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3-D Topology Optimization of Claw-Pole Alternator Using Gaussian-Basis Function with Global and Local Searches

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This paper proposes a two-step topology optimization method based on the normalized Gaussian functions. The proposed method is shown effective for design of a claw-pole alternator. In this method, the global search using the micro-genetic algorithm is followed by the local search using the sensitivity analysis based on the adjoint variable method. The three dimensional structure of the rotor is optimized using the proposed method under low and high speed conditions.

***Index Terms*—Adjoint variable method, Claw-pole alternator, Genetic algorithm, NGnet, Topology optimization.**

I. Introduction

Recently, highly efficient alternators for automobiles have been required because of increase in electric load. A typical shape of the claw-pole alternator which is widely used as a generator for vehicle is shown in Fig. 1. To improve the performance of the claw-pole alternator, the parameter optimization of the rotor core based on field analysis has been carried out [1]-[4]. There are, however, difficulties in the parameter optimization to find novel structures with excellent performance which have never been proposed. On the other hand, the topology optimization in which shape is freely deformed allowing generation and annihilation of holes can lead to novel structures. In particular, the topology optimization based on the normalized Gaussian network (NGnet) has been shown fairly effective for the design of rotating machines [5]-[7]. In this method, the genetic algorithm (GA) is employed because of its excellent ability in global search. There is weakness in GA, however, that the local search is not well performed for the topology optimization problems with many unknown variables. To overcome this problem, the two-step topology optimization method which combines the on/off method with the level set method has been proposed [8]. In this method, the global search based on the on/off method and GA is followed by the local search based on the level set method. However, this method relies on the complex shape representation using two different basis functions: NGnet for global search and level set function for local search.

In this paper, we propose a novel two-step topology optimization method for 3-D topology optimization, which is effective for design of alternators as well as other machines. In the present method, NGnet is used for both in global and local searches in contrast to the above-mentioned approach. In the proposed method, after the global search is performed by GA, the local search is carried out using the sensitivity analysis based on the adjoint variable method. For verification, the proposed method is applied to the 3D optimization of the rotor core shape of a claw-pole alternator.

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II. Two-Step Optimization Method

A. NGnet-Based on/off Method with μGA

The NGnet-based on/off method is schematically shown in Fig. 2. The material attribute in the design region Ω_{core} is determined from the value of the shape function defined by

$$y(\boldsymbol{x}, \boldsymbol{w}) = \sum_{i=1}^{N} w_i b_i(\boldsymbol{x}) \tag{1}$$

where w_i, $\boldsymbol{x}$ and N denote the weighting coefficient, position vector and number of Gaussian functions, respectively, and $\boldsymbol{w}$ is a vector defined by $\boldsymbol{w} = [w_1, w_2, \ldots, w_N]^{\mathrm{t}}$. Moreover, $b_i(\boldsymbol{x})$ is the normalized Gaussian function given by

$$b_i(\boldsymbol{x}) = G_i(\boldsymbol{x}) \Big/ \sum_{j=1}^{N} G_j(\boldsymbol{x}) \tag{2}$$

$$G_i(\boldsymbol{x}) = \frac{1}{(2\pi)^{\frac{3}{2}}\sigma^3} \exp\left\{-\frac{1}{2\sigma^2}|\boldsymbol{x} - \boldsymbol{x}_i|^2\right\} \tag{3}$$

where σ and $\boldsymbol{x}_i$ denote the standard deviation and center of Gaussian basis, respectively. The material attribute M_e of finite element e in Ω_{core} is determined from

$$M_e = \begin{cases} \text{iron}, & y(\boldsymbol{x}, \boldsymbol{w}) \geq 0 \\ \text{air}, & y(\boldsymbol{x}, \boldsymbol{w}) < 0 \end{cases} \tag{4}$$

It is remarked that the topology optimization is now reduced to the parameter optimization with respect to $\boldsymbol{w}$. In the global search process, $\boldsymbol{w}$ is determined so as to maximize the objective function $F(\boldsymbol{w})$ by the micro genetic algorithm (μGA) [9]

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subjected to given constraints. During the optimization, the performance of the alternator is evaluated by solving the finite element (FE) equation of magnetostatic field, $\mathrm{K}\boldsymbol{A} = \boldsymbol{b}$. When $\boldsymbol{w}$ changes, the material distribution as well as K also change. Hence the field $\boldsymbol{A}$ is the implicit function of $\boldsymbol{w}$.

