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Investigation of Field Excitation Switched Flux Motor with Segmental Rotor

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***Abstract*— In this paper a three-phase field excitation switched flux (FESF) motor where both field excitation (FE) coil and armature coil placed on the stator is investigated. The rotor is design with separately segmental pole so that flux generated from FE Coil can be fundamentally placed in adjacent with flux of armature coil. Thus, the coil end length of both FE Coil and armature coil are reduced, hence increasing the motor efficiency when compared with FESF motor with single piece rotor, and overlapped FE Coil and armature coil windings. In this paper design investigation and analysis of 12S-8P and 24S-10P FESF motor with segmental rotor are investigated. Moreover, coil test analysis, FE Coil flux characteristics, flux interaction between FE Coil and armature coil, flux distribution, and torque characteristics are also compared. As conclusion, the 24S-10P FESF motor with segmental rotor gives much higher performance when compared with 12S-8P FESF motor.**

***Index Terms*—Field excitation switched flux motor (FESFM), field excitation (FE) coil, segmental rotor, flux, torque.**

I. INTRODUCTION

In recent years, a new machine namely Flux switching machine (FSM) has been developed that consist of all flux sources in the stator. Beside the advantage of brushless machine, it has single piece iron rotor structure which is robust, can be used for high speed applications and total control is maintained over the field flux. They can be further classified into three groups that are (i) permanent magnet (PM) FSM, (ii) field excitation (FE) FSM, and (iii) hybrid excitation (HE) FSM. Main flux sources are only PM in PMFSM and field excitation (FE) coil in FESF motor while HEFSM combines both PM and FE Coils [1-3].

In the mid 1950s, the word flux switching machine (FSM) has been originated from different theories and printed. A permanent magnet (PM) FSM i.e. permanent magnet single-phase limited angle actuator or more well-known as has been developed [4], and it has been modified to a single phase generator with four stator slots, and four or six rotor poles (4S-4/6P) [5]. In the last decade, new FSMs topologies have been built up for different applications, ranging from low cost domestic appliances, automotive, wind power, and aerospace, etc. When compare with other FSMs, the FESF motor has advantages of low cost, magnet-less machine, simple construction, and variable flux control capabilities suitable for various performances. Furthermore, to manufacture the FESF motors, the PM on the stator of conventional PMFSMs is replaced by DC FE Coil as illustrated in Fig. 1. In other words, the FESF motors having salient-rotor structure is a novel topology, merging the principles of the inductor generator and the SRMs [6-7].

The notion of the FESF motor is based on switching the polarity of the flux linking with the armature coil windings, following the rotor position. Fig. 2 shows an example of single-phase 4S-2P FESF motor that employs with a DC FE Coil on the stator, a toothed-rotor structure and fully-pitched windings on the stator [8]. From the figure, it is obvious that both armature coil and FE Coil windings are placed in the stator which overlapped each other. The feasibility of this design has been verified in different applications requiring high power densities with a good level of durability [9-10]. The originality of this design is that the single-phase ac arrangement might be realized in the armature windings by use of DC FE Coil and armature winding, to provide the required flux orientation for rotation. Variable mutual inductance of windings helps in generating the required torque. The single-phase FESF motor coupled with a power electronic controller is machine, easy to manufacture, and having the advantage of extremely low-priced machine in high volume applications. Moreover, being an electronically commutated brushless machine, it has longer life, very flexible and accurate control of torque, speed, and position at no extra cost as compare to other machines.

