Development of Single Phase FEFSM and its Excitation Circuit for Evaluating the Control Algorithm

F. Amin, E. Sulaiman, W.M. Utomo, H. Soomro, F. Omar and R. Kumar
Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia,
Parit Raja, Batu Pahat, 86400 Johor, Malaysia.
faisalamin1303@gmail.com

***Abstract*—Popularity of Field Excitation Flux Switching Motors (FEFSMs) has been significantly increased in modern high-speed applications due to their features such as variable flux control and the rotor structure which is free from any magnet and windings. However, most of the FEFSM structure is comprising of overlapped windings between the armature and field teeth which ends up in taking more space, more copper losses and increasing material costs as well. This paper emphasis on a particular structure of single phase FEFSM having a segmented rotor and non-overlapped stator windings. This structure offered more efficiency and eliminated all the drawbacks mentioned above of having overlapped windings. Design of this new topology and its characteristics such as speed, torque, and power has been analyzed through a 2D Finite Element Analysis (FEA) using JMAG Designer. The proposed FEFSM shows drastic improvements in terms of flux production, torque and power performances in contrast with FEFSM with salient rotor structure. Furthermore, a very efficient control strategy is proposed for this new FSM topology. Since existing technics require high-end DSPs and expensive sensors, however, the proposed strategy can be implemented in any 8-bit microcontroller and only need Infrared transceiver sensor, which is more appropriate for developing a low-cost drive for house hold applications.**

***Index Terms*—FEFSM; Segmental Rotor; FSM Drive; Control Strategy**

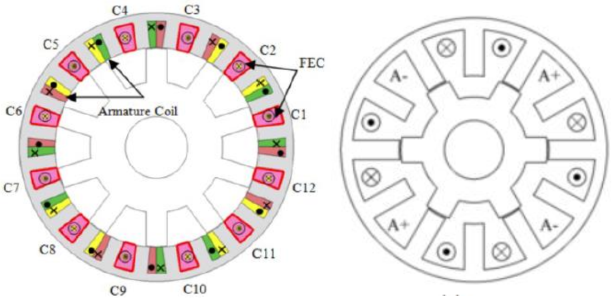
I. INTRODUCTION

The AC machine commonly consists of two fundamental components, an external stationary part called stator, and an internal part called rotor usually attach to the output shaft. There are three common structures of AC machines: synchronous machine (SM), asynchronous or induction machine (IM) and switch reluctance machine (SRM). The synchronous machine is further categorized into permanent magnet SM (PMSM), field excitation SM (FESM), hybrid excitation SM (HESM) and flux switching machines (FSM) [1].

The design principles of FSM were first introduced in 1955, and over the years it became famous among researchers to carry out research on FSM [2]-[6]. FSM are double salient structured brushless machine having all the excitation sources (armature windings and permanent magnet or field windings) built on the stator, leaving the rotor structure simple and robust [7] FSM structure is inspired from inductor alternator and SRM and can be subdivided into Field excitation FSM (FEFSM), Permanent magnet FSM (PMFSM), and Hybrid excitation FSM (HEFSM) [8], [9]. Due to concern about the cost and supply of rare earth PM, the FEFSM are presently under extensive examination.

Referring to previous topologies, the overlapped armature and field windings give significant impact on the expansion of motor size due to high copper consumption and reduction of efficiency due to higher copper losses. Besides, a considerable distance between rotor poles is found to lead an extended magnetic flux path flowing from stator to the rotor and vice versa, producing a weak flux linkage as well as a low torque performance [10], [1]. By considering these issues, the non-overlap structure is preferred for this research, which significantly improved the performance in terms of flux linkage and torque performance.

Based on the existing literature of FEFSM, three-phase FEFSM is considered suitable for industrial applications which require high torque and power [11]-[12]. On the contrary, Single phase FSM structure suits better for general house hold applications. Figure 1(a) and 1(b) shows the example of three phase FEFSM and single-phase FEFSM, respectively [13].



