A Novel 6/5 Switched Reluctance Motor with Short Flux Path: Concept, Design and Analysis

Marully Tanujaya*, Dong-Hee Lee*, Young-Joo An and Jin-Woo Ahn***

Abstract – A novel 6/5 switched reluctance motor (SRM) with short flux path is presented in this paper. The concept of this proposed motor is a novel SR motor with six stator and five rotor poles. The stator is constructed with three independent and physically separate C-core segments, and the rotor is composed of five poles. This motor, with a new selection for the number of stator/rotor poles, achieves a short flux path, which reduces the magnetomotive force required to drive the motor. To verify the performance of the proposed motor, a comparison with conventional SR motors with the same dimensions is executed. The comparison demonstrates that the proposed motor offers better performance in terms of maximum torque production. Furthermore, Finite Element Analysis (FEA) and Matlab/Simulink software are used to predict and simulate the performance of the proposed motor.

Keywords: Switched reluctance motor, 6/5, short magnetic path, C-core

1. Introduction

The SR motor is a doubly-salient and singly-excited machine wherein the stator carries the winding and the rotor is simply made of stacked silicon steel laminations. Compared with the other types of motors, an SR motor has several advantages, such as: less maintenance, higher fault tolerance, rugged construction, no permanent magnet, simple structure, and very wide range of speed [1-5]. Furthermore, the SR motor has several outstanding characteristics, such as good reliability and lower hysteresis loss [2-3]. With these advantages, the SR motor has gained more attention recently and has been treated as a good alternative for the electric motor drive application.

In contrast, the SR motor possesses several disadvantages, including torque ripples, which are produced in an SR motor because of its operation principle and magnetic structure. The torque ripples contribute to mechanical wear and acoustic noise. These torque ripples can be reduced, and performance of the SR motor can be improved by modifying the geometry or by using an appropriate control method. The optimal control method to reduce the torque ripple is not discussed in this paper.

An SR motor can operate with any number s of phase windings. The number of phases influences the number of poles used in a motor. A three-phase 6/4 SR motor has six stator and four rotor poles. The number of stator poles per rotor pole influences the characteristics of a SR motor. An increase in the number of phases is related to an increase in the number of poles and a reduction in the torque ripple, while the cost of converter will rise. Therefore, a small number of phases with lower torque ripple is a good selection.

Many pole combinations have been investigated over the past decades. It has been reported that a three-phase 6/4 SR motor has an overload capacity and wide speed range in the constant power region [6]. In this paper, a novel three-phase 6/5 SR motor with short flux path is designed and analyzed. A novel three-phase 6/5 SRM has six stator and five rotor poles without permanent magnet (PM) in both sides.

In order to verify the proposed design, a comparison between the proposed motor and the various structures with the same dimensions is executed. Furthermore, FEA and Matlab/Simulink are used to simulate the performance of the proposed motor.

2. Concept of the 6/5 SRM

The concept of the proposed motor is based on the conventional 6/4 3-phase SR motor. The 6/4 SR motor employs a long magnetic flux path. This magnetic path is related to the core loss of a motor. A short magnetic path is better than long ones. To realize a short magnetic path in the 3-phase motor, the stator-rotor poles of a 6/4 motor must be modified. The stator pole should be able to stream the magnetic flux through the shortest path, while the rotor poles should be able to drain the magnetic flux in any rotor position.

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The modified structure makes the 6/4 SR motor into a 6/5 SR motor with a short magnetic path. The concept of the proposed 3-phase 6/5 SR motor, with its winding connection, is shown in Fig. 1.

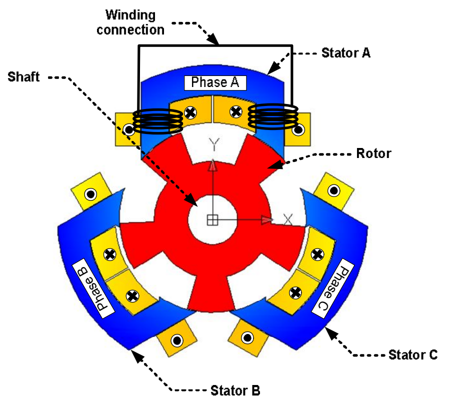


Fig. 1. Concept of a 3-phase 6/5 SR motor

The 6/5 SRM has six stator poles which are divided into three 'C' shape independent stator groups. Each 'C' shape stator group contains two connected poles, while among the stator there are no logical connections. The stator shape is not like a regular structure. Each stator pole does not centralize to the origin, but each group of 'C' shape stator poles centralizes to it. Small pole tip is employed to keep the winding in the proper position. Three 'C' shape stator pole groups are evenly spaced 1200 from each other, while the rotor of the proposed motor employs five rotor poles with 720 separation. This odd number of rotor poles is used to deliver the magnetic flux flow from one stator pole to another.

