Comparative Study of 24Slot-10Pole and 24Slot-14Pole Three-Phase Wound Field Salient Rotor Switched-Flux Motor

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***Abstract*—For high speed operation, two new structures of three-phase wound field salient rotor (WFSR) switched-flux motor (SFM), with 24 stator slot and 10 or 14 rotor poles, respectively, are proposed and comparatively studied in this paper. 24Slot-10Pole WFSR SFM structure is superior to the 24Slot-14Pole in the aspects of flux linkage and average torque. 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 motors 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 and average torque of both machines are analyzed and compared by two-dimensional finite element analysis(2D- FEA).**

***Index Terms*—Low cost, wound field switched-flux motor, 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 field excitation SFM 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 they have overlapping armature and field windings 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 in [13-15]. 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 24Slot-10Pole and 24Slot-14Pole WFSR SFM having toothed-rotor structure and non-overlap armature and field windings. Design feasibility, working principle and performance analysis of 24 slots (12 slots for field excitation coil and 12 slots for armature coil) with 10 and 14 rotor pole numbers are compared on the basis of coil arrangement test, peak armature flux linkage, back emf, cogging torque and average torque. 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.

II. Design Methodology Of The Proposed WFSR SFM

In this paper, design study and performance analysis of the 24Slot-10Pole and 24Slot-14Pole WFSR SFMs are investigated. The WFSR SFMs configurations and dimensions are illustrated in Fig. 5 and Table I, respectively. From the structure, it is clear that 24Slot-10Pole WFSR SFM is having 24 stator teeth and 10 rotor poles while in 24Slot-14Pole WFSR SFM, 24 stator teeth are allocated for armature and field windings with 14 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**.**

The proposed motors have very simple structure where all the FEC and armature slots are in trapezoidal shape and all coils are concentrated windings. In this study, the possible number of rotor pole and stator slot is defined by

$$N_r = N_s\left(1 \pm \frac{k}{2q}\right) \tag{1}$$

where N_r is the number of rotor poles, N_s is the number of stator slots, k is the natural entity having value 1,2,3,… and q is the number of phases. Whereas, the electrical frequency, f_e of

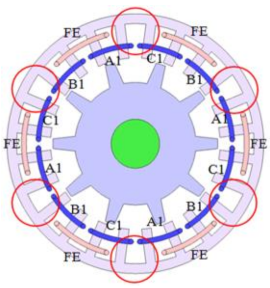


Fig. 1 Three-phase 24S-10P Wound Field SFM

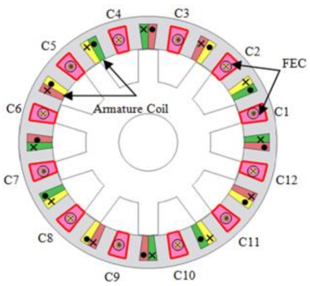


Fig. 2 24S-10P single DC Field Excitation SFM

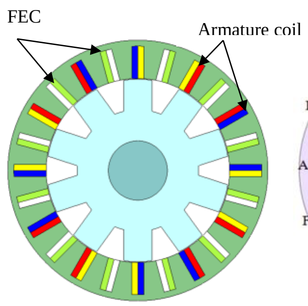


Fig. 3 Three-phase Wound Field SFM with overlap windings

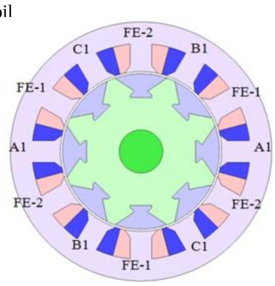
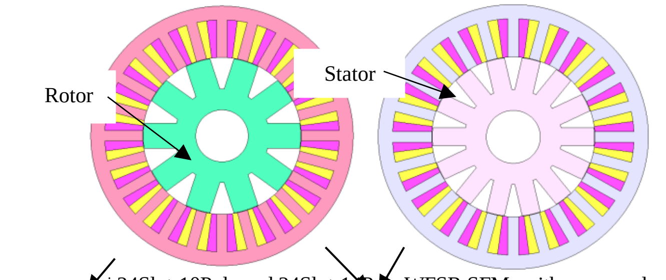


Fig. 4 Three-phase Wound Field SFM with non-overlap windings



; 24Slot-10Pole and 24Slot-14Pole WFSR SFMs with non-overlap winding … nt rotor

the proposed motors can be expressed by

$$f_e = N_r \cdot f_m \tag{2}$$

where f_e is the electrical frequency, f_m is the mechanical rotation frequency and N_r is the number of rotor poles respectively.