(a) (b)

Figure 1: (a) Example of 3-Phase FEFSM 12S-10P non-segmental rotor. (b) Example of Single Phase FEFSM with overlap windings 12S-6P

In this paper, a new topology of single-phase 12S-6P FEFSM is introducing having a segmental rotor and non-overlap windings. A noticeable factor to be considered in the proposed design is the shorter magnetics flux line which results in increasing magnetic flux linkage and reducing the flux leakage. Dramatic improvements in torque and power have been seen. Through 2D-FEA of JMAG Designer 14.1, characteristics of the proposed motor such as flux, torque, power, and speed have been analysed.

In this paper, an effective yet simple control strategy is also presented as well which can be easily implemented in any Digital signal processors and even in low cost microcontrollers too. For exciting the single phase FEFSM, a hardware setup is also demonstrated in terms of a block diagram. Oscilloscope readings for observing the relation among inverter signals and motor performance are also discussed.

II. METHODOLOGY

A. *Design Methodology and Specification Parameters of FEFSM with Segmental Rotor*

In Table 1, design restrictions, specifications, and parameters of the proposed single phase 12S-6P FEFSM with segmental rotor are listed. Maximum current density limit for both FEC and armature windings is set to 30Arms/mm2 [13]. The machine structure and windings configuration for the proposed FEFSM are illustrated in figure 2.

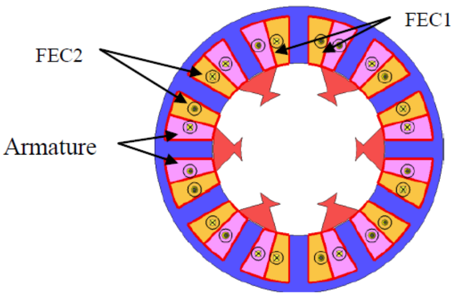


Figure 2: Single Phase 12S-6P FEFSM with the segmental rotor

According to figure 2, both FEC and armature coil are wounded in non-overlap fashion. Commercial FEA package, JMAG-Designer ver. 13.1, by the Japan Research Institute (JRI) is used as a solvent for this design. In the first stage, stator, rotor, FEC and armature coil of the proposed 12S-6P FEFSM were designed using Geometry Editor. Then the second stage was to setup of materials, circuits, condition, and properties of the design topology in JMAG. The electrical steel 35H210 is used for rotor and stator body. Moreover, coil arrangement tests are examined to certify the operating principle of the machine and to situate the position of each armature coil phase. [13]

Table 1
Design Restrictions, Specifications and Parameters for 12S-6P FEFSM

Symbol	12S-6P FEFSM with Segmental
Number of phases	1
Nmber of slots	12
Number of poles	6
Stator outer radius (mm)	75
Stator inner radius (mm)	70
Stator back inner width (mm)	5
Stator tooth width (mm)	10
Armature coil slot area (mm2)	251
FEC slot area (mm2	251
Rotor outer radius (mm)	44.5
Rotor inner radius (mm)	30
Rotor pole radius (mm)	33.5
Rotor tooth width (mm)	23
Rotor shaft	30
Air gap length (mm)	0.5
Number of turns per field tooth coil (FEC)	75
Number of turns per armature coil slot (AC)	11

B. *Methodology for Developing Control Strategy and Hardware for Operating FEFSM:*

Figure 3 illustrates the general flow of the methodology that we are followed to fulfill the objectives of this research. In the initial phase, the working principle of single phase FEFSM has been identified and then its control mechanism has been developed. During Second phase, the hardware including an inverter circuit, gate drivers, sensor circuitry has been developed then interfaced them with the DSP. During the third phase, several algorithms have been designed for the startup process of FEFSM and tested the codes with the prototype motor. In the fourth phase, algorithms and programs will be designed for controlling the speed of the motor then optimize its performance.

