OPTIMIZATION OF SWITCHED RELUCTANCE MOTOR BASED ON QUASI-NEWTON METHOD

Le Luong Huong Thao*, Nguyen Thi Bich Hau

Ho Chi Minh City University of Food Industry

*Email: *thaollh@hufi.edu.vn*

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ABSTRACT

Optimization for electrical machines is widely developed to achieve high performance. In this paper, a numerical optimization for switched reluctance machine design based on the Quasi-Newton method has been investigated. The geometrical parameters of the machine are firstly optimized to enhance the mean torque and torque density, this static torque is analyzed by two-dimensional finite element simulation and is considered a key constraint in the optimization program. Finally, the electromagnetic characteristics of the optimal switched reluctance machine including static torque, and magnetic flux density are given and evaluated. The effectiveness of the proposed method has verified for switched reluctance machines by the simulation using MATLAB plus Finite Element Method Magnetics (FEMM) software.

Keywords: Switched reluctance machine, optimization, finite element analysis.

1. INTRODUCTION

In recent decades, the Switched Reluctance Machine (SRM) has been widely used in many industrial applications such as electric vehicles, home appliances, and aerospace [1, 2]. It has a simple structure without rotor winding and with concentrated stator winding which leads to low production cost, high robustness, high reliability and high fault tolerance capability. However, low torque density, high torque ripple, and high vibration are the challenges of this machine [3].

Improving the performance of machines is really important in the process of machine design. Within the past decade, many optimization algorithms [4-6] such as genetic algorithms, particle swarm optimization, and Quasi-Newton-based algorithms, which can solve complex optimization problems effectively, have been applied to electrical machine design. The quasi-Newton method is a stochastic algorithm that uses the gradient information for solving convex optimization problems. This method is stable and achieves a fast convergence rate in a local neighborhood of the optimal argument [6]. It has been applied in many applications including the design optimization of power systems [7], multi-objective optimization problems [8], and communication networks [9].

Moreover, several researches in [4, 10, 11] described the efficient methodologies which associate analytical model or finite element model to optimize the SRM. In which, the analytical model is limited to linear studies. Building an accurate analytical model for SRM design is really challenging. On the other hand, the finite element model has become a popular method because it offers reliable results when analyzing electromagnetic fields within electrical machines with complex geometries and nonlinear properties. A numerical model based on the finite element method, has advantages of a fast development and of a high accuracy, will be used in the optimization process.

In this study, numerical optimization based on Quasi-Newton based algorithm is used to minimize external volume of 3 phase, 8/6 SRM, keeping the static mean torque fixed. The optimal design parameters are therefore obtained and then the machine performance is analyzed through 2D finite element simulation by developing fine mesh in FEMM.

2. OPTIMIZATION PROBLEM

The optimization problem includes fixed parameters, variables, a mono-objective function and constraints. In this paper, the optimization is addressed for minimizing the external volume with defined constant mean static torque. The objective function as well as the volume of the proposed SRM is calculated by analytical equation and the static torque constraint is analyzed by finite element simulation. The formulation of the local optimization problem under constraints with variables is defined as follows [12]:

$$\begin{cases} \min_{x_k \in \mathbb{R}^n} f(x) \\ Under\ constraints: \\ g_i(x) \leq 0\ \forall i \in \{1, \ldots, p\} \\ h_j(x) = 0\ \forall j \in \{1, \ldots, q\} \end{cases} \quad (1)$$

Where f is the objective function of the optimization, x_k are variables, g_i and h_j are inequality and equality constraints.

2.1. Parameters and Variables

2.1.1. Fixed parameters

The suitable number of phases and poles, the slot fill factor, and the current density of armature winding are chosen based on the limit of manufacturing and the empirical quantities given by experienced designers. The proposed machine has 3 phases, 8 stator poles, and 6 rotor poles. The current density of armature winding is limited to 6 A/mm^2 for the machine without a cooling system. The copper slot fill factor is 0.7 for armature winding. Moreover, the M-27 steel in the FEMM library is used for the rotor and stator laminations with a non-linear magnetization curve.

