A Novel Switched Reluctance Motor With Wound-Cores Put on Stator and Rotor Poles

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This paper presents a novel switched reluctance (SR) motor with wound-cores placed on stator and rotor poles. The wound-core is made of grain-oriented silicon steel, which exhibits high saturation magnetic flux density and less core loss. These contribute to reducing the volume and weight of the motor. We investigate the operating characteristics of the novel SR motor using a coupled analysis method proposed by authors. The characteristics of the proposed motor are compared with that of conventional one.

***Index Terms*—Coupled analysis, grain-oriented silicon steel, nonlinear magnetic circuit model, switched reluctance (SR) motor, wound-core.**

I. Introduction

A SWITCHED RELUCTANCE (SR) motor has a doubly salient pole structure and concentrated windings on independent stator poles. A rotor is only made of a laminated core. Thus, the SR motor possesses desirable features such as a simple and robust structure, high reliability, and low cost. The advance of the power electronics technology has made the SR motor more useful [1]–[3], and now it is employed for an electric washing machine and a vacuum cleaner.

For further developing the SR motor, it is necessary to make it lightweight and smaller, and improve the efficiency. It is regarded generally that the motor made of grain-oriented silicon steel exhibits better performance comparing with that made of nonoriented silicon steel. The investigation, however, is not thoroughgoing enough.

In this paper, we propose a novel SR motor with wound-cores made of grain-oriented silicon steel. We calculate the operating characteristics of the proposed motor using a coupled analysis method proposed by authors [4], [5]. The characteristics of the proposed motor are compared with that of the conventional one.

II. Novel SR Motor With Wound-Cores

Fig. 1 shows a schematic diagram of the novel SR motor with wound-cores and the cross section of a stator and rotor poles. The proposed motor has the structure that two wound-cores are placed on a stator and rotor poles of the conventional SR motor. The wound-cores are made of grain-oriented silicon steel, and the other laminated cores are made of nonoriented silicon steel. The number of winding turns per stator pole is 110. The gap length is 0.3 mm. In this paper, the rotor position θ is set to 0° when the rotor pole is in the align position, as shown in the figure. Fig. 2 shows the $B-H$ curves and core loss characteristics of grain-oriented and nonoriented silicon steels.

In a previous paper, we have proposed a method for calculating the operating characteristics of SR motors considering nonlinear magnetization [5]. The proposed method uses a relationship between linkage flux and magnetomotive force (MMF), which is calculated by finite-element analysis (FEA), for constructing a nonlinear magnetic circuit model of a SR motor.

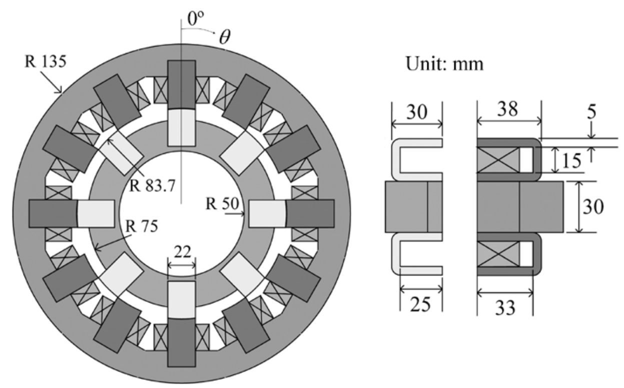

Fig. 1. Schematic diagram of the novel SR motor with wound-cores and the cross section of a stator and rotor poles.

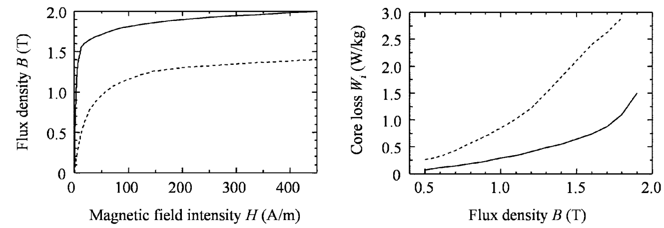

Fig. 2. $B-H$ curves and loss characteristics of the core materials (solid line: grain-oriented silicon steel; dotted line: nonoriented silicon steel).

Fig. 3 shows the flux-MMF curves of the novel SR motor calculated by FEA. These curves can be expressed as follows:

$$Ni = a_1(\theta)\phi + a_m(\theta)\phi^m \quad (1)$$

where the coefficients are $a_1(\theta)$ and $a_m(\theta)$, which are a periodic function of the rotor position θ. The nonlinear reluctance $R(\phi, \theta)$, which expresses the SR motor is obtained from (1)

$$R(\phi, \theta) = a_1(\theta) + a_m(\theta)\phi^{m-1}. \quad (2)$$

The magnetic circuit model obtained from the flux-MMF curves is combined with the motor drive circuit and the motion

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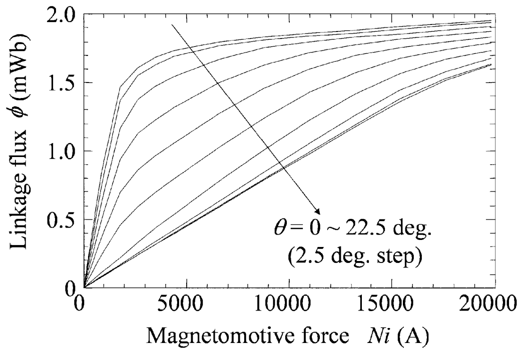


Fig. 3. Flux-MMF curves of the novel SR motor calculated by FEA.

