IEEE
INDONESIA SECTION

ISBN : 978-1-5386-6724-8

PROCEEDINGS OF

icaiti 2018

The 1st International Conference on Applied Information Technology and Innovation

"Toward a new Paradigm for the design of assistive technology in smart home care"

September 4-5, 2018
in Padang, Indonesia

Organized by
Teknologi Informasi
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Assalamu’alaykum wrwb,

On behalf of the technical program committee (TPC), we warmly welcome to you to the 1st International Conference on Applied Information Technology and Innovation (ICAITI 2018) in Padang, Indonesia. The committee has organized exciting technical program for ICAITI with conference theme “toward a new paradigm for design of assistive technology in smart home care”. ICAITI is the international conference organized by Politeknik Negeri Padang. As a intenational conference , ICAITI provides excellent platform to share idea and experiences, exchange information and explore collaboration among researchers, engineers, practitioners and scholars in the field of information technology, communications, and electrical engineering.

All 76 submitted papers throughout the world went through a rigorous review process and each paper was evaluated by independent reviewers in accordance with standard blind review process. Based on the result of process, 43 papers have been selected, which constitute the acceptance rate of 56.6%. ICAITI also features world-class keynote/plenary speeches and distinguish-invited speakers that reflect the current research and development trends in the aforementioned fields.

We are deeply indebted to all of our TPC members as well as our reviewers, who volunteered a considerable amount of their time and expertise to ensure a fair, rigorous, and timely review process. Many thanks should be given to our keynote and invited speakers who will share their experience in this conference. Last but not least, our sincere gratitude should be given to all authors for submitting their work to ICAITI 2018, which has allowed us to assemble a high quality technical program. Welcome to Padang and hope you will enjoy a wonderful experience in West Sumatra.

With best regards

Humaira, MT
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Comparison of Three Topologies Rotor to Improve Efficiency and Torque for High-Speed Spindle Motor Applications

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***Abstract*—This paper presents the design of three closed slot rotor topologies as circular, round, and oval. The design generated using the Taguchi, equivalent circuit, and finite element method (FEM) for high-speed, high-torque, and high-efficiency. For a fair comparison, the topologies are tested using FEM under the same conditions and specifications and an equivalent circuit is used for verifying and analyzing their output powers, torques, and efficiencies. The results help simplify rotor selection for various spindle motor applications requiring high efficiency and torque.**

***Keywords*—closed rotor, finite element method, spindle motor, Taguchi method, equivalent circuit**

I. INTRODUCTION

In high-speed spindles known as spindle units, the motors are placed inside spindle [1]. The desired characteristics of a spindle motor are quick response, high torque, and efficiency, compact structure, small inertia force, and dynamic properties [2]. In spindle motors, torque and efficiency must be large in a wide constant-power speed range. Maximizing motor efficiency is equivalent to minimizing motor loss.

Motor losses are the sum of core, iron, stator and rotor winding, and fiction windage losses. Estimating losses and their causes is fundamental in increase efficiency in spindle motors [5]. Rotor configurations substantially influence the constant-speed range, efficiency and loss. Especially, appropriate rotor slot geometry can improve motor performance [3], [4].

Several rotor slot geometries are used, including rectangular, double cage, rounded, polygonal, closed and circular with the characteristics of each rotor slot suitable for difference applications. Stator slot Optimization improves the electrical characteristics of the motor [6], [7]. Slot rotor design to generate the geometry of existing designs has been carried out and the results are not much different depend on intuition and experience of the designer. Multi-Objective optimization can predict the effect of polygonal, double cage, rounded and rectangular rotor slot geometries on the starting torque [3], [4].

Totally closed and semi closed rotor slots have been designed using finite element method for current monitoring for detecting static air-gap eccentricity in squirrel-cage motors [8]. Optimal design of robust speed t-s fuzzy controller for a wounded rotor motors coupled with nonlinear loads was reported in [9]. Closed rotor slots are more appropriate for decreasing the mechanical problems associated with high speed motors [10]. The closed rotor slot geometry exploits the skin effect for obtaining specific performance characteristics, such as high starting and breakdown torques [11].

