International Journal of Engineering & Technology, 7 (2.23) (2018) 157-161

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Preliminary Design Analysis of a New Field Excitation Flux Switching Machine with Segmental Rotor and Non-overlap Winding

M. F. Omar *, E. Sulaiman, H. A. Soomro, G. M. Romalan, S. M. N. S. Othaman

*Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Johor, Malaysia. **
**Email: fairoz.omar@yahoo.com*

Abstract

Recently, a three-phase Field Excitation Flux Switching Motor (FEFSM) with salient rotor structure has been introduced with their advantages of easy rotor temperature elimination and controllable FEC magnetic flux particularly meet for high torque, high power as well as high speed diverse performances. Nevertheless, the salient rotor structure is found to lead a longer magnetic flux path between stator and rotor producing weak flux linkage along with low torque performances. Therefore, a new structure of a single-phase FEFSM using segmental rotor with non-overlap windings is proposed. Segmental rotor and non-overlap windings are the clear advantages of these topologies as the copper losses gets reduce and rotor becomes less weight as well as more robust. Detailed analysis on winding arrangement test analysis, armature and FEC flux linkage, back-EMF and average torque characteristics have been performed by using 2D Finite Element Analysis (FEA) through JMAG version 15 software. The results show that the proposed motor with segmental rotor and non-overlap windings produce short flux path, high flux linkage and the highest torque capability achieved is 0.91 Nm.

Keywords: *Coil test; Single-phase; Flux switching machine; Field excitation; Segmental rotor; Non-overlap windings.*

1. Introduction

Over the last decade, numerous flux switching motor (FSM) topologies have been presented for different application i.e. car, household machines, aviation etc. FSM can be classified into three bunches that are Permanent magnet (PM) FSM, Field Excitation (FE) FSM and Hybrid Excitation (HE) FSM. Permanent magnet and field winding are the fundamental sources of flux in PMFSM and FEFSM, respectively while in HEFSM, both field winding and permanent magnet produces the flux [1]-[4]. In all these FSMs the armature winding and field winding or Permanent magnets are found on the stator. Compare with other FSMs, the FEFSM motor has preferences of low cost, simple construction, magnet-less machine, and variable flux control capabilities reasonable for different performances. Besides, FEFSMs have the advantage of cost-saving materials as the PM on stator used in PMFSMs is replaced by excitation from DC coils. In addition, the FEFSM machine with salient rotor is a standards combination of SRM and inductor generator technology [5], [6]. The motor's reliability also has been verified in variety of applications requiring high power and high torque density [7]-[9].

Fig. 1 demonstrates a single-phase 12S-6P FEFSM and a three-phase 24S-10P FEFSM with salient rotor design [10], [11]. The authors in [10] claim that the FEFSM with salient rotor has robust rotor due to single stack of iron structure and hence, it is suitable for high speed applications. In 2014, author of [11] introduced a single phase FEFSM using salient rotor with overlap windings. The proposed motor consists of 4 armature slots, 4 field excitation slots, 12 stator teeth and 6 rotor poles (12S-6P). The author claims that the FEFSM has high power density and good flux weakening capabilities at high speed due to absent of PMs and variable flux field excitation.

However, the salient rotor structure of FEFSM causes the flux path to be longer lead and extended magnetic flux path flowing from stator to the rotor and vice versa, higher volume, heavier and increase the rate of iron loss. In addition, the overlapping winding technique applied between the armature and the field excitation coil (FEC) causes the size of the motor increased and the efficiency decreases as copper losses increase due to the use of high copper wire. This paper presents a new single-phase 12S-6P FEFSM with segmental rotor and non-overlap windings. The proposed motor has 12 slots for copper winding and 6 segmental rotor have provided a short flux path from the stator to the rotor and vice versa. Consequently, the proposed motor enable higher flux yields and increases the output torque. 2D-FEA through JMAG Designer version 14.1 is use to analyse the winding arrangement test, coil test, magnetic flux

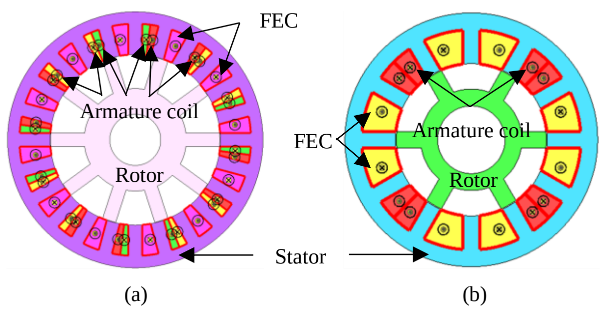


Fig. 1: FEFSM with salient rotor (a) 3-phase 24S-10P and (b) Single-phase 12S-6P.

linkage, back-EMF, and torque characteristics of the proposed motor.