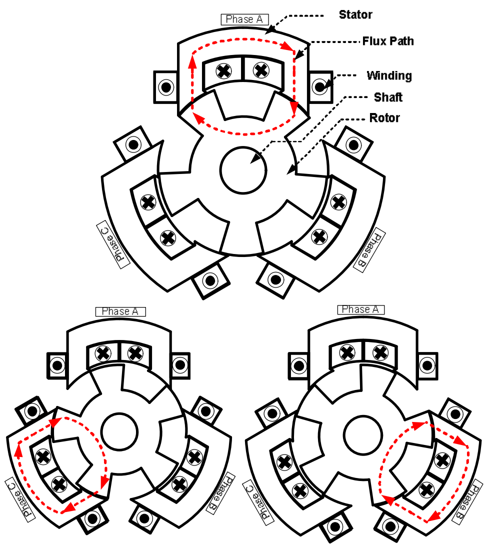
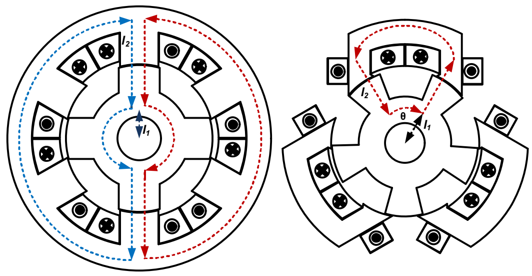


Fig. 2. Magnetic path of each phase

A short magnetic flux path can be achieved by incorporating two adjacent stator poles into one magnetic circuit. This flux configuration needs a different winding arrangement. The winding arrangement of the proposed 6/5 motor is shown in Fig. 1, while Fig. 2 shows the magnetic flux path of each phase.

Since there is no connection among the 'C' shape groups of the stator, the flux-linkage cannot flow through the motor structure's diameter. Therefore, short magnetic flux paths are achieved in the proposed motor. A short magnetic flux path can reduce the core loss. The core loss in a motor is related to the length of the flux path. The shorter the magnetic flux path, the lower the core loss of the motor. A comparison of the flux paths between a conventional 6/4 SR motor and the proposed 6/5 SR motor is shown in Fig. 3.



(a) (b)

Fig. 3. Flux path of (a) conventional 6/4 SRM and (b) proposed 6/5 SRM

Assume that l1 and l2 are the distance from the origin to the center of the flux path in the rotor, and the distance from the center of the flux path in the rotor to the center of the flux path in the stator, respectively; while θ is the angle between excited poles. The length of the magnetic flux path in one excited phase can be determined through (1) - (5).

$$l_{6/4} = 2.l_2 + \pi.l_1 + \pi.(l_1 + l_2)$$
$$l_{6/4} = 2.l_2 + \pi.(2.l_1 + l_2) \quad (1)$$

$$l_{6/5} = 2.l_2 + \theta.l_1 + \theta.(l_1 + l_2)$$
$$l_{6/5} = 2.l_2 + \theta.(2.l_1 + l_2) \quad (2)$$

$$\frac{l_{6/5}}{l_{6/4}} = \frac{2.l_2 + \theta.(2.l_1 + l_2)}{2.l_2 + \pi.(2.l_1 + l_2)} \quad (3)$$

$$\theta = \frac{360^0}{5} = 72^0 \quad (4)$$

$$\frac{l_{6/5}}{l_{6/4}} \approx 0.4 \quad (5)$$

From (5), it can be seen that the proposed motor can reduce the flux path distance down to about 40% of that of the conventional 6/4 SR motor. This reduction of flux path distance will improve the efficiency of a motor.

3. Design of the 6/5 SRM

Fig. 2 shows the flow of magnetic flux for each phase. Because each phase and winding are independent in the construction, the magnetic flux will flow only through the excited pole, with no flux flowing through the other poles. This condition may generate an unbalanced radial force and, furthermore, it may generate higher acoustic noise compared to a conventional SR motor. The unbalanced radial force can be overcome through the proper choice of bearings and with modifications to the stator construction. Specifically, a thin yoke can be used to join the stator poles into one piece. This additional small ring, called a thin yoke, does not contribute to the magnetic flux. As a principle, this thin yoke's function is only to increase the strength of the proposed motor. Bored holes are placed in such a way so as to reduce the possibility of magnetic flux flowing through the thin yoke. The proposed 6/5 SR motor construction with the additional thin yoke is shown in Fig. 4.