In this paper, three close rotor topologies as circular closed, round and oval closed for spindle motors are compared. The rotors are produced from the same stator geometry obtained from a high-performance spindle motor manufacturer. The model will be designed using Taguchi method, with torque and efficiency as the objective functions, tested using FEM, and analyzed using an equivalent circuit. Finally, the results are validated through testing and comparisons for obtaining the rotor geometry and rotor slot most appropriate for high-speed, torque, and efficiency spindle motor applications.

II. ROTOR SLOT DESIGN THEORY

In the rotor slots design, the number of stator and rotor slots must be chosen carefully for reducing parasitic torque, additional losses, radial forces, noise, and vibration. Moreover, it affects the starting behavior, air-gap magnetic flux density harmonic content and improved the performance characteristics [15], [16]. In addition, in appropriate rotor slot combination increases noise levels and undesirable dips in the starting torque, which decreases efficiency, power factor, and rotor heating [15].

The induced voltages create circulating currents in the closed rotor slots depending on the impendence of the rotor winding, which is a function of the frequency, number and sharp of the slots, and permeability of the iron. The current develop mmf waves with a theoretically infinite number of harmonics and new ordinal λ because of the rotor slotting. The interaction of the mmf waves of the rotor mmf waves and air-gap permeance waves generates other flux density waves. Disruption of the supply voltage causes a circulating current unbalance in the rotor slots, which in turns increases rotor unbalance, noise, and temperature of the motor. Thus, rotor slot design is crucial for improving spindle motor performance.

III. OPTIMIZATION METHODOLOGY

A. Identification of Spindle Motor Design

A spindle motor with 15 kW, 4 Poles, Δ connection, operating at 380 V and 18000 rpm is used in this study. The spindle motor was constructed using a rounded semi-closed stator slot obtained from spindle motor manufacturer. Stator geometry is associated with the number of conductors per slot, which in this study is 8 and the wire diameter is 1.725 mm. The general specifications of the stator and rotor are listed shown in Table 1. The top and bottom tooth width of the stator composed of 35CS250 is 6 mm and 5.12 mm, respectively. The optimization steps are illustrated in Fig. 1.

TABLE I. MOTOR SPECIFICATIONS

Parameter	Value
Inner diameter of stator (mm)	106
Outer diameter of stator (mm)	170
Length of the stator core (mm)	150
Outer diameter of rotor (mm)	105
Inner diameter of rotor (mm)	62
Number of stator slot	36
Number of rotor slot	34

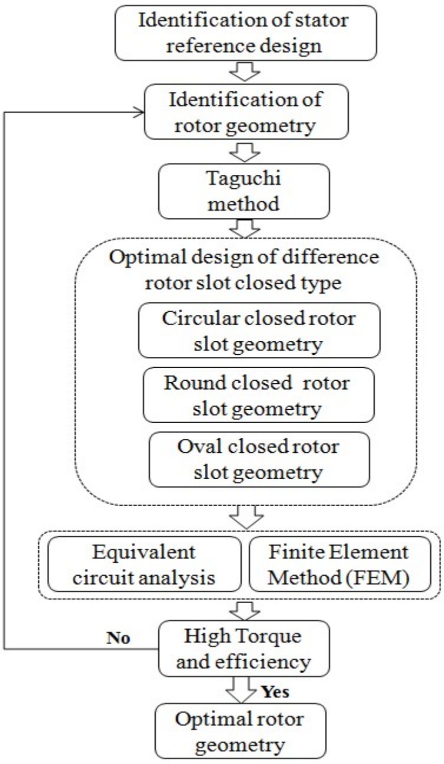

Fig. 1. Optimization flowchart

B. The Optimal Design Process

TABLE II. DESIGN VARIABLE AND LEVELS

Factor	Definition	Level		
		1	2	3
A	hs_0 (mm)	1.5	2	2.5
B	hs_2 (mm)	0	0.1	0.2
C	bs_1 (mm)	3	4	5

In this paper, the Taguchi method used four factors and three levels for the round closed slot rotor, and three factors and three levels for circular and oval closed rotor slot. As described in [12], [13]. L9 orthogonal array is used to obtain the optimal combination rotor slots geometry. The design variables and levels for the circular closed rotor slots are listed in Table 2. The spindle motor performance in L9 matrix experiments obtained using two-dimensional FEM for circular closed rotor slots as reported in Table 3.

