



COMPARISON BETWEEN SINGLE-PHASE AND THREE-PHASE FEFSM WITH NON-OVERLAP WINDINGS AND SALIENT ROTOR

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ABSTRACT

This paper presents a comparison between single-phase 12S-6P and three-phase 12S-10P field excitation flux switching machine (FEFSM) with non-overlap windings and salient rotor. Based on the previous designs, three-phase FEFSM and single-phase FEFSM have been developed with the overlap windings between armature and FEC which create problems of high end coil, increase the size of the motor and high copper losses. Moreover, the previous designs has odd number of pole caused unbalance magnetic forces. Therefore, a single-phase 12S-6P FEFSM and three-phase 12S-10P FEFSM with non-overlap windings and salient rotor is introduced to reduce the coil end problem. In this study, the operating principle of single-phase and three-phase salient rotor is also investigated. Then, flux line, flux distribution, induced voltage, torque and power versus speed validated with 2D-finite element analysis. Finally, the comparison of torque and power versus speed between two designs is highlighted. As a conclusion, three-phase 12S-10P FEFSM design is much better because at the based speed of 3597r/min, torque obtained is 13.5Nm, while the maximum power achieved is 3.2kW.

Keywords: comparison, field excitation flux switching machine (FEFSM), single-phase, three-phase, non-overlap winding, salient rotor.

INTRODUCTION

AC machine have three kinds namely induction motor (IM), switched reluctance motor (SRM) and synchronous motor (SM). Induction motors use shorted wire loops on a rotating armature and obtain their torque from currents induced in these loops by the changing magnetic field produced in the stator coils. The switched reluctance motor is an electric motor that runs by reluctance torque (Yanling and Weiping, 2010), while the synchronous motor is driven by AC power consisting of two basic components a stator and rotor. At present, the flux switching machine (FSM) is one of a new category in the hierarchy electric motor, where it belongs in the category of synchronous motor as illustrated in Figure-1.

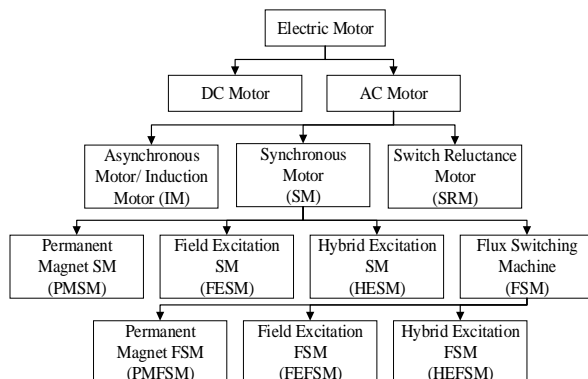


Figure-1. The hierarchy of the electric motors.

FSM is a machine in which all sources flux (armature coil and FEC) is placed in the stator with the single rotor and this had enabled it to be used at various performances as well as various speed applications (Sulaiman, Kosaka, and Matsui, 2010b), (Sulaiman, Kosaka, and Matsui, 2010a). The early growth of FSM that is a single-phase 4S-4P permanent magnet FSM with limited angle actuator or more well-known as Laws relay has been introduced and published in 1952 (A.E. Laws, 1952). It has been extended to a single-phase generator with 4 stator slots and 4/6 rotor poles (4S-4P and 4S-6P) (Rauch and Johnson, 1955). Many novel and new FSMs topologies have been developed for various applications, ranging from low cost domestic appliances, automotive, wind power, aerospace, as well as traction drive over the last decade (Amara, Hoang, Gabsi, Lécrivain, and Allano, 2005), (Hua, Cheng, and Zhang, 2009). FSMs is divided into three main groups, namely permanent magnet FSM (PMFSM), field excitation FSM (FEFSM) and hybrid excitation FSM (HEFSM). Each type of FSM has different features, where PMFSM and FEFSM use PM and FE, respectively in the stator as the primary source for generating flux, while HEFSM combine PM and FE in the stator as the main flux sources (Pollock *et al.*, 2003), (Sulaiman, Kosaka, and Matsui, 2011).

