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Performance Comparison of 24Slot-10Pole and 12Slot-8Pole Wound Field Three-Phase Switched-Flux Machine

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Abstract—This paper presents a comparative study of two types of wound field three-phase switched-flux machine (SFM) with non-overlap winding and salient rotor. Both armature and field winding are located on the stator and rotor is composed of only stack of iron. Non-overlap armature and field windings and toothed-rotor are the clear advantages of these machines as the copper losses gets reduce and rotor becomes more robust. Initially, the motor general construction, the working principle and design concept of proposed machines are outlined. Then, coil arrangement test, peak armature flux linkage, back emf, cogging torque, average torque and torque-speed characteristics of both machines are analyzed and compared by two-dimensional finite element analysis(2D- FEA).

Index Terms—Low cost, wound field switched-flux machine, salient rotor, non-overlap winding, field excitation coil

I. INTRODUCTION

Switched -flux motor (SFM), a new class of electric motor having high torque and power density is used in HEV which is the combination of the switched reluctance motor and the inductor alternator [1-2]. SFM can be classified into three groups that are permanent magnet SFM, field excitation SFM and hybrid excitation SFM. The main source of flux in permanent magnet SFM is permanent magnet and field excitation coil (FEC) in field excitation SFM while both permanent magnet and field excitation coil in hybrid excitation SFM [3-6]. Armature winding and field winding or permanent magnet are located on the stator in these SFMs. The field excitation SFM has advantages of low cost, simple construction, magnet-less machine, and variable flux control capabilities suitable for various performances when compare with others SFMs. Due to these advantages, a 24Slot-10Pole three-phase wound field SFM has been developed from 24Slot-10Pole permanent magnet SFM in which the permanent magnet is replaced by field excitation coil as shown in Fig. 1 [7]. The total flux generation is limited because of adjacent DC field excitation coil isolation and thus machine performance is affected. To overcome the drawbacks, a new structure of 24Slot-10Pole and 24Slot-14Pole FEFM with single DC polarity have been introduced and compared

as depicted in Fig. 2[8]. Although less leakage flux and uncomplicated manufacturing of single DC field excitation coil are the advantages of proposed machine but it have overlapping armature and field winding which increase the cost, copper losses and thus reduce the efficiency.

The performance of SFM is enhanced by using segmental rotor configuration in recent research [9]. Segmental rotor is designed in a manner such that to achieve bipolar flux in armature winding, which has neither magnets nor winding. To produce bipolar flux linkages in this way, a toothed-rotor structure may be used but it requires overlap windings on the stator [10]. Non-overlap winding has been used in [11] to increase the efficiency by reducing the copper losses and enhanced the speed torque characteristics of SFM. A three-phase SFM using a segmental rotor has been proposed in [12] to improve fault tolerance to a reduction in torque pulsations and power converter rating per phase. Figure 3 [10] and Figure 4 [12] shows SFMs having toothed-rotor with overlap winding and segmented-rotor with non-overlap winding at the stator. A single-phase wound field SFM machine was comprehensively investigated [13-15] by Pollock. In that machine, armature and field windings are fully pitched and hence the end-winding is long. Two single phase wound field SFMs topologies with DC field and AC armature windings having the same coil-pitch of 2 slot-pitches and having different coil-pitches of 1 and 3 slot-pitches respectively are discussed [16]. It is shown that the iron loss and copper loss of wound field SFM has been reduced and thus increased the efficiency.

This paper compares analysis of 12Slot-8Pole and 24Slot-10Pole wound field three-phase SFM having toothed-rotor structure and non-overlap armature and field winding. Design feasibility, working principle and performance analysis of 12 slots (6 slots for field excitation coil and 6 slots for armature coil) with 8 rotor pole numbers and 24 slots (12 slots for field excitation coil and 12 slots for armature coil) with 10 rotor pole numbers are compared on the basis of coil arrangement test, peak armature flux linkage, back emf, cogging torque, average torque and torque speed characteristics. FEA simulations, conducted via JMAG-Designer ver. 13.0 released

by Japan Research Institute (JRI) are used to study various characteristics of design. The term, “flux switching”, is created based on the changes in polarity of each flux in each stator tooth, depending on the motion of the rotor. When the rotor rotates, the fluxes generated by FEC link with the armature coil flux alternately.