2. Parameter and Configuration of FEFSM

The machine configuration for single-phase 12S-6P FEFSM using segmental rotor with non-overlap windings is demonstrated in Fig. 2. From the figure, the design has 6 segmental rotor poles in the middle of stator with non-overlap windings between armatures and FECs coil. The windings coils of FECs are placed in between of armature coil, while the winding configurations of both winding coils are in clockwise polarity and counter clockwise polarity. Table 1 shows the design specifications and parameters for the proposed machine. The main function of the segmental rotor is to modulate and change the magnetic flux polarisation in armature coils, and this also shows the elementary principles of FEFSMs operation. The outer diameter of rotor is estimated to be 60% of the stator outer diameter as standard motor design requirement. In short, equal stator back inner and stator pole widths are introduced so that the flux linkage is predictable to reduce flux saturation as well as provide enough space for flux to flow in the stator yoke with equal magnetic flux distribution.

3. Design Methodology

Fig. 3 shows design implementation of the proposed FEFSM. There are three main sections in the implementation of this study: Geometry Editor, JMAG Designer and Simulation Test. The Geometric Editor and JMAG Designer sections are the process of designing each motor structure and the internal setup of the proposed motor, respectively. The simulation test is divided into 3 parts, namely coil test, no load test and load test.

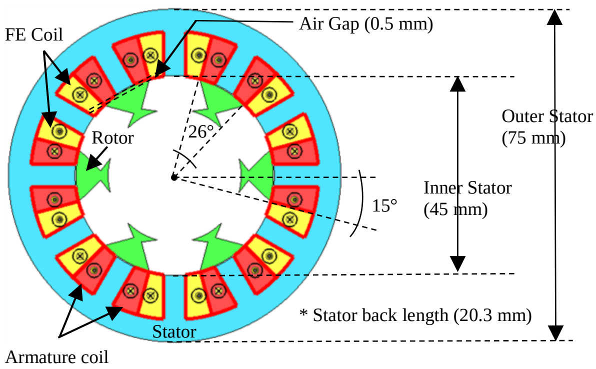


Fig. 2: Structure of proposed FEFSM using segmental rotor.

Table 1: Design Specifications and Parameters

Specifications	Parameters
Phase type	1
Slot number	12
Pole number	6
Outer stator radius (mm)	37.5
Inner stator radius (mm)	22.5
Stator back inner radius (mm)	5
Armature coil area (mm^2)	47
FEC area (mm^2)	47
Outer rotor radius (mm)	22.25
Inner rotor radius (mm)	15
Segmental span (degree)	15
Space of Air gap (mm)	0.5
FEC number of turns	93
Armature coil number of turns	93

There are 17 winding arrangements (WAs) with non-overlap configurations to be tested to form six armature sinusoidal flux with same phase on six armature coils. This possibility arrangement is tested based on the current flow on each armature coil and FEC. The direction of current flow on each coil is classified into 3 types, clockwise (CW), anti-clockwise (ACW) and alternate. The 17 winding configurations is illustrated in Table 2. The single-phase 12S-6P FEFSM with segmental rotor and non-overlap windings is