The FEC and armature coil current are calculated using (3) and (4), respectively. The motor's filling factor is set at 0.5, the number of turns have fixed value while the slot area of armature coil slot and FEC slot is set, correspondingly. To ensure flux moves from stator to rotor equally without any flux leakage, the design of the proposed machines is defined as in (5).

$$I_e = \frac{J_e \alpha S_e}{N_e} \tag{3}$$

$$I_a = \frac{J_a \alpha S_a}{N_a} \tag{4}$$

$$\sum \text{Stator Tooth Width} = \sum \text{Rotor Tooth Width} \tag{5}$$

Where N, J, α, S and I are number of turns, current density, filling factor, slot area and input current, respectively. The subscript a and e represent armature coil and FEC.

PARAMETER SPECIFICATIONS OF THE 24SLOT-10POLE AND 24SLOT-14POLE WFSR SFMS

Parameters	24Slot-10Pole	24Slot-14Pole
Number of rotor poles	10	14
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	500rev/min	500rev/min
No. of turns of FEC	44	44
No. of turns of armature coil	44	44
Total armature slot area	94.36mm^2	94.36 mm^2
Total field slot area	94.36mm^2	94.36 mm^2
Stator pole width	6mm	6mm

Rotor pole width	14.4mm	10.28mm

Commercial FEA package, JMAG-Designer ver.13.0, released by Japan Research Institute (JRI) is used as 2D-FEA 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 WFSR 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, Ja of both wound field SFMs is also analyzed.

III. FEA Based Performance Analysis

A. Coil arrangement test

Coil arrangement test are normally performed to confirm the operating principle of three-phase WFSR SFM and set the position of each armature coil phase. The field excitation coils are wounded in alternate direction. Field winding of 24Slot-10Pole and 24Slot-14Pole is excited by applying 32.16A current. Then flux linkage at each coil is observed. By comparing the flux linkages of different coils, the armature coil phases have 120^0 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 24Slot-14Pole. This means that 24Slot-10Pole configuration has possibility to provide higher torque.

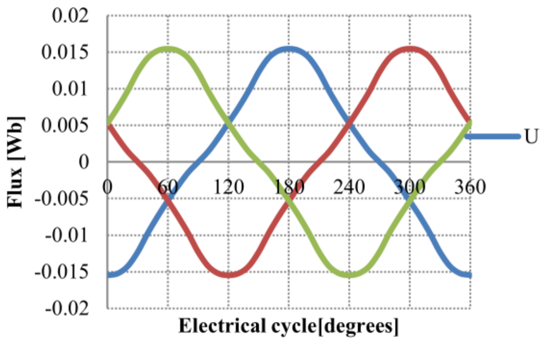
B. Back Emf and Cogging Torque Analysis

At no load such that armature current, Ia=0, the induced voltage generated from field excitation coil with the speed of 500 rev/min for both machines are illustrated in Fig. 7. It is noticed that 24Slot-10pole has highest amplitude back emf of approximately 12.75 V, as compared to 24Slot-14Pole which has approximately 4.97 V.

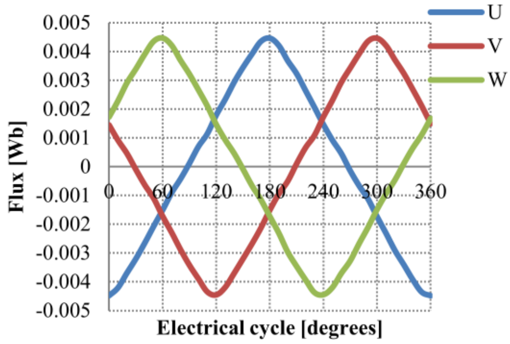
The cogging torque analysis for both machines are examined by setting armature current density, Ja=0 and field current density Je at maximum value such that Je of 30 A/mm^2. Figure 8 shows the cogging torque investigation of WFSR SFMs. 24Slot-10Pole WFSR SFM has highest peak to peak cogging torque of approximately 4.5 Nm while 24Slot-14Pole has least peak to peak cogging torque which is about 4 Nm. Therefore, by further design refinement and optimization, it is expected that the cogging torque of the proposed motors can be reduced into an acceptable condition.

C. Flux linkage and Torque versus Armature Current Density and Field Current Density Curves

Flux linkages at maximum armature current density, Ja of 30 Arms/mm^2 for various field current densities, Je are shown in Fig. 9. From the figure, it is obvious that the magnitude of flux linkage increases by increasing Je while the value decreases at Je of 15 A/mm^2 due to flux cancellation effect.