2.1.2. Variables

The major geometrical variables of the SRM which are used to determine the static torque and the volume of the machine are shown in Figure 1. The stator geometrical variables include the outer diameter of the stator, the stator pole arc, and the stator yoke height. The rotor geometrical variables include the outer diameter of the rotor, the diameter of the shaft, the rotor yoke height, and the rotor pole arc. The pole arc is usually used to vary the shape of the pole shoe which affects torque ripple.

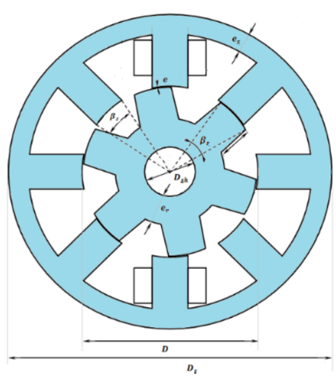

Figure 1. Major dimensional variables of the SRM

The value of the thickness of the air gap should be chosen as low as possible. It was found that the torque decreases slowly when the air gap increases, but the copper losses increase rapidly due to the high magnetizing current [13]. However, the minimization of the air gap thickness is limited by mechanical constraints (mechanical tolerance, centrifugal forces).

Nine real variables represent the geometrical structure of the machine are summarized in Table 1.

Table 1. Optimization variables

Variables	**Symbol**
Stator outer diameter (mm)	D_s
Stator inner diameter (mm)	D
Stack length (mm)	L
Stator pole arc (rad)	β_s
Rotor pole arc (rad)	β_r
Air gap length (mm)	e
Shaft diameter (mm)	D_{sh}
Stator yoke thickness (mm)	e_s
Rotor yoke thickness (mm)	e_r

2.2. Constraints

The static torque is analyzed by 2D numerical simulation via the FEMM program based on the finite element method. This software is useful and free for electrical machine design. It is compatible with MATLAB and therefore, the torque can be analyzed automatically. FEMM enables calculating the potential vector at all mesh nodes. This vector potential is used to compute the torque by the Maxwell tensor method [14]. The accuracy of the result strongly depends on the fineness of the mesh, especially the mesh of the air gap. Figure 2 shows the mesh of the 8/6 SRM and Figure 3 indicates the fine mesh of the air-gap.

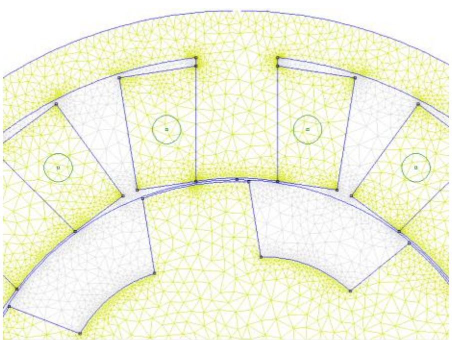

Figure 2. Mesh in SRM

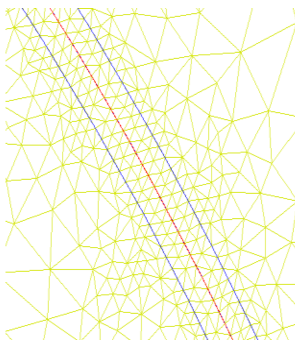

Figure 3. Mesh in Air-gap

The mean static torque is calculated by 2D numerical simulation and it is considered as a constraint in the optimization program as follows:

$$T_{mean} \approx T_{desired} \tag{2}$$

The stator yoke thickness e_s is determined based on the maximum allowable flux density and acoustic noise effect. The flux density in the stator yoke is approximately half the flux passing the stator pole [15]. Considering the mechanical robustness and the minimization of vibrations, the stator yoke thickness must satisfy the following conditions:

$$0.5t_s < e_s < t_s \tag{3}$$

Where $t_s = D \times \sin\left(\frac{\beta_s}{2}\right)$ is the stator pole width.

The pole arcs of the stator β_s and rotor β_r are considered in the ranges as follows to obtain self-starting requirements and static torque shaping [4]:

$$0.6\frac{2\pi}{qP_r} \leq \beta_s \leq 1.4\frac{2\pi}{qP_r} \tag{4}$$

$$0.6\frac{2\pi}{qP_r} \leq \beta_r \leq 1.4\frac{2\pi}{qP_r} \tag{5}$$

Where P_r is the number of rotor poles and q is the number of phases.