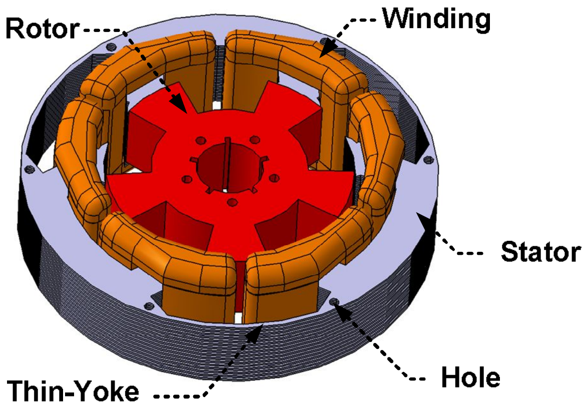


Fig. 4. The construction of 6/5 SR motor

In order to keep the eddy current losses as low as possible, the proposed 6/5 SR motor is constructed with thin steel laminations in both the stator and the rotor. To keep the rotor laminations in the proper position, a lock-nut and bearings are used on both sides. The proposed motor is designed to be used with an external encoder at the back end of the motor, so the shaft of the proposed motor is made longer at both ends. The overall assembly of the stator-rotor is fastened into the housing with four bolts.

4. Analysis of the 6/5 SRM

4.1 FEA Analysis

SRM has very high nonlinear magnetization characteristics. FEA is used to obtain the nonlinear magnetization data. An electromagnetic 2-dimensional (2D) FEA is performed in the conduction region for 5-Ampere (A) excitation current (full-load), and the magnetic flux distribution is analyzed. The FEA analysis proves that magnetic flux, due to the exciting phase current, flows only through the excited phase poles, with no flux flowing through the other poles. Fig. 5 shows the flux distribution of the proposed motor. Figs. 5(a) to 5(c) show the magnetic flux of each phase and Fig. 5(d) shows the flux distribution at the un-aligned rotor position.

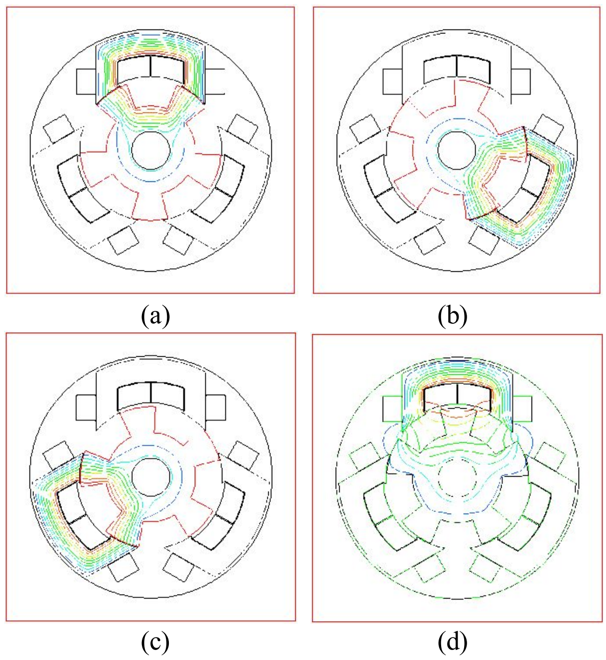


Fig. 5. Flux distribution of (a) phase A; (b) Phase B; (c) Phase C; and (d) un-aligned rotor position

SRM is normally designed to operate in the saturated-energy region. The torque of an SR motor is produced by the attraction of the rotor poles to the excited stator phase, according to the reluctance principle. Torque produced by the SR motor is independent of the polarity of the phase current. When a stator phase is energized, the nearest rotor-pole pair is attracted toward the energized stator in order to minimize the reluctance of the magnetic path; in this condition the positive torque is produced. The torque (T) of an SR motor, which is related to the rotor position (θ) and phase current (i), can be expressed as:

$$T_{ph}(\theta,i) = \frac{1}{2} i_{ph}{}^{2} \frac{dL_{ph}(\theta)}{d\theta} \qquad (6)$$

Fig. 6 shows torque versus rotor position for various excitation currents for the proposed motor.