TABLE III. METRIX OF DESIGN VARIABLES AND LEVELS

No. Exp	A (hs_0)	B (hs_2)	C (bs_1)	Eff (%)	T (Nm)
1	1.5	0	3	92.72	15.05
2	1.5	0.1	4	93.3	15.28
3	1.5	0.2	5	93.57	15.48
4	2	0	4	92.91	11.52
5	2	0.1	5	93.25	11.87
6	2	0.2	3	93.3	11.08
7	2.5	0	5	92.43	8.97
8	2.5	0.1	3	87.66	8.05
9	2.5	0.2	4	91.98	8.54

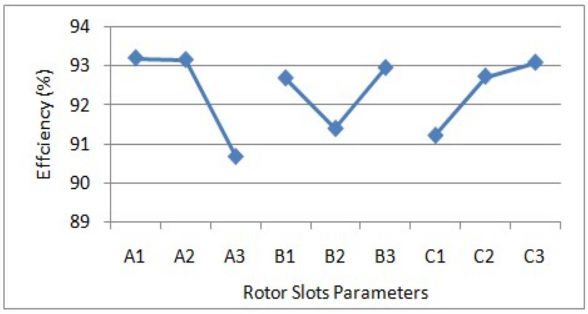

Fig. 2. Effect plot of eficiency

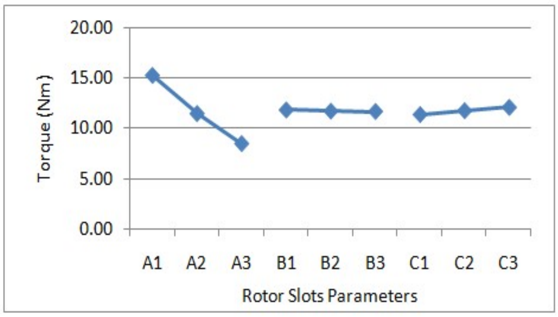

Fig. 3. Effect plot of torque

TABLE IV. ANOVA OF EFFICIENCY

Parameter	SS	% effect	DOF	MS
A (hs_1)	12.35327	46.28	2	6.18
B (hs_2)	4.108467	15.39	2	2.05
C (bs_1)	5.832067	21.85	2	2.92
error	4.3994	16.48	2	2.20
Total SS	26.6932			

TABLE V. ANOVA OF TORQUE

Parameter	SS	% effect	DOF	MS
A (hs_1)	68.6718	98.80607	2	34.3359
B (hs_2)	0.035467	0.05103	2	0.017733
C (bs_1)	0.765067	1.10079	2	0.382533
error	0.029267	0.042109	2	0.014633
Total SS	69.5016			

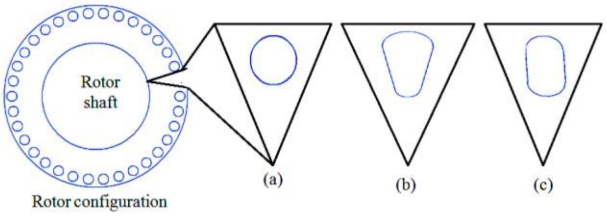

Fig. 4. Three topologies of closed rotor slots, (a) circular closed (CC), (b) round closed (RC), (c) oval closed (OC)

TABLE VI. OPTIMIZATION RESULTS OF ROTOR SLOTS GEOMETRY

Parameter	CC	RC	OC
Hs_0 (mm)	1.5	1.5	1.5
Hs_1(mm)	1.5	1.5	1.5
Hs_2(mm)	0.2	6	6
Bs_0(mm)	0	0	0
Bs_1(mm)	5	4	5
Bs_2(mm)	5	2	5

Effect plots from the matrix experiment are used to determine the optimal combination of the rotor slot parameters. Fig. 2 and 3 present the effect plot of efficiency and torque for circular closed rotor slots, respectively. Differences are observed in the optimal of efficiency and torque, in the efficiency of hs_2 level 3 produces higher efficiency and torque hs_2 level 1 produces higher torque. Analysis of variance (ANOVA) was used to determine the optimal combination. Tables 4 and 5 represent the ANOVA results for efficiency and Torque. Efficiency hs_2 has a higher effect than does the torque. Therefore, hs_2 level 3 is the optimal value of this optimization, the optimal combination revealed by the Taguchi method is hs_0 level 1, hs_2 level 3, and bs_1 level 3. This result is verified by using FEM and equivalent circuit analysis. The optimum results obtained using Taguchi method for round and oval closed rotor slots are reported in Figure 4. The Taguchi method results of the three investigated topologies are summarized in Table 6.