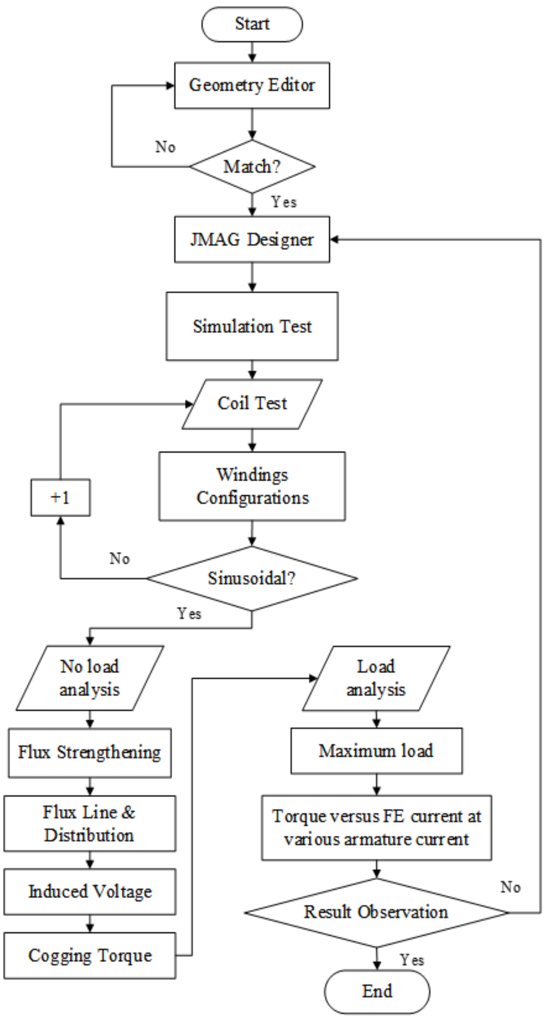


Fig. 3: Design implementation of the proposed FEFSM

Table 2: Winding Configurations of Armature Coils and FECs

Windings Arrangements	Armature Coils Configuration	FECs Configuration
WA1	All ACW	Alternate
WA2	All ACW	All CW
WA3	All ACW	All ACW
WA4	All ACW	3 CW, 3 ACW
WA5	All ACW	3 ACW, 3 CW
WA6	All CW	Alternate
WA7	All CW	All CW
WA8	All CW	All ACW
WA9	All CW	3 CW, 3 ACW
WA10	All CW	3 ACW, 3 CW
WA11	3 CW, 3 ACW	All ACW
WA12	3 CW, 3 ACW	All CW
WA13	3 ACW, 3 CW	All ACW
WA14	3 ACW, 3 CW	All CW
WA15	Alternate	All ACW
WA16	Alternate	All CW
WA17	Alternate	Alternate

analysed in two conditions, namely open circuit analysis and short circuit analysis. Armature coils and FECs materials is made from copper, while electrical steel sheet 35A250 is used for stator and rotor.

4. FEA Based Performance Analysis

4.1. Winding Arrangement Test

Winding arrangement (WA) test is important in FEFSM design because it is a basis key for forming of flux in the same phase. The proposed machines have 6 armature coils, 6 FECs and 17 possibility of WAs. Fig. 4 shows the four samples of WA. From Fig. 4(a), all armature coils are set to ACW and all FECs are set to CW. While in WA9, all armature coils are set to CW, 3 FECs CW and another 3 FECs ACW is illustrated in Fig. 4(b). Meanwhile, Fig. 4(c) and Fig. 4(d) show the WA12 and WA13, respectively. From figure, the 6 armature coils is divided into two directions, 3 CW and 3 ACW. Whereas 6 FECs are set in all CW and ACW states. Fig. 4(b) shows the WA17 with both armature coils and FECs are set to alternate configuration.

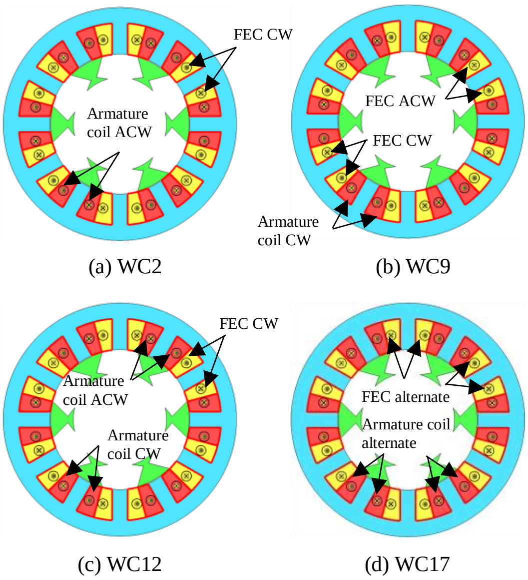


Fig. 4: Four samples of winding configurations, (a) all armatures ACW, all FECs CW, (b) all armatures CW, 3 FECs CW 3 FECs ACW, (c) 3 armatures CW 3 armature ACW, all FECs CW, (d) armatures alternate, FECs alternate.