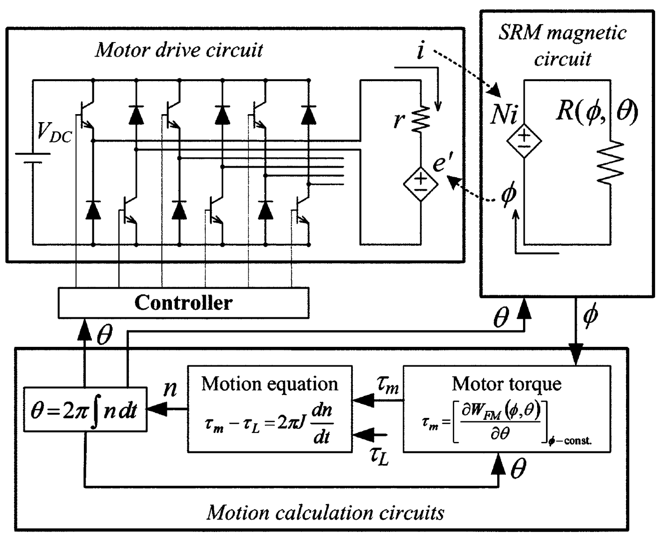


Fig. 4. Electromagnetic and motion coupled analysis model for the SR motor.

calculation circuits, as shown in Fig. 4. In the coupled model, when the rotor position θ is given, the controller generates transistor gate signals, and the phase current i is calculated. The phase current gives the MMF source Ni, and then the flux ϕ is calculated by the magnetic circuit model. The induced voltage e' is obtained from the flux based on Faraday's law. The motor torque τ_m is calculated from magnetic energy. The rotational speed n is given by the motion equation. An integral of the rotational speed gives the rotor position θ. All the above calculations are performed on "SPICE," which is a general purpose circuit simulator.

III. Operating Characteristics of the Novel SR Motor

Fig. 5 shows the calculated operating characteristics of the novel SR motor in various dc voltages V_{DC}. Fig. 5(a) is the rotational speed characteristics, Fig. 5(b) is the phase current characteristics, and Fig. 5(c) is the output power characteristics. It is understood that the rotational speed corresponding to the same torque varies in proportion to the dc voltage. This property is the general characteristic of the SR motors. The rating torque, which is decided by the maximum current of 43 A, is 33 Nm, and it does not depend on the dc voltage. The short-time rating torque is 59 Nm. The rating output power is 13 kW at a dc voltage of 300 V.

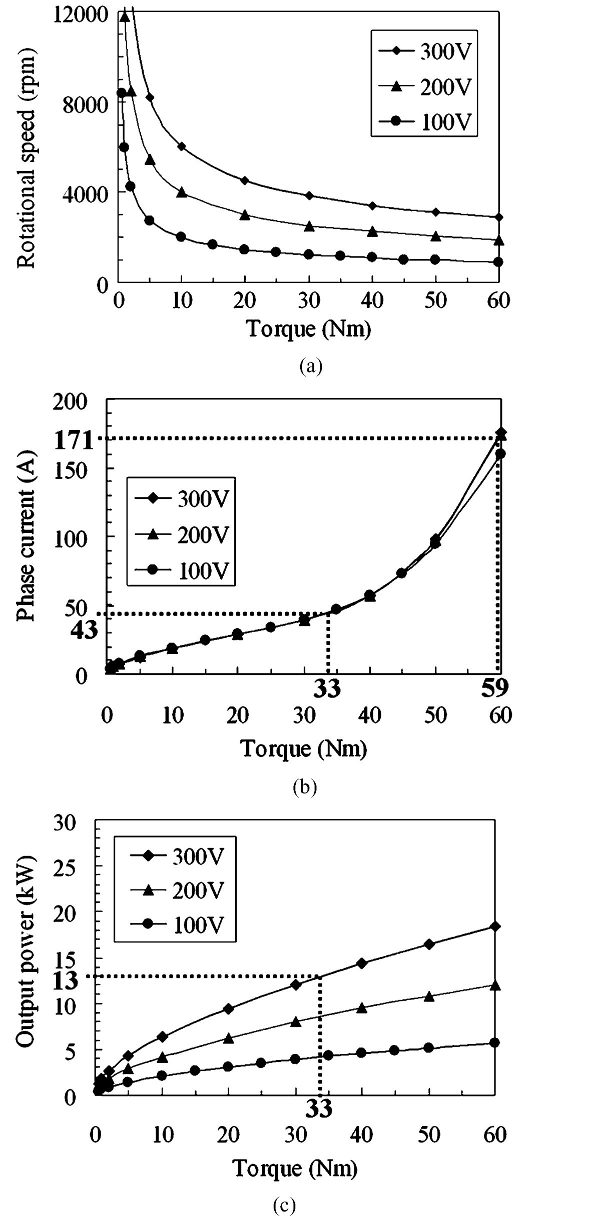
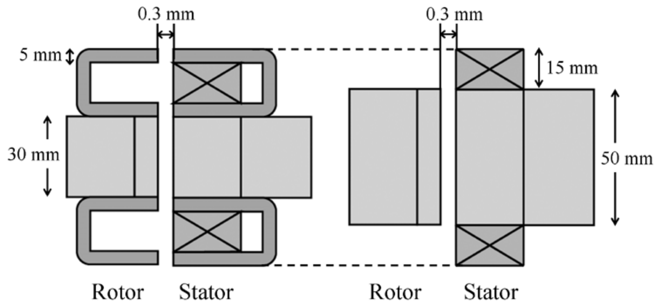