C. Performance calculations

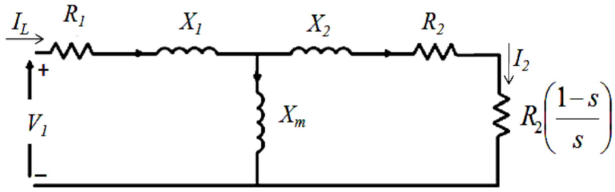

Fig. 5. Equivalent circuit analysis

Fig. 5 presents a phase equivalent circuit of a three-phase spindle motor, where V_1, R_1, X_1, X_m, R_2, and X_2 are phase voltage, stator resistance, stator reactance, magnetizing reactance, rotor resistance, and rotor reactance, respectively. The Cross-sectional area of the rotor slots substantially affects the rotor resistance and high rotor resistance affects rotor and magnetization currents.

An appropriate the rotor slot with rotor current relationship generates high magnetization currents, which influences the conversion of electrical energy into torque. If the stator and rotor current are not included in the magnetization current, leakage reactance is generated and the high leakage reactance in the stator and rotor lead to high additional loss, which decreases of the spindle motor efficiency.

After designing the machine, stator, and rotor, their characteristics can be determined using an equivalent circuit. Estimating machine loss is necessary for predicting machine performance. Generally, the core loss in the machine has two components, eddy current loss and hysteresis loss in the stator core. Under the normal operating conditions, the rotor core loss can be ignored because of the low rotor frequency, which is caused by distortions in the spindle motor supply current and voltage. The stator and rotor current are obtained using (1) and (2), respectively. The magnitude of the stator current is obtained using (3), where s is motor slip and R_{TH} and X_{Th} are thevenin resistance and reactance. R_{TH} and X_{Th} are obtained using (4) and (5), respectively.

$$I_s = \frac{V_\phi}{R_1 + jX_1 + R_f + jX_f} \tag{1}$$

$$I_r = \frac{V_\phi}{\left[\left(R_1 + \frac{R_2}{s}\right)^2 + j\left(X_1 + X_2\right)\right]} \tag{2}$$

$$I_{LR} = \frac{V_{ph}}{\sqrt{\left(R_{th} + \frac{R_1}{s}\right)^2 + \left(X_1 + X_2\right)^2}} \tag{3}$$

$$R_{TH} = \left(\frac{X_m}{X_1 + X_m}\right)^2 R_1 \tag{4}$$

$$X_{TH} = \left(\frac{X_m}{X_1 + X_m}\right) X_1 \tag{5}$$

The power transferred from the stator to rotor (air gap power) is:

$$P_g = 3I_s^2 \frac{R_2}{s} \tag{6}$$

The mechanical torque at a specific slip is expressed as follows [16-18]:

$$T_{mech} = \frac{1}{\omega_s}\left(\frac{3V_{1eq}^2\left(\frac{R_1}{s}\right)}{\left(R_{1eq} + \left(\frac{R_2}{s}\right)\right)^2 + \left(X_{1eq} + X_2\right)^2}\right) \tag{7}$$

where ω_s is synchronous speed, V_{1eq} and $Z_{1eq} = R_{1eq} + jX_{1eq}$ are defined, V_{1eq} can calculation with:

$$V_{1eq} = \left|\frac{jX_m V_\phi}{R_1 + j\left(X_1 + X_m\right)}\right| \tag{8}$$

$$Z_{1eq} = \frac{jX_m\left(R_1 + jX_1\right)}{R_1 + j\left(X_1 + X_m\right)} \tag{9}$$

