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# A NOVEL STRUCTURE OF HYBRID EXCITATION FLUX SWITCHING MOTOR WITH SEGMENTAL ROTOR

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**ABSTRACT**

The majority of electrical energy consumed in most industrial facilities is used to run electric motors. Therefore it is a persuasive need for researchers to develop advanced electric motors with less cost and high efficiency. There has been a recent interest in flux switching motor (FSM) in which all flux sources are positioned in stator that make the rotor simple, robust and brushless. Development of research has been with toothed rotor structures which exploits changes of paths for the stator teeth but this structure produces less torque and power. Hence, the use of a segmental rotor structure has been developed, which gives significant gains. The primary function of the segments is to provide a defined magnetic path for conveying the flux to adjacent armature coil in stator as rotor rotates. This design gives shorter end-winding than with toothed rotor structure which requires fully-pitched coils. Hence, permanent magnet FSM (PMFSM) and field excitation FSM (FEFSM) with segmental rotor have been developed, but due to their infirmity of less torque generation inherit from less flux linkage, a novel structure of hybrid excitation FSM (HEFSM) is proposed. The proposed design of HEFSM has simple structure with only three Field excitation coils (FECs) and three permanent magnets (PMs) is analysed using commercial 2D FEA package, JMAG-designer ver. 13.0, released by JSOL Corporation. This paper presents the coil test analysis of HEFSM to confirm the working principle besides this cogging torque, back emf and torque vs current densities have been presented.

**Keywords:** flux switching motor, hybrid excitation, segmental rotor, torque.

## INTRODUCTION

In recent years, a new machine namely (FSM) has been developed that consist of all flux sources in the stator. Beside the advantage of brushless machine, it has single piece of 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 FEFS motor while HEFSM combines both PM and FE Coils (Zhu, 2011), (Sulaiman, 2011), (Sulaiman, 2012).

In the mid 1950s, the word flux switching machine (FSM) has been originated from different theories and printed. A permanent magnet (PM) FSM that is permanent magnet single- phase limited angle actuator has been developed and it has been modified to a single phase generator with four stator slots, and four or six rotor poles (4S- 4/6P) (Laws, 1952), (Rauch,1955). 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 FEFS motor has advantages of low cost, magnet-less machine, simple construction, and variable flux control capabilities suitable for various performances. Furthermore, to manufacture the FEFS motors, the PM on the stator of conventional PMFSMs isreplaced by DC FE Coil. In other words, the FEFS motors having salient-rotor structure is a novel topology, merging the principles of the inductor generator and the SRMs (Walker, 1942), (Miller, 1993). Figure-1 shows an example of single- phase 4S-2P FEFS motor that employs with a DC FE Coil on the stator, a toothed-rotor structure and fully-pitched windings on the stator (Pollock andWallace, 1999). 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 (Pollock and Walter, 2003), (Pollock and Brackley, 2003).

Eight stator slots and four rotor poles FEFS motor is shown in Figure-2 (Pollock and Barron, 2006). 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 (Bangura, 2006), and when single-phase and induction machine (IM) are compared, 8S-4P FEFS motor has higher output power density and efficiency. However, the 1-phase FEFS 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.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 (Bangura, 2006), and when single-phase and induction machine (IM) are compared, 8S-4P FEFS motor has higher output power

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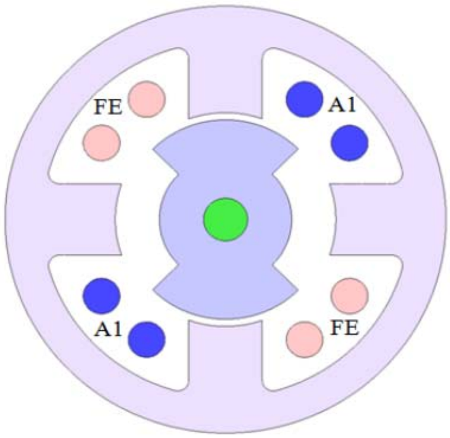