The three-phase FEFSM and single-phase FEFSM has been developed with the overlap windings between armature and FEC have several complications such as high end coil and it gives the effect of increasing the size of the motor and losses. In the meantime, odd number of pole caused unbalance magnetic forces (Sulaiman, Teridi, Husin, Ahmad, and Kosaka, 2013),



(Zhou and Zhu, 2013), (Zulu, Mecrow, and Armstrong, 2010). Figure-2 shows the single-phase and three-phase topologies of FEFSM. Therefore, a single-phase 12S-6P FEFSM and three-phase 12S-10P FEFSM with non-overlap winding and salient rotor is introduced to reduce the coil end problem, also reduce copper loss and robust rotor enhance their capability to be applied for various speed application.

This paper presents a comparison between single phase 12S-6P and three phase 12S-10P field excitation flux switching machine (FEFSM) with non-overlap winding and salient rotor.

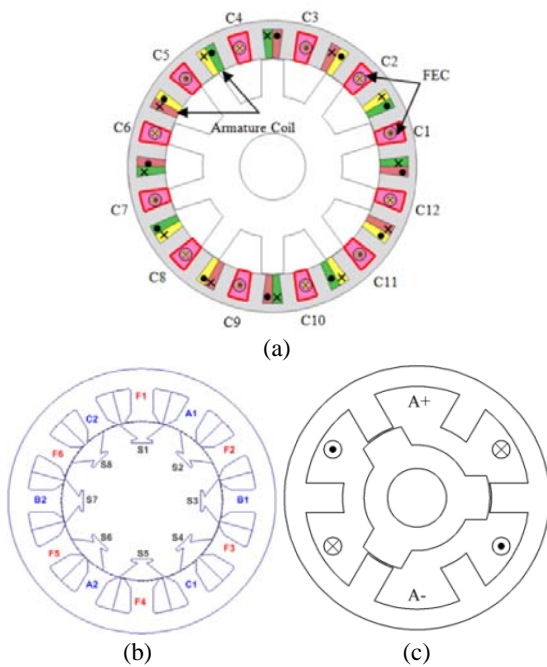


Figure-2. FEFSM (a) 3-Phase 24S-10P with overlap winding (b) 3-phase 12S-8P with segmental rotor (c) 1-phase 6S-3P with odd number of rotor poles.

Parameters and configurations of FEFSM

The machine configurations for three-phase 12S-10P FEFSM and single-phase 12S-6P FEFSM are demonstrated in Figure-3 and Figure-4, respectively. From the machine structure, both designs have non-overlapping windings and in the middle of stator has the salient rotor that have even number of poles. The windings coils of armature are placed in between of FE coils, while the winding directions of the FECs are in counter clockwise polarity and clockwise polarity.

Table-1 shows the design restrictions, specifications and parameters for both FEFSMs. 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 FEFSMs.

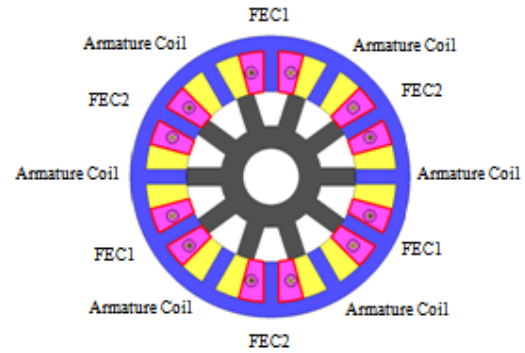


Figure-3. Three-Phase 12S-10P FEFSM.

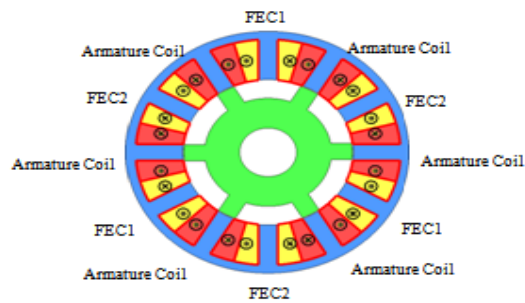


Figure-4. Single-Phase 12S-6P FEFSM.

