J Electr Eng Technol.2018; 13(5): 1978-1985
http://doi.org/10.5370/JEET.2018.13.5.1978
ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

Design and Analysis of a High Speed Single-phase Hybrid 4/4 poles SRM for Hammer Beaker Application

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Abstract – In this paper, a novel single-phase hybrid switched reluctance motor (HSRM) is proposed for hammer breaker application. The hammer breaker requires only unidirectional rotation and high-speed operation. To satisfy the requirements and eliminate torque dead-zone, the rotor of the proposed 4/4 poles SRM is designed with wider pole arc and non-uniform air-gap. This motor has a simple structure and produces low torque ripple. Permanent magnets (PMs) are mounted on the inner stator at a certain position which enables it to park the rotor for self-start and create positive cogging torque in the torque dead-zone. Compared with conventional single-phase switched reluctance motor, HSRM has an increased torque density and relatively low torque ripple. To verify effectiveness, finite element method (FEM) is employed to analyze the performance of the proposed structure. Then, the proposed motor is compared with the existing motor drive system for the same application. The proposed HSRM is easy to manufacture along with competitive performance.

Keywords: Hybrid single-phase SRM, Non-uniform air-gap, Low-cost, Torque-ripple, Hammer breaker.

1. Introduction

Recently, researchers are focusing on the development of high-speed motor drive such as blower, vacuum cleaner, compressor, pump to create a more compact drive with higher power density. Diverse range of electric machines such as permanent magnet motor, brushless motor, and induction motor are usually investigated for high-speed applications [1-3].

SRM is a doubly salient and singly-exited motor, in which windings are located at the stator and no windings or permanent magnets (PMs) are located on the rotor. The motor structure has many merits, such as good fault tolerance, robustness, low cost and applicability in harsh environments, such as high speed or high temperature [4, 5]. For these reasons, SRM has become one of the strongest candidates for high-speed drive systems.

Single-phase SRM drive system is selected for its less power electronic switches and least number of phases. However, the motor has a large torque dead-zone occupying half of one electrical period, which causes high torque ripple and self-starting problem. To solve this problem, general single-phase SRMs utilize parking permanent magnets [6-10]. The PMs at parking positions do not only allow self-starting of the motor, but also provide positive cogging torque in the torque dead-zone, thus reducing torque ripple. In [6], a single-phase SRM is proposed with PMs constructed in a v-shape flux concentration manner, which offers more flexibility in controlling and shaping the magnetic field. However, the stator comprises several segments, resulting in a weaker stator mechanical structure compared to a solid stator construction. Furthermore, due to its segmented stator design, it is not easy to place every stator segments on the same stator inner radius during assembly. Also, mismatched stator segments may cause a degraded machine performance.

To enhance the stator structure and improve the permanent magnet field, a π-shape flux concentration structure is proposed in [7]. A structure with four stator reluctance poles and two PM-poles is also proposed in [8-10]. Another structure for hammer breaker application which is shown in Fig. 1 was proposed and it is called Cyrano. The rotor has four reluctance poles with no windings and PM poles are directly mounted on the inner surface of the stator. The rotor and PM poles in Cyrano structure are asymmetrically shaped, so it only has one predetermined start direction, and its controller is very simple and inexpensive. However, the structure itself is very complex and increases the manufacturing cost significantly. Thus, a simpler structure is needed.

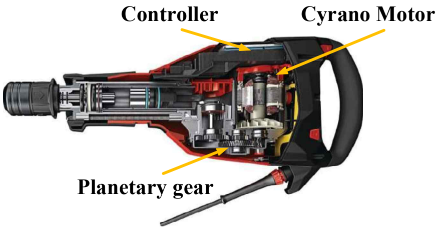

Fig. 1. Structure of hammer beaker

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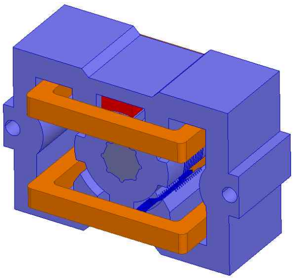
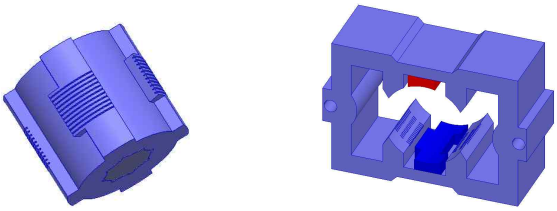
Received: April 5, 2018; Accepted: May 12, 2018