**Figure-1.** 1-phase 4S-2P FEFS motor.

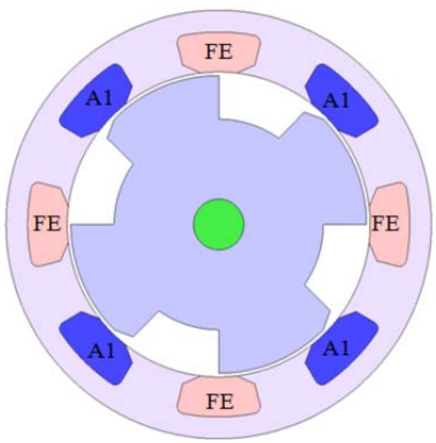


**Figure-2.** 1-phase 8S-4P FESF motor.

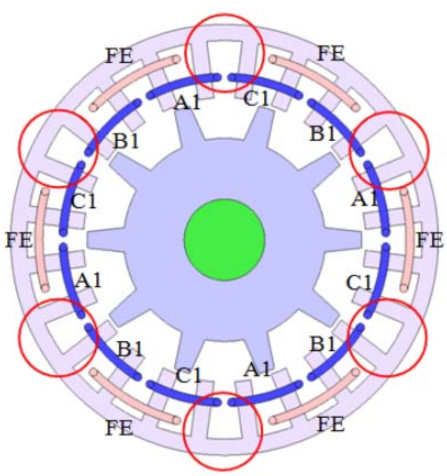


**Figure-3.** 3-phase 24S-10P FESF motor.

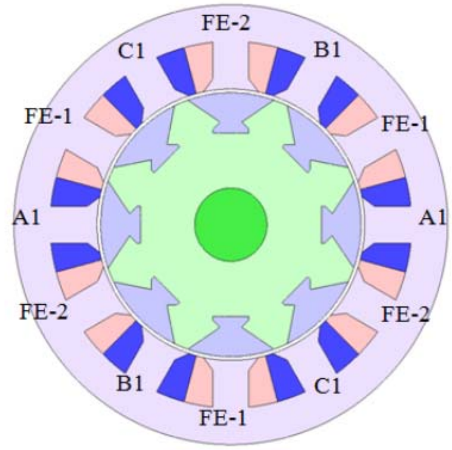


**Figure-4.** 3-phase 12S-8P segmental rotor.

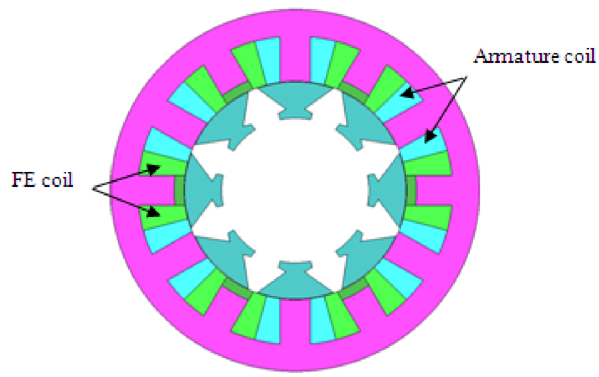


**Figure-5.** 12S-8P HEFSM segmental rotor.

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 FEFS 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 Figure-3 (Chen, 2010). 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 FEFS motor for various applications have also been reported in (Sulaiman, 2011), (Sulaiman, 2012).

Since all FEFS motor discussed above posses an overlapped winding between DC FE Coil and armature coils that cause higher coil end length, a 12S-8P FEFS motor with adjacent DC FE Coil and armature coils and segmental rotor has been proposed as illustrated in Figure-

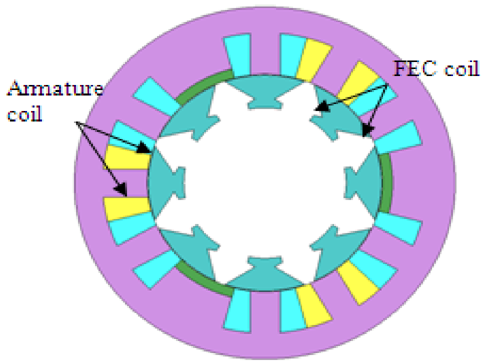


**Figure-6.** Novel structure of HEFSM with segmental rotor.

4 (Zulu, 2010). 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 (Zulu and Mecrow, 2010), (Zulu and Armstrong, 2010).