The output power can be expressed as [11]:

$$P_{Out} = \frac{3I_s^2 R_1 \omega_r}{s\omega_s} \tag{10}$$

From (10) the efficiency can be obtained as:

$$\eta = \frac{P_{out}}{3V_\phi I_s \cos\theta} \tag{11}$$

In the rotor slots, magnetic saturation is clearly influential. Frequency can be easily increased by increasing rotor slot width, thereby reducing rotor bar resistance. However, widening the slot increases tooth saturation and may deteriorate of the spindle motor performance. In addition, accurate prediction of the starting performance is required and the model used must also consider the deep-bar effect. Because FEM analysis is capable of modeling both these effects, FEM is suitable for calculation rotor parameters. Alternatively, equivalent circuit model yield accurate performance predictions [11].

IV. Test Result and Discussions

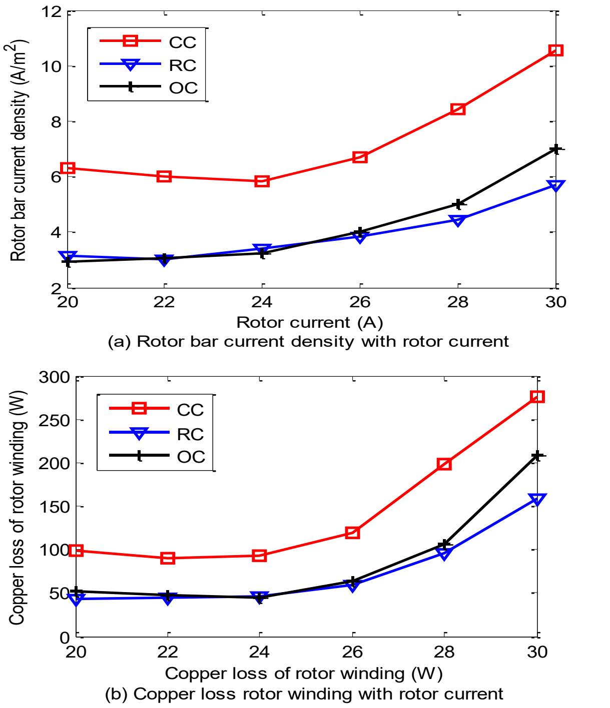

Fig. 6. Rotor current density and copper loss rotor winding characteristics

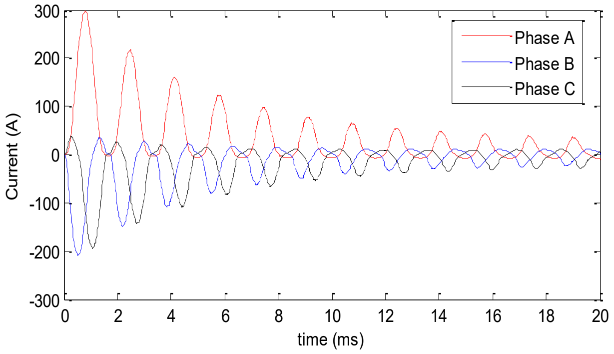

Fig. 7. Current characteristics in circular closed rotor slot

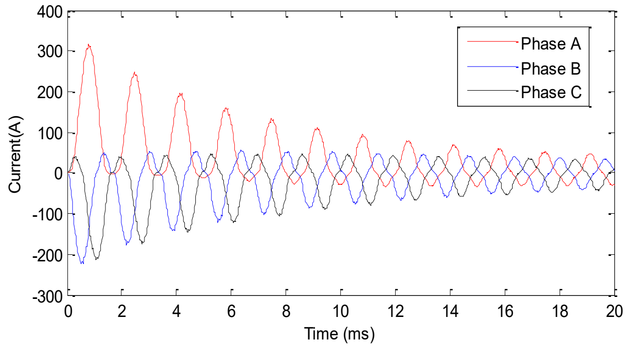

Fig. 8. Current characteristics in round closed rotor slot

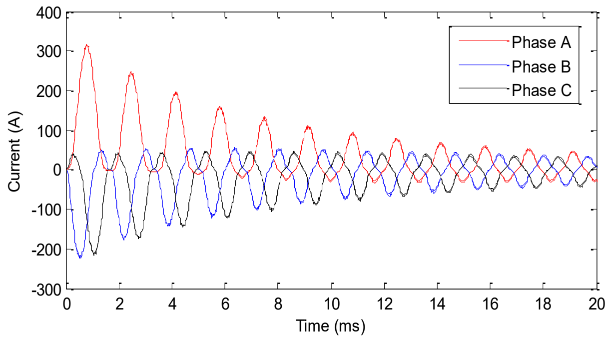

Fig. 9. Current characteristics in oval closed rotor slot

Test, analyses, and comparison were conducted to investigate the characteristics of the rotor design. For a fair comparison, the tests were performed under the same operating conditions. The cross-sectional area of the slots substantially affects winding, iron, and total losses. Moreover, rated current affects the radial force, vibration, and noise in motors [14]. Current characteristics and spindle motor performance was the main focus of the tests. As shown in Table 7, circular closed rotor slots produce the highest copper loss rotor winding because their cross-sectional area is the smaller, this in turn increases rotor bar current density. Fig. 6 (a) presents