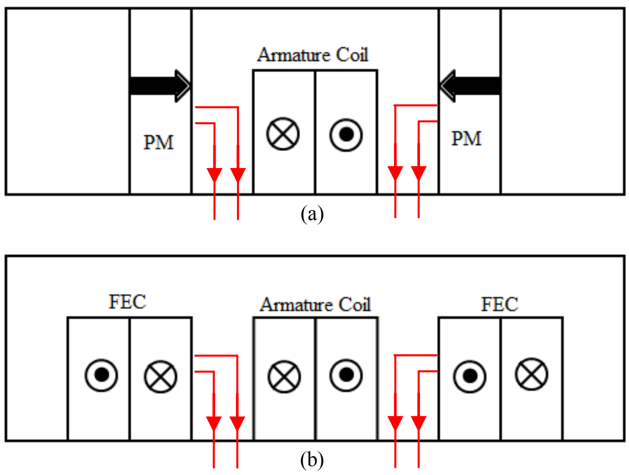


Fig. 1. PMFSM to FESF motor (a) PMFSM (b) FESF motor

Eight stator slots and four rotor poles FESF motor is shown in Fig.3 [11].It is clear from the figure that four pole magnetic field is established when direct current is applied to the FE Coil winding in four of the slots. The other four slots hold an armature winding that also pitched over two stator teeth. A set of four stator poles carrying flux and the position of the rotor is decided by direction of the current in the armature winding. As the FE Coil is excited by current having single polarity, it will have direct connection either in parallel or in series with the dc-supply of power converter which supplies the bipolar current into the armature winding. The design theory is explained in [12], and when single-phase and induction machine (IM) are compared, 8S-4P FESF motor has higher output power density and efficiency. However, the 1-phase FESF motors have certain major problems such that low starting torque, fixed rotating direction, large torque ripple, and overlapped windings between armature coil and FE Coil.

To achieve the desire performances, a three-phase 24S-10P FESF motor have been developed from the 24S-10P PMFSM in which the PM is replaced by FE Coil at the stator and FE Coil winding are placed at the upper half layer of armature coil slots as shown in Fig. 4[13]. 24S-10P PMFSM has alternate flux polarities from nearby PM while the FE Coil in this proposed machine is set with a single polarity of DC current source. The total flux generation is limited due to adjacent DC FE Coil isolation and thus affecting the performances of machine. Several structures and performances of FESF motor for various applications have also been reported in [14-15].

To overcome the drawbacks, a new structure of 24S-10P and 24S-14P FESF motor with single DC polarity have been introduced and compared as depicted in Fig. 5 [16]. A single polarity of DC current source is set for DC FE Coil of the FESF motors. Uncomplicated manufacturing of single DC FE Coil windings, low copper loss due to less volume of FE Coil, less flux leakage are the main advantages of proposed machine when compared with dual FE Coil adjacent windings, and has freedom of FE Coil design for different performances.

Since all FESF motor discussed above posses an overlapped winding between DC FE Coil and armature coils that cause higher coil end length, a 12S-8P FESF motor with adjacent DC FE Coil and armature coils and segmental rotor has been proposed as illustrated in Fig. 6 [17]. Segmental rotor has the ability to provide magnetic path for transmitting the field flux to nearby stator armature coil with respect to rotor position. This design presents shorter end windings with non overlapping coil when compares to salient rotor arrangement having overlapping coils. It has considerable gains due to the reason that it utilizes less conductor materials and has further improvement in overall machine efficiency [18-19].