Table 3: Summary of Sinusoidal Result s of WA

Windings Arrangements	Armature flux linkage	
	Phase	Sinusoidal
WA1	Different phase	Invalid
WA2	Single phase	Invalid
WA3	Single phase	Invalid
WA4	Different phase	Invalid
WA5	Different phase	Invalid
WA6	Different phase	Invalid
WA7	Different phase	Invalid
WA8	Different phase	Invalid
WA9	Different phase	Invalid
WA10	Different phase	Invalid
WA11	Different phase	Invalid
WA12	Different phase	Invalid
WA13	Different phase	Invalid
WA14	Different phase	Invalid
WA15	Different phase	Invalid
WA16	Different phase	Invalid
WA17	Single phase	Valid

Table 3 shows the summary of sinusoidal armature flux linkage result of 17 WAs. Obviously, it can be seen that non-overlap windings with alternate WA between armature coils and FECs have produced 6 sinusoidal armature flux in the same phase.

4.2. Coil Test

The proposed single-phase FEFSM using segmental rotor operating principle is proved by coil test on both armature and FECs where it meets the standard of phase difference 90°. The magnetic flux characteristics of the proposed single-phase 12S-6P FEFSM using segmental rotor is depicted in Fig. 5, at the point when armature coil current density, J_A and FEC current density, J_E are set to maximum of 30 A_{rms}/mm^2 and 30 A/mm^2, respectively. The graph shows that the flux linkage at highest J_A is 0.0718 Wb, 39.4% higher than magnetic flux at maximum J_E of 0.0435 Wb. This is comprehensible that J_E flux linkage generated from DC source (FEC) will move around the stator and rotor before reaching the armature windings. The flux linkage of FEC lead 90° of armature coil flux linkage for maximum torque production. However, the magnetics flux profile at J_A only shows unbalance between positive and negative cycles due to the high flux leakage occurs when magnetics flux flows from stator to rotor as illustrated in Fig. 6. The resulting magnetic flux of 0.074 Wb at maximum J_E and J_A conditions, proves the interaction and addition of both magnetic flux sources.

4.3. Flux Strengthening and back-EMF

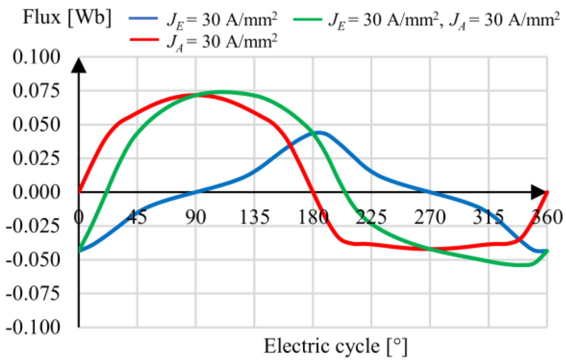


Fig. 5: Coil test of FEFSM using segmental rotor.

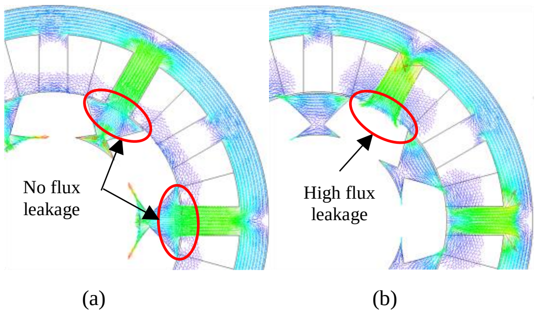


Fig. 6: (a) Rotor at 90 degrees, (b) rotor at 270 degrees.

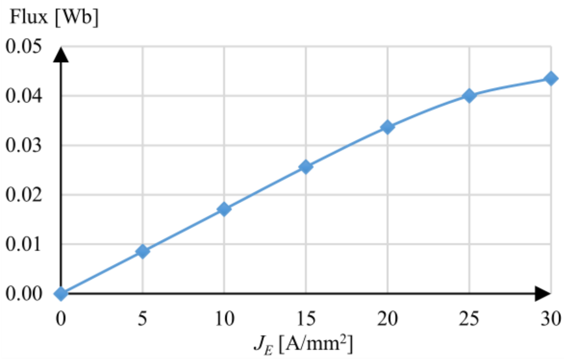


Fig. 7: Flux strengthening of FEFSM using segmental rotor.