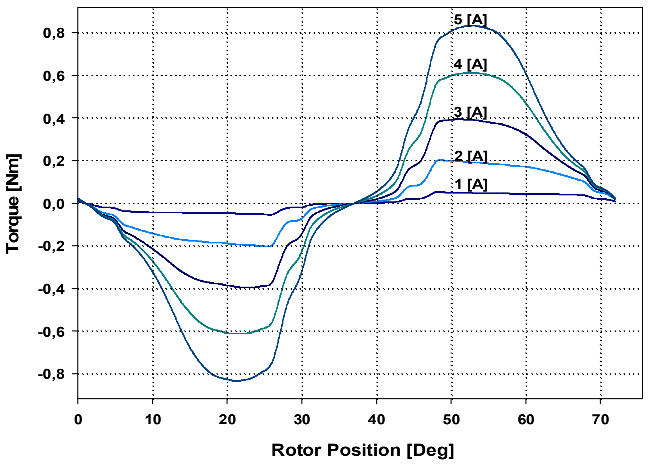


Fig. 6. Torque characteristic of the proposed motor

The electromagnetic behavior of each motor phase is commonly analyzed independently, since the magnetic interactions between phases are typically very small for conventional motors and can be ignored for simplicity reason. But, in this case, in order to analyze the average torque, the continuous torque of the proposed SRM is required. Fig. 8 shows the continuous torque of the proposed 6/5 SR motor.

The maximum torque produced by a 5A-excitation current is 0.83 Newton-meters (Nm). The continuous torque, as shown in Fig. 8, is based on the neutral commutation angle (36 mechanical degrees), with no over-lap among the phases. However, to achieve low torque ripple, usually there is an overlap between phases since, in the overlapping region, both phases contribute torque production to the machine. The average torque produced by the proposed SR motor without overlap angle is 0.48 Nm.

The inductance profile has considerable effect on the motor operation and is also related to the torque production. The aligned position of a phase is defined to be the orientation when the stator and rotor poles of the phase are fully aligned, attaining the minimum reluctance position. The phase inductance is maximized in this position. Phase inductance decreases gradually as the rotor poles move away from the aligned position in either direction. When the rotor poles are symmetrically misaligned with the stator poles of a phase, the position is said to be the unaligned position, and the inductance is minimized in this position.

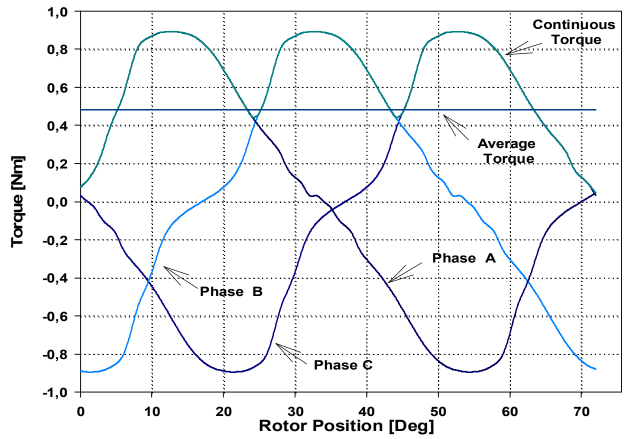


Fig. 7. Continuous torque of the proposed motor

In most SRM applications, saturation occurs, resulting in a nonlinear inductance and flux linkage (see Fig. 8 - Fig. 9). Since the proposed SRM has five rotor poles, a rotation of 36^0 from alignment to un-alignment is sufficient to obtain the inductance profile characteristics of one electrical cycle. The initial rotor position of the motor is the full-aligned position and the rotor rotates in the counterclockwise direction. In the case of the aligned stator-rotor position (0^0 and 72^0), the inductance is at its highest and the magnetic reluctance of the flux is at its lowest. The inductance curve with respect to the rotor position is shown in Fig. 9 for various excitation currents.

