Design and Characteristic Investigations of 12Slot-8Pole and 12Slot-10Pole Wound Field Three-Phase Switched-Flux Machines

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Abstract

In this paper, a new wound field salient rotor (WFSalR) switched-flux machine (SFM) with 12 stator poles and 10 rotor poles is designed, investigated, and compared with the same stator but 8 rotor poles WFSalR SFM. The main advantage of these SFMs when compared with induction machines, direct current (DC) machines etc is that, all the active parts such that armature coil and field excitation coil (FEC) are located on the stator while the rotor part consists of only single piece iron. This makes the machine more robust, simple structure and more suitable to be used for high speed applications. Concentrated windings at the stator reduce the copper consumption and also the copper losses. Initially, the general construction of WFSalR SFMs and design specifications are outlined. Then, finite element analysis (FEA) is used to investigate and compare the flux linkage, induced emf, cogging torque, average torque and torque speed characteristics of proposed WFSalR SFMs.

1 Introduction

Switched-Flux Machine (SFM) is a relatively new category of electric motor and over the last decade many novel and new SFM topologies have been developed for various applications, including automotive [1], home appliance [2], and aerospace [3]. High torque density and high efficiency dominated research on SFM by using permanent magnet (PM) for primary excitation. However, its application is limited by the high cost of rare earth magnet material i.e NdFeB and working environmental temperature. Additionally, it is difficult to operate the PMSFM at high speed in flux-weakening region due to fixed PM excitation. In order to reduce the cost, one of the possible solutions is to replace the PM by FEC. For this reason, some wound field SFMs are proposed for low cost applications [4-6].

Armature winding and field winding are located on the stator in these SFMs. The wound field SFM has advantages of low cost, simple construction, magnet-less machine, and variable flux control capabilities suitable for various performances when compare with other SFMs. Due to these advantages, a 24S-10P three-phase WFSalR SFM has been developed from 24S-10P PMSFM in which the permanent magnet is replaced by field excitation coil as shown in Figure 1 [7]. The total flux generation is limited because of adjacent DC field excitation coil isolation, as marked by red circles and thus machine performance is affected. To overcome the drawbacks, a new structure of 24S-10P and 24S-14P WFSalR SFM with single DC polarity have been introduced and compared as depicted in Figure 2 [8]. Although less leakage flux and uncomplicated manufacturing of single DC FEC are the advantages of proposed machine, but it has overlapping armature and field windings which increases the cost, copper losses and thus reduce the efficiency.

The performance of SFM is enhanced by using the segmental rotor configuration in recent research [9]. Segmental rotor is designed in a manner such that to achieve bipolar flux in the 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 wound field segmental rotor (WFSegR) SFM 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 4 [12] shows WFSalR SFM with overlap winding and WFSegR with non-overlap winding at the stator. A single-phase wound field SFM machine was comprehensively investigated in [13-15]. In that machine, armature and field windings are fully pitched and hence the end-winding is longer. Two single phase WFSalR 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 of WFSalR SFM has been reduced and thus increased the efficiency. These topologies have problems of overlap windings and unbalanced magnetic force.

This paper explains design comparison and characteristic investigations of 12Slot-8Pole and 12Slot-10Pole three-phase WFSalR SFM with non-overlap armature and field windings. FEA simulations, conducted via JMAG-Designer ver. 13.0 released by Japan Research Institute (JRI) are used to study various characteristics of these designs i.e flux linkage, back emf, cogging torque and average torque.
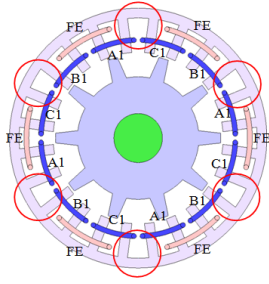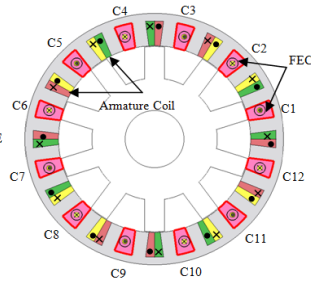
Fig. 1. Three-phase 24S-10P WFSalR SFM