2.3. Optimization Algorithm

Quasi-Newton-based algorithms are widely developed to achieve high performance in electrical machines. It enables solving the constrained problems based on the calculations of the derivatives of the objective function and of the constraints [16]. In MATLAB, the *fmincon* solver is based on the Quasi-Newton updating method is developed to deal with the optimization problem which is defined in the following equation. In which, the optimization objective is the external volume of the machine and it is calculated as $V_{ext} = \pi D_s^2 L/4$.

$$(\mathcal{P}_f) = \begin{cases} \quad min \qquad V_{ext} \\ x \in (L, D_s, D, \dots) \\ U.C: \\ \qquad T_{mean} = T_{desired} \\ \qquad 0.5t_s < e_s < t_s \\ \qquad 0.6\frac{2\pi}{qP_r} \leq \beta_s \leq 1.4\frac{2\pi}{qP_r} \\ \qquad 0.6\frac{2\pi}{qP_r} \leq \beta_r \leq 1.4\frac{2\pi}{qP_r} \end{cases} \tag{6}$$

This method requires a gradient to determine the search direction and calculates the search distance where the Hessian Lagrangian function is approximated by updating at each iteration with the function values and gradients from previous iterations [17]. The basic form of *fmincon* in MATLAB is:

$$X = fmincon(F_{obj}, x_o, A, b, A_{eq}, b_{eq}, lb, ub, Cont, option) \tag{7}$$

Where X is the optimal solution, F_{obj} is the objective function, x_o is the starting point, A, b are the inequality constraint $Ax < b$, A_{eq}, b_{eq} are the equality constraint $A_{eq}x = b_{eq}$, lb and ub are the interior and exterior bounds of the variables, $Cont$ is the constraint function, $option$ is the selected algorithm.

The flowchart of the optimization progress is presented in Figure 4.

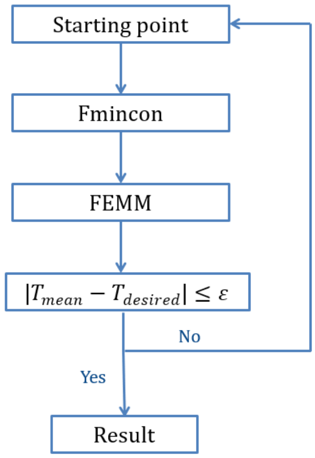

Figure 4. Optimization progress

3. OPTIMAL RESULT

The *fmincon* function based on the Quasi-Newton algorithm is used to minimize the external volume of the machine with the constant mean static torque of 2 Nm. The values of the geometrical parameters indicated in Table 2 are the best local optimum that we found so far. The computation time is significant and approximately equal to 26 hours for achieving one local solution from a starting point. The minimum external volume of the machine achieved after the optimization of the 3-phase 8/6 SRM is $4.6181 \times 10^{-4}\ m^3$.

Table 2. Optimal results

Variables	Symbol	Value
Stator outer diameter (mm)	D_s	140
Stator inner diameter (mm)	D	80
Stack length (mm)	L	25
Stator pole arc (rad)	β_s	0.38
Rotor pole arc (rad)	β_r	0.40
Air gap length (mm)	e	4
Shaft diameter (mm)	D_{sh}	22
Stator yoke thickness (mm)	e_s	8
Rotor yoke thickness (mm)	e_r	11

Flux density distribution in the optimal SRM under unaligned to aligned conditions, when one phase is excited, is shown in Figures 5 and 6. The magnetic flux densities in the stator yoke and rotor yoke are lower than the magnetic flux densities of the stator and rotor poles. The magnetic flux density of the rotor pole is smaller than that of the stator pole over all the rotor rotation angles. The maximum values of the flux density on the stator pole in the aligned position is 1.82 T. The optimal machine is obtained at the point that magnetic flux densities at the rotor and stator poles are close to the knee of the magnetization curve of the lamination's material.

