Design of Cylindrical Permanent Magnet Linear Generator for Ocean Wave Energy Conversion with Level-Set Method

Hongwei Fang, and Hongxu Chen

School of Electrical and Information Engineering, Tianjin University, Tianjin 300072, China, hongwei_fang@tju.edu.cn

The level set based curve evolution method is applied to the design process of topology evolution of permanent magnet for cylindrical permanent magnet linear generator (CPMLG). The main contribution is to use the level-set method to reduce the magnetic field distortion of the CPMLG. The corresponding optimization procedure includes: 1) setting the objective air gap magnetic field and selecting proper measure points; 2) performing topology evolution on the permanent magnet based on level-set function; 3) using FEM to analyze the CPMLG with the updated PM by ANSYS Maxwell. Results show that the proposed design method for CPMLG can improve the output performance of the generator.

***Index Terms*—Permanent magnet linear generator; level set method; motor design; topology optimization; wave energy conversion**

I. INTRODUCTION

THE linear generator for direct drive wave power system can reduce the complexity of mechanical transmission so as to improve the reliability and efficiency of the system [1-4]. The level set method is employed to the topology optimization of rotor in synchronous reluctance motor [5] and the torque ripple reduce for permanent magnet (PM) excited machine [6-7]. In this paper, a cylindrical permanent magnet synchronous linear generator used for wave power generation is designed by using the level set function theory in order to weaken the air-gap magnetic field distortion, improve the quality of back-EMF and power generation, and increase the wave energy capturing efficiency.

II. LEVEL SET FUNCTION

The main idea of the level set method is to take time-evolved curves or surfaces as zero-level sets and apply them in higher-dimensional functions to obtain new functional evolution equations. If we can find out the solution of the new function evolution equation and then deduce the position of each point for permanent magnets on the zero level set, the result of evolution curve or surface is obtained.

Suppose $\phi\ (x, y) = 0$ is the curve implicit expression. Then, according to the curve evolution theory, with the given level set function $\phi\ (C\ (x, y), t)$, the curve $C\ (t)$ obtained at time t is the zero level set $\phi\ (C\ (x, y), t)$ solution. Thus, the level set evolution equation can be obtained as

$$\frac{\partial \emptyset}{\partial t} = F|\nabla \emptyset| \tag{1}$$

In this paper, the third-order WENO scheme is used to obtain the discrete numerical solutions of ϕ. When the level set method is applied to the topology optimization, $\phi(C(x, y), t)$ is a continuous, differentiable and smooth function. Further, the surface formed by $\phi = 0$ always corresponds to the moving surface depicted by the level set, and it can describe the change of C more easily. By using the level set, it is easy to obtain the geometric features of the surface, and the results can be directly applied to permanent magnet shape design with less error.

III. DESIGN OF CYLINDRICAL PERMANENT MAGNET LINEAR GENERATOR WITH LEVEL SET TOPOLOGICAL OPTIMIZATION

The electromagnetic model of the cylindrical permanent magnet synchronous linear generator is shown in Fig. 1.

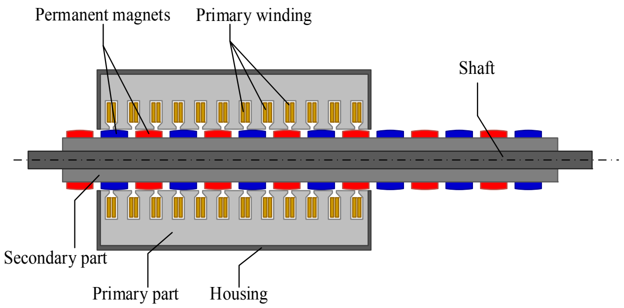


Fig. 1 Schematic diagram of CPMLG.

Table I gives the basic structure parameters of the designed linear generator modeled in Maxwell.

TABLE I
BASIC STRUCTUE PARAMETERS OF THE CPMLG

Parameters	Value	Parameters	Value
Pole pairs p	12	Primary yoke height h_j (cm)	3.3
Pole pitch τ (cm)	8	Primary tooth width b_t (cm)	2.37
Pole-arc coefficient ξ	0.8	Armature effective length (cm)	158
Primary slots' number	9	Air gap width δ (cm)	0.4

In addition, the motion direction is along the z-axis, and the movement of the displacement is 128cm. The solution step is 0.0005s.

The initial shape of the permanent magnet is chosen as a contour ring, thus the cross-sectional shape is rectangular. Further, according to the principle of zero level set initialization, i.e., the constructed zero level set function must be a symbol distance function, so the corresponding matrix is characterized by: the permanent magnet boundary value being 0, the internal value and the external value equal to -1 and 1 respectively. Then select the n+1 shape variables $K_i^{(0)}\left(x_i^{(0)}, y_i^{(0)}\right)$ in the required optimization of the permanent magnet edge evenly. Since the optimized shape is the outer edge of the permanent magnet, a curvature evolution scheme is applied. The third-order TVD scheme is used to discretize the time variables, so that the discrete solution of the level set function ϕ, and the coordinates of the K_i are obtained.