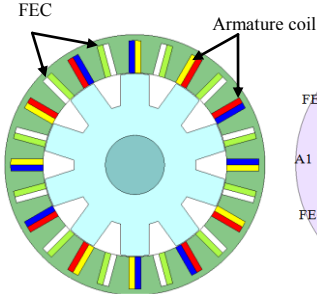Fig. 2. 24S-10P single DC WFSalR SFM

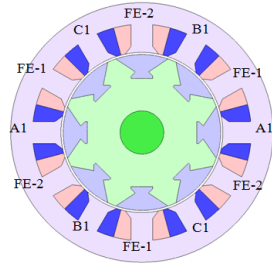Fig. 3. Three-phase WFSalR SFM with overlap windings

Fig. 4. Three-phase WFSegR SFM with non-overlap windings

2 SFM Construction

Figure 5 shows the two initially designed three-phase WFSalR SFMs with non-overlap windings. Both machines have 12 stator slots in which 6 slots are located for armature coil and another 6 for FEC while the rotor pole numbers is different. It should be noted that the position of phase V and W in 12Slot-10Pole WFSalR SFM have interchanged as compared to those in the 12Slot-8Pole WFSalR SFM, as can be seen from figure 5. To ensure flux moves from stator to rotor equally without any flux leakage, the summation of all stator tooth width is made equal to rotor tooth width. The dimensions of both WFSalR SFMs with non-overlap windings are illustrated in Table 1.

Parameters	12Slot-8Pole WFSalR SFM	12Slot-10Pole WFSalR SFM
Number of rotor poles	8	10
Outer radius of stator	75mm	75mm
Outer radius of rotor	45mm	45mm
Motor stack length	70mm	70mm
Air gap length	0.3mm	0.3mm
Rated speed	500 rev/min	500 rev/min
Turns per FEC slot	44	44
Turns per armature slot	44	44
Total armature slot area	232.22 mm^2	232.22 mm^2
Total FEC slot area	232.22 mm^2	232.22 mm^2
Width of stator pole	8mm	8mm
Width of rotor pole	12mm	9.6mm

Table 1: Design parameters of WFSalR SFMs
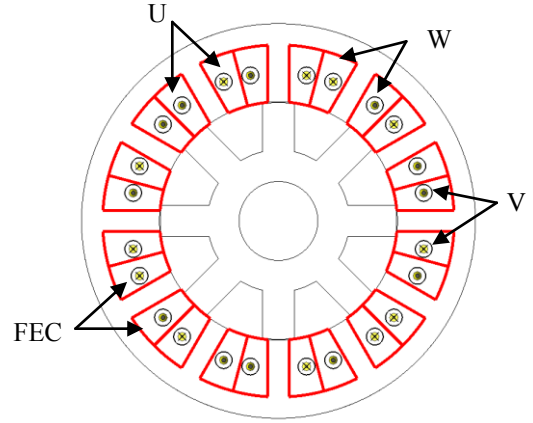
(a)
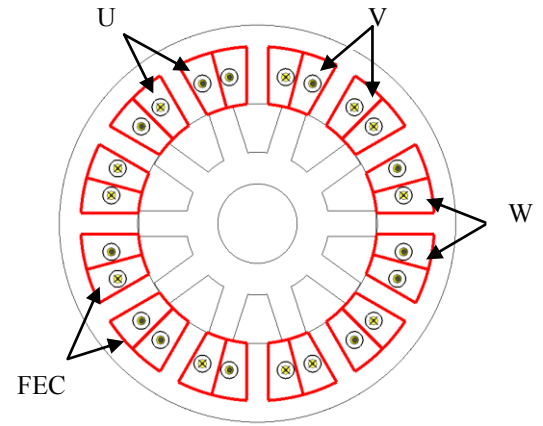
(b)

Fig. 5 WFSalR SFM with non-overlap windings (a) 12Slot-8Pole (b) 12Slot-10Pole

The selection of initial design parameters is based on the following assumptions: the initial rotor radius selected is approximately 60% to 70 % of total machine radius; the FEC slot area and armature coil slot area are set to be trapezoidal shape with same slot area.