B. *Local Search Method*

Starting from the solution obtained by the global search, the local search based on the sensitivity analysis with respect to $\boldsymbol{w}$ is performed. Since it is difficult to directly evaluate the derivative of $F(\boldsymbol{w})$, we adopt here the adjoint variable method. In this method, $F(\boldsymbol{w})$ is approximated by the modified objective function defined by

$$\bar{F}(\boldsymbol{w}) = F(\boldsymbol{w}) + \boldsymbol{\Phi}^{\mathrm{t}}(\mathrm{K}\boldsymbol{A} - \boldsymbol{b}) \tag{5}$$

where $\boldsymbol{\Phi}$ denotes the adjoint variable. Note that $\bar{F} \approx F$ if $\boldsymbol{A}$ is a numerical solution to $\mathrm{K}\boldsymbol{A} = \boldsymbol{b}$. The derivative of $\bar{F}(\boldsymbol{w})$ with respect to p-th weighting coefficient w_p is given by

$$\frac{\partial \bar{F}(\boldsymbol{w})}{\partial w_p} = \boldsymbol{\Phi}^{\mathrm{t}} \frac{\partial \mathrm{K}}{\partial w_p}\boldsymbol{A} + \left[\left(\mathrm{K} + \frac{\partial \mathrm{K}}{\partial \boldsymbol{A}}\boldsymbol{A}\right)\boldsymbol{\Phi} + \frac{\partial F(\boldsymbol{w})}{\partial \boldsymbol{A}}\right]^{\mathrm{t}} \frac{\partial \boldsymbol{A}}{\partial w_p} \tag{6}$$

The second term in (6) can be eliminated by imposing $\boldsymbol{\Phi}$ to satisfy the adjoint equation given by

$$\left(\mathrm{K} + \frac{\partial \mathrm{K}}{\partial \boldsymbol{A}}\boldsymbol{A}\right)\boldsymbol{\Phi} = -\frac{\partial F(\boldsymbol{w})}{\partial \boldsymbol{A}} \tag{7}$$

By substituting $\boldsymbol{\Phi}$ into the first term in (6), we can determine the derivative of the objective function. In order to update the material attribute so as to make $F(\boldsymbol{w})$ larger in the optimization, we have to evaluate the derivative of $\partial \mathrm{K}/\partial w_p$ from

$$\frac{\partial \mathrm{K}_{ij}}{\partial w_p} = \int_{\Omega_{\mathrm{core}}} \mathrm{rot}\boldsymbol{N}_i \frac{\partial \nu(\boldsymbol{x}, \boldsymbol{w}, \boldsymbol{B})}{\partial w_p} \mathrm{rot}\boldsymbol{N}_j d\Omega \tag{8}$$

where $\boldsymbol{N}_i$, $\nu(\boldsymbol{x}, \boldsymbol{w}, \boldsymbol{B})$ and $\boldsymbol{B}$ denote the vector interpolation function, magnetic reluctivity and magnetic induction, respectively. To evaluate $\partial \nu(\boldsymbol{x}, \boldsymbol{w}, \boldsymbol{B})/\partial w_p$, the magnetic reluctivity is expressed in the form

$$\nu(\boldsymbol{x}, \boldsymbol{w}, \boldsymbol{B}) = \nu_0 + \frac{\nu_{\mathrm{m}}(\boldsymbol{B}) - \nu_0}{1 + \exp\{-\alpha y(\boldsymbol{x}, \boldsymbol{w})\}} \tag{9}$$

where α, $\nu_{\mathrm{m}}(\boldsymbol{B})$ and ν_0 denote a constant and the magnetic reluctivity of core with saturation and air, respectively.