(a) Motor with winding



(b) Rotor (c) Stator with PM

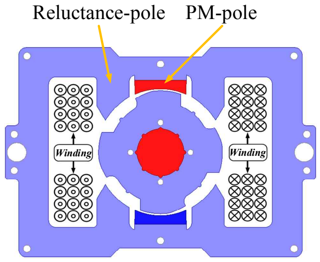
Fig. 2. Structure of Cyrano motor

The air-gap of the rotor can be modified to enable self-starting ability and lower torque ripple [8-10]. By using this technique, a 2-phase SRM can be operated at any rotor position without torque dead-zone and with reduced torque ripple. Because of the non-uniform air-gap, the motor has an asymmetric inductance and torque characteristics with wider positive torque region. The proposed single-phase hybrid switched reluctance motor (HSRM) also uses the similar principle of non-uniform air-gap to enable self-starting. However, due to the existence of PM, the flux linkage of PM has to be considered when designing the non-uniform air-gap.

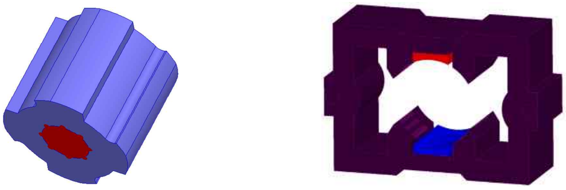
In this paper, a novel single-phase hybrid switched reluctance motor for hammer breaker application is presented. The average torque of the motor is the summation of both reluctance torque and positive cogging torque. Cogging torque is the torque produced by permanent magnets, and reluctance torque is the torque produced by both winding excitation and permanent magnets. Finite element method (FEM) is employed to analyze and predict the performance. Proposed SRM has four stator poles and four rotor poles, and two PMs between stator poles. In order to verify the design, a prototype of the proposed motor is manufactured. The characteristics of the proposed SRM is then compared with Cyrano motor.

2. Structure of Proposed Single-Phase SRM

Fig. 3 shows the structure of the proposed single-phase HSRM. The PM poles are mounted directly on the inner surface of the stator unlike in Cyrano-motor structure where the PMs are embedded inside the stator, as can be seen in Fig. 3(a). Also, the proposed rotor poles have non-uniform air-gap, as shown in Fig. 3(b).



(a) Structure of proposed HSRM



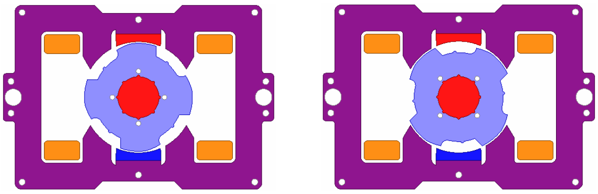
(b) Rotor (c) Stator with PM

Fig. 3. Structure of proposed motor

Single-phase SRM has torque dead-zone in the commutation region between phases and the motor cannot be operated because of this reason. Therefore, a non-uniform air-gap is implemented to enable self-start ability with unipolar rotational direction by modifying the shape of the rotor. Meanwhile, each coil consists of a winding that embraces the two neighborhood stator poles. These winding can be connected in parallel or series to form a phase, but the proposed HSRM windings are connected in parallel.

The working principle of the motor could be described as follows:

- **Stage 0** (starting position): when there is no current flowing in the motor, the rotor parks at the position shown in Fig. 4(a) due to the two PMs on the stator. This position is defined as the zero degree of rotor position or starting position.
- **Stage 1** (winding excitation period): when voltage is applied to winding terminals, the generated current produces a positive reluctance torque pulling the rotor to rotate until the rotor poles are aligned with the stator reluctance poles, which is around 45 mechanical degrees as shown in Fig. 4(b). At this point, the total flux is generated by both PM and winding current.
- **Stage 2** (PM only period): after 45 mechanical degrees, the current in winding coils should then be made and



(a) Unaligned position (b) Aligned position

Fig. 4. Operating principle of proposed motor

maintained at zero until the next aligned position. During this stage, the rotor rotates by PM only as shown in Fig. 4.