Fig. 5. Operating characteristics of the novel SR motor calculated by the proposed method. (a) Rotational speed characteristics. (b) Phase current characteristics. (c) Output power characteristics.

In this paper, we compared the novel SR motor with the conventional one. Both motors have the same diameter of the stator and rotor, and the gap length. The number of winding turns is also same. The flux linkage area of the conventional motor is larger than that of the novel one, since the height of the motors including winding is equal to each other, as shown in Fig. 6. As the result, the estimated weight is about 18% lighter than the conventional SR motor.

Fig. 7 shows the comparison of rotational speed characteristics of the SR motors in various dc voltages. The figure reveals that the rotational speed of the novel SR motor at the same toque is higher than the conventional one.

Fig. 8 shows the comparison of the phase current. It indicates that the rating torque of the conventional motor, which is 37 Nm, is a little bigger than the novel one. The main cause is that the



	Novel SR motor	Conventional SR motor
Stator core	7.6 kg	9.7 kg
Rotor core	3.7 kg	4.3 kg
Windings	2.1 kg	2.3 kg
Total	**13.3 kg**	**16.3 kg**

Fig. 6. Cross section of a stator and rotor poles of the novel and conventional SR motors, and a comparison of the weights.

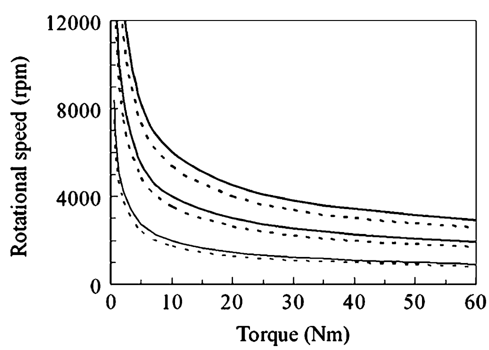


Fig. 7. Comparison of rotational speed characteristics of the SR motors.

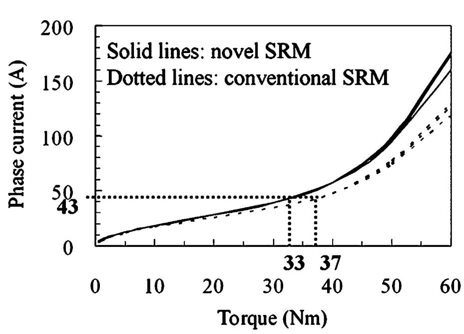


Fig. 8. Comparison of phase current characteristics of the SR motors.

conventional motor has a larger area of flux linkage. In regard to the rating output power, however, both are almost the same, as

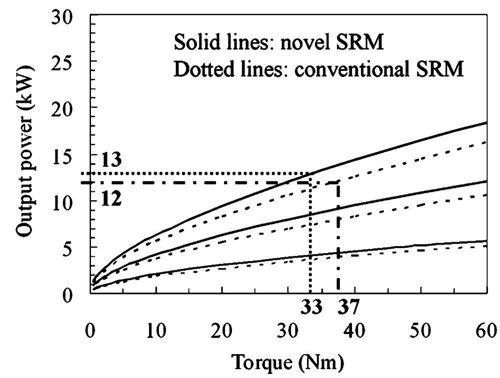


Fig. 9. Comparison of output power of the SR motors.

shown in Fig. 9. Thus, the output power per unit weight is lager than the conventional SR motor.

IV. Conclusion

We proposed the novel SR motor with wound-cores put on stator and rotor poles, and evaluated the operating characteristics of the motor using the proposed coupled analysis method.

Comparing with the conventional SR motor, the proposed motor exhibits a higher rotational speed at the same torque. Though the rating torque is a little lower than the conventional motor, the output power is almost the same. These results indicate that the characteristics of the proposed motor change a higher speed and lower torque. Since the power density of the proposed motor is higher, we can make it compact and lightweight.

In general, since a core loss of grain-oriented silicon steel is less than that of nonoriented silicon steel, there is a possibility that the SR motor with wound-cores also improves the efficiency. A continual investigation will hereafter be made on the matter.

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