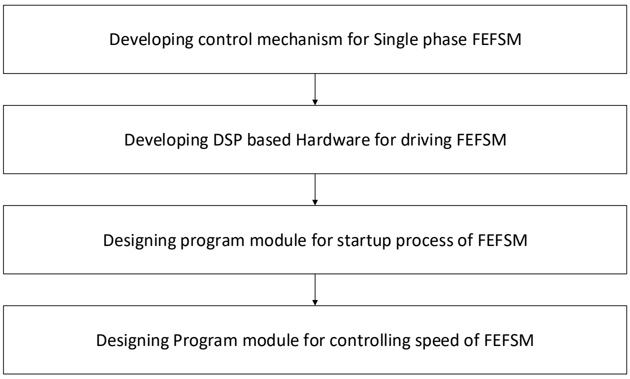
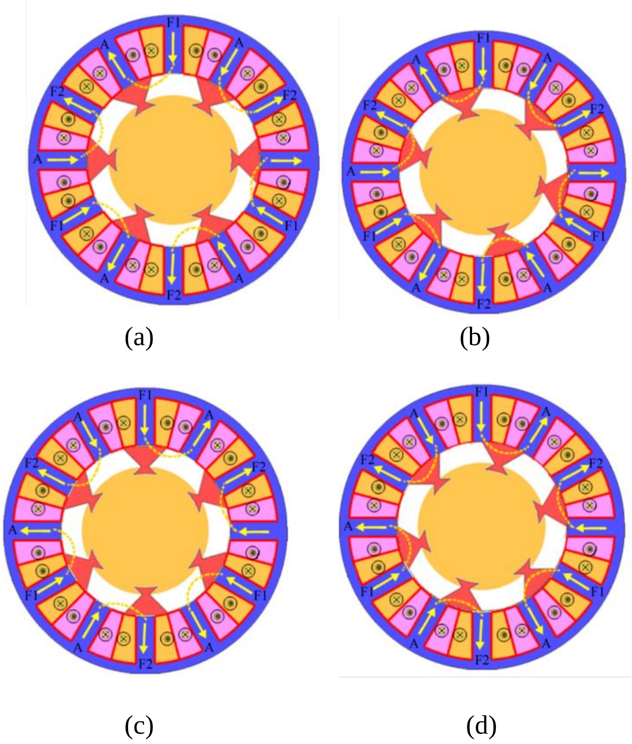


Figure 3: General Flow of the Methodology for FEFSM drive

C. *Proposed Control Strategy of Single Phase FEFSM*

The fundamental strategy of the proposed control mechanism is to change the polarity of the armature coils whenever rotor teeth align with specific stator teeth, which include both field and armature windings. In this way flux due to mutual induction switches to the next stator teeth pair and attract the rotor teeth towards it, i.e., torque generates and continuous rotation of rotor occurs. According to the example of figure 5, we want to rotate the motor in a clockwise direction. Initially, rotor coils are set to align with field coils then the controller will switch the armature coils flux in the opposite direction as compared to the field coils shown in figure 4(a). Rotor teeth rotate in a clockwise direction until they align with the air gap between field and armature to strengthen the mutual induction between them as shown in figure 4(b), Due to inertia rotor will rotate further. When rotor become align with the next stator teeth that are, with the armature teeth, the controller again will switch the armature flux direction; Now armature coils are mutually inducted with the field coil on the other side as shown in figure 4(c). Rotor again rotates clockwise to strengthen the mutual induction, and this process continues [14]-[15].



(a) (b)

(c) (d)

Figure 4: Driving Principle of Single Phase FEFSM

D. Developing DSP based Hardware for Drving FEFSM

According to figure 5, single phase FEFSM need DC voltage for exciting field coils and variable frequency AC voltage for armature coils. Because of this 220V, AC should be converted into DC voltage of the same rating through a converter circuit. Furthermore, DC voltage should be shifted down to 5 voltages to power DSP. Controller gets rotor position feedback from an optical position sensor. Variable frequency AC voltage for the armature coil is generated by single phase inverter circuit, Variable DC voltage for field coil is generated by the field driver circuit. Both of them are controlled by DSP.

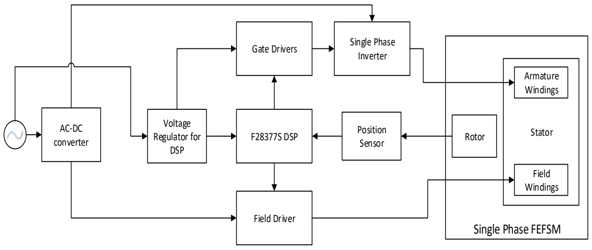


Figure 5: Block Diagram of FEFSM drive hardware

E. Flow Chart of Control Algorithm for Driving FEFSM

Flow chart of figure 6 represents the algorithm for driving single phase FEFSM with the segmental rotor. This algorithm is based on the proposed control strategy of figure 5.