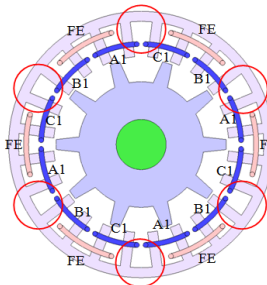


Fig. 1 Three-phase 24Slot-10Pole Wound field SFM

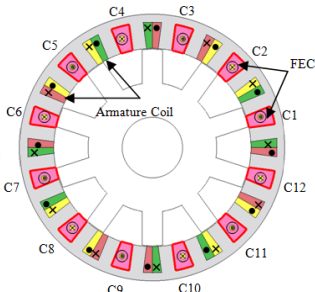


Fig. 2 24Slot-10Pole field excitation SFM with single DC FE Coil polarity

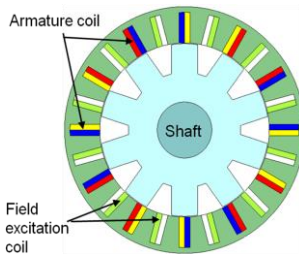


Fig. 3 Toothed-rotor wound field three-phase SFM

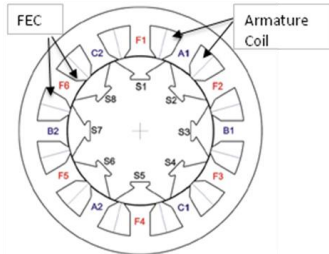


Fig. 4 Segmented-rotor wound field three-phase SFM

II. DESIGN METHODOLOGY OF THE PROPOSED WOUND FIELD SFM

In this paper, design study and performance analysis of the 24Slot-10Pole and 12Slot-8Pole wound field SFMs are investigated. The wound field SFMs configurations and dimensions are illustrated in Fig. 5 and Table I, respectively. From the structure, it is clear that 24Slot-10Pole wound field SFM is having 24 stator teeth and 10 rotor poles while in 12Slot-8Pole wound field SFM, 12 stator teeth are allocated for armature and field winding with 8 rotor poles. The DC FEC is wound in counter-clockwise polarity, while the three-phase armature coils are placed in between them. Salient rotor is used to modulate and switch the polarity of the flux linkage in the armature winding and this is the basic principle of operation of these types of machines.

Commercial FEA package, JMAG-Designer ver.13.0, released by Japan Research Institute (JRI) is used as 2D-FEA

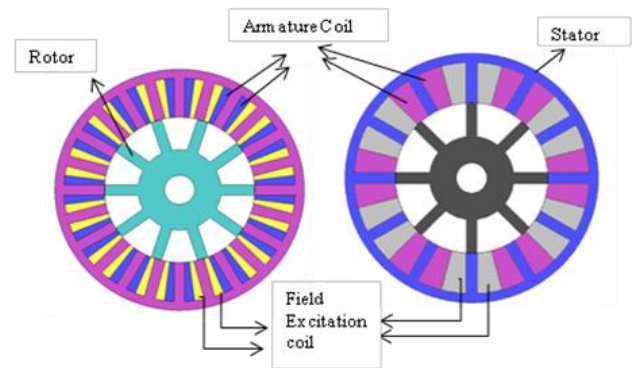


Fig. 5 24Slot-10Pole and 12Slot-8Pole Wound field SFMs with non-overlap winding and salient rotor

solver for this design. Firstly, JMAG Editor is used to draw the rotor, stator, armature coil and DC FEC. Then, the materials, conditions, circuits and properties of the machine are set in JMAG Designer. Furthermore, coil arrangement tests are examined to validate the operating principle of both wound field SFMs and to set the position of each armature coil phase. Then, the flux linkage, induced voltage and cogging torque are compared. Finally, the torque at various armature current densities, J_a of both wound field SFMs is also analyzed.