The proposed motors have the privilege of being able to control the flux by diversifying the value of the incoming DC supply into the FEC windings. Thus, to examine the flux flexibility, J_E is varied from 0 A/mm^2 to 30 A/mm^2, and J_A is set to 0 A_{rms}/mm^2. The input current of FEC, I_E value is calculates based on (1) while Fig. 7 shows maximum flux linkage at J_E 0 to 30 A/mm^2. Obviously, from the figure flux is increased linearly until the maximum of 0.0435 Wb at J_E of 30 A/mm^2 and prove the coil test analysis. High odd harmonic, especially on the third and fifth harmonic causes the back-EMF profile to be disrupted as illustrated in Fig. 8. The highest amplitude of the back-EMF is recorded at 13.4 V.

$$I_E = (J_E \alpha S_E)/N_E \quad (1)$$

Where,

I_E	=	FEC Input current
J_E	=	FEC current density
α	=	Filling factor (set to 0.5)
N_E	=	FEC winding
S_E	=	Area of FEC slot

4.4. Flux Lines

The flux line formed by FECs excitation with the maximum J_E of 30 A/mm^2 at 0° or 360°, 90°, 180°, and 270° electric cycle are illustrated in Fig. 9. Flux focused at the red circles in Fig. 9(b) and Fig. 9(d) because the flux cannot flow perfectly to form a full cycle which results in high flux density in the area. The proposed FEFSMs have a short flux path because a complete cycle of flux is connected with two adjacent stator teeth through one segment rotor tooth as illustrated in Fig. 9(a) and 9(c).

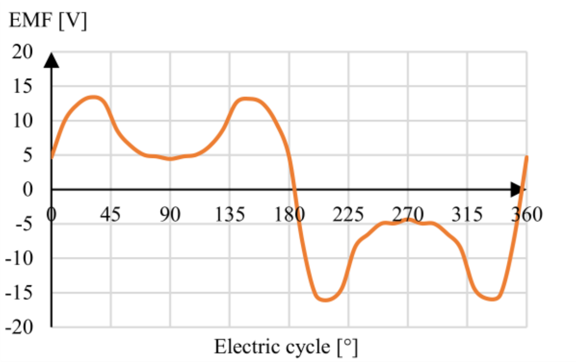
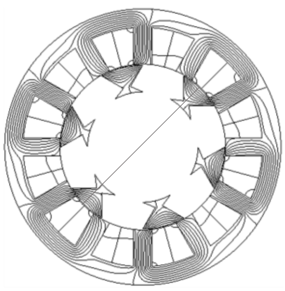
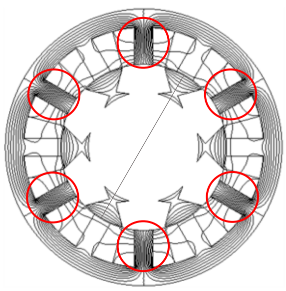


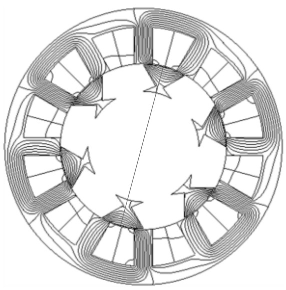
Fig. 8: Back-EMF of FEFSM using segmental rotor.



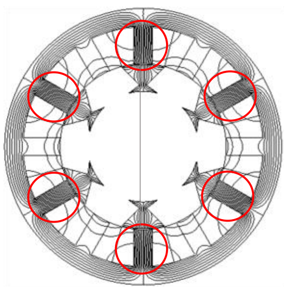
(a) At 0° and 360° electric cycle



(b) At 90° electric cycle



(c) At 180° electric cycle



(d) At 270° electric cycle

Fig. 9: Magnetic flux when J_E=30 A/mm^2 and J_A=0 A_{rms}/mm^2.

4.5. Torque at various J_A and J_E

The torque versus J_E at various J_A characteristics are plotted in Fig. 10. Clearly, from the plots the highest torque of 0.91 Nm is achieved when the J_A and J_E are set to 30 A_{rms}/mm^2 and 30 A/mm^2, respectively. From the Fig. 10, torque characteristics are increased gradually with the increase of J_A and J_E. At J_A is 5 A_{rms}/mm^2 and 10 A_{rms}/mm^2, the torque becomes constant when the J_E is high, while at high J_A, the torque keeps increasing until the optimum torque is achieved.