3   Comparison of 12Slot-8Pole and 12Slot-10Pole WFSalR SFMs on basis of FEA

3.1 Flux linkage, Back emf and Cogging torque at open circuit condition

At no load such that armature current, I_a of 0A, the flux linkage of 12Slot-8Pole and 12Slot-10Pole WFSalR SFMs is shown in Figure 6. It is obvious form the graph that flux linkage of 12Slot-8Pole is not sinusoidal due to harmonics while the flux linkage of 12Slot-10Pole is sinusoidal. Similarly, the induced voltage generated from FEC with the speed of 500 rev/min for 12Slot-8Pole is distorted due to harmonics, as illustrated in Figure 7. It is noticed that, 12Slot-10Pole has high amplitude back emf of approximately 1.93 V whereas 12Slot-10Pole has the back emf amplitude of 1.4 V. Back emf at no load condition of both designs is less than applied voltage which makes it easy to provide

protection when the inverter is in off state due to some faults. The cogging torque analysis is examined by setting armature current density, J_a of 0 A_{rms}/mm^2 and field current density, J_e at maximum value of 30 A/mm^2. Figure 8 shows the cogging torque characteristics of WFSalR SFMs. 12Slot-8Pole WFSalR SFM has highest peak to peak cogging torque of approximately 22 Nm while 12Slot-10Pole has least peak to peak cogging torque which is almost half of 12Slot-8Pole
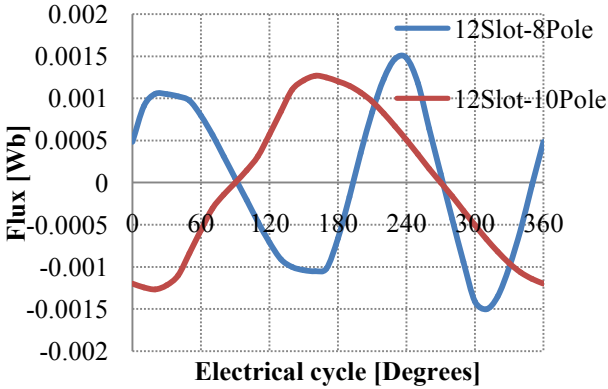

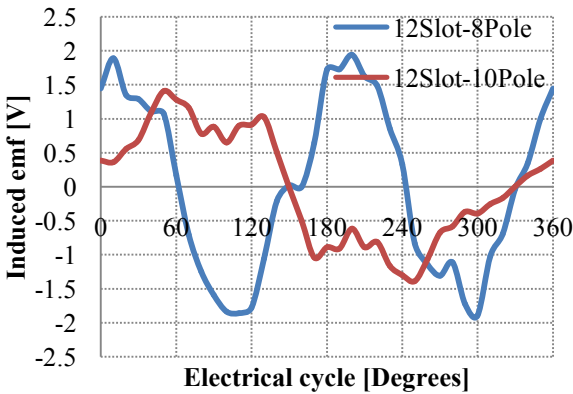Fig. 6. U-Phase flux linkage of WFSalR SFMs

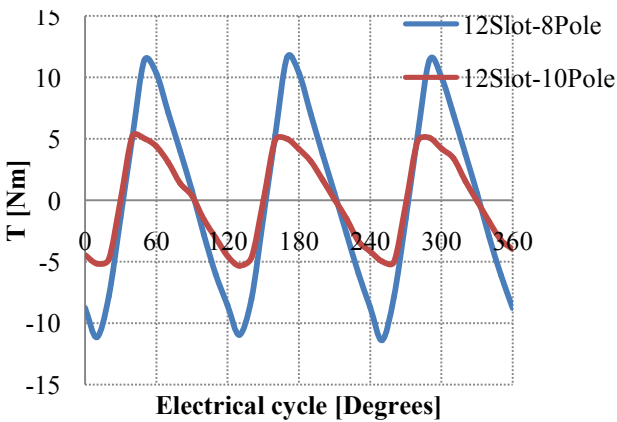
Fig. 7. Induced EMF at 500 rev/min

Fig. 8. Cogging torque

WFSalR SFM. As high cogging torque increases mechanical stress on rotor, causes vibration in machine and makes it noisy, therefore by further design refinement and optimization, the cogging torque of both designs can be reduced to an acceptable condition.