TABLE I. PARAMETER SPECIFICATIONS OF THE 24SLOT-10POLE AND 12SLOT-8POLE WOUND FIELD SFMS

Parameters	24Slot-10pole	12Slot-8pole
Number of rotor poles	10	8
Outer radius of stator	150mm	150mm
Outer radius of rotor	90mm	90mm
Motor stack length	80mm	80mm
Air gap length	3mm	3mm
Rated speed	1200rev/min	1200rev/min
Number of turns per field excitation coil slot	44	44
Number of turns per armature coil slot	44	44
Total armature slot area	414.14mm ²	1145.017 mm ²
Total field slot area	414.14mm ²	1145.017 mm ²
Back iron depth of stator	11mm	11mm

III. FEA BASED PERFORMANCE ANALYSIS

A. Coil arrangement test

Coil arrangement test are normally performed to confirm the operating principle of three-phase wound field SFM and set the position of each armature coil phase. The field excitation coils are wound in alternate direction. Field winding of 12Slot-8Pole is excited by applying 390.34A current and 141.185A is applied to the field winding of

24Slot-10Pole. Then flux linkage at each coil is observed. By comparing the flux linkages of different coils, the armature coil phases have 120° phase shift. The three-phase flux linkage waveforms, defined as U, V, and W are depicted in Fig. 6. From Fig. 6 it is obvious that 24Slot-10Pole has high flux linkage as compare to 12Slot-8Pole. This means that the 24Slot-10Pole configuration has possibility to provide higher torque and power. Flux linkage of 12Slot-8Pole is distorted due to harmonics and will further investigate in future.

B. Back Emf and Cogging Torque Analysis

At no load such that armature current, $I_a=0$, the induced voltage generated from field excitation coil with the speed of 1200 r/min for both machines are illustrated in Fig. 7. It is noticed that 24Slot-10pole has highest amplitude back emf of approximately 138.68 V, as compared to 12Slot-8Pole which has approximately 26.76 V.

The cogging torque analysis for both machines are examined by setting armature current density, $J_a=0$ and field current density J_e at maximum value such that J_e of 30 A/mm². Figure 8 shows the cogging torque investigation of wound field SFMs. 24Slot-10Pole wound field SFM has highest peak to peak cogging torque of approximately 32Nm while 12Slot-8Pole has least peak to peak cogging torque which is about 12Nm. Therefore, by further design refinement and optimization, it is expected that the cogging torque of the proposed machines can be reduced into an acceptable condition.

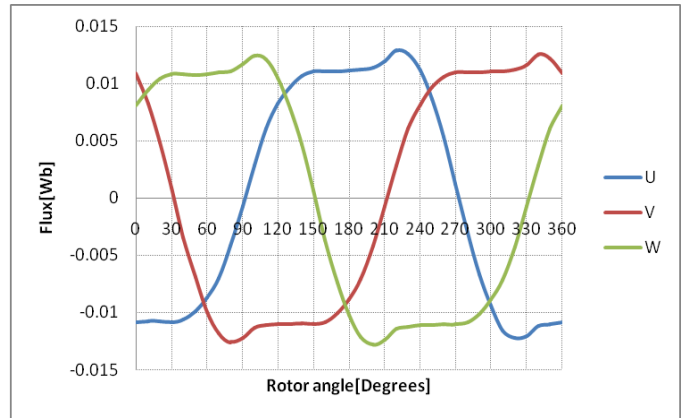


Fig. 6 Flux linkage of (a) 24Slot-10Pole and (b) 12Slot-8Pole in terms of U, V and W