The operation of the motor starts from stage 0 to 2. Stage 1 and 2 are repeated simultaneously to achieve steady state. When the motor is turned off, the rotor will be pulled automatically to the permanent magnets due to the absence of reluctance flux, thus the operation is back to stage 0.

3. Design of Proposed Single-Phase SRM

From (1), output torque will be constant if $d\lambda / d\theta$ is constant with given current.

$$T_e = \frac{1}{2} i^2 \frac{d\lambda}{d\theta} \tag{1}$$

The presence of PM flux affects the total flux during excitation. This total flux is called reluctance flux as shown in Fig. 5. As can be seen from the figure, the reluctance flux starts to reduce while the flux of PM starts to increase at 45°, the connecting point. This affects the output torque as shown in Fig. 6. After that, the motor switches from using both PM and winding to PM only. However, negative torque is already produced before the motor switches to PM only mode. Thus, adding PM may solve the self-start problem but not exactly for torque ripple, since negative torque region is present now.

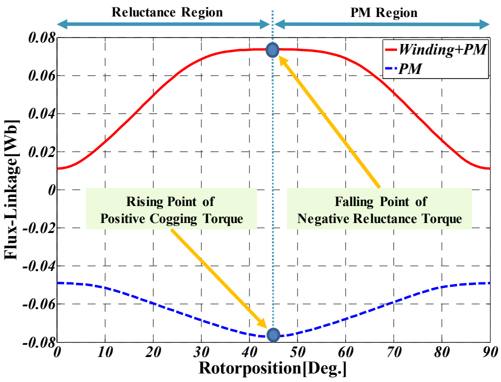


Fig. 5. Flux linkage of uniform air-gap

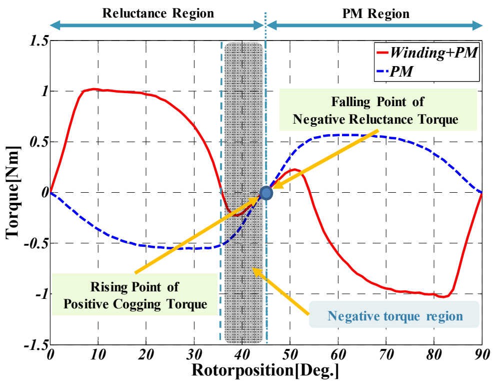


Fig. 6. Output torque with uniform air-gap

In order to further reduce the torque ripple, non-uniform air-gap is implemented by modifying the rotor shape. First, the area which has to be improved is analyzed. Since the point of the negative torque is at 45°, the improvement area is selected around 45°. At this region, the non-uniform air-gap has to be designed to eliminate negative torque by widening the reluctance torque before the negative region. To achieve this, the connecting point of reluctance flux and PM flux seen in Fig. 5 should not meet at the same point. Each flux must be controlled separately. The difference of each connecting point must be made as wide as possible. Therefore, a non-uniform air-gap is used as shown in Fig. 6. The proposed rotor structure with the non-uniform air-gap is shown in Fig. 7. Fig. 8 and 9 show the flux linkage and torque after optimization. It can be seen that there is no negative torque. The final dimensions of the proposed HSRM are presented in Table 1.

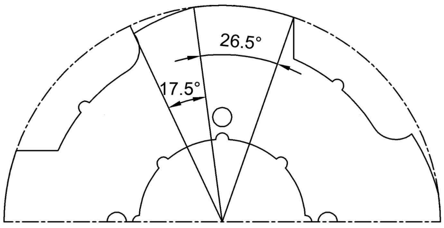


Fig. 7. Non-uniform air gap

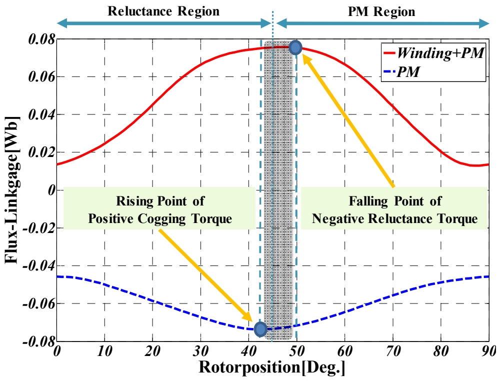


Fig. 8. Flux linkage of non-uniform air-gap

Table 1. Motor dimensions

Parameter	Cyrano HSRM	Proposed HSRM
Number of stator poles	4	←
Number of rotor poles	4	←
Outer diameter (mm)	78	←
Bore diameter (mm)	34	33 – 31.6
Stack length (mm)	30	←
Air gap (mm)	0.5	0.5 – 1.2
Stator pole arc (deg)	30	←
Rotor pole arc (deg)	42	←

