Comparison of Three Phase and Single Phase FE-FSM with Segmental Rotor

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***Abstract*— A new machine Switching Flux machine (SFM) has been highlighted during recent research, having all the active parts on the stator with robust structure of rotor. SFM has three major types with respect to their excitation source. Permanent Magnet Switching Flux Motor (PM-SFM) Field Excitation Switching Flux Motor (FE-SFM) and Hybrid Excitation Switching Flux Motor (HE-SFM). PM and FE coil are the main sources of flux generation in the stator of (PM-SFM) and (FE-SFM) respectively. While in HE-SFM both PM and FE coil are combined to produce flux linkage in the armature coil. This paper presents the comparison between single phase FE-SFM and three phase FE-SFM with segmental rotor. By the use of segmental rotor flux is switched in the armature circuit as rotor rotates. Initially, the coil arrangement tests are examined to confirm the operating principle of the motor. Furthermore, the profile of flux linkage, induced voltage, cogging torque, flux strengthening, and torque characteristics at various armature current densities are observed based on 2D- finite element analysis (FEA).**

Keywords—Field Excitation Switching Flux Motor (FE-SFM); segmental rotor;field excitation coil; torque.

I. INTRODUCTION

The first concept of switching flux machine (SFM) has been founded and printed in the mid of 1950s. Using 4 stator slots and 4 rotor poles permanent magnet (PM) SFM i.e. permanent magnet single-phase limited angle actuator or more well-known as Laws relay has been developed [1], and then single phase generator with 4 stator slots, and 4or 6 rotor poles has been invented [2].

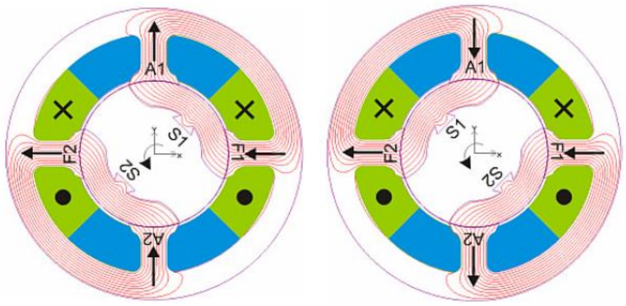
Over the last decade, many topologies of SFM have been introduced for a variety of application i.e. domestic appliances, automotive, aerospace etc. SFM can be classified into three groups that are Permanent magnet (PM) SFM, Field Excitation (FE) SFM and Hybrid Excitation (HE) SFM. Main sources of flux linkage in PM-SFM and FE-SFM are permanent magnet and field Excitation winding respectively. While in case of HE-SFM both PM and FE windings are combined to generate the flux in the stator [3, 6]. In SFMs all the active parts like field excitation winding PM and armature coil winding are situated on the stator. When compare with other SFMs, the FE-SFM motor has many advantages of low cost, simple construction, magnet-less machine, and variable flux control capabilities suitable for various performances. Furthermore, to manufacture the FE-SFM motors, the PM on the stator of conventional PM-SFMs is replaced by DC field excitation coil. In other words, the FE-SFM motors having salient-rotor structure is a novel topology, merging the principles of the SRMs and inductor generator. SFM is a form of salient rotor reluctance machine with a novel topology combining the principles of the inductor generator and the switched reluctance machine (SRM) [7, 9]. The SFM works on the concept of changing the polarity of the flux linking in the armature winding by motion of the rotor. In early principles motor having DC field winding on the stator and toothed rotor structure with fully pitched windings on the stator [10]. The feasibility of this design was verified in applications requiring high power densities and a good level of durability [11-14]. The novelty of the invention was that single-phase ac working could be realized in the armature winding by using DC excitation on the stator and an armature winding connected to an AC supply to provide the required flux orientation for rotation. By changing the mutual inductance of the windings torque is produced. In previous works the novelist developed the use of a segmental rotor construction for SRMs [15] and two phase switching flux motors [16], which gives significant gains over other topologies. Whereas segmental rotors structures are used conventionally to control the saliency ratio in synchronous reluctance machines [17,18], the basic function of the segments using in this design is to provide a defined magnetic path for conveying the field flux to adjacent stator armature coils as the rotor rotates. As each coil arrangement is around a single tooth, this design gives shorter end-windings than with the toothed rotor structure which requires fully-pitched coils. There are many advantages of this arrangement, as it uses less conductor materials and may improve the overall motor efficiency.