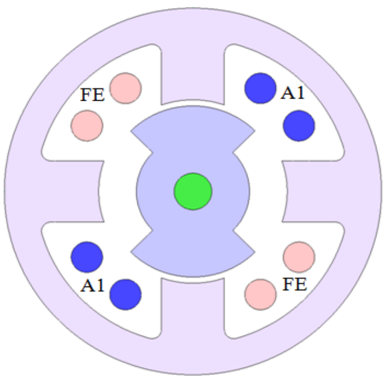


Fig. 2. 1-phase 4S-2P FESF motor

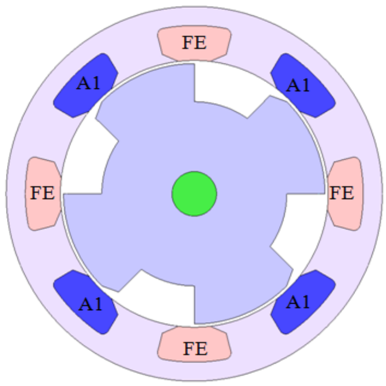


Fig. 3. 1-phase 8S-4P FESF motor

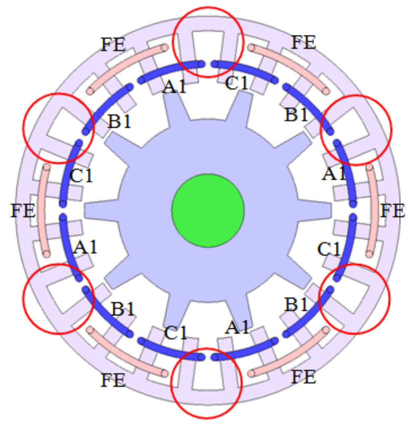


Fig. 4. 3-phase 24S-10P FESF motor

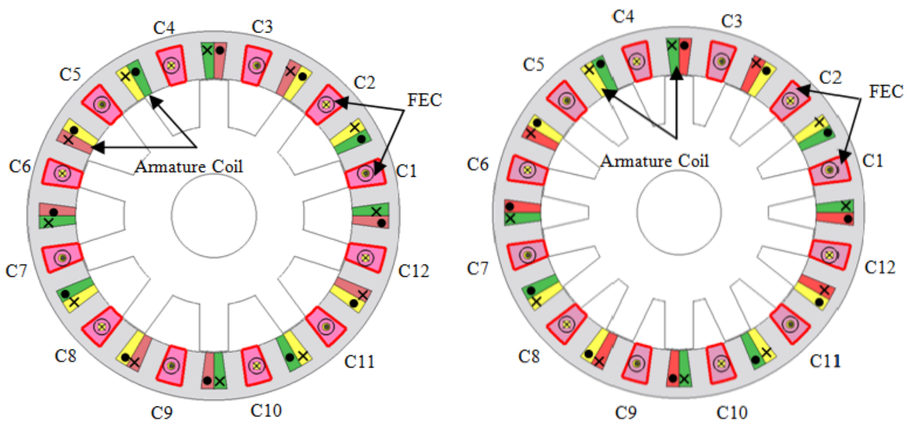


Fig. 5. FESF motor with single DC FE Coil polarity (a) 24S-10P (b) 24S-14P

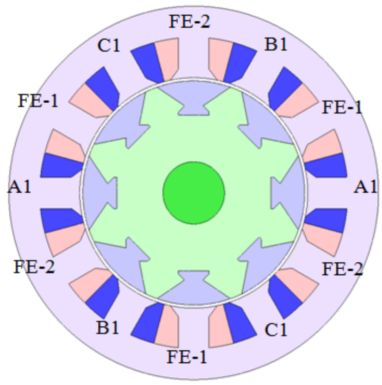
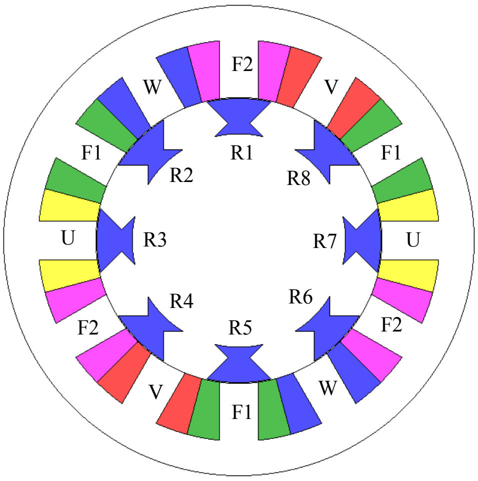


Fig. 6. 3-phase 12S-8P segmental rotor

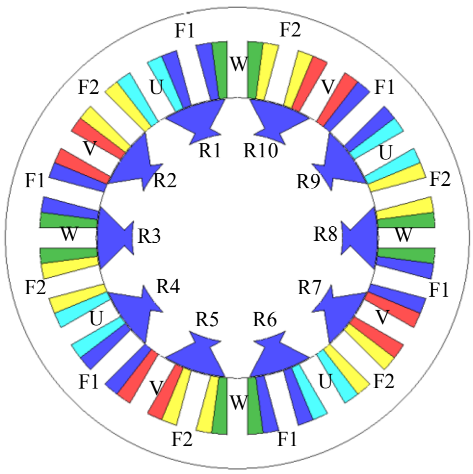
This paper presents a design study and performance analysis of 12S-8P and 24S-10P FESF motor with segmental rotor are investigated. Furthermore, coil arrangement test, FE Coil flux linkages at various FE Coil current densities characteristics, flux interaction of FE Coil and armature coil, flux distribution and torque profiles are also examined.