4. Analysis of Proposed Single-Phase SRM

SRM has very high nonlinear magnetization characteristics. Hence, to verify the proposed structure, finite element method (FEM) is employed to get motor characteristics.

4.1 Static Characteristics

4.1.1 Magnetic flux distribution

Fig. 9 shows the magnetic field distribution of the proposed HSRM. Fig. 10(a) shows the flux provided by PMs only at unaligned position and Fig. 10(b) shows the reluctance flux provided by motor windings and PMs at aligned position. This verifies that PMs also participate in the electromagnetic energy conversion.

As shown in Fig. 11(a), during PM only operation, the magnetic flux from the PM at the top of the motor flows into the rotor, and returns via stator yoke on both sides of the stator. However, the situation is different with the phase winding excited since there are two types of magnetic fluxes in the motor. One is generated by PMs, and the other is generated by the phase winding. Furthermore, the direction of the flux generated by the phase winding is completely the opposite of that of PMs. This changes the flux path generated by PMs, as shown in Fig. 11 (b).

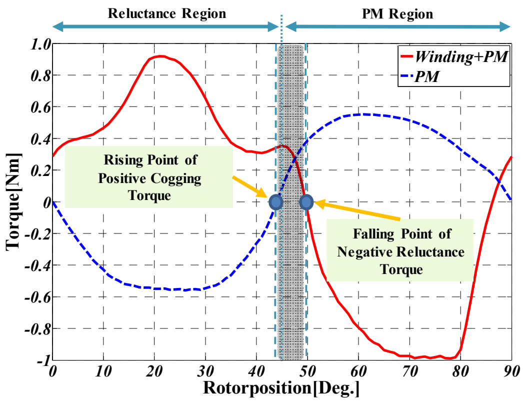
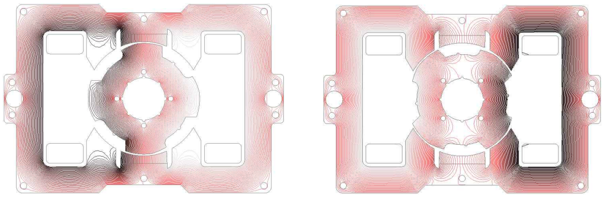
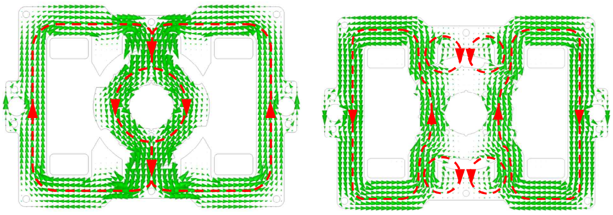


Fig. 9. Output torque with non-uniform air gap



(a) Permanent magnet (b) Reluctance magnetic

Fig. 10. Magnetic flux distribution



(a) Permanent magnet (b) Reluctance magnetic

Fig. 11. Magnetic field vector of proposed HSRM

4.1.2 Magnetic Field Density

SRM is designed to operate in the saturated region. Fig. 12 shows the magnetic flux density of the proposed structure at aligned position at rated condition. The material used for the cores are 35PN440 and the maximum flux density is less than 1.8 Tesla, which satisfies the material requirement.