A single-phase, 8-tooth, 4-segmented, field excitation machine developed in [16] demonstrated these attributes, and is a precursor to this work. As expected of single phase arrangements, the armature mmf induces appreciable current ripple in the DC field circuit, which can affect the control of field current.

This paper explains the comparison of three phase FE-SFM and single phase FE-SFM using segmental rotor and different tests will be compared and analyzed to find the best candidate of FE-SFM using segmental rotor.

II. Operating Principle Of FE-SFM With Segmental Rotor

Operating principle of Flux switching machine using segmental rotor to achieve flux is illustrated in Fig. 1, Having four stator poles (F1,F2,A1,A2) and two rotor segments (S1,S2) with DC field excitation in coils F1 and F2. For the two aligned positions as shown, coupling of coils on the stator pole is through segments. The motion of the rotor from position (a) to (b) varies flux in the armature coils A1 and A2, and also changes its polarity. Due to this bipolar AC magnetic field is produced in the armature coil with induction of EMF. Practically, the design is put into practice on a stator with an even number of stator poles, with half the number of poles designated as field winding and the other half as armature winding. The field pole alternate in position with the armature pole, with the polarity of each field poles arranged to be opposite that of the next field pole.



(a) First alignment position (b) Second alignment position

Fig. 1 Basic segmental rotor principle with field excitation

III. Design Restrictions And Specifications

The design restrictions and the target specifications and parameters of the single phase 12S-6P FE-SFM with segmental rotor and three phase 12S-8P FE-SFM with segmental rotor are listed in Table 1. The maximum limit of the current density for armature winding and FE coil is set up 30Arms/mm^2. Fig. 2, and fig. 3, shows the basic designs of single phase and three phase FE-SFM with segmental rotor.

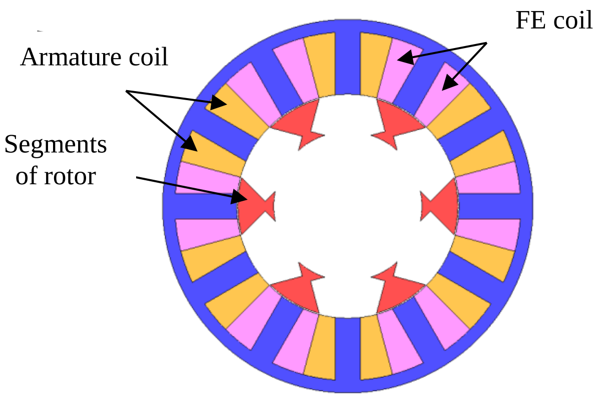


Fig. 2 Single phase 12S-6P FE-SFM with segmental rotor

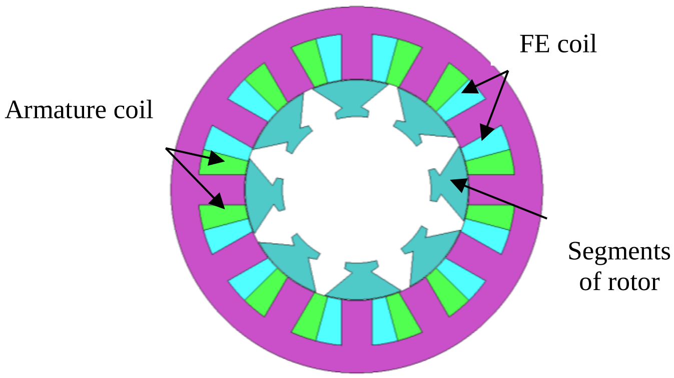


Fig. 3 Three phase 12S-8P FE-SFM with segmental rotor

TABLE I. Design Restrictions, Specifications And Parameters For 12S-6P FE-SFM And 12S-8P FE-SFM With Segmental Rotor