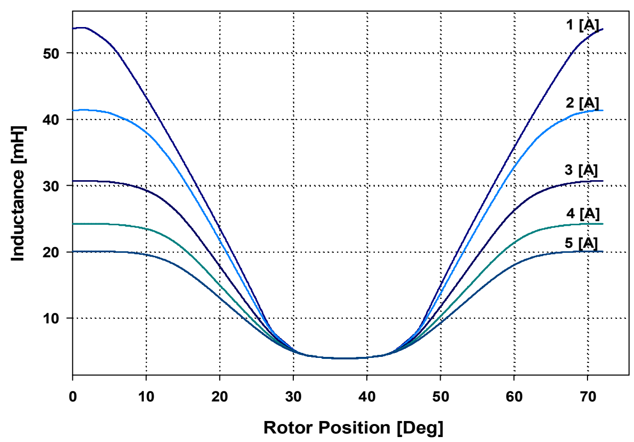


Fig. 8. Inductance profile of the proposed motor

4.2 Matlab Simulation

A simple Matlab simulation is used to analyze the characteristics of the proposed motor. In this simulation, the motor is assumed to drive a load at a constant speed, and the acceleration resistance in the motor rotation is neglected.

The motor speed will appear to be constant at any rotor position. The SR motor model is fed by a three-phase asymmetrical power converter having three legs, each of which consists of two Insulated Gate Bipolar Transistors (IGBTs) and two free-wheeling diodes.

A base speed of 2000 rpm is used to analyze the motor performance. The back electromotive force (EMF) has a significant effect on the phase current, and the back EMF increases as the mechanical speed increases. The simulation is run with no optimal-control method applied. The Matlab simulation model of the 6/5 motor is shown in Fig. 10, while Fig. 11 shows the simulation results of the torque production, the phase-current, and the flux of the winding, respectively.

The simulation result indicates that the output torque that the proposed model can achieve is 0.85 Nm, with less than 20% torque ripple. This small torque ripple is caused by the overlap commutation angle for each phase. This overlap angle can be seen from the phase-excitation-current graph as shown in Fig. 10(b). The maximum flux-linkage is 15 millivolt-seconds (mVs) for 5A-current excitation. The Matlab simulation results are slightly different than the FEA analysis results.

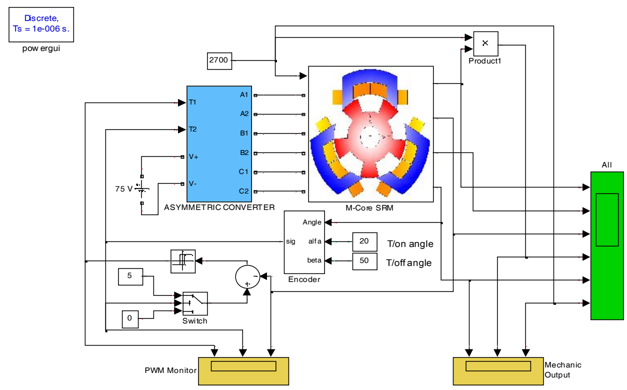


Fig. 9. Simulation model of the proposed motor

4. Comparison

The 6/5 proposed motor is a novel three-phase SRM with some advantages and some disadvantages. The disadvantage of the proposed motor is the unbalanced radial force. This unbalanced radial force may generate acoustic noise higher than that of a motor with balanced radial force. But, this disadvantage is outweighed by the torque production of the proposed motor, which is higher than that of conventional motors. Next, a comparison between the proposed motor and conventional SR motors (6/4, 12/8 and 6/8) is executed in order to compare the motors torque performances. This comparison is done through the FEA simulation only.

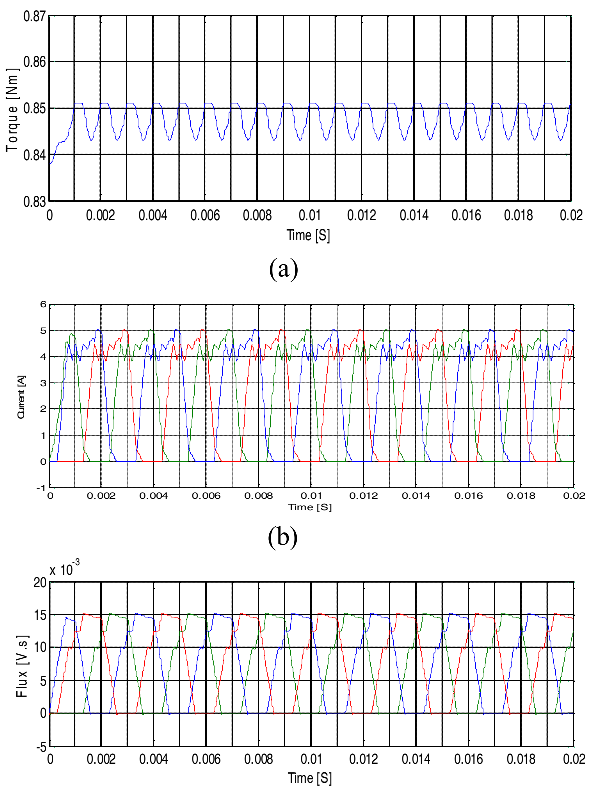


Fig. 10. Simulation result: (a) Torque production; (b) Phase current; (c) Flux of the winding.