4.1.3 Flux linkage and torque characteristics

Fig. 13 shows the flux-linkage of the proposed structure with/without PMs, respectively. Because the flux-linkage is a vector, the positive and negative value in the figure not only stands for the intensity of the flux, but also stands for the direction of the flux. In this figure, the positive flux direction is defined as the direction of the flux generated

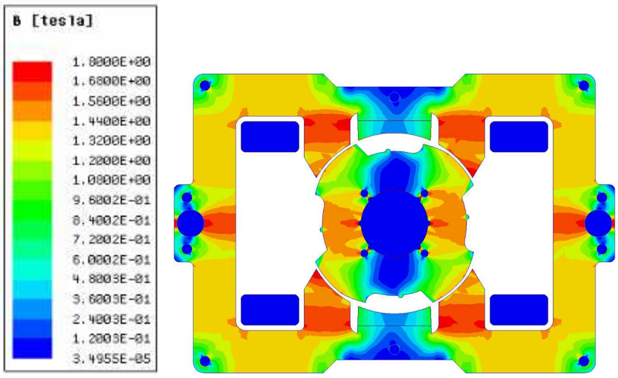


Fig. 12. Magnetic flux density

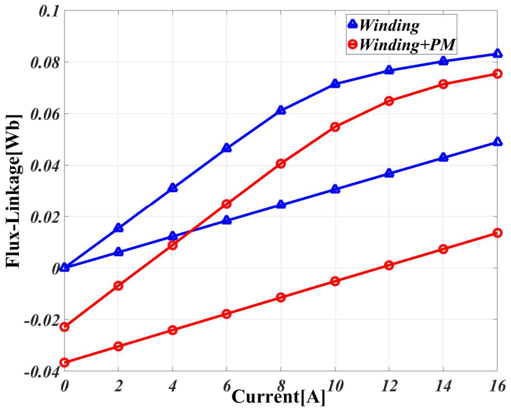


Fig. 13. Flux-linkage of proposed HSRM

by the phase windings. Accordingly, the flux generated by PMs is negative. When the proposed structure does not use PMs, it can be seen as a conventional single phase SRM. The flux linkage at aligned and unaligned position is shown as the red curves in the figure. As seen in the figure, the flux linkage is zero as the phase winding current is zero and it is positive at all other current levels. However, as PMs are inserted in the manner as shown in Fig. 3 (a), the flux-linkage at aligned and unaligned position is moved to the negative region at some current levels. From the figure, it also can be easily seen that the enclosed area between the aligned and unaligned curves for the same current in the proposed structure with PMs is increased compared with that of the proposed structure without of PMs. As is generally known, the area enclosed between the aligned and unaligned curves is the change in co-energy, which corresponds to the energy converted to torque in a single stroke. Hence, the output torque of the proposed structure with PMs inserted is larger than that without PMs. This increase is due to the additional PMs interaction torque component.

Fig. 14 shows the torque profiles of the proposed structure. After the phase winding current reaches zero, the torque is generated only by the PMs. Generally, it is called cogging torque. It should be pointed out that the cogging torque has no contribution to the average torque. It is used to move some positive torque produced by the winding current to the region where the current is zero.

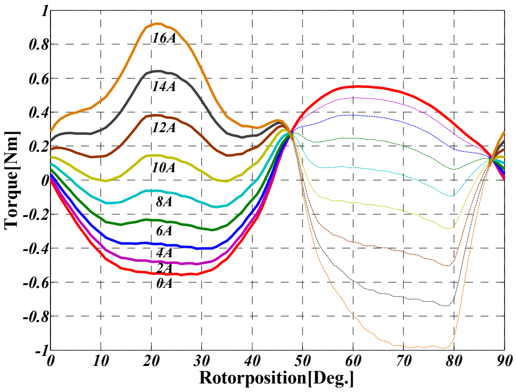


Fig. 14. Torque profiles of proposed HSRM

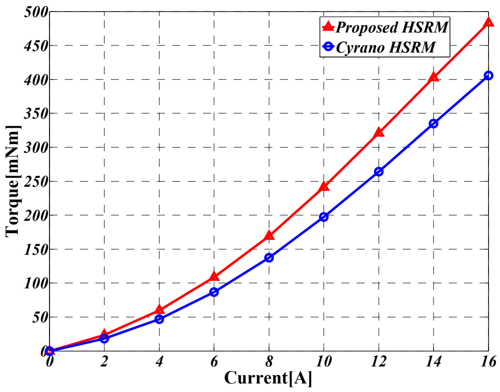


Fig. 15. Average torque of proposed and Cyrano HSRM

Fig. 15 shows the average output torque of the Cyrano-motor and proposed structure. From the figure, it can be seen that the proposed structure has higher torque characteristics compared to that of Cyrano motor.