Furthermore FEFSM and PMFSM with segmental rotor have been developed, but due to their infirmity of less torque generation inherit from less flux linkage, both existing designs FEFSM and PMFSM with segmental rotor have been combined and a new structure of hybrid excitation FSM (HEFSM) is proposed as shown in Figure-5 (Soomro, 2015).

However in new structure of HEFSM there is still flux cancellation of PM and FEC fluxes therefore a novel structure of HEFSM with segmental rotor has been proposed in this paper having three FEC coils and three PMs. Due to less slots of FEC there is enough space on the stator side to combine fluxes of PM and FEC easily and make the structure simple as shown in Figure-6. Besides, this coil test is performed to validate the working principle of motor after that the performance results with no-load and load characteristics are also examined on the basis 2-D FEA.

## DESIGN METHODOLOGY

The design specification and parameters of novel structure of HEFSM with segmental rotor are listed in Table-1. Using FEA simulation, designs of HEFSM is examined, conducted via JMAG-designer ver. 13.0 released by Japan Research Institute (JRI) and make a discussion on the attributes of each design based on the flux linkages, emf production flux distribution and cogging torque. Firstly the stator of the motor, rotor with segments, armature coil and DC field excitation coil are designed using JMAG Editor. After that material, conditions, circuits and properties of the machines are assigned in JMAG designer. For stator core and rotor segments the electromagnetic steel of 35H210 is used. In addition, coil arrangement tests are examined to confirm the operating principle of (HEFSM) with segmental rotor and to set the position of each armature coil phase.

**Table-1.** Design specification and restrictions of novel HEFSM with segmental rotor.

| Items | (HEFSM) with segmental rotor |
|---|---|
| Number of slots | 12 |
| Number of rotor segments | 8 |
| Stator outer radius (mm) | 75 |
| Stator back inner width (mm) | 11 |
| Stator tooth width (mm) | 12.5 |
| Armature coil slot area ($mm^2$) | 250 |
| FEC slot area ($mm^2$) | 250 |
| Rotor outer radius (mm) | 45 |
| Rotor inner radius (mm) | 30 |
| Air gap length (mm) | 0.3 |
| Span of the Segment | $40^0$ |
| Number of turns per field tooth coil (FEC) | 44 |
| Number of turns per armature coil slot (AC) | 44 |

## PERFORMANCE ANALYSIS BASED ON 2D FEA

### Coil test analysis

To verify the operating principle of novel structure of HEFSM with segmental rotor, and find the proper position of each armature coil phase, arrangement of coil tests are performed separately. Figure-7 shows that all the armature coils and FE coils are arranged in alternate direction and DC current of 51.27 A is applied to confirm the operating principle of HEFSM with segmental rotor structure. With this arrangement of coils the three phase flux linkage is defined as U, V, and W and maximum flux linkage of 0.056Wb is attained as illustrated in Figure-8.