the rotor bar current density and speed characteristics, and the copper loss rotor winding characteristics are shown in Fig. 6 (b). The starting current produced by the circular closed rotor slots is lowest as shown in Figure 7, which affords current stability and low noise. The cross-sectional area of the rotor slots is in agreement with the stator slots, affords the stator current stability. Under the normal spindle motor rotating conditions, round and oval closed rotor slots generate more stable stator current than the circular rotor, as shown in Fig. 8 and 9.

TABLE VII. Performance Comparison of the Rotor Topologies

Parameter	CC	RC	OC
Stator Phase Current (A)	19.33	19.28	19.25
Rotor Phase Current (A)	16.04	15.98	15.97
Copper Loss of Rotor Winding (W)	189.76	48.40	52.46
Total Loss (W)	1031.9	980.98	984.64
Output Power (kW)	15	15	15
Efficiency (%)	93.57	93.85	93.84
Power Factor	0.71	0.71	0.72
Torque (Nm)	15.49	15.58	15.95
Rotor Bar Current Density (A/mm^2)	6.32	3.15	3.51
Rotor Ring Current Density (A/mm^2)	7.39	3.53	3.52

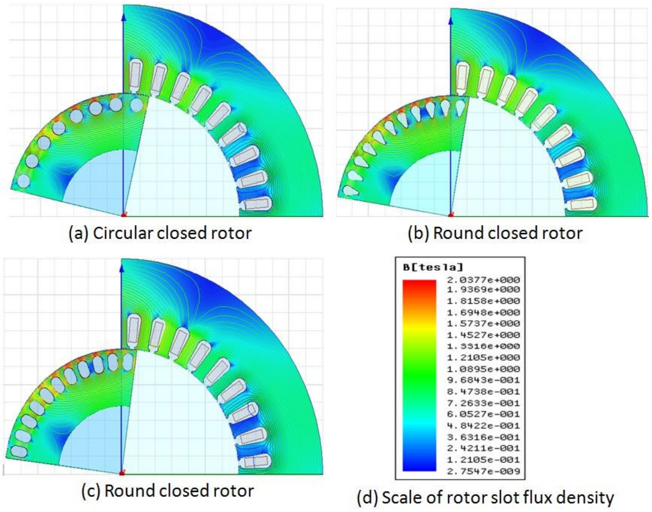

Fig. 10. Rotor flux current density

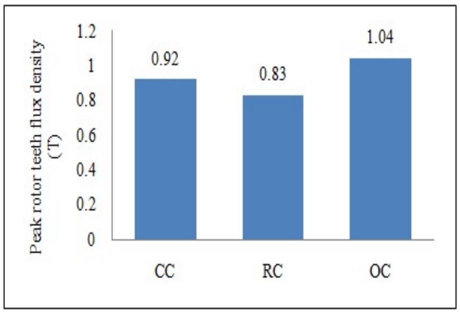

Fig. 11. Peak rotor flux density

The induction spindle motor can be considered as two winding systems in an inductive current relationship. The current that produces fluxes can be classified into two components. The first component, termed useful or magnetizing fluxes are those involved in energy transfer, are linked with both windings, and are associated with the fundamental field wave. The second component named leakage flux are not involved in transfer energy [15]. Changes in the cross-sectional area of rotor slots affect tooth rotor flux density and rotor yoke flux density. Fig. 10 compares the flux density obtained using FEM simulation and Fig. 11 plots the peak rotor teeth flux density. The oval closed rotor slots produce the highest rotor teeth flux density.