Fig. 16 shows the torque comparison of Cyrano motor and proposed single-phase hybrid SRM. Both motors have the same dimension and input parameters. The torque ripple of the motor can be calculated as,

$$Torque\ ripple = \frac{T_{Max} - T_{Min}}{T_{Ave}} \times 100\% \quad (2)$$

in which, T_{max}, T_{min} and T_{ave} are the maximum, minimum and average torque, respectively. The torque ripple of proposed SRM is similar but slightly lower than that of Cyrano, and it also produces higher average torque as shown in Table 2.

4.2 Experiments

In order to further compare the performances of Cyrano

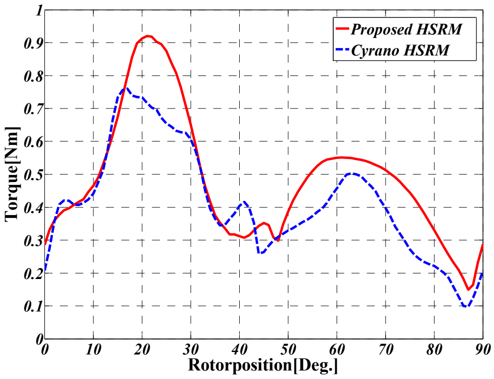


Fig. 16. Continuous torque of Cyrano and proposed HSRM

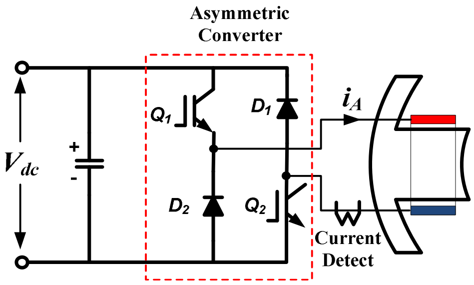


Fig. 17. Topology of asymmetric converter

Table 2. Torque ripple comparison

Motor type	Torque ripple	Avg. Torque	Min. Torque	Max. Torque
Cyrano	159.8%	0.414Nm	0.149Nm	0.919Nm
Proposed	159.4%	0.489Nm	0.097Nm	0.759Nm

and proposed single-phase HSRM, dynamic analysis is executed.

4.2.1 Asymmetric converter

Due to its many advantages, such as the capability of independent control for each phase and four switching modes, asymmetric converters are adopted. Fig. 17 shows the topology of the asymmetric converter circuit.

4.2.2 Copper loss

The copper loss is proportional to the square of phase RMS current and phase winding resistance. Hence, according to the current waveform, the copper loss can be calculated as,

$$P_{cu} = mI_{phrms}^2 R_{ph} \tag{3}$$

$$I_{phrms} = \sqrt{\frac{1}{T}\int_0^T I_m^2 dt} \tag{4}$$

$$R_{ph} = \frac{l}{\sigma A_c} \tag{5}$$

where, m is the number of phase, I_{phrms} is the RMS current of phase, R_{ph} is the phase resistance, T is the time of one period, I_m is the phase current, l is the length of the winding, σ is the conductance of the winding, A_c is the cross-sectional area of the winding.

4.2.3 Core loss

The core loss is composed of hysteresis loss, excessive loss, and eddy-current loss. It can be calculated as,

$$P_{losses} = P_h + P_c + P_e \tag{6}$$

$$P_h = k_h f\left(B_m\right)^2 \tag{7}$$

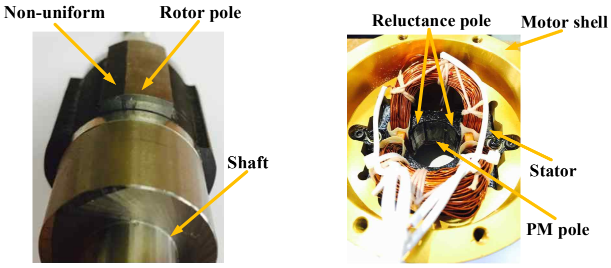
$$P_e = k_e\left(fB_m\right)^{1.5} \tag{8}$$

$$P_c = k_c\left(fB_m\right)^2 \tag{9}$$

in which, P_h, P_e, P_c are the hysteresis loss, excessive loss, and eddy-current loss, respectively; k_h, k_e and k_c are the coefficient of hysteresis loss, excessive loss, and eddy-current loss, respectively. In the analysis, M19_29G is used as the stator and rotor material. From the data sheet, k_h, k_e and k_c are given as 0.01642, 0 and 0.0000409, respectively.