III. Optimization Problems

In the optimization, we determine the rotor shape of the 3-D optimization model shown in Fig. 3 (a) so that the electric generation of the claw-pole alternator is maximized. To shape the rotor core, 432 Gaussian functions are uniformly deployed in the design region as shown in Fig. 3 (b), where their distribution is represented by the spheres with radius of the standard deviation. As the first example, we optimize the

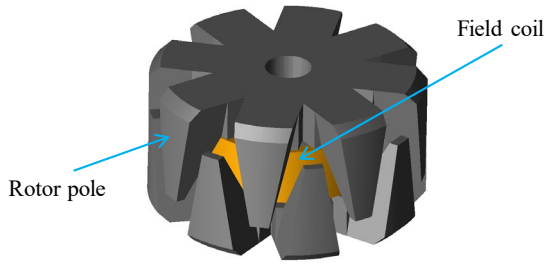


Fig. 1. Convenitonal claw-pole alternator

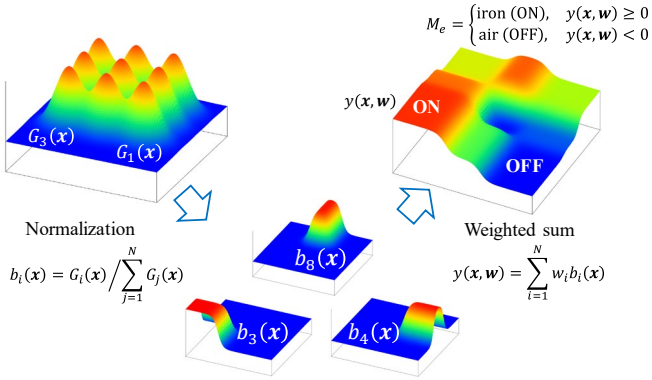
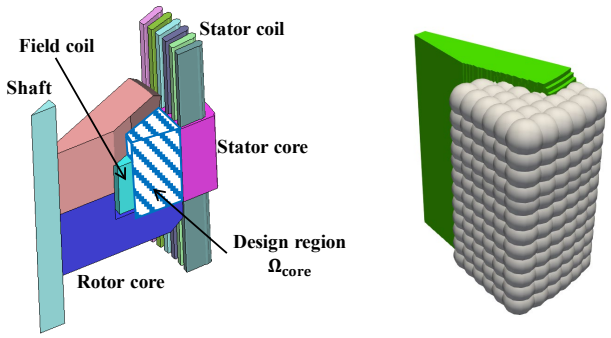


Fig. 2. On/off method using normalized Gaussians (2D example)



(a) Optimization model (1/16 fraction is shown.)

(b) Distribution of Gaussian functions (σ = 4.0 mm)

Fig. 3. Optimization model and distribution of Gaussian functions

performance of an alternator under low rotational speed condition in which the diamagnetic field generated by the stator currents can be ignored. Because the line voltage between the stator coils, which directly affects the electric generation, is maximized:

$$\max_{\boldsymbol{w}} F_1(\boldsymbol{w}), \quad F_1(\boldsymbol{w}) = V_{\mathrm{UV}}^{1000}(\boldsymbol{w}) \tag{10}$$

where $V_{\mathrm{UV}}^{1000}(\boldsymbol{w})$ denotes the open voltage between U and V phase coils at 1000 r/min rotational speed.

In the second example, we consider the influence of the stator currents on the optimization under the high speed condition where the diamagnetic field generated by the stator currents cannot be ignored. The coupling between the alternator with the battery charging circuit would have to be considered for accurate evaluation of the stator currents. Since this strong coupling leads to large computational cost, the stator currents shown in Fig. 3 (a) are assumed to be constant during

optimization. We found that this remedy is not effective for the topology optimization in [2]. To consider the effect of the stator current and simultaneously avoid the time-consuming coupling analysis, we maximize the total flux due to the rotor and stator currents as follows:

$$\max_{\boldsymbol{w}} F_2(\boldsymbol{w}), \quad F_2(\boldsymbol{w}) = \Phi_{\mathrm{R}}^{6000}(\boldsymbol{w}) - \Phi_{\mathrm{S}}^{6000}(\boldsymbol{w}) \tag{11}$$