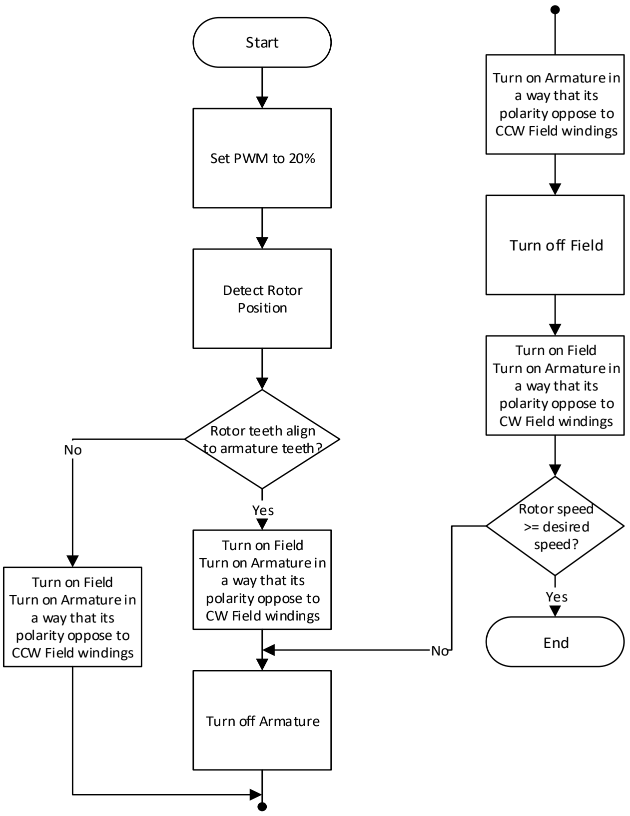


Figure 6: Flow chart of the control algorithm of Single phase FEFSM with the segmental rotor

III. RESULTS

A. Result and Performance of 12S-6P FEFSM based on 2D Finite Element Analysis (2D-FEA)

1. Flux Strengthening

To analyze flux strengthening and weakening effect, the armature current density (JA) is set to 0 Arms/mm2, and FEC coil current density (J_E) is set between 0A/mm2 to 30A/mm2. The number of turns of FEC (N_E) and magnitude of FEC input current (A_E) was calculated using Equation (1) and Equation (2). Figure 7 shows maximum flux value at different FEC current densities (J_E). Analyzing the plot pattern, initially, flux increases linearly and then after J_E equal to 10A/mm2; it constantly decreases because opposite flow of flux inside the motor make flux cancels each other

$$N_E = \frac{J_E \alpha_E S_E}{A_E} \tag{1}$$

where;
AE = Input current FEC (Max. 50A)
JE = FEC current density (Max. 30A/mm2)
αE = FEC filling factor (set to 0.5)
NE = FE Coil turn
SE =Slot area of FEC

$$A_E = \frac{J_E \alpha_E S_E}{N_E} \tag{2}$$

where;
A_E = Input current FEC
J_E = FEC current density (Max. 30A/mm$_2$)
α_E = FE coil filling factor (set to 0.5)

2. *Torque versus FEC Current Density (J_E) at Various Armature Current Density (J_A)*

Figure 8 illustrates the plot of torque versus FEC current density (J_E) at various armature current densities (J_A). Increasing of armature and FEC current densities simultaneously, torque increases. However, at J_A is equal to 5Arms/mm2 and 10Arms/mm2 torque decrease in the condition when J_E is higher than 10Arms/mm2 because J_E cancels the total flux as proven by flux strengthening test. At armature current is equal to 30Arms/mm2, there is a linear increment of torque can be observed with the increment of FEC current (J_E) until we get the maximum torque which is 16.6Nm.