II. Design Specifications & Limitations

The design specifications and limitations of the proposed FESF motor with segmental rotor are given in Table I, while the cross sectional views of 12S-8P and 24S-10P FESF motor with segmental rotor are illustrated in Fig. 7, correspondingly. From the figure, it is understandable that the 12S-8P FESF motor is having 12 stator teeth, 6 armature coil slots, 6 DC FE coil slots and 8 segmental rotor poles, while the 24S-10P FESF motor is having 24 stator teeth, 12 armature coil slots, 12 FE coil slots and 10 segmental rotor poles, respectively. The DC FE Coil is wound in anti-clockwise polarity, whereas the three phase armature coils are located among them. It is obvious that, both DC FE Coil and armature coil are wounded separately at their own slots with non-overlapped windings. Thus the design proves much shorter end windings and less conductor materials that can improve the machine efficiency.



(a)



(b)

Fig. 7. FESF motor with segmental rotor (a) 12S-8P (b) 24S-10P

TABLE I. Design Specifications & Limitations of FESF Motor with Segmental Rotor

Parameters	**12S-8P**	**24S-10P**
Number of phase	3	3
No of poles	8	10
Stator outer diameter (mm)	150	150
Stator back iron depth (mm)	11	11
Stator tooth width (mm)	12.5	6.25
Rotor diameter (mm)	90.6	90.6
Core axial length (mm)	150	150
Air gap length (mm)	0.3	0.3
Number of turns per FE Coil slot	44	22
Number of turns per armature coil slot	44	22

Commercial FEA package, JMAG-Designer ver.12.0, released by Japan Research Institute (JRI) is used as 2D-FEA solver for this design. Firstly, all parts such as rotor, stator, armature coil and DC FE Coil slots of the 12S-8P and 24S-10P FESF motor are sketched using JMAG Editor. Then, JMAG Designer is used to set the materials, conditions, circuits and properties of the machine. Then, coil arrangement tests are performed to confirm that how the machine operate and to set the position of each armature coil phase.

The operating principle of the FESF motor with segmental rotor is shown in Fig. 8 where A1 and A2 are the armature flux, F1 and F2 are the FE Coil flux, and S1 and S2 are the rotor segments. The FE Coil fluxes circulating between stator and rotor segments produce a complete flux cycle at four typical rotor positions under one electric cycle. The term "flux switching" is used to explain a machine in which the stator tooth flux switches polarity following the motion of a salient-pole rotor. For the designed FESF motor with segmental rotor, all excitation sources namely FE Coil and armature coil are placed alternately between stator teeth, hence giving the advantages of non-overlapped windings.

Furthermore, Fig. 8 also demonstrates in a simplified rectilinear arrangement that proved the segmental rotor achieved flux switching for an idea of four stator teeth and two rotor segments. Under this condition, the DC FE Coil current is applied to slots F1 and F2, hence producing FE Coil fluxes into the rotor segments. For all different rotor positions shown in Figs. 8(a) to (d), segments is used to couple the adjacent coils on the teeth. The flux in the armature teeth A1 and A2 and its polarity is changed with respect to rotor position. Armature coils on teeth A1 and A2 experiencing a bipolar ac magnetic field, as a result an electromotive force is being induced.

At two points in a cycle, armature tooth flux switches polarity and has two different presentations of the rotor segment. The first presentation for flux to switch polarity is when the trailing edge of one segment and the leading edge of the next segment have equal overlap over the armature tooth, while the second presentation is when a segment is centered with the armature tooth, as illustrated in Figs. 8(b) and (d). Although the flux linkage of the armature winding is zero at these positions, there is significantly higher flux density at the