(a)



(b)

Fig. 6 Flux linkage of (a) 24Slot-10Pole and (b) 24Slot-14Pole in terms of U, V and W

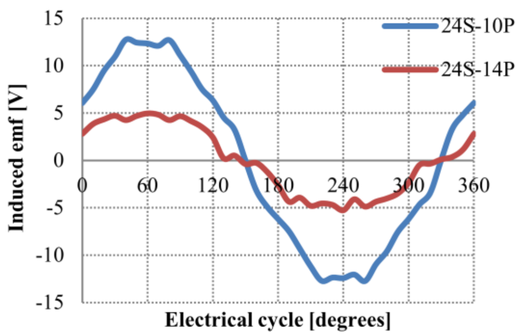


Fig. 7 Induced emf waveform of wound field SFMs at 500 rev/m

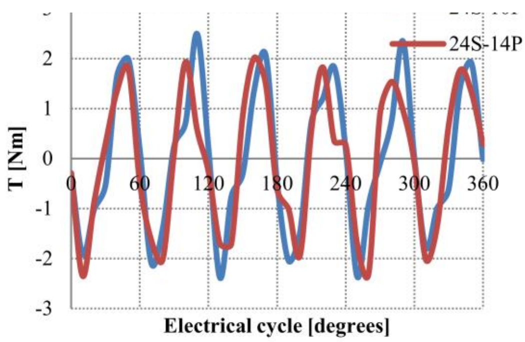


Fig.8 Cogging Torque

The torque versus armature current density, Ja characteristics of 24Slot-10Pole and 24Slot-14Pole WFSR SFMs at maximum field current densities, J_e of 30 A/mm^2 are plotted in Fig. 10. The maximum torque of 4.73 Nm for 24Slot-10Pole WFSR SFM is obtained at maximum Je and Ja of 30A/mm^2 while for 24Slot-14Pole, the maximum torque obtained is 2.62 Nm at Je and Ja of 30 A/mm^2. Since the torque generated by 24Slot-14Pole WFSR SFM are almost half of 24Slot-10Pole WFSR SFM, design improvement and optimization will be conducted in future.

The maximum torque obtained is still far from the target requirements. In order to satisfy the target performances, design free parameters of X1 to X7 are defined as illustrated in Fig. 11 will be conducted in the future. The design parameters are divided into three groups such as those related with rotor core shape, FEC slot shape and armature coil slot shape as follows:

(i) Rotor parameters including rotor radius (X1), rotor pole depth (X2) , and rotor pole width (X3)
(ii) Armature coil slot parameters including armature coil slot width (X4) and armature slot depth (X5).
(iii) FEC slot parameters including FEC slot width (X6), and FEC slot depth (X7).