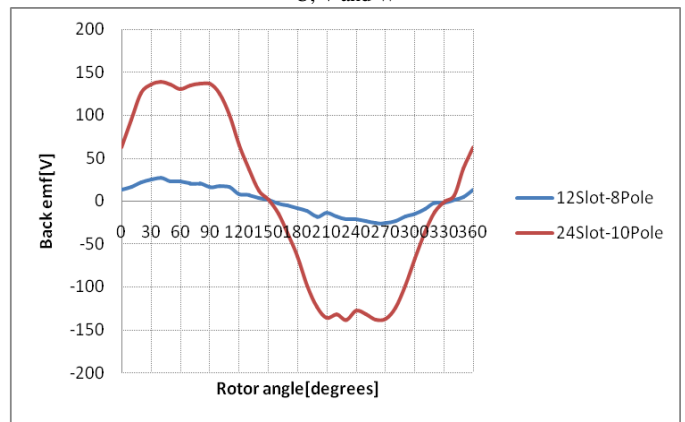


Fig. 7 Back emf waveform of wound field SFMs at 1200 rpm

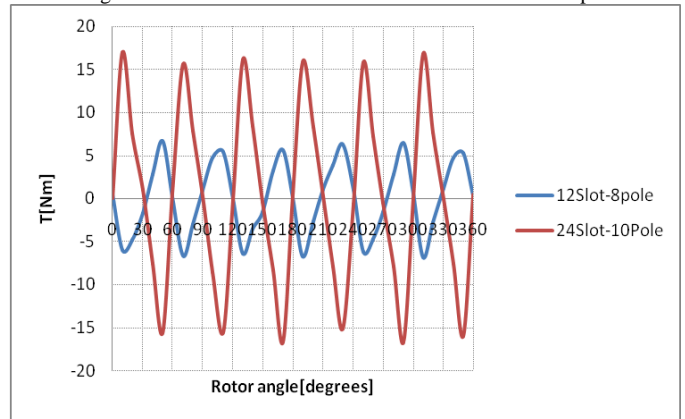


Fig.8 Cogging Torque

C. Torque Vs. Armature Current Density and Field Current Density Curves

The torque versus armature current density, J_a characteristics of 24Slot-10Pole and 12Slot-8Pole wound field SFMs at various field current densities, J_e are plotted in Figs. 9 and 10, respectively.

At low field current density, J_e of 5A/mm², the torque of 24Slot-10Pole is increased to 10Nm until armature coil current density, J_a of 10Arms/mm² and becomes constant when

armature current density is further increased. This is due to low field coil flux that limits the force to move the rotor. While in case of 12Slot-8Pole wound field SFM, the torque starts to increase at field coil current density, J_e of 5A/mm² until armature current density, J_a of 20 A/mm² and then decreases. At other values of field coil current densities, the torque increases by increasing armature current densities. Therefore, a good balance between field coil and armature coil current densities should be determined to get the required torque at specific condition while minimizing the copper loss.

The maximum torque of 72.36Nm for 24Slot-10Pole wound field SFM is obtained at maximum J_e and J_a of 30A/mm² while for 12Slot-8Pole, the maximum torque obtained is 57.97 Nm at J_e of 15A/mm² and J_a of 30 Arms/mm². Since the torque generated by 12S-8P wound field SFM are slightly less than 24S-10P wound field SFM, design improvement and optimization will be conducted in future.