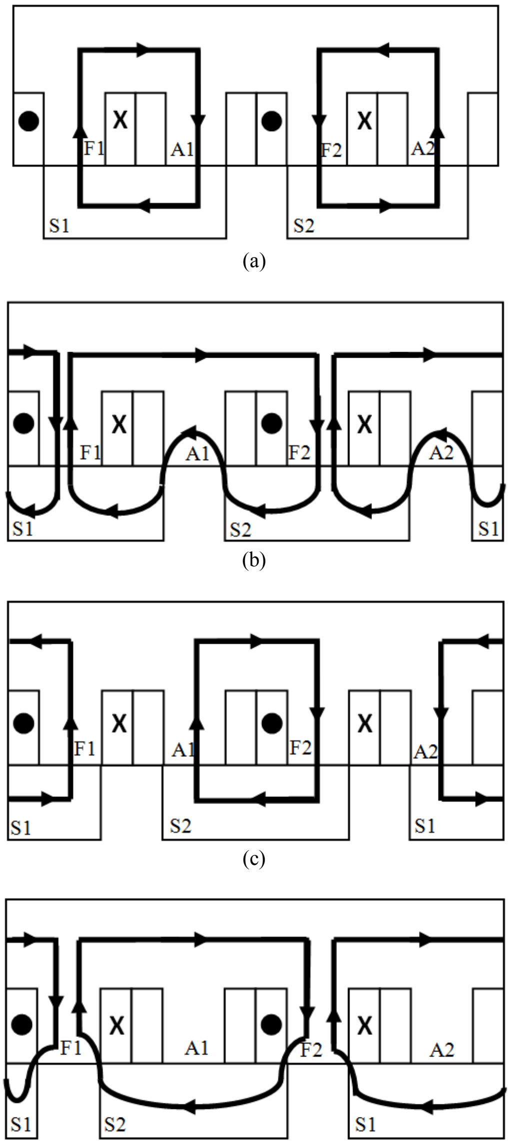


Fig. 8. FESF motor operating principles under DC FE Coil flux (a) segments at initial position (b) segments at one-fourth(1/4) of cycle (c) segments at half (1/2)of cycle (d) segments at three-fourths(3/4) of cycle.

tip and the root of the armature tooth for position (b) than for position (d). This causes the armature tooth to saturate more rapidly, starting from position (b) than from position (d). As such, the alternation of the induced EMF in the armature winding associated with the position (d) is due to linearly changing flux linkages and gives rise to a flat-topped alternation, while that associated with (b) is due to flux linkages that change in a curvilinear manner and results in a peaky alternation. This substantially contrasts with a toothed rotor or a magnetically polarized rotor, in which the mode of switching flux from negative to positive is the same as that for switching from positive to negative.

III. Open Circuit Analysis

A. Armature Coil Test

Coil arrangement tests are studied for each armature coil independently to confirm the operating principle and to set the position of each armature coil phase. First of all, the DC FE Coil current is fed into the system and the flux linkage at each armature coil is examined. The resulting flux linkages are evaluated and the armature coil phases are classified according to conventional three-phase system. Figs. 9 and 10 illustrate the three-phase flux linkage of 12S-8P and 24S-10P FESF motors, respectively at FE Coil current density, J_e of 30A/mm^2, for comparisons. It is clear that both designs have successfully achieved the fundamental principles of three -phase flux linkage. However, the 12S-8P design produced large distortion when compared with sinusoidal flux linkage in 24S-10P FESF motor. Further design reconsideration to reduce the distortion of 12S-8P FESF motor will be investigated in future.

B. DC FE Coil Field Strengthening Analysis

The DC FE Coil field strengthening analysis and flux linkage at different FE Coil current densities, J_e is also examined to know about the flux pattern with increasing J_e. The FE Coil flux linkages at U phase versus electric cycle are plotted in Figs. 11 and 12 for 12S-8P and 24S-10P FESF motor, respectively, while Fig. 13 shows the comparisons of maximum flux versus J_e for both designs. From the graph, both fluxes of 12S-8P and 24S-10P FESF motor are increased with increasing $J_{e\ \text{and}}$ can be expressed as:

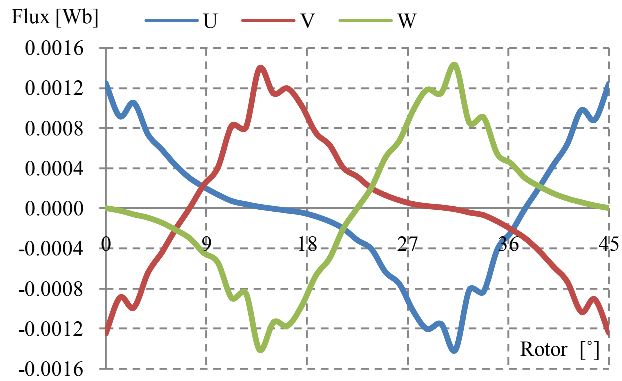


Fig. 9: 3-phase flux linkage of 12S-8P FESF motor

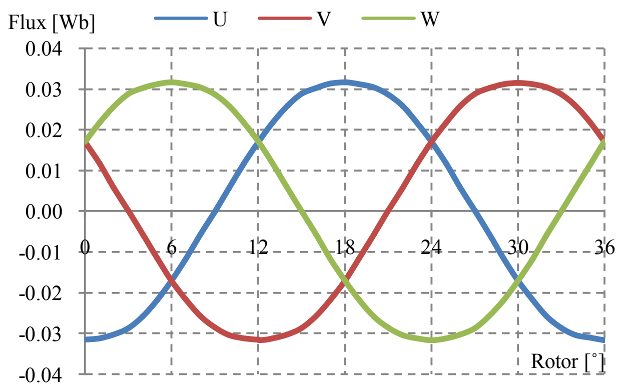


Fig. 10: 3-phase flux linkage of 24S-10P FESF motor

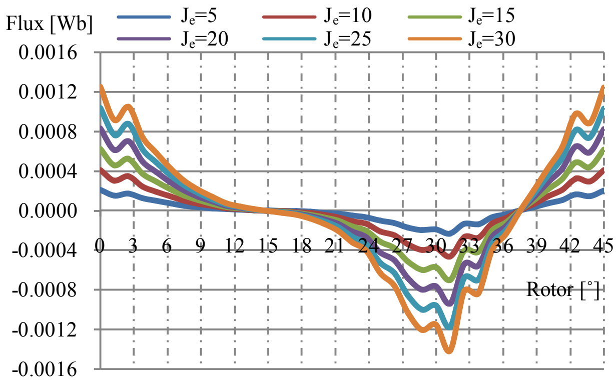


Fig. 11: Flux characteristics at various J_e for 12S-8P FESF motor

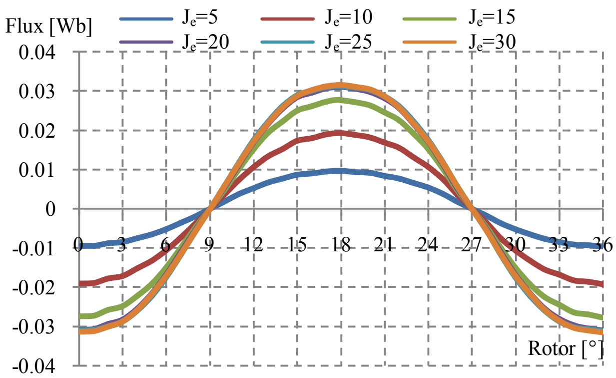


Fig. 12: Flux characteristics at various J_e for 24S-10P FESF motor

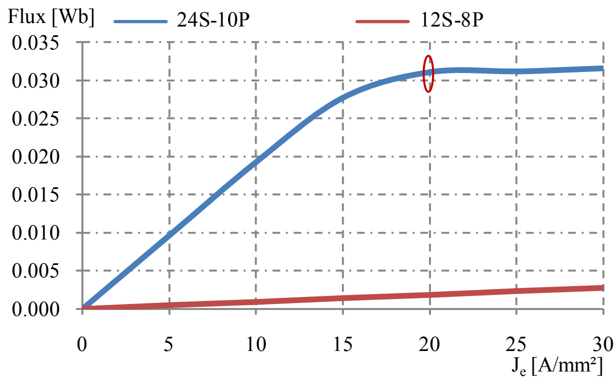


Fig. 13: Comparisons of maximum flux vs J_e for 12S-8P and 24S-10P FESF motor

$$\varphi = KJ_e \qquad (1)$$

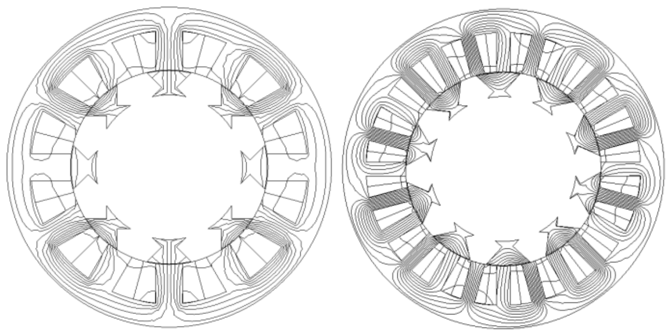
The maximum flux obtained for 12S-8P and 24S 10P FESF motors at J_e of 30A/mm^2 are 2.76mWb and 31.5mWb, respectively. With similar size of rotor segments in both designs, the 24S-10P FESF motor produced much higher flux due to sufficient path for 12 DC FE Coil flux to circulate between stator slot and 10 rotor poles. When compared with 12S-8P FESF motor, the flux generated from 6 DC FE Coil slots is distributed for 8 rotor segments, thus creating more flux leakage, unnecessary flux flows and flux cancellation. Thus, higher DC FE Coil slot with less rotor segments produced much more stable and higher flux linkage suitable for high torque applications. Moreover, torque control by way of adjusting DC FE Coil current is more flexible and provides a large number of characteristics by coupling with armature current control.