Items	**Single phase 12S-6P FE-SFM with Segmental**	**Three phase 12S-8P FE-SFM with Segmental**
Number of slots	12	12
Number of rotor segments	6	8
Stator outer radius (mm)	75	75
Stator back inner width (mm)	5	11
Stator tooth width (mm)	10	12.5
Armature coil slot area (mm^2)	251	250
FEC slot area (mm^2)	251	250
Rotor outer radius (mm)	44.5	45
Rotor inner radius (mm)	30	30
Air gap length (mm)	0.5	0.3
Number of turns per field tooth coil (FEC)	75	44
Number of turns per armature coil slot (AC)	11	44

IV. Design Methodology

Both the designs of FE-SFM using segmental rotor examined by FEA simulations, conducted via JMAG-Designer ver. 13.0 released by Japan Research Institute (JRI) and make discussion on the attributes of each design based on the flux linkages, EMF production, flux distribution and cogging torque. Initially, the rotor of the motor, stator, armature coil and DC Field excitation coil are drawn by using JMAG Editor. Then, the materials, conditions, circuits and properties of the machine are assigned in JMAG Designer. The design process of part drawing and condition setting are demonstrated in Fig. 4. The electromagnetic steel, 35H210 is used for the rotor segments and stator core. Furthermore, coil arrangement tests are examined to validate the operating principle of FE-SFM and to set the position of each armature coil phase.

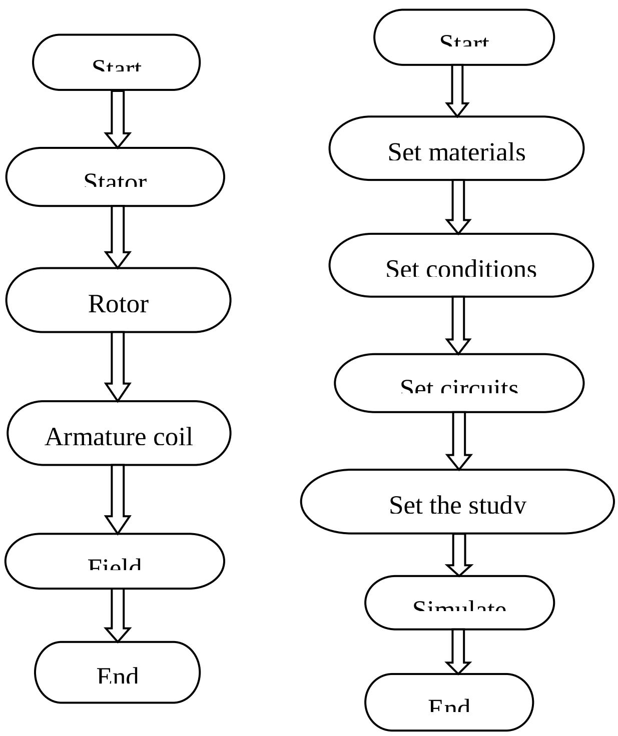
There are several concepts in designing the single phase and three phase configuration using segmental rotor. This paper focuses on the designs of single phase and three phase FE SFM using segmental rotor having non-overlapping winding, low copper losses and cost with high efficiency of motor.

V. PERFORMANCE ANALYSIS BASED ON FEA

A. Coil test analysis

In order to get proper position of each armature coil phase to confirm the operation principle of both the single phase and three phase FE-SFM with segmental rotor, the coil arrangement tests are performed for each armature coil separately for single phase and three phase FE-SFM with segmental rotor. The coil test arrangement of both the single phase FE-SFM and three phase FE-SFM using segmental rotor structure are shown in fig. 5(a), and fig. 5(b), respectively.