Use the coordinates of K_0, K_1 ... K_n in ANSYS Maxwell software to obtain the final profile of the edges of the permanent magnets. Then the magnetic flux density $B(x_m,y_m)$ at the detection points D_0, D_1 ... D_m is achieved, as well as the corresponding x and y axis components $B_x(x_i,y_i)$ and $B_y(x_i,y_i)$. By using $B_x(x_i,y_i), B_y(x_i,y_i)$ and their target magnetization values $B_{x0}(x_i,y_i)$ and $B_{y0}(x_i,y_i)$, we can get the objective function as

$$g(x,y)=\frac{1}{m}\sum_{i=1}^{m}\left[\frac{\left(B_x(x_i,y_i)-B_{x0}(x_i,y_i)\right)^2+\left(B_y(x_i,y_i)-B_{y0}(x_i,y_i)\right)^2}{\left(B_{x0}(x_i,y_i)\right)^2+\left(B_{y0}(x_i,y_i)\right)^2}\right] \tag{2}$$

The j^{th} objective function is denoted by $g^{(j)}(x,y)$.

Keep F and t unchanged, repeat the above mentioned steps, resolve the new solution of ϕ, and the corresponding $B_x(x_i,y_i)$, $B_y(x_i,y_i)$, and $g\,(x,y)$.

The minimum value of the target values of the N groups $g\,(x,y)$, i.e.,

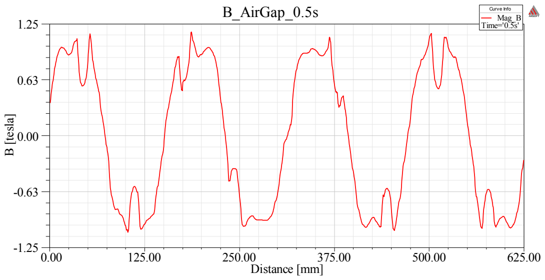
$$\min[g(x,y)] \le \varepsilon \tag{3}$$

is used as the optimization objective.

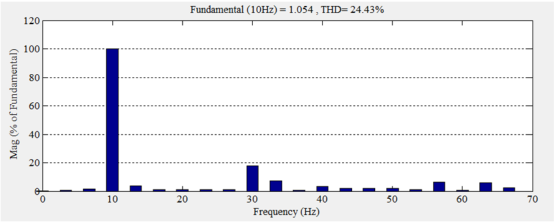
If this inequality holds, the evolution is stopped. If not, then renew the values of F, t, and N, and resolve the level set function $\min[g(x,y)]$, until the inequality holds. In this design example, the error ε is set to be 3.

IV. SIMULATION RESULTS

Fig. 2 shows the generator flux density and its FFT decomposition results without level-set optimization.



(a) Flux density



(b) FFT decomposition

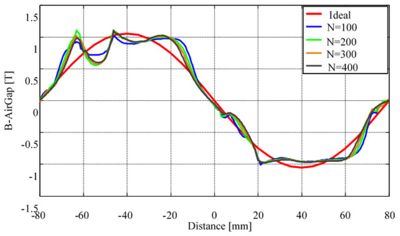
Fig.2 Flux density and its FFT decomposition without optimization

It can be seen from Fig. 2 that the THD value of air-gap flux density reaches to 24.43% before optimization.

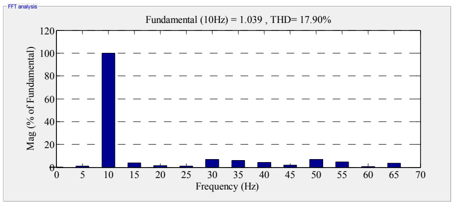
The optimization results are shown in Fig. 3. The THD of harmonic content is lower than that before optimization. During the optimization procedure, there are $g^{(100)}(x,y) = 8.16$, $g^{(200)}(x,y) = 4.18$, $g^{(300)}(x,y) = 7.47$ and $g^{(400)}(x,y) = 2.85$.

From Fig. 2 and Fig. 3, we can see that the THD of harmonics of flux density is decreased to 17.9%.

Fig. 4 presents the optimized permanent magnets model of the generator.



(a) Flux density



(b) FFT decomposition

Fig.3 Flux density and its FFT decomposition with level-set optimization

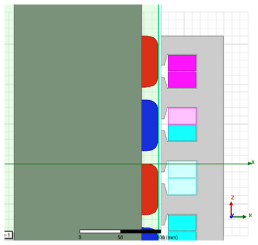


Fig.4 Permanent magnet model optimized with level-set method

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