C. FE Coil Flux Lines & Flux Distributions

The FE Coil flux lines and flux distributions under zero rotor position of both 12S-8P and 24S-10P FESF motor at J_e of 30A/mm^2 are illustrated in Figs. 14 and 15, respectively for comparisons. For 12S-8P FESF motor, most of the FE Coil fluxes are circulated in rotor segments R2, R4, R6 and R8, no flux flows in R3 and R7, while the leakage flux flow in R1 and R5. In contrast with 24S-10P FESF motor, all FE Coil fluxes circulate in all rotor segments producing much stable and higher flux linkage in the system as discussed in Figs. 11 to 13. The contour value of magnetic flux density distribution is 0.5500 maximum. In Fig. 13, there is knee point at Je=20A/mm^2 which shows that the core will be saturated if the value of Je is exceeded from 20. Additionally, the comparisons of flux distributions in Fig. 15 also prove that the flux distributions of 24S-10P FESF motor are much higher than 12S-8P FESF motor.

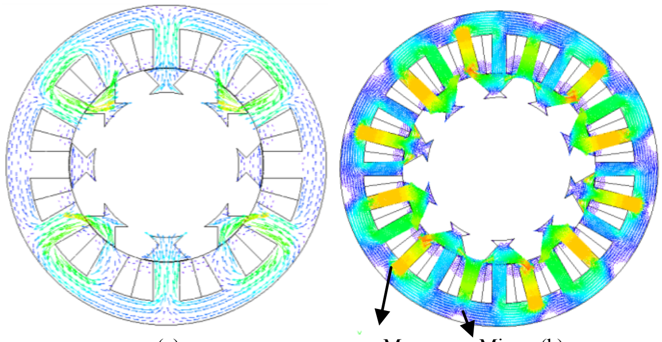
D. *D. Torque vs Ja at various Je*

Torque versus Ja is analyzed to observe the torque characteristic at various Je. Fig. 16 and Fig. 17 illustrate torque versus Je for 6S-8P and 12S-10P FESF motor



(a) (b)

Fig. 14: FE Coil flux lines at J_e of 30A/mm^2
(a) 12S-8P FESF motor (b) 24S-10P FESF motor



(a) (b)

Fig. 15: FE Coil flux distributions at J_e of 30A/mm^2
(a) 12S-8P FESF motor (b) 24S-10P FESF motor