For single phase FE-SFM with segmental rotor armature coils and FECs are wounded in clockwise and counter-clockwise direction, with this arrangement the operating principle of single phase FE-SFM with segmental rotor is verified. Also by this arrangement of armature coils the flux produced is smooth having maximum flux linkage of 0.015Wb with no distortion as shown in fig. 6(a).On the other hand fig. 5(b), shows the coil arrangement of three phase FE-SFM with segmental rotor where the FECs and the armature coils both are arranged in alternate direction and DC current of 51.27 A is applied to validate the operating principle FE-SFM with segmental rotor. Fig. 6(b) illustrates the flux linkage of three-phase flux linkage defined as U, V, and W, with maximum value of 0.054Wb which much less as compare to single phase FE-SFM with segmental rotor.



(a) (b)

Fig. 4 FE-SFM with segmental rotor Design Methodology (a) Drawing of Parts (b) Setting the conditions

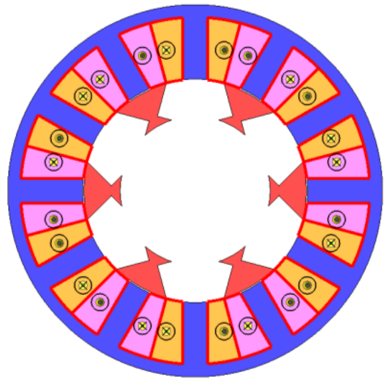


Fig. 5(a) Single phase FE-SFM coil test arrangements

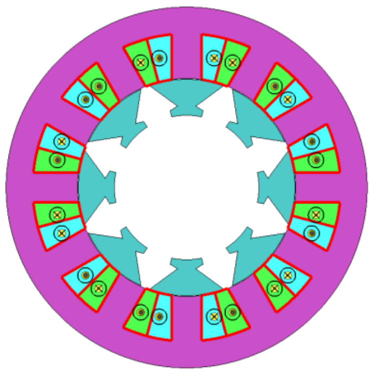


Fig. 5(b) Three phase FE-SFM coil test arrangements

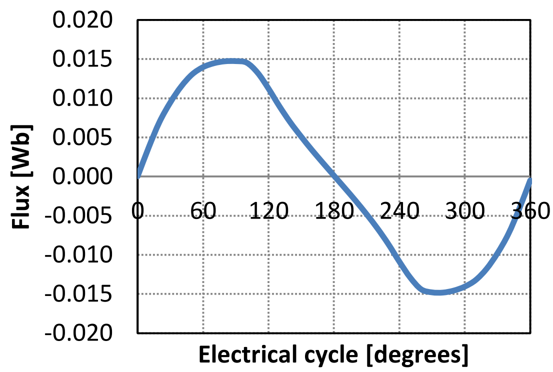


Fig. 6(a) Flux linkage of single phase FE-SFM with segmental rotor

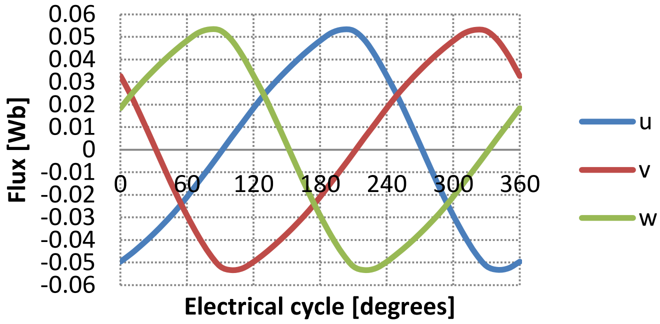


Fig. 6(b) Flux linkage of three phase FE-SFM with segmental rotor in terms of U, V, W

B. Induced Voltage at No load condition

The induced voltages produced from FE coil with speed of 1200 r/min and 500 r/min for single phase FE-SFM with segmental rotor and three phase FE-SFM with segmental rotor respectively at no load condition shown in fig. 7, & fig. 8. For single phase FE-SFM the highest amplitude value of induced voltage is approximately 18.8V while in case of three phase FE-SFM with segmental rotor has the highest value of induced voltage is approximately 39.15V, there is also distortion in the waveforms due to the odd harmonics. By these results the values of back emf of both the motors are very less as compared to applied voltage that shows both the motors single phase and three phase FE-SFM with segmental rotor will work on safe region.