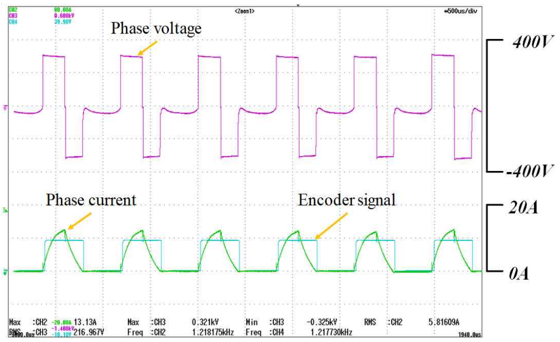
4.2.4 Windage and friction loss

In the dynamic analysis, the windage and friction losses can be estimated as 2~3% of rated output power, 750W. But in this paper 2.5% is adopted in the both type.

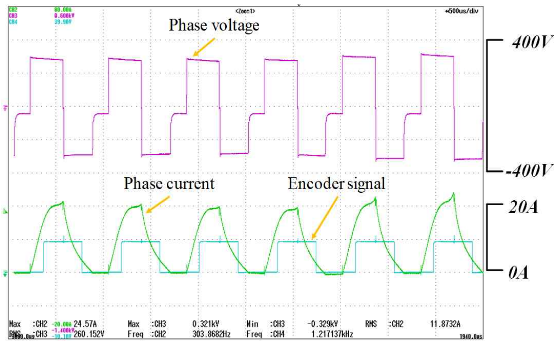


(a) Rotor (b) Stator with motor shell

Fig. 18. Prototype of the proposed HSRM



(a) Load torque = 0.1[Nm] and speed = 18000[RPM]



(c) Load torque = 0.5[Nm] and speed = 18000[RPM]

Fig. 19. Experimental result of prototype motor

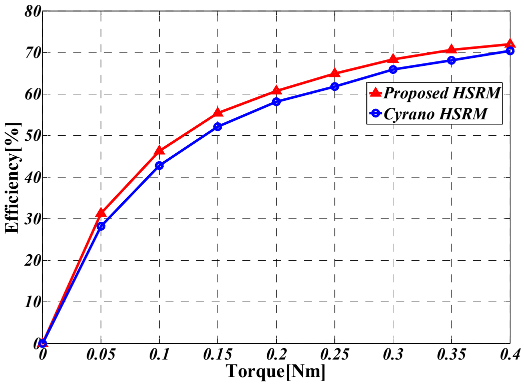


Fig. 20. Efficiency of Cyrano and proposed HSRM

Table 3. Motor performance

Parameter	Value
Speed[rpm]	18,000
Torque[Nm]	0.4
Efficiency[%]	72
Core loss (W)	256.5885
Copper loss (W)	36.627

4.2.5 *Experimental results*

To further verify the validity of the proposed HSRM, a prototype of the proposed structure is designed and manufactured as shown in Fig. 18. The motor shell, shown in Fig. 18(b), is only used to fix the motor to make it easier to connect with dynamometer for load test. The test results show acceptable performances as well as efficiency, which is higher than Cyrano's.

5. Conclusions

A new single-phase hybrid switched reluctance motor is proposed in this paper. The motor uses permanent magnets and non-uniform air-gap to enable self-starting and reduce torque ripple. The operating principle of the proposed HSRM is also presented in detail. Meanwhile, FEM is employed to analyze and predict the performance of the proposed structure. To verify the simulation results, the prototype of the motor is manufactured and tested. From the experimental result, it is known that the proposed motor is easy to manufacture and the performance is comparable to the existing motor for hammer breaker application.

Acknowledgment

This work was supported by the Human Resources Program in Energy Technology of the Korea Institute of Energy Technology Evaluation and Planning(KETEP) granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea(No. 20184010201700).

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