Furthermore, the cross-sectional area of the rotor slots affects the rotor resistance, which in turn affects the energy conversion as output power. The characteristics of output power and speed for the three topologies are presented in Fig. 12 (a) and Table 3. These output power characteristic do not different much and are consistent with the specification of 15 kW.

At low speeds, circular closed rotor slots produce the highest output power. The differences in output power at low speeds in a circular closed rotor slots cause differences in efficiency and torque. Fig. 12 (b) and 12(c) show that the efficiency and torque produced in it rotor is the highest. An increase in output power increases efficiency. The leakage reactance does not very much different among the three designs. Nevertheless, the round closed rotor slot produces the lowest leakage reactance. Minimizing the leakage reactance maximizes energy transfer in the stator and rotor, as shown in Fig. 12 (d). Thus, the input energy is converted into the optimal spindle motor torque.

Fig. 13, 14, and 15 present the torque and time characteristics of the three topologies, the starting current influences starting torque, the starting power, and efficiency. The closed circular rotors produce high starting torque and respond quickly as shown in Fig. 13. Round and oval rotor slots produce high starting current and high starting torque ripple, as shown in Fig. 14 and 15.

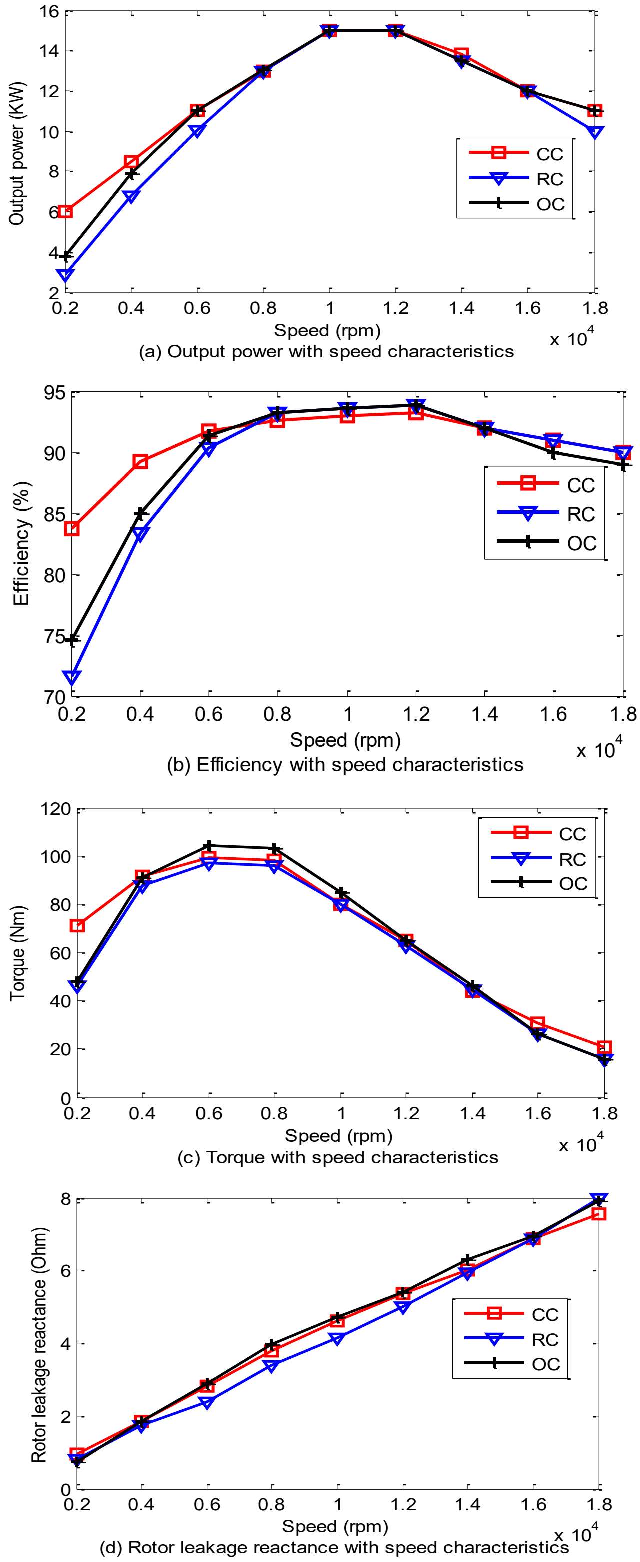