Table-1. Design restrictions, specifications and other parameters.

Items	3-Ø 12S-10P FEFSM	1-Ø 12S-6P FEFSM
Type of phases	3	1
Number of slots	12	12
Number of poles	10	6
Outer radius of stator(mm)	75	75
Inner radius of stator (mm)	68	70
Back inner of stator (mm)	7	5
Tooth width of stator (mm)	8	10
Armature coil area (mm ²)	232.2	251.2
FEC area (mm ²)	232.2	251.2
Outer radius of rotor (mm)	45	44.5
Inner radius of rotor (mm)	14	15
Tooth width of rotor (mm)	9.6	10
Radius of shaft (mm)	14	15
Space of Air gap (mm)	0.3	0.5
Turns per FEC slot area	44	75
Turns per armature coil slot area	44	11



Commercial 2D-FEA package, JMAG-Designer ver. 13.0 is used as a 2D-FEA solvent for this design. Firstly, with JMAG Geometry Editor, the rotor, stator, armature coil and FEC of the proposed 3-phase 12S-10P FEFSM and 1-phase 12S-6P FEFSM is drawn. Then JMAG Designer used to set up of circuits, conditions, materials and properties of the machine. The design, implementation of the proposed FEFSM is drawn as in Figure-5.

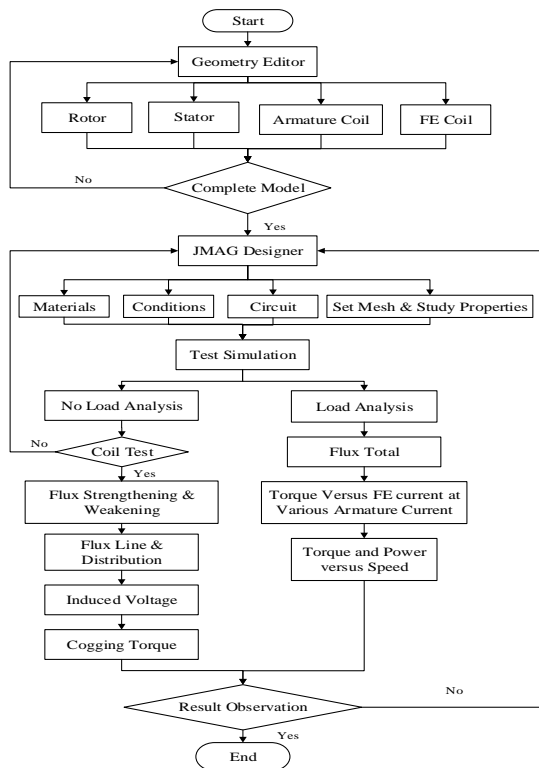


Figure-5. Design implementation of the proposed FEFSM.

The body of the stator and rotor materials is made from an electrical steel 35H210, while the copper is used for armature coil and FEC. The FEFSMs was tested in the form of two main parts, namely the analysis of the no-load analysis and load analysis. At no-load analysis, the coil test arrangement test need to be evaluated in order to verify the operating principle of the machine and to situate the position of each armature coil phase. Furthermore, to ensure the machine operates under the principle of FEFSMs, coil tests have been carried out. The strength of flux, flux line and distribution, induce voltage and the cogging torque are also investigated in the no load analysis.

PERFORMANCES OF FEFSMS

Coil arrangement test

The coil arrangement test is examined from 6 armature coils 3-phase FEFSM and 1-phase FEFSM separately in order to confirm the principle of the FEFSMs. Then, a DC and AC is supplied to the FECs as well as armature coils at maximum current density, J of 30 A/mm². The resulting flux linkages at each armature coil are compared and the three-phase armature coils are defined according to the conventional 120° phase shifted between all phases. Figure-6 illustrates the three-phase flux linkage of 12S-10P FEFSM defined as U, V, and W, respectively. The maximum flux linkages produce is 0.013Wb. Figure-7 illustrates the maximum flux linkage for single-phase 6P-12S is 0.09Wb and the graph indicates that flux linkage at armature coil 90° leads the flux linkage of FE coils. Thus, single-phase and three-phase sinusoidal flux linkages are successfully achieved which confirmed the basic principle of operation of FEFSMs.