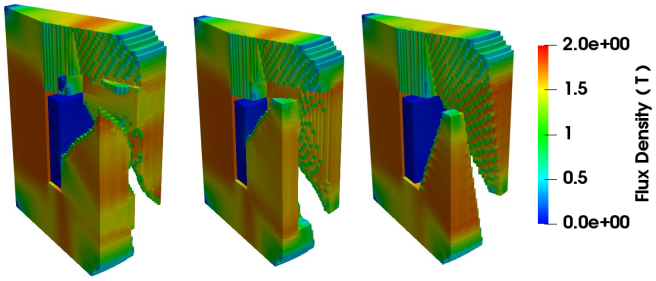
where $\Phi_{\mathrm{R}}^{6000}(\boldsymbol{w})$ and $\Phi_{\mathrm{S}}^{6000}(\boldsymbol{w})$ denote the rotor and stator fluxes at 6000 r/min rotational speed, respectively and minus sign comes from the inverse direction of the magnetic field.

IV. Optimization Results

A. Optimization Under Low Speed Condition

To solve optimization problem (10) using μGA for the global search, the number of individuals is set to 5 and the evolution process is continued for 120 generations. Note that random material distributions are generated in the first generation of μGA to obtain an optimal solution which is independent of the initial shape. On the other hand, the local search process after the global search is performed for 120 iterations. In this setting, it takes about three weeks to obtain the optimization results using the Intel Xeon CPU (3.5 GHz, five cores). It is remarked that 70 % of the computing time is spent for the global search.

The optimized results using global search and two-step optimization, represented by "Optimized (Global)" and "Optimized (Two-step)", respectively, are shown in Fig. 4 (a) and (b). For comparison, the conventional rotor shape [2] is shown in Fig. 4 (c). It is evident that the optimized shapes (a) and (b) have different geometrical features in comparison with that in (c). The convergence history of the local search and line voltages for no load condition are plotted in Figs. 5 and 6, respectively. In Fig. 5, the reason why the initial value of the local search is smaller than those of the conventional method



(a) Optimized (Global) (b) Optimized (Two-step) (c) Conventional

Fig. 4. Optimized and conventional rotor core shapes and magnetic induction for low speed condition.

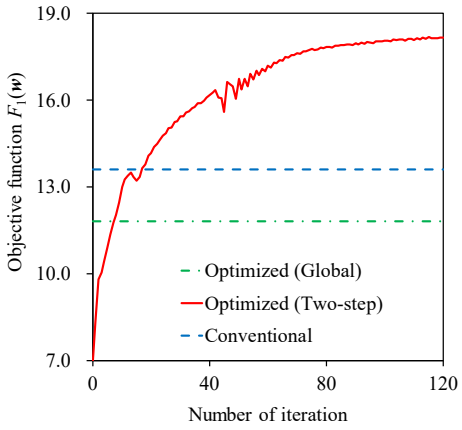


Fig. 5. Convergence history of local search

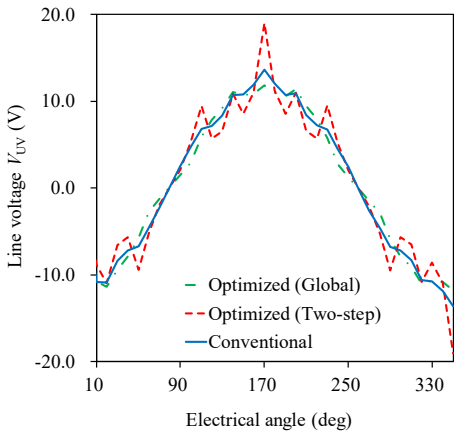
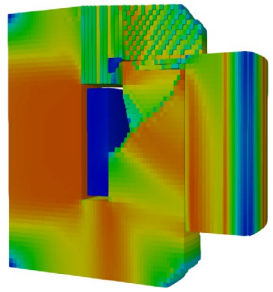
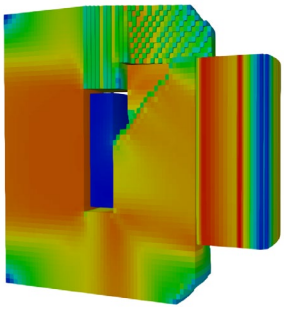


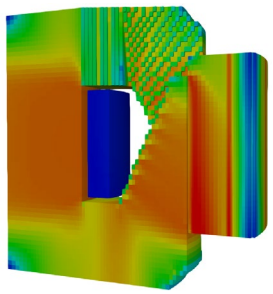
Fig. 6. Comparison results of line voltage without load



