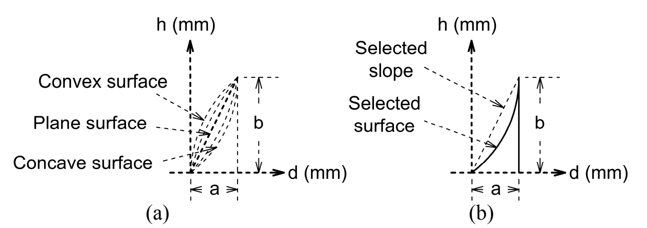

Fig. 2. (a) Selection of proper surface and (b) selected surface of the pole teeth.

The curvature lies between C_1e^{kx} and $C_2(1-e^{-kx})$, where, *k* is the coefficient which determines the degree of curvature, and C_1 and C_2 are constants. Fig. 3 depicts the proposed GA for graphical optimization for stator tooth shape. When the slope and curvature are both optimized, it converges to a solution.

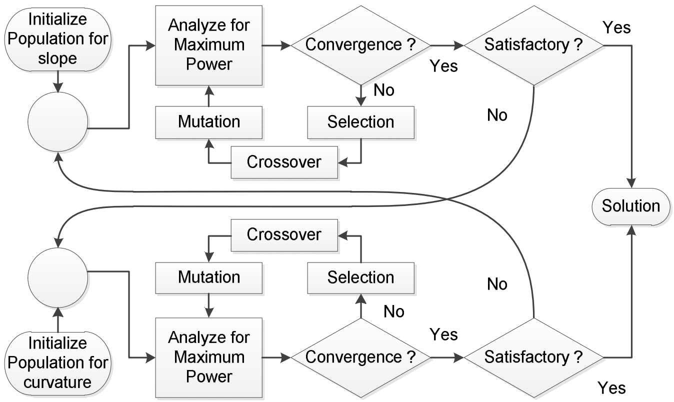

Fig. 3. (a) The proposed method for optimization.

The generated voltage, E_g, of the PMLG can be expressed as

$$E_g(t) = K_g \cos\left(\frac{\pi}{\tau_p} z_{tr} + i\frac{2\pi}{n}\right) v_{tr}(t) \qquad (1)$$

where n=5, i=−2, −1, 0, 1, and 2, k_g is the constant representing the machine construction, z_{tr}, τ_p, and v_{tr} are the vertical displacement, velocity, and the pole pitch of the translator, respectively.

III. Simulation Results

Fig. 4 illustrates the magnetic flux lines, A, flux density, B, and air gap field intensity, H, of the PMLG before and after the graphical optimization, and Fig. 5 the waveforms of voltage, current, and power of the PMLG.

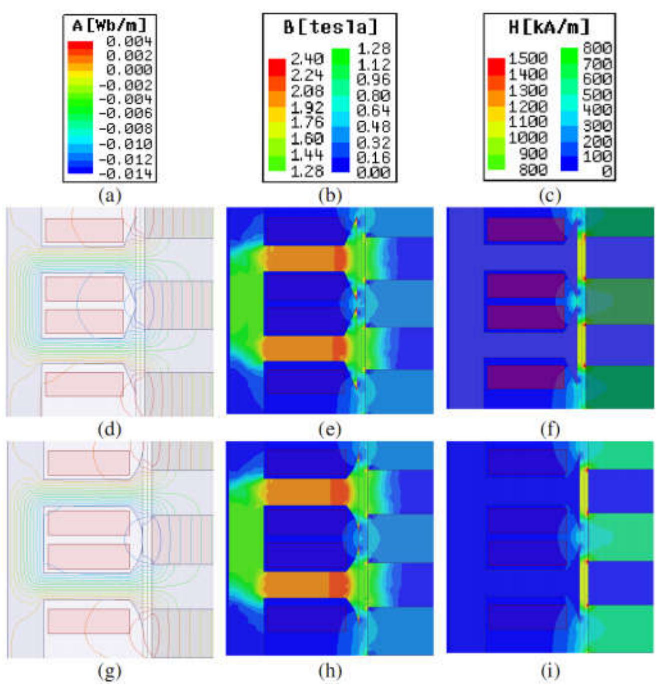

Fig. 4. Scale of (a) A, (b) B, and (c) H. (d) A, (e) B, and (f) H of the PMLG with slope optimization only. (g) A, (h) B, and (i) H of the PMLG with slope and curvature optimization.

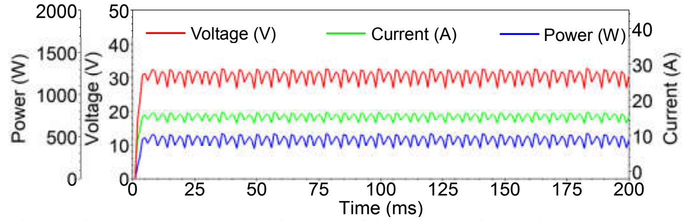

Fig. 5. The voltage, current, and power of the PMLG after optimization.

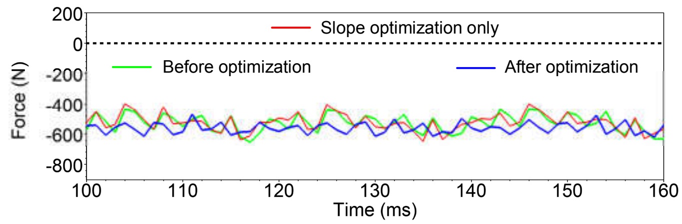

Fig. 6. Applied force to the PMLG before and after optimization.

The electromagnetic force ripples are shown in Fig. 6. The standard deviation of the electromagnetic force ripples has been determined 59.3 before optimization and 36.8 after optimization, showing that the force ripples are minimized successfully. After proposed optimization, the value of a, b, and the pole thickness have been determined 6 mm, 3 mm, and 7 mm, respectively.

IV. Conclusion

The proposed stator tooth shape optimization can effectively increase the power density and minimize the electromagnetic force ripples. The proposed method can also improve the efficiency considering the same power output. The efficiency of the PMLG is maintained around 83.5% at full load. The proposed method is applicable to other types of PMLGs.

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