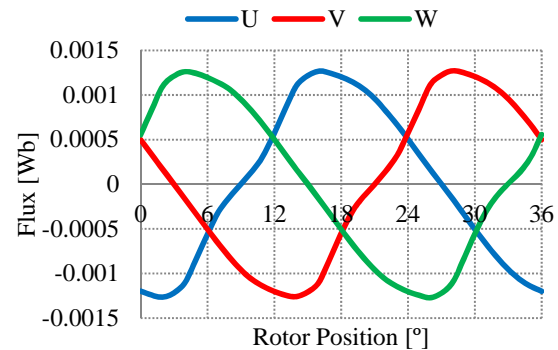


Figure-6. Flux linkage of three-phase 12S-10P FEFSM.

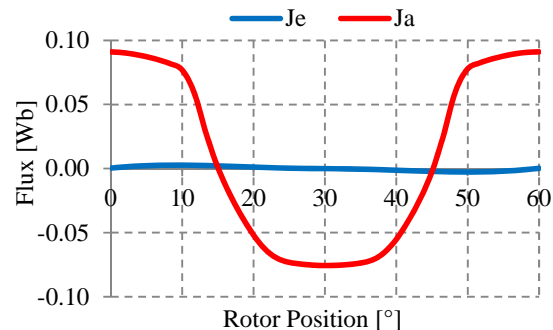


Figure-7. Flux linkage of single-phase 12S-6P FEFSM.

Flux scattering at various FEC current densities, J_E

Figure-8 shows the flux distribution at various FEC current densities, J_E .

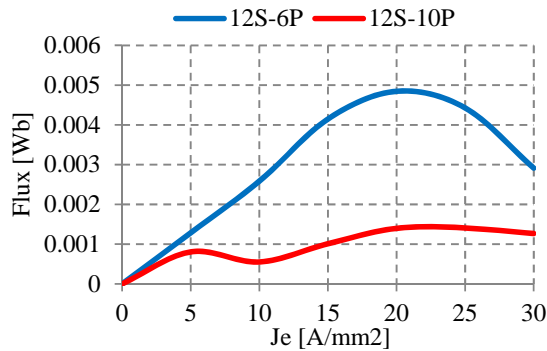


Figure-8. Flux distribution at various FEC Current Densities, J_E .

From graph, it is obvious that flux increase linearity until FEC current density, J_E of 20A/mm² for single-phase 12S-6P FEFSM. For three-phase 12S-10P FEFSM flux distribution is fluctuating, such that the distribution of the flux increase at the initial stage, and slightly decreased at J_E 5A/mm² and slightly increased again until J_E 25A/mm². Table-2 shows the value input current FEC, A_E for each FEC current density, J_E . The flux patterns increase linearly and then decrease due to several factors: (i) the flux flows in the opposite direction cancel the main flux, (ii) leakage flux decreased flux distribution in the stator and rotor core.

Table-2. Various input FEC current densities, J_E .

FEC current density, J_E (A/mm ²)	Input current, A_E for 3-Phase 12S-10P	Input current, A_E for 1-Phase 12S-6P
5	13.19	8.37
10	26.38	16.75
15	39.56	25.12
20	52.75	33.49
25	65.94	41.87
30	79.13	50.24

In the meantime, the resulting flux in the three-phase 12S-10P FEFSM less than single-phase 12S-6P FEFSM due to the number of rotor poles which will affect the rotor tooth width. The 6 rotor poles of single-phase 12S-6P FEFSM has much larger area to flow the flux easily. The flux lines and flux distribution at J_A and J_E of 30A/mm² for both 12S-6P and 12S-10P FEFSMs are illustrated in Figure-9 and Figure-10, respectively. It is clear that all flux lines flow from stator to rotor and return through adjacent rotor to make a complete flux cycle.