3. *Power and Torque versus Speed*

Figure 9 shows the characteristic curve of power and torque against speed. At the base speed of 4977r/min and 16.6Nm torque value, power rises to 8.66kW. Maximum power achieved is 10.74kW, which is obtained at 9782 r/min speed. Up to base speed, torque is maximum and linear, then decrement of torque is observed with the increment of speed after 5000r/min. From the figure, power is almost directly proportional to speed until 10000 r/min. After that slight reduction of power is observed at above speed.

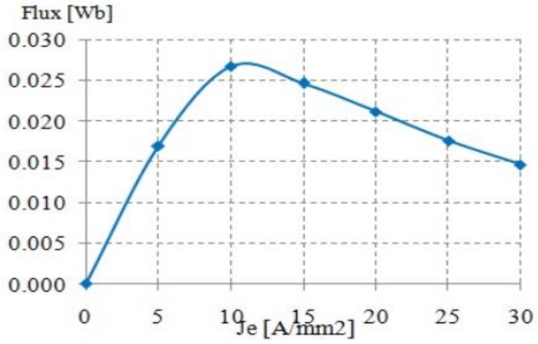


Figure 7: Flux Strengthening and Weakening

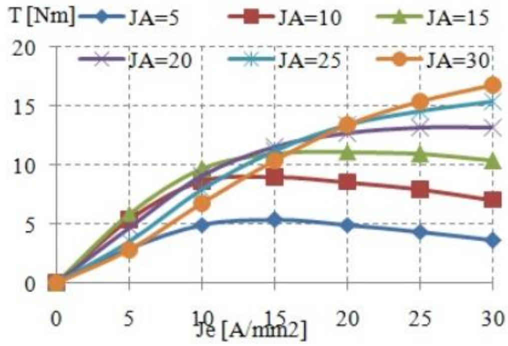


Figure 8: Torque vs J_E at various J_A

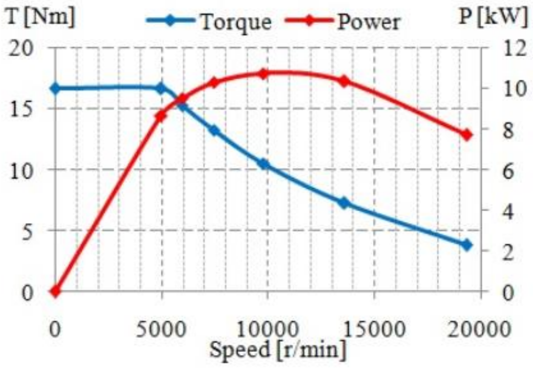


Figure 9: Torque and Power versus Speed Characteristics

B. *Hardware Setup for Drive System*

Hardware modules such as IR transceiver circuit, single phase inverter, field controller, gate drivers for the inverter and for field control has been designed and simulated in Proteus software. Figure 10 illustrates the complete hardware setup for driving FEFSM.

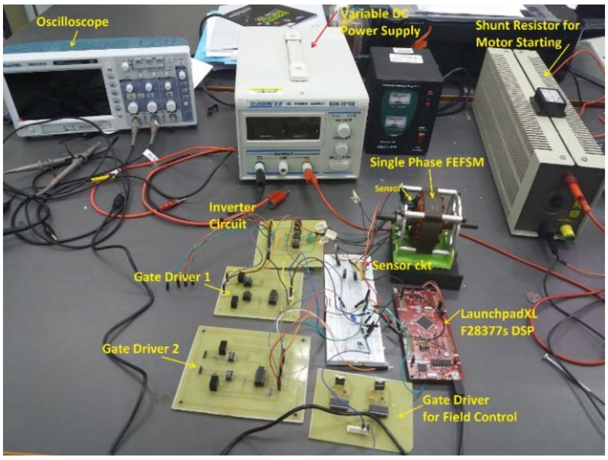


Figure 10: Hardware setup for Single Phase FEFSM Drive

C. *Oscilloscope Reading for Comparing Motor Phase Voltage and Sensor Value*

Figure11 shows motor voltage reading in the response of the sensor. Motor gets positive voltage when the rotor aligns with the field and gets positive voltage when the rotor aligns with armature as indicated in the secondary start up mode flow chart.