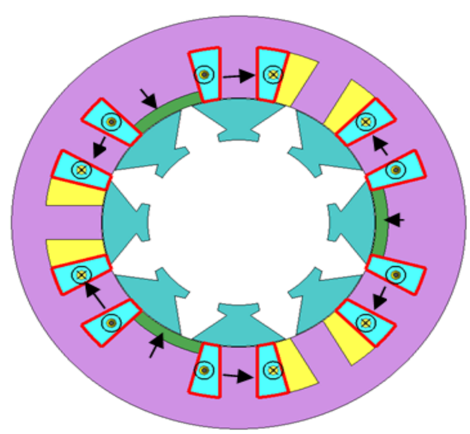

**Figure-7.** Armature coil arrangments of HEFSM with segmental rotor.

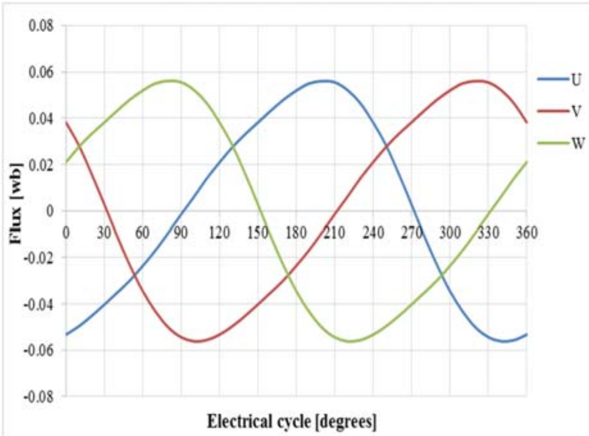


**Figure-8.** Flux linkage of HEFSM in terms of U, V, W.

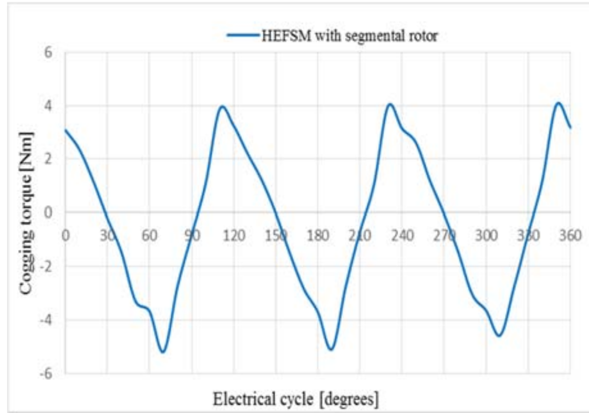


**Figure-9.** Cogging torque of HEFSM with segmental rotor.

**Cogging torque analysis**

The cogging torque analysis of three phase HEFSM with segmental rotor is shown in Figure-9. From figure it is very obvious that HEFSM with segmental rotor has moderate peak to peak value of cogging torque that is approximately 4.021Nm. From the analysis of cogging torque, it is observed that HEFSM with segmental rotor has achieved the better result of very less cogging torque due to the simple structure as there are only thre FECs and three PM used leaving much free space in the stator. Less cogging torque results that motor will work at high speed without vibration. This cogging torque can be further reduced by design optimization and refinement.

**Magnetic flux strengthening**

Magnetic flux strengthening of novel HEFSM with segmental rotor is shown in Figure-10 and is conducted on the basis 2-FEA. From Figure. it obvious that the maximum magnetic flux strength achived by HEFSM with segmental rotor is approximately 0.065Wb at maximum current density of 10 A/mm$^2$, as the fluxes of PMs and FECs are combined properly. Furthermore magnetic flux strengthening is slightly decreases as the current density is increased due to to the reason of flux saturation in the stator. There is some flux saturation at the tips of stator poles, However by further optimization refinement these fluxes of FE coil and PMs will be easily combined at maximum current densities and transferred from stator to rotor segments and able to generate more magnetic flux strength

**Induced Emf of novel HEFSM with segmental rotor**

The induced voltage produced from PM and FEC at maximum current density of Je=30A/mm$^2$ under speed of 500 rpm for novel HEFSM with segmental rotor is illustrated in Figure-11 and is observed on the basis of 2-D FEA. it is noticeable that the value of novel design of HEFSM with segmental rotor is approximately 42V. However there exists some distortion in the wave form due to odd harmonics but the value of HEFSM is much less than the applied voltage that confirms the motor to be worked on safe region.

**Torque Vs Je, at various armature current densities of Ja**

Torque vs. field excitation current densities Je, at various armature current densities Ja, of HEFSM with segmental rotor is shown in Figure-12. From figure it is obvious that shows that the value of torque is increasing linearly in each case of field current density Je, and reaches to the maximum value of approximately 36.68Nm at armature current density of 30Arms/mm$^2$. The novel structure of HEFSM with segmental rotor has achieved the maximum value of torque than the previous design of HEFSM and confirms that the fluxes of FECs and PMs are combined properly due the the enough space in the stator with smooth distribution. From figure it is also clear that the with increase of current densities the torque is increased it shows that there is no any magnetic saturation or flux cancellation. The torque of novel design further can be increase up to optimum value by design refinement and optimization.