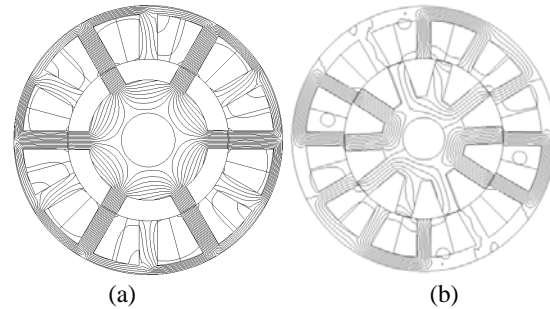


Figure-9. Flux line at maximum J_A and J_E of 30A/mm² (a) 1-phase 12S-6P FEFSM (b) 3-phase 12S-10P FEFSM.

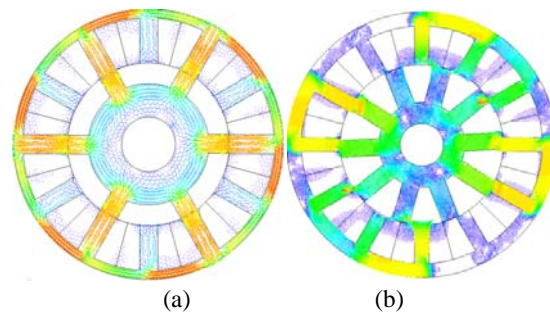


Figure-10. Flux distribution at maximum J_A and J_E of 30A/mm² (a) 1-phase 12S-6P FEFSM (b) 3-phase 12S-10P FEFSM.

Induced voltage at open circuit condition

The induced voltage generated from FEC with the speed of 1200r/min at open circuit condition for different rotor pole numbers are illustrated in Figure-11. Single-phase 12S-6P FEFSM configuration has highest amplitude approximately of 4.3V compare to the three-phase 12S-10P FEFSM configuration, which condition has approximately 1.4V. The back EMF generated in both designs are in an acceptable condition such that less than the supplied voltages.

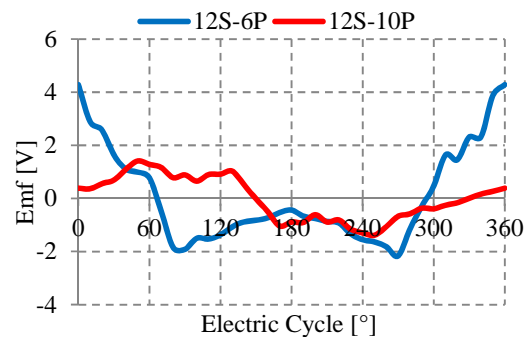


Figure-11. Back EMF at FEC current densities, J_E of 30A/mm².



Torque against FEC current density, J_E at various armature current density, J_A

Figure-12 and Figure-13 show the graphs of torque versus FEC current density, J_E at various armature current densities, J_A . Torque produced at three-phase 12S-10P FEFSM is approximately two time greater than the single-phase 12S-6P FEFSM. From figures, it obvious that when J_E set to 20A/mm² and J_A is set to 30A/mm² for three-phase 12S-10P FEFSM, the torque produced is 14Nm. While for single-phase 12S-6P FEFSM, the highest torque value is 6Nm when J_E set to 25A/mm² and J_A set to 30A/mm².

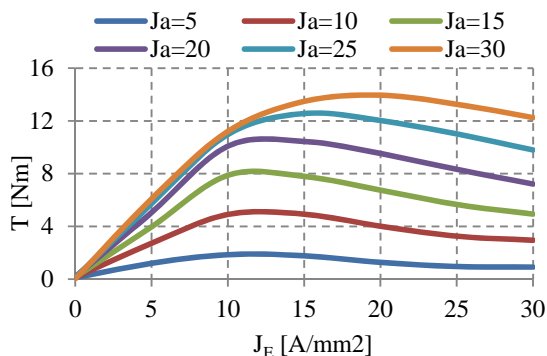


Figure-12. Torque versus J_E at various J_A of 3-phase 12S-10P FEFSM.