3.2 Effect of rotor pole width on 12Slot-8Pole WFSalR SFM with non-overlap windings

The flux linkage and back emf waveforms of 12Slot-8Pole WFSalR SFM is distorted due to odd harmonics which are investigated in this section. The effect of harmonics can be reduced by rotor pole width variation. The waveform of flux linkage became sinusoidal, and the cogging torque is reduced from 22 Nm to 5 Nm, as the rotor pole width is decreased from 12mm to 6mm, illustrated in Figure 9 and Figure 10. It is noticed that, when the rotor pole width is varied from 12mm to 6mm, the amplitude of flux linkage is increased and the magnitude of odd harmonics 5,7,11 etc are also decreased, as depicted in Figure 11. 12Slot-8Pole WFSalR SFM with 6mm rotor pole width will be considered for further evaluation, as the flux linkage became sinusoidal and the cogging torque is reduced.
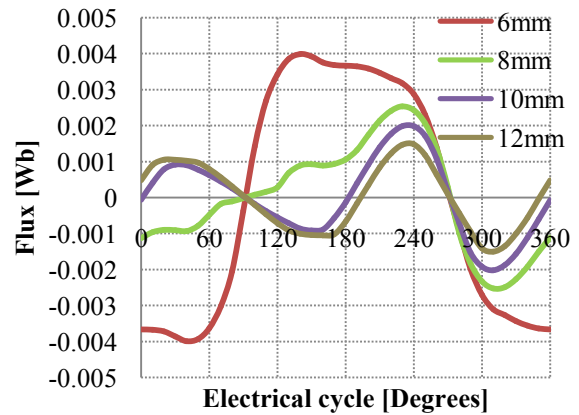

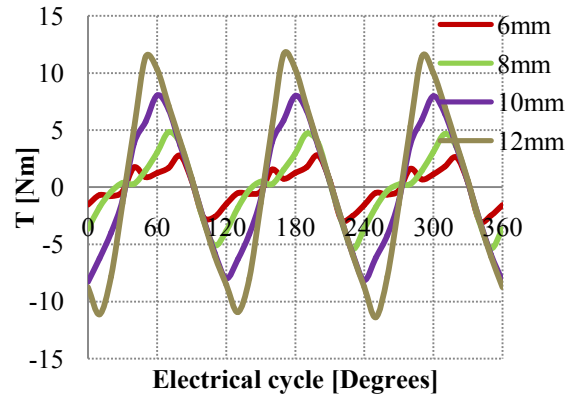Fig. 9. U-phase flux linkage with rotor pole width variation

Fig. 10. Cogging torque with rotor pole width variation

3.3 Torque vs. Armature current density and Field current density

The torque vs. armature current density, J_a curves for various field current density, J_e is shown in Figure 12 and Figure 13. Form both graphs, the same pattern of linear increment of torque with respect to increase in J_e and J_a is observed. At field current density, J_e of 20A/mm^2 and 25A/mm^2, the torque produced by 12Slot-8Pole WFSalR SFM is 7.61 Nm. The torque of 12Slot-10Pole is 13.21 at J_e of 20 A/mm^2 and J_a of 30 A$_{rms}$/mm^2 approximately double to 12Slot-8Pole WFSalR
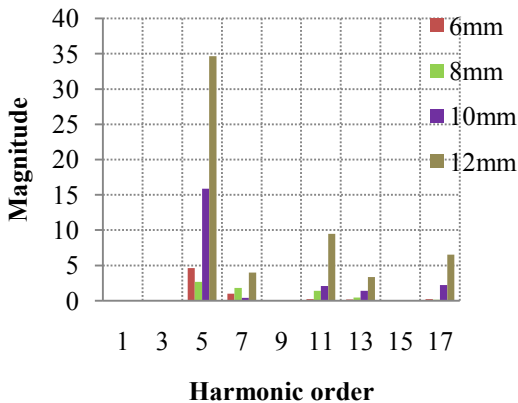