Fig. 12. Performance comprison of three closed rotor slots

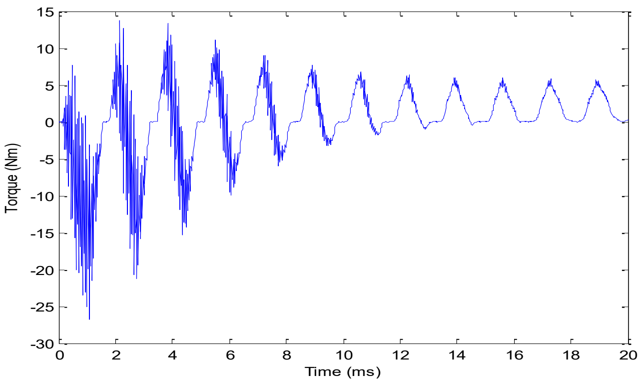

Fig. 13. Torque with time characteristics in circular closed rotor slots

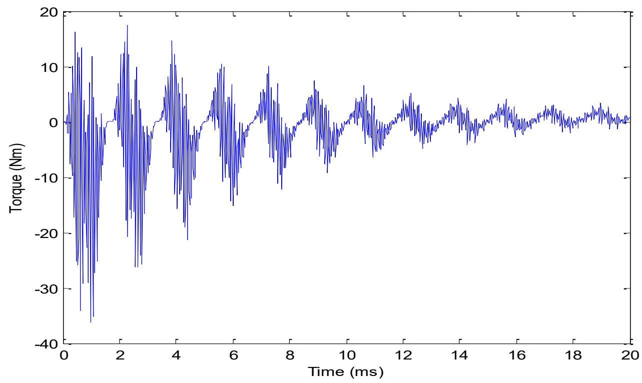

Fig. 14. Torque with time characteristics in round closed rotor slots

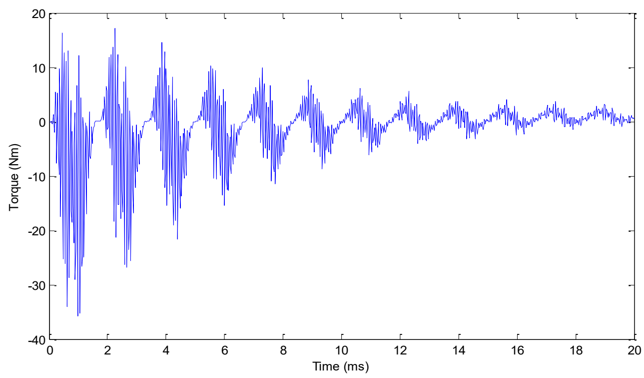

Fig. 15. Torque with time characteristics in oval closed rotor slots

V. Conclusion

In this paper, the performances of three closed rotor spindle motor topologies were predicted using FEM and analyzed using an equivalent circuit. The performance comparison revealed that circular closed rotor slots produce the highest copper loss of rotor winding because their cross-sectional area is the smallest. Oval closed rotor slots produce the highest rotor teeth flux density. At low speeds, circular closed rotor slot produces the highest output power. The differences in output power at low speeds in circular closed rotor slots cause differences in efficiency and torque. The leakage reactance produced by the three designs, and leakage reactance produced by the round closed rotor slots is the lowest. Thus, the Taguchi, equivalent circuit, and FEM method are effective in optimally designing of closed rotor slots to improve the performance in spindle motor.

Acknowledgment

This project was supported by Pendapatan Negara Bukan Pajak (PNBP) UNP with contract no. 1363/UN35.2/PG/2018

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