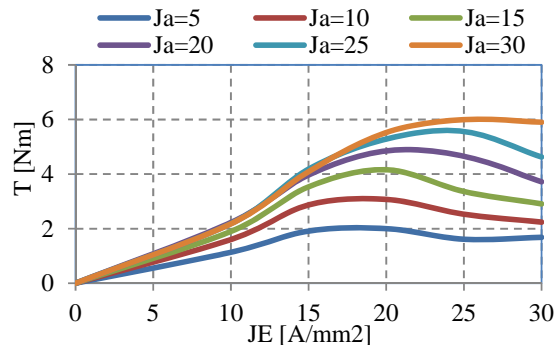


Figure-13. Torque versus J_E at various J_A of 1-phase 12S-6P FEFSM.

Torque and Power versus Speed

The torque and power versus speed curves of three-phase 12S-10P FEFSM and single-phase 12S-6P FEFSM are plotted in Figure-14 and Figure-15, respectively. From Figure-14, at initial speed of 2263r/min, the resulting 15 at the based speed of 5696r/min, the resulting torque is 5.98Nm, while the maximum power reaches 3.57kW and the average power is 2.83kW.

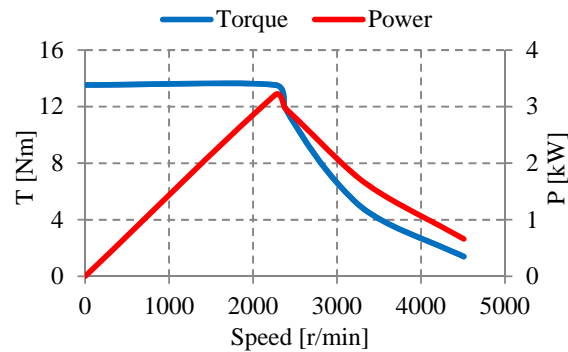


Figure-14. Torque and power versus speed for 3-phase 12S-10P FEFSM at speed of 500r/min.

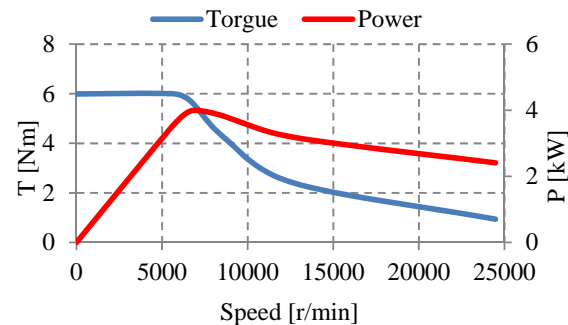


Figure-15. Torque and power versus speed for 1-phase 12S-6P FEFSM at speed of 1200r/min.

CONCLUSIONS

This paper presents a comparison between single-phase 12S-6P FEFSM and three-phase 12S-10P FEFSM with non-overlap winding and salient rotor. The procedure to design the FEFSMs 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 FEFSMs such as flux capability and initial torque have been investigated. The proposed machine has very simple configuration as well as no permanent magnet and thus, it can be expected as very low cost machine. The machine has the advantages of easy manufacturing due to salient structure types of rotor, low copper loss due to less FEC and less flux leakage when compared with alternate FEC polarity of adjacent windings. In addition, at speed 500r/min, initial torque and maximum power for three-phase 12S-10P FEFSM is 83% and 72%, respectively higher than single-phase 12S-6P FEFSM. However, at the initial torque the speed of the single-phase 12S-6P FEFSM is 37% higher than three-phase 12S-10P FEFSM.



ACKNOWLEDGEMENT

This work funded by Research Innovation, Commercialization and Consultancy management (ORICC) with Vot No E15501, FRGS 1508 and ERGS 030, Universiti Tun Hussein Onn Malaysia (UTHM) and Ministry of Education Malaysia (MOE).

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