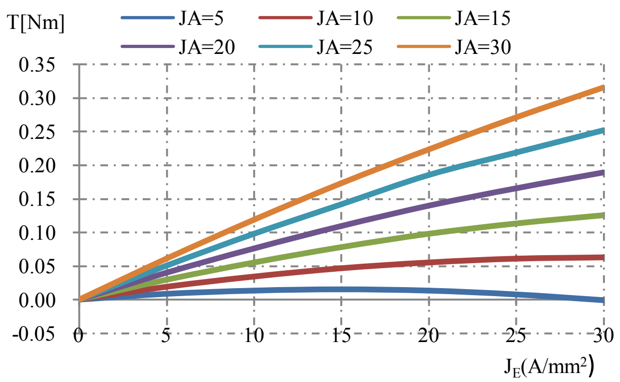


Fig. 16: Torque Vs Je 6S-8P

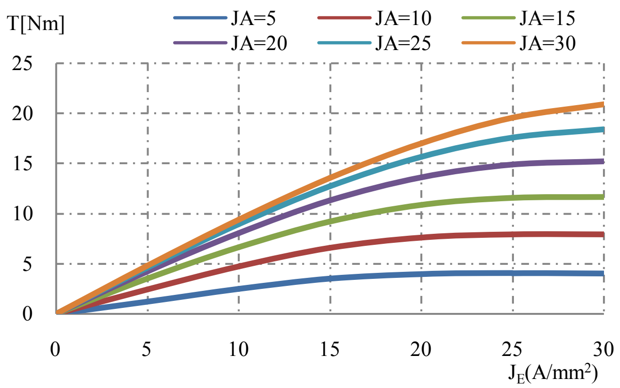


Fig. 17: Torque Vs Je 12S-10P

respectively. The torque of 12S-10P is 21Nm at J_E =30 A/mm^2 much higher as compared to 6S-8P which is 0.31Nm.These figures also show that higher the values of Je and Ja, the higher torque is produced.

IV. CONCLUSION

This paper demonstrates the viability and comparisons of a three-phase 12S-8P and 24S-10P FESF motors with single-tooth non-overlapped armature coil and DC FE Coil windings on the stator body using a segmental rotor. The coil arrangement test for both designs has been studied to confirm each armature coil phase and to verify how the machine operate. The flux analysis shows that 24S-10P FESF motor has better characteristics suitable for wide range and much higher performances.

REFERENCES

[1] Z. Q. Zhu, "Switched flux permanent magnet machines: Innovation continues", in Proc. Int. Conf. on Electrical Machines and Systems (ICEMS), pp.1-10, 2011.

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

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

[4] A.E. Laws, "An electromechanical transducer with permanent magnet polarization," Technical Note No.G.W.202, Royal Aircraft Establishment, Farnborough, UK, 1952

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

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

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

[8] C. Pollock and M. Wallace, "The flux switching motor, a DC motor without magnets or brushes," *Proc. Conf. Rec. IEEE IAS Annual Meeting*, vol.3, pp.1980–1987, 1999.

[9] H. Pollock, C. Pollock, R. T. Walter, and B. V. Gorti, "Low cost, high power density, flux switching machines and drives for power tools," *Proc. Conf. Rec. IEEE IAS Annual Meeting*, pp.1451–1457, 2003.

[10] C. Pollock, H. Pollock, and M. Brackley, "Electronically controlled flux switching motors: A comparison with an induction motor driving an axial fan", *Proc. Conf. Rec. IEEE IAS Annual Meeting*, pp.2465–2470, 2003.

[11] 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.

[12] J. F. Bangura, "Design of high-power density and relatively high efficiency flux-switching motor", *IEEE Trans. Energy Convers.*, vol.21, no.2, pp.416–424, June 2006.

[13] J. T. Chen, Z. Q. Zhu, S. Iwasaki, and R. Deodhar, "Low cost flux-switching brushless AC machines", *Proc.IEEE Vehicle Power and Propulsion Conf.*, VPPC 2010, Lille, France, Sept. 2010.

[14] E. Sulaiman, T. Kosaka, and N. Matsui, "A New Structure of 12Slot-10Pole Field-Excitation Flux Switching Synchronous Machine for Hybrid Electric Vehicles", Proc. of 14th European Conf. on Power Electronics and Appl. (EPE), UK, Paper No.362, 2011.

[15] E. Sulaiman, T. Kosaka, and N. Matsui, "Design Study and Experimental Analysis of Wound Field Flux Switching Motor for HEV Applications", Prof. of Int. Conf. on Electric Machines, France, pp. 1269-1275, Sept 2012.

[16] 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", Proc. on Int. Power Eng. & Optimization Conf., pp. 46-51, 2013.

[17] A. Zulu, B. C. Mecrow, and A. Armstrong, "A wound-field three-phase flux-switching synchronous motor with all excitation sources on the stator", *IEEE Trans. Ind. Appl.*, vol.46, pp.2363-2371, Nov. 2010.

[18] A. Zulu, B. C. Mecrow, and A. Armstrong, "Topologies for Wound-Field Three-Phase Segmented-Rotor Flux-Switching Machines" Proc. of The 5th IET Int. Conf. on Power Electronics, Machine and Drives (PEMD), 2010.

[19] A. Zulu, B. C. Mecrow, and A. Armstrong, "Permanent-Magnet Flux-Switching Synchronous Motor Employing a Segmental Rotor", *IEEE Trans. Ind. Appl.*, vol.48, no.6, pp.2259-2267, Nov. 2012.