The first step is carried out by updating the rotor

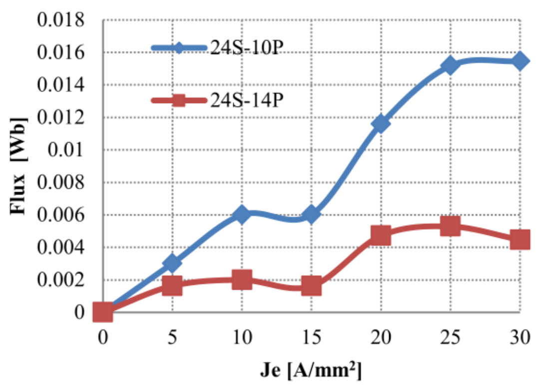


Fig. 9 Flux linkage vs. various field current densities, Je at no load condition

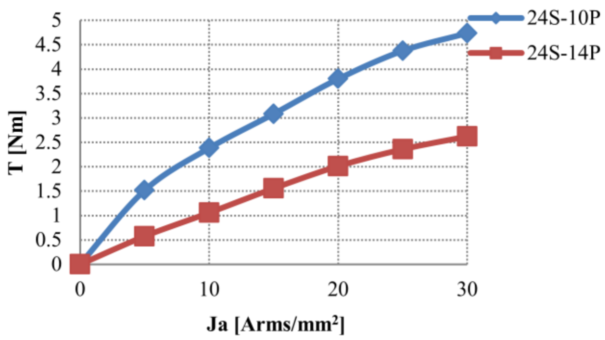


Fig. 10 Torque vs. Ja at Je of 30 A/mm^2 for 24Slot-10Pole and 24Slot-14Pole

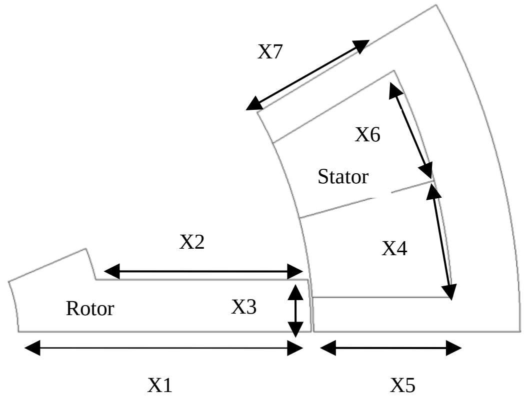


Fig. 11 Design parameters of WFSR SFM

parameters, X1, X2 and X3 while keeping X4 to X7 as constant. According to general theory in which the torque is directly proportional to the rotor radius, X1 that can be declared as one of the dominant parameter to increase the torque, is firstly updated. In this condition, X5 and X7 are simply shifted to the new position by following the change of X1, while X2, X3, X4, and X6 are kept constant.

Subsequently, keeping X1 at the optimum value producing the highest torque, the rotor pole depth and width X2 and X3, respectively, are adjusted. In turn, keeping X1, X2 and X3 at each optimum value producing the highest torque, the second step is executed by changing the armature coil slot parameters X4 and X5 while keeping X6 and X7 as given initially. Then, the best combination of X4 and X5 which bring out well balanced performance in terms of the maximum torque and power capabilities can be found under the given ampere turns of FEC windings corresponding to the given X6 and X7.

Finally, the FEC width, X6 and the FEC depth, X7 are also considered as the most important parameter that is possible to extract much performance of the machine. This will easily increase the performance of the machine. The design methods explained above are treated repeatedly by changing X1 to X7 until the maximum torque and power are achieved [17-19].

IV. CONCLUSION

In this paper design study and performance comparison of 24Slot-10Pole and 24Slot-14Pole three-phase WFSR with non-overlap armature and field windings have been investigated. The procedure to design the WFSR 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 WFSR SFMs such as flux capability and torque have been investigated. Both 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 24Slot-14Pole can be further improved by design refinement and optimization.

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References

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

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

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

[4] 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, Oct. 2011, pp. 4453-4456.

[5] 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 , Jan 2012, pp.211-218.

[6] F.Khan, E. Sulaiman, M.Z. Ahmad "Coil test analysis of wound-field three-phase flux switching machine with non-overlap winding and salient rotor" *IEEE 8th International Power Engineering and Optimization Conference (PEOCO)*, 2014, pp.243-247.

[7] 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,pp.1-6.

[8] 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.*, 2013, pp. 46-51.

[9] B.C. Mecrow, E.A. El-Kharashi, J.W. Finch, and A.G.Jack, "Segmental rotor switched reluctance motors withsingle-tooth windings", *IEE Proc. on Power Applications*, vol. 150, no. 5, 2003, pp. 591-599.

[10] Erwan Bin Sulaiman, Takashi Kosaka and Nobuyuki Matsui "Design Study and Experimental Analysis of Wound Field Flux Switching Motor for HEV Applications" *2012 XXth International Conference on Electrical Machines (ICEM*), Sep 2012, pp. 1269 -1275

[11] A. Zulu, B.C. Mecrow, M. Armstrong"Topologies for three-phase Wound field Segmented-Rotor flux switching Machines" *5th IET International Conference on Power Electronics, Machines and Drives (PEMD)*, 2010, pp.1-6

[12] Ackim Zulu, Barrie C. Mecrow, and Matthew Armstrong "A Wound-Field Three-Phase Flux-Switching Synchronous Motor With All Excitation Sources on the Stator" *IEEE Transactions on Industry Applications*, Vol. 46, NO. 6, November/December 2010, pp.2363-2371

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

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

[15] 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, Sep./Oct. 2006, pp. 1177-1184.

[16] Y. J. Zho, and Z. Q. Zhu "Comparison of low-cost single-phase wound-field switched-flux machines" *Electric Machines & Drives Conference (IEMDC), 2013 IEEE International,* 2013, pp. 1275 - 1282

[17] X. D. Xue, K. W. E. Cheng, T. W. Ng, N. C. Cheung, "Multi objective optimization design of in-wheel switched reluctance motors in electric vehicles", *IEEE Trans. Ind. Electron.*, vol.57, no.9, pp.2980-2987, Sept. 2010.

[18] 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. on Industry Appl., vol. 132, No. 2, Sec. D*, pp. 211-218, 2012.

[19] E. Sulaiman, T. Kosaka, and N. Matsui, "FEA-based Design and Parameter Optimization Study of 6-slot 5-pole PMFSM with Field Excitation for Hybrid Electric Vehicle," *IEEE International Conference on Power and Energy (PECon 2010)*, pp. 206-201, Dec 2010.