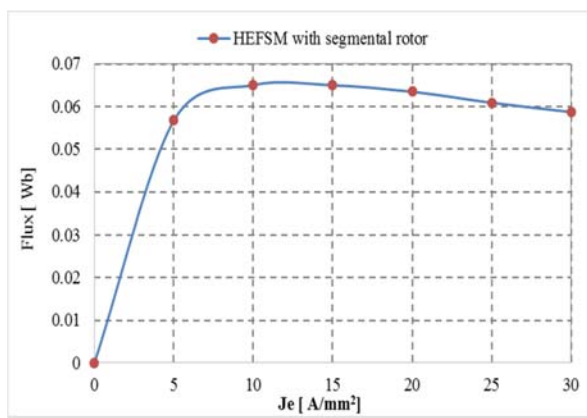


**Figure-10.** Magnetic flux strengthening of HEFSM with segmental rotor.

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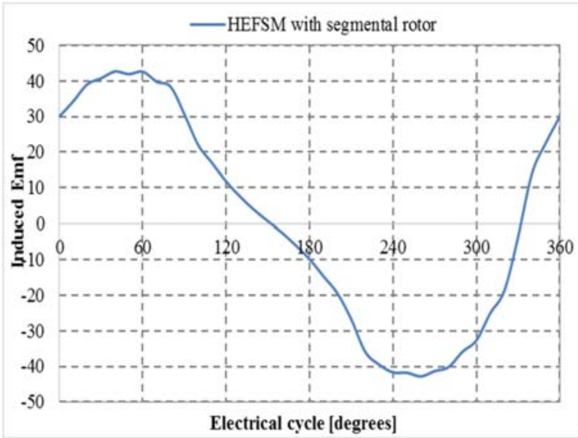


**Figure-11.** Induced emf of HEFSM with segmental rotor.

**Power characteristics**

Power vs armature current densities Ja at maximum current density of 30A/mm$^2$ for HEFSM is illustrated in Figure-13. From figure it is obvious that power of the novel design is increases linearly as the armature current density is increased. Furthermore at speed of 500 rpm the HEFSM achieved the maximum value of approximately 15.4 kw at maximum armature density of 30 Arms/mm$^2$. As there are only three FE coils are used therefore reduced the the copper cost as well copper losses and results maxinun power is achived. The power of novel design HEFSM with segmental rotor can be further increased by design refinement and optimization.

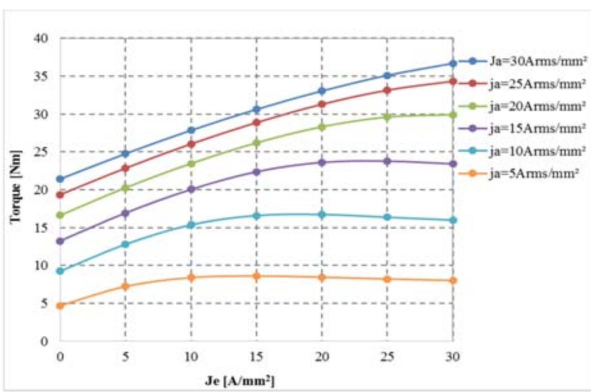


**Figure-12.** Torque vs Je of HEFSM with segmental rotor.

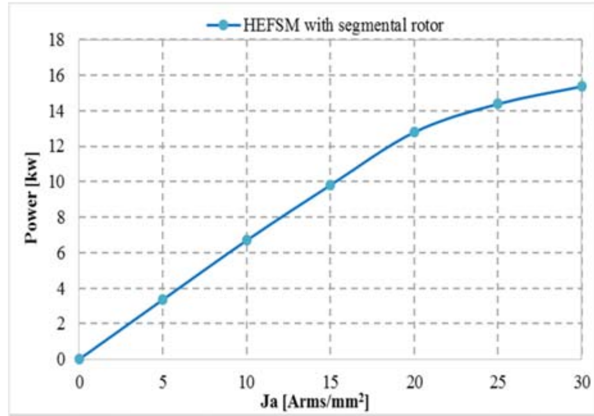


**Figure-13.** Power vs Ja of HEFSM with segmental Rotor at maximum Je.

## CONCLUSIONS

In this paper the design study and analysis of novel structure of HEFSM with segmental rotor has been introduced. Initialy the coil test analysis of novel structure has been investigated to confirm the working principle with segmental rotor based on 2-D FEA. As the novel structure uses only three FECs and three PMs to confirm the simple structure and smooth flow of magnetic fluxes along the stator. Besides this three FECs confirms the less copper losses as compared to the existing designs. Furthermore cogging torque, back emf and flux strengthening has been analysed and validated that the novel structure will work on safe region with adequate results. However by design refinement and optimization it is also expected that the novel structure will achieve more better results.

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