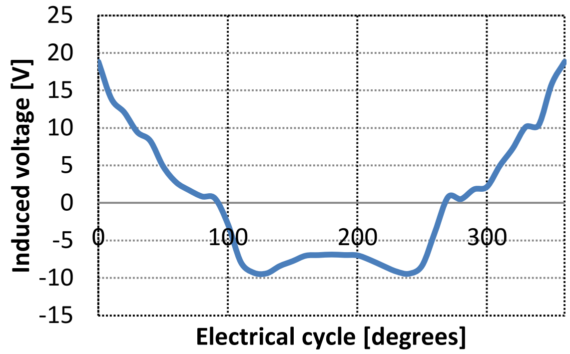


Fig. 7, Induced voltage for single phase FE-SFM with segmental

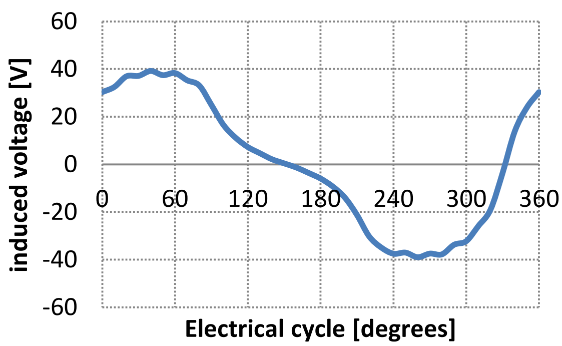


Fig. 8 Induced voltage for three phase FE-SFM with segmental

C. Cogging torque analysis

Fig. 9 shows the analysis of cogging torque for single phase and three phase FE-SFM with segmental rotor. The figure illustrates the single phase FE-SFM has the highest peak to peak cogging torque of 41.1Nm followed by three phase FE-SFM that has the least value of 2.88Nm. Therefore, to reduce the cogging torque value of single phase FE-SFM up to reasonable value further work will be held on the design refinement and optimization.

D. Flux strengthening/weakening

The flux strengthening and weakening of both the single phase FE-SFM and three phase FE-SFM is analyzed by comparing the characteristics of DC FE coil flux at various DC current densities, Je as illustrated in figure 10. From figure it is clear that initially the flux pattern is increased with the increase in current density until DC FEC current density, Je of 11A/mm^2. However, the flux generated starts to reduce when higher DC FEC current density is injected to the system It is expected that this phenomena occurs due to some flux leakage and flux cancellation that will be investigated in future. In addition, although the flux generated from single phase FE-SFM is slightly less than three phase FE-SFM with segmental rotor.

VI. Torque Vs. Field Current Densities Je, At Various Armature Current Dnsities Ja

Torque vs. field current densities Je at various armature current densities for single phase FE-SFM and three phase FE-SFM with segmental rotor are shown in fig. 11, and fig. 12, respectively. From figures it is clear that the torque of three phase FE-SFM is approximately 33 Nm at Ja 30 Arms/mm^2 which is much higher than the single phase FE-SFM i-e approximately 17 Nm at Ja 30 Arms/mm^2. In both the cases of single phase FE-SFM and three phase FE-SFM the value of torque is increased linearly as armature current density is increased but at the lower values of armature current density the torque value initially increased up to a certain value of 15 Arms/mm^2 after that it begins to decrease slightly, that shows by increasing the value armature current density Ja, further torque can be increased in future work in both cases.