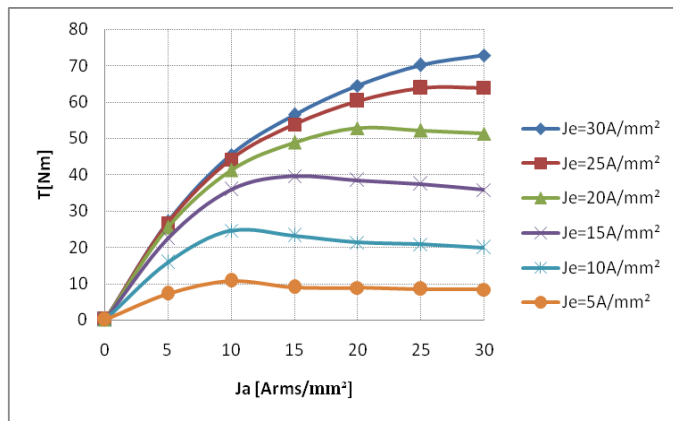


Fig. 9 Torque Vs. J_a at various J_e for 24Slot-10Pole

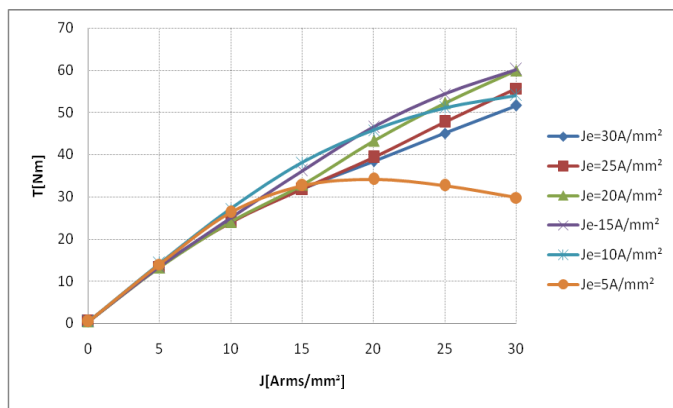


Fig. 10. Torque Vs. J_e at various J_a for 12Slot-8Pole

D. Torque Vs. Speed Characteristics

The torque vs. speed curves of wound field SFM are plotted in Fig. 11 and Fig. 12. At the base speed of 965.55 rev/min and 2106.83 rev/min, the maximum torque of 72.36Nm and 57.97Nm are obtained for 24Slot-10Pole and 12Slot-8Pole wound field SFMs. It is obvious from both figures that torque

starts to decrease if the machine is operated beyond the base speed.

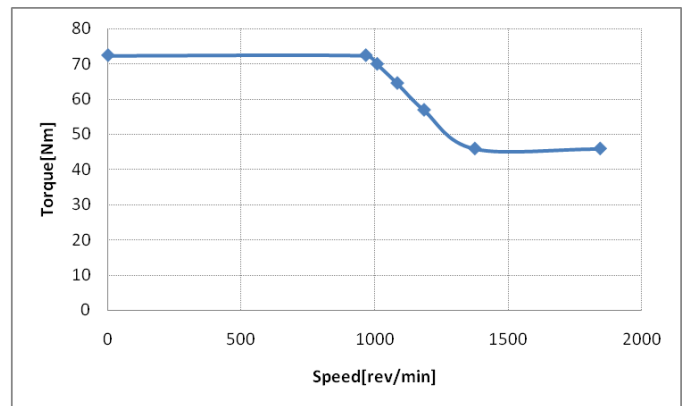


Fig. 11. Torque Vs. Speed characteristics for 24Slot-10Pole

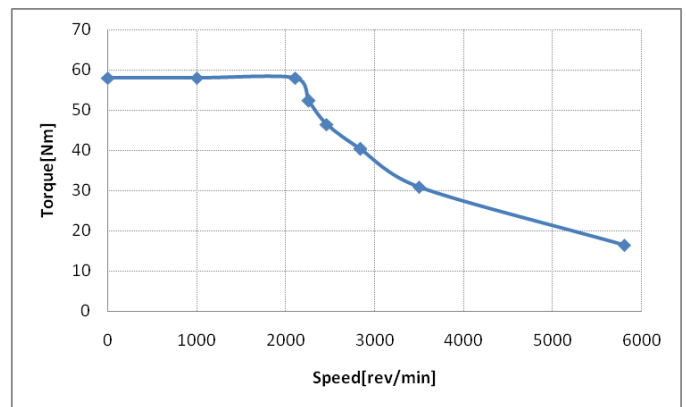


Fig. 12. Torque Vs. Speed characteristics for 12Slot-8Pole

IV. CONCLUSION

In this paper design study and performance comparison of 24Slot-10Pole and 12Slot-8Pole wound field three-phase salient rotor SFM with non-overlap armature and field winding have been investigated. In comparison with permanent magnet AC machines, these machines have low cost due to no permanent magnet and the field flux can be easily controlled. The procedure to design the wound field SFMs has been clearly explained. The coil arrangement test has been examined to validate each armature coil phase and to proof the operating principle of the machine. The performances of both wound field SFMs such as flux capability and torque have been investigated. The proposed machines have robust rotor construction and non-overlap winding and thus, they can be defined as simple configuration, low cost and high efficiency machines. Cogging torque of 24Slot-10Pole can be reduced and the flux linkage of 12Slot-8Pole can be further improved by design refinement and optimization.

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