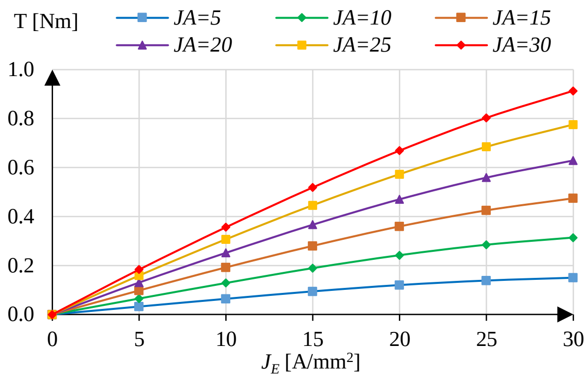


Fig. 10: Torque characteristics of FEFSM using segmental rotor.

5. Conclusion

In conclusion, a new structure of single-phase 12S-6P FEFSM using segmental rotor with non-overlap windings has been presented. The procedure to design the FEFSMs has been clearly explained. The analyses of the FEFSMs such as winding arrangement test, coil test, flux strengthening, back-EMF, flux line and torque versus J_A at various J_E characteristics have been investigated. Based on 2D FEA, the best WA is non-overlap windings with armature coils and FECs are set to alternate configuration. Besides, the proposed FEFSM has a short flux, high flux and good torque characteristics. However, the single-phase FEFSM with segmental rotor can be further improved in future in terms of back-EMF and flux linkage by design refinement and optimization.

Acknowledgement

This work funded by Research, Innovation, Commercialization, Consultancy Office (ORICC), Universiti Tun Hussein Onn Malaysia (UTHM) with Vot No FRGS 1651, and Ministry of Education Malaysia (MOE).

References

[1] Sulaiman E, Kosaka, T, Matsui N. “High power density design of 6slot-8pole hybrid excitation flux switching machine for hybrid electric vehicles”, *IEEE Trans. on Magn*, Oct. 2011, vol.47, no.10 pp. 4453-4456.

[2] Sulaiman E, Kosaka T, Matsui N. “Design optimization and performance of a novel 6-slot 5-pole PMFSM with hybrid excitation for hybrid electric vehicle”, *IEEJ Trans. Ind. Appl*., 2012, vol.132, no.2, sec.D, pp.211-218.

[3] E. Sulaiman, M. Z. Ahmad, T. Kosaka, and N. Matsui, “Design Optimization Studies on High Torque and High Power Density Hybrid Excitation Flux Switching Motor for HEV”, *Procedia Engineering*, Mar 2013, Vol. 53, pp. 312–322.

[4] E. Sulaiman, M. F. M. Teridi, Z. A. Husin, M. Z. Ahmad, and T. Kosaka, "Performance comparison of 24S-10P and 24S-14P field excitation flux switching machine with single DC-coil polarity" *IEEE Int. Power Engineering and Optimization Conference*, June 2013, pp.46-51.

[5] J. H. Walker, "The theory of the inductor alternator," *J. IEE*, June 1942, vol.89, no.9, pp.227–241.

[6] T. J. E. Miller, "Switched Reluctance Machines and Their Control", Hillsboro, OH: *Magna Physics*, 1993.

[7] C. Yu, S. Niu, S. L. Ho and W. N. Fu, "Design and Analysis of a Magnetless Double-Rotor Flux Switching Motor for Low Cost Application," *IEEE Trans. Magn.*, vol. 50, no. 11, pp. 1-4, Nov. 2014.

[8] S. M. Yang, J. H. Zhang and J. Y. Jiang, "Modeling Torque Characteristics and Maximum Torque Control of a Three-Phase, DC-Excited Flux-Switching Machine," *IEEE Trans. Magn.*, vol. 52, no. 7, pp. 1-4, July 2016.

[9] H. Q. Nguyen, J. Y. Jiang and S. M. Yang, "Design of a 12-slot 7-pole wound-field flux switching motor for traction applications," *2016 IEEE Int. Conf. on Industrial Technology (ICIT)*, Taipei, 2016, pp. 1275-1280.

[10] E. Sulaiman, M. F. M. Teridi, Z. A. Husin, M. Z. Ahmad, and T. Kosaka, "Performance Comparison of 24S-10P and 24S-14P Field Excitation Flux Switching Machine with Single DC-Coil Polarity," *IEEE 7th International Power Engineering and Optimization Conference (PEOCO),* Langkawi, 2013, pp. 46-51.

[11] Y. J. Zho and Z. Q. Zhu, "Comparison of low-cost single phase wound-field switched-flux machines," *IEEE Trans. Ind. Appl.*, vol. 50, no. 5, pp. 3335-3345, Sept.-Oct. 2014.