Fig. 11. Magnitude of harmonics with different rotor pole width
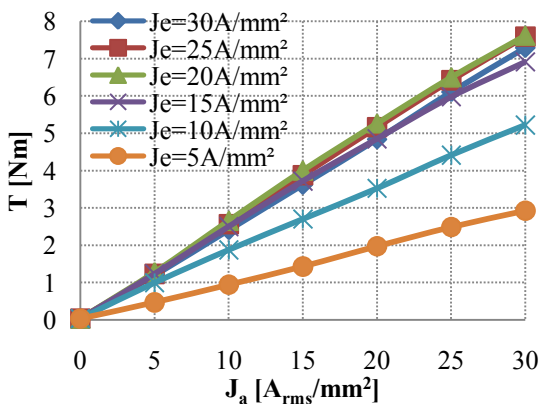

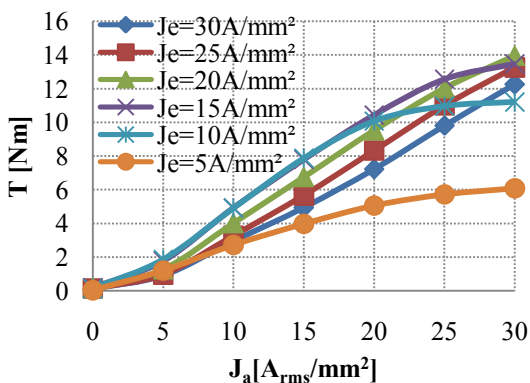Fig. 12. Torque Vs. J_a at various J_e for 12Slot-8Pole

Fig. 13. Torque Vs. J_a at various J_e for 12Slot-10Pole

SFM. 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.

3.4 Torque and Power vs. Speed Characteristics

The torque and power versus speed curves of 12Slot-8Pole and 12Slot-10Pole WFSalR SFMs are plotted in Figure 14. At the base speed of 3145.27 rev/min and 2263.31 rev/min, the maximum torque of 7.61 Nm and 13.94 Nm is obtained and torque starts to decrease if the machine is operated beyond the base speed. Moreover, both WFSalR SFMs has high speed at light load condition and the speed reduces by increasing the load. Various speed control methods can be used in future to operate these motors at variable load conditions. The power accomplished by 12Slot-8Pole WFSFM at base speed of 3145.27 rev/min is 2.49 kW and starts to reduce until 1.1 kW at higher speed of 6080.85 rev/min due to increase in iron loss while the power achieved by 12Slot-10Pole WFSFM is 3.2 kW at maximum torque and base speed of 2263.31 rev/min.
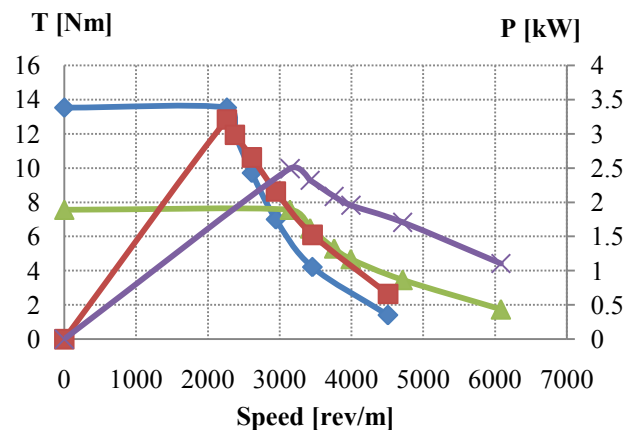

Fig. 14. Torque and power vs. speed characteristics for 12Slot-8Pole and 12Slot-10Pole WFSalR SFMs

4   Conclusion

Two types of WFSalR SFMs 12Slot-8Pole and 12Slot-10Pole with non-overlap armature and field windings are designed and 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 performances of both WFSalR SFMs such as flux capability and torque have been examined. The proposed machines have robust rotor construction and non-overlap windings and thus, they can be defined as simple configuration, low cost and high efficiency machines. Due to replacement of segmental rotor by salient rotor, the mechanical strength of the WFSalR SFM is improved and becomes more suitable for high speed applications. Cogging torque of 12Slot-8Pole is reduced and the flux linkage is improved by rotor pole width variation. Average torque of both designs can be further improved by design refinement and optimization.

Acknowledgements

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