(a) Optimized (Global)



(b) Optimized (Two-step)



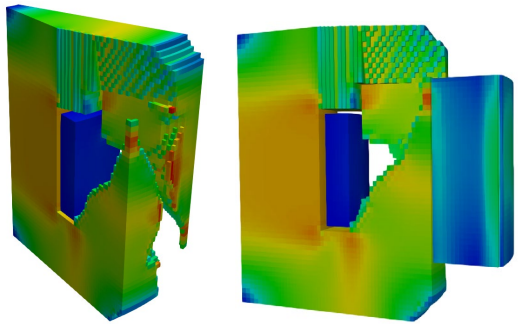
(c) Conventional

Fig. 7. Distribution of magnetic induction in the stator and rotor cores for low speed condition

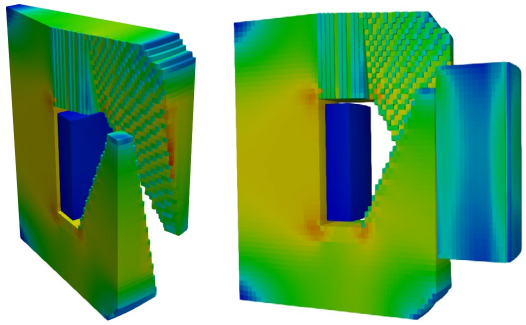
and global search is due to the fact that the gray permeability coming from (9) exists in the initial configuration. However, the final value of the local search is much greater than the latter two results. To interpret the different performance among the alternators, the flux density distributions are compared in Fig. 7. It can be seen that the stator core in (b) is strongly saturated over the core because the rotor shape is optimized so that the net interlinkage flux effectively increases. On the other hand, there are non-saturated regions in the stator cores of (a) and (c). In particular, the magnetic flux in the stator of (a) is weaker than that of (c). This result would be due to the weakness of μGA that the local search is not well performed for the topology optimization problems with many unknown variables. It is concluded that the proposed two-step method is effective to increase the induced voltage under the low speed condition.

B. Optimization Under High Speed Condition

Optimization problem (11) is solved using the proposed method. The distribution of the magnetic induction in the rotor and stator cores considering stator currents are shown in Fig. 8. It can be seen that the surface area of the optimized rotor core increases to effectively cancel the diamagnetic field due to the stator currents. Thus, the magnetic induction of the optimized rotor cores is higher than that of the conventional rotor core. To verify the effectiveness of the optimized rotor shape, we compare the generated currents I_{DC} shown in Fig. 9. The resultant values of I_{DC} are shown in the caption of Fig. 8. We find that I_{DC} in (a) is much larger than that of (b). It is concluded from these results that the proposed method is effective to improve the performance of a claw-pole alternator.



(a) Optimized (Two-step), $I_{\mathrm{DC}} = 194$ A



(b) Conventional, $I_{\mathrm{DC}} = 176$ A

Fig. 8. Distribution of magnetic induction in the stator and rotor cores for high speed condition

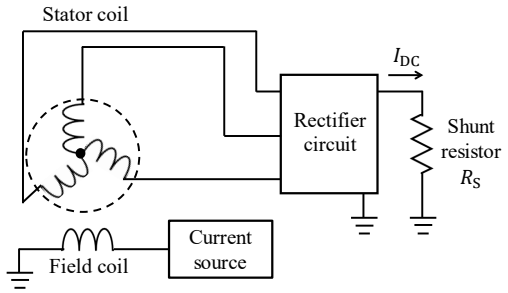


Fig. 9. Power generation circuit
(Rotating speed: 6,000 rpm, Field coil current: 6 A, $R_{\mathrm{S}} = 0.1\ \Omega$)

V. Conclusion

In this paper, we have proposed a novel two-step topology optimization method based on the NGnet method to effectively improve the performance of a claw-pole alternator. It has been shown that the proposed method works well for low and high speed conditions. The proposed method can also be applied to the topology optimization considering the eddy current loss in the rotor core, which will be discussed elsewhere. In future, we plan to manufacture the optimized rotor to verify its performance by experiments.

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