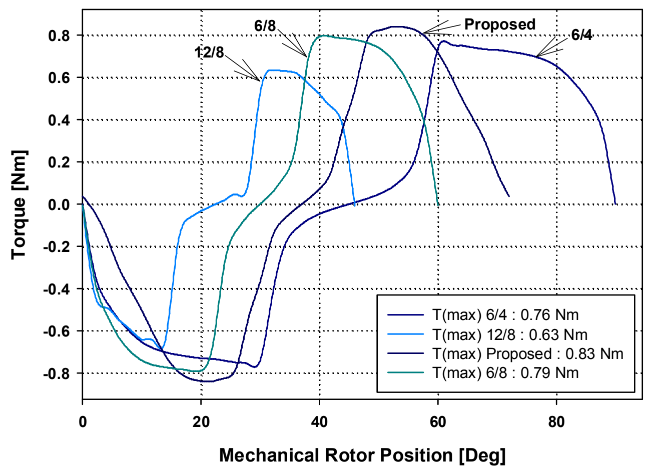


Fig. 11. Torque comparison of the proposed 6/5 SR motor and various conventional SR motors

All of the comparison models have the same motor dimensions and volume (although with different numbers of turns in the windings) in order to keep the current density as close as possible to 10A/cm2, and the flux density as close as possible to 1.8 Tesla (T). Because the motors in the comparison do not have the same number of phases, the comparison is based only on the single exciting phase for each motor. The comparison between the proposed 6/5 motor and the conventional motors is shown in Fig. 11.

The comparison between the proposed motor and the conventional motors shows that the proposed motor has the highest maximum output torque (0.83 Nm) compared with the others. That is an 8% improvement over the 6/4 SRM with the same dimensions, which can generate a torque of 0.76 Nm. The number of phases and the number of rotor poles influence the commutation angle. A 12/8 SRM is a 3-phase motor with eight rotor poles. It has a 22.5^0 commutation angle. The relationship between number of phases, number of rotor poles, and commutation angle can be expressed as (7).

$$C_A = \frac{\pi}{R_p} \tag{7}$$

In (7), C_A is the commutation angle (radians), and R_p is the number of rotor poles.

The number of stator-rotor poles affects the switching frequency of the supply. The switching frequency will increase as the number of stator-rotor poles is increased. This switching frequency has a linear relationship with the switching loss of the converter. The relationship among switching frequency (f_s), number of stator phases (q), number of rotor poles (P_r), and rotor speed in rad/sec (ω) is shown in (8).

$$f_s = \frac{qP_r\omega}{2\pi} \tag{8}$$

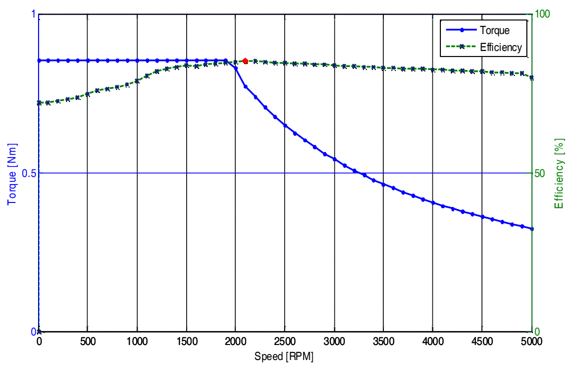


Fig. 12. Efficiency curve of the proposed 6/5 SR motor

Fig. 12 shows the relationship between speed, torque, and efficiency of the 6/5 SR motor. The y-axis represents the torque production and efficiency of the proposed motor, while the x-axis represents the motor speed in rpm. Based on a speed of 2000 rpm, the efficiency of the proposed motor is 85%. The efficiency curve in Fig. 12 is based on the FEA and Matlab simulations only.

5. Conclusion

A novel 6/5 three-phase SRM is proposed in this paper. The 6/5 SRM utilizes a new selection for the number of stator-rotor poles. The proposed 6/5 SR motor has independent stators groups with short magnetic flux paths. The comparison between the proposed 6/5 SR motor and various other motor structures demonstrates that the 6/5 proposed motor offers better performance in terms of maximum torque production.

Acknowledgment

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