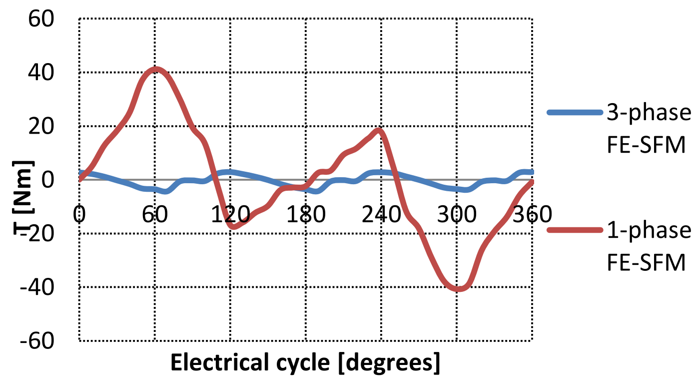


Fig. 9 Cogging torque

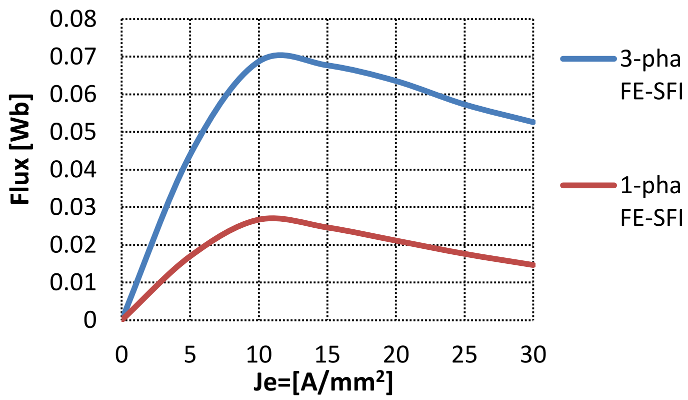


Fig. 10 Flux strengthening at various current densities,Je

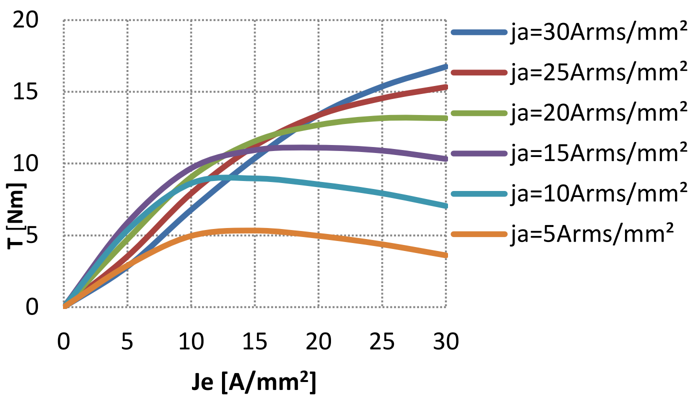


Fig. 11 Torque vs. Je at various Ja for single phase FE-SFM

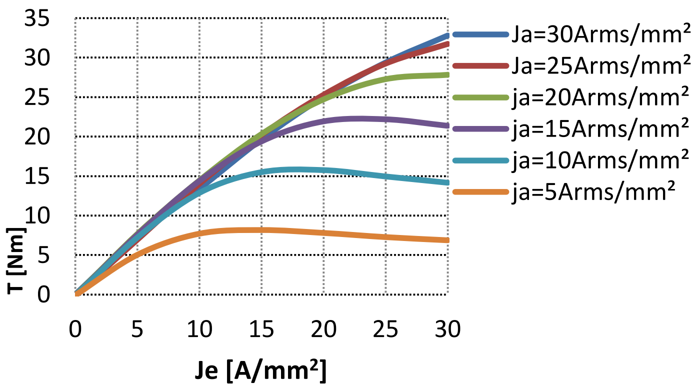


Fig. 12 Torque vs. Je at various Ja for three phase FE-SFM

VII. Conclusion

This paper presents the feasibility and comparison between single phase FE-SFM and three phase FE-SFM using segmental rotor. With clear advantages of short end winding and low copper losses and cost due to non-overlap armature windings and FE coil windings. Coil test analysis, cogging torque, flux strengthening and torque vs. field current densities Je at different armature current densities Ja has been investigated on the basis on 2D FEA. By this investigation three phase FE-SFM with segmental rotor has better results as compared to single phase FE-SFM with segmental rotor.

Therefore, in future work by design refinement and optimization, the single phase FE-SFM with segmental rotor will be enhanced to achieve the required targets and improved results.

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