Figure 11: Motor voltage reading in the response of the sensor

IV. CONCLUSION

In this paper, the design of 12S-6P FEFSM with non-overlapped winding and the segmental rotor has been investigated. The specifications and machine configuration of the proposed topology explained clearly. The performance characteristics of the structure such as torque, speed, and power have been investigated. The rotor configuration is the simplest one as compared to conventional motors which generally have PM built on the rotor body. So this FEFSM can be expected to be a very low cost machine.

Finally, the proposed algorithm for exciting and operating the prototype motor is verified through developing DSP based drive system. The performance of motor and the drive is quite satisfactory, but performance can be drastically improved by applying sine wave pwm signals and detecting the absolute angular position of the rotor.

ACKNOWLEDGMENT

This work was supported by FRGS (Vot 1508) under Ministry of Education Malaysia, and ORICC Research Fund (Vot U632), University Tun Hussein Onn Malaysia (UTHM), Batu Pahat, Johor, Malaysia.

REFERENCES

[1] Omar, M. F., Sulaiman, E., Khan, F., Romalan, G. M., & Hassan, M. K. (2015, October). Performances comparison of various design slot pole of Field Excitation Flux Switching Machines with segmental rotor. In Energy Conversion (CENCON), 2015 IEEE Conference on (pp. 320-324). IEEE.

[2] S. E. Rauch and L. J. Johnson, “Design principles of flux-switching alternators,” AIEE Trans. 74III, pp. 1261-1268, 1955.

[3] H. Pollock, C. Pollock, R. T. Walter, and B. V. Gorti, “Low cost, high

[4] power density, flux switching machines and drives for power tools,” in Conf. Rec. IEEE IAS Annu. Meeting, 2003, pp. 1451–1457.

[5] C. Pollock, H. Pollock, R. Barron, J. R. Coles, D. Moule, A. Court, and R. Sutton, “Flux-switching motors for automotive applications,” IEEE Trans. Ind. Appl., vol. 42, no. 5, pp. 1177–1184, Sep./Oct. 2006.

[6] Y. J. Zho, and Z. Q. Zhu “Comparison of low-cost single-phase woundfield switched-flux machines” Electric Machines & Drives Conference

[7] S. E. Rauch and L. J. Johnson, “Design principles of flux-switching alternators,” AIEE Trans. 74III, pp. 1261-1268, 1955.s. O. Young, “Synthetic structure.

[8] J. H. Walker, “The theory of the inductor alternator,” J. IEE, vol.89, no.9, June 1942, pp.227-241.

[9] T. J. E. Miller, “Switched Reluctance Machines and Their Control”, Hillsboro, OH: Magna Physics, 1993.

[10] Omar, M. F., E. Sulaiman, M. Ahmad, M. Jenal, and G. M. Romalan. "Magnetic flux analysis of a new Field Excitation Flux Switching Motor with segmental rotor." (INTERMAG), 2017 IEEE International, pp. 1-1, 2017.

[11] Kannan, S., "Novel rotor and stator swapped switched reluctance motor", Power Electronics, Drives and Energy Systems (PEDES), 2012 IEEE International Conference on , vol., no., pp.1,4, 16

[12] Sulaiman, E.; Teridi, M.F.M.; Husin, Z.A; Ahmad, M.Z.; Kosaka, T., "Performance comparison of 24S-10P and 24S-14P field excitation flux switching machine with single DC-Coil polarity," Power Engineering and Optimization Conference (PEOCO), 2013 IEEE 7th International , vol., no., pp.46,51, 3-4 June 2013

[13] Omar, M.F., Sulaiman, E. and Soomro, H.A., 2015. New topology of single-phase field excitation flux switching machine for high density air-condition with segmental rotor. Applied Mechanics and Materials, 695, pp.783-786.

[14] Pollock, C., H. Pollock, and M. Brackley. "Electronically controlled flux switching motors: A comparison with an induction motor driving an axial fan." In Industrial Electronics Society, 2003. IECON'03. The 29th Annual Conference of the IEEE, vol. 3, pp. 2465-2470. IEEE, 2003.

[15] Gorti, B., Black & Decker Inc., 2005. Excitation circuit and control method for flux switching motor. U.S. Patent 6,943,510.