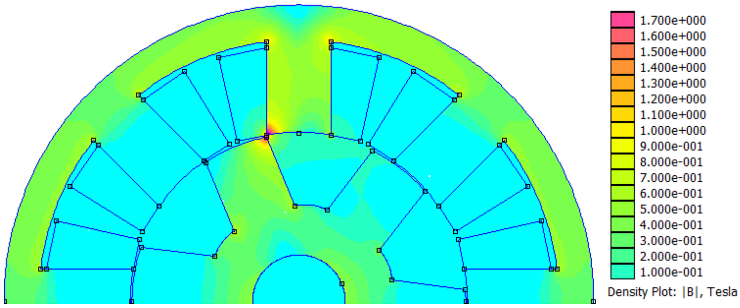

Figure 5. Flux density distribution in the machine under unaligned condition

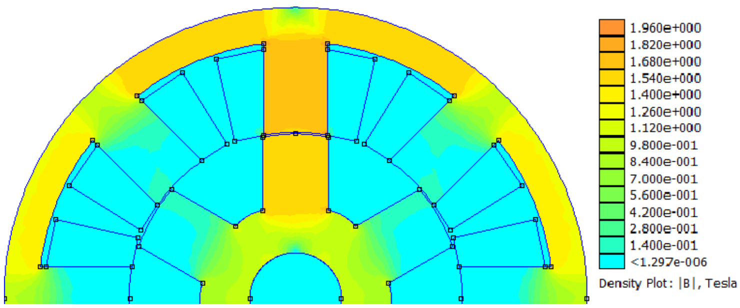

Figure 6. Flux density distribution in the machine under aligned condition

The static torque of the optimal machine is represented in Figure 7 with fine mesh. As can be seen, the mean static torque is $2.05\ Nm$, while the maximum static torque of the SRM is $3.46\ Nm$. The percentage of the error between the mean static torque and the required one ($2\ Nm$) is 2.5%. Also, the torque density is relatively high and its value is about $4.4395 \times 10^3\ Nm/m^3$. The optimal results of the design machine obtained, are satisfied all of the constraints in (6).

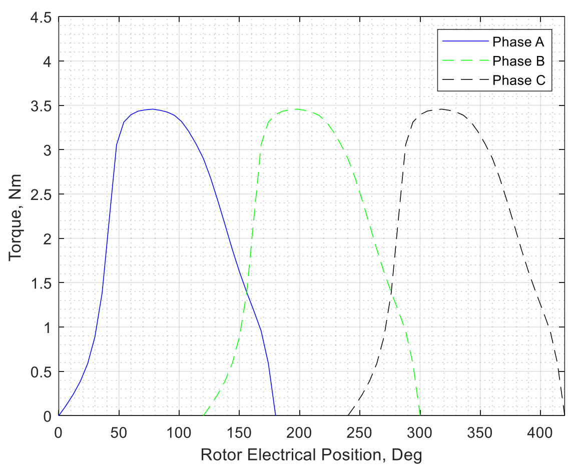

Figure 7. The static torque profile of the optimal machine

4. CONCLUSION

In this paper, the SRM is optimized by a Quasi-Newton-based algorithm combined with finite element analysis to minimize the external volume of the machine with the constant static mean torque. The main characteristics of the SRM including magnetic flux lines, magnetic flux density, and static torque were automatically analyzed using MATLAB and FEMM. The optimization algorithm is applied, in which a local minimum is converged with the external volume of $4.618 \times 10^{-4}\ m^3$. The optimized results for the design machine have been satisfactory about the required constraints.

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TÓM TẮT

TỐI ƯU HÓA ĐỘNG CƠ TỪ TRỞ THAY ĐỔI DỰA TRÊN PHƯƠNG PHÁP QUASI-NEWTON

Lê Lương Hương Thảo*, Nguyễn Thị Bích Hậu

Trường Đại học Công Thương Thành phố Hồ Chí Minh

*Email: *thaollh@hufi.edu.vn*

Tối ưu hóa cho máy điện được phát triển rộng rãi để nâng cao đặc tính kỹ thuật của máy. Trong bài báo này, thuật toán Quasi-Newton kết hợp với phương pháp phần tử hữu hạn được sử dụng để tối ưu hóa thể tích bên ngoài của động cơ từ trở thay đổi với mô-men xoắn tĩnh trung bình không đổi. Các đặc tính điện từ của động cơ tối ưu bao gồm mật độ từ thông, mômen tĩnh được đưa ra và đánh giá. Tính hiệu quả của phương pháp đề xuất đã được kiểm chứng bằng mô phỏng sử dụng phần mềm MATLAB và FEMM cho động cơ từ trở thay đổi.

Từ khóa: Động cơ từ trở thay đổi, tối ưu hóa, phương pháp phần tử hữu hạn.