New Structure of Single-Phase Field Excitation Flux Switching Machine for High Density Air Conditioner with Segmental rotor

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Abstract

Based on literature, a three-phase 12S-10P Field Excitation Flux switching Machine with overlap windings between armature and FEC has been developed. However the design motor has a problem of high end coil which increase the size of the motor as well as copper losses. In this paper, a single-phase 12S-6P FEFSM with adjacent armature and FEC is introduced, which permanently eliminate the end coils problem. Furthermore the operating principle of the proposed single-phase 12S-6P FEFSM with segmental and non-segmental rotor are investigated. Then finite element analysis is used to validate the flux distribution, induced voltage, torque, speed and power characteristics. Finally, 12S-6P FEFSM with segmental rotor can be designed for high density air-conditioner with 1kW power, 1.8Nm torque and corresponding speed of 4977r/min.

1 Introduction

Nowadays most of the air conditioner system used AC electric motor, namely induction motor (IM), synchronous motor (SM) and switched reluctance motor (SRM) [1]. This induction motor is commonly used on the blower and fan of air conditioner. An induction motor's rotor can be either wound type or squirrel-cage type. It has winding at rotor and stator. Induction motors (IM) 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 (stationary) coils. These motors use carbon brush and it indirectly involves the maintenance process. In addition, the iron loss will increase as the use of the rotor winding. The switched reluctance motor (SRM) is a type of an electric motor that runs by reluctance torque [2]. The synchronous motor (SM) is an electric motor that is driven by AC power consisting of two basic components a stator and rotor. Flux switching machines (FSM) is a new category of synchronous machines.

Fig. 1 shows three types of FSM. Both PMFSM and HEFSM used permanent magnet (PM) that produced constant magnetic flux, while FEFSM used DC field excitation that makes it easy to control the magnetic flux. Operation of this machine is based on flux switching machine principles. But the principle of switching flux in this design affected by structure of a segmental rotor. In previous studies, stator having a toothed rotor structure with fully-pitched DC field winding has been discussed [3]. This design has been used in applications in need of high density and requires high durability [4-7].

The flux switching machine (FSM) is a form of salient-rotor reluctance machine with a novel topology, combining the principles of inductor generator [8-9] and switched reluctance machine (SRM) [10]. The rotor consists of iron core at center of stator and has a simple shape and has high strength, while both field and armature winding are placed on the stator. The term "flux switching" is to describe machines in which the stator teeth flux switches polarity following the motion of a salient pole rotor and this is basic principle of operation [11-12].

Based on the literature, three-phase 12S-8P FEFSM and three-phase 24S-10P FEFSM have been developed and only suitable for applications that required high speed, due to its robust and single rotor structure [13-16]. Fig. 2 shows the three-phase FEFSMs 24S-10P non-segmental rotor and 12S-8P with segmental rotor topologies. Fig. 2(a) shows the overlap windings between armature and FEC create problem of the high end coil which increase the size of the motor, while Fig. 2(b) shows the non-overlap winding with segmental rotor make it a complex structure. Therefore a 12S-6P FEFSM with non-overlap winding is introduced to reduce the coil end problem. A single-phase AC can be realized in the armature winding with the field winding position with DC excitation on the stator and armature winding is connected to the AC supply to allow the rotor to rotate. Torque is developed from the changing mutual inductance of the windings [17-18].

There are some advantages when both field winding and the armature winding are placed on stator such as elimination of carbon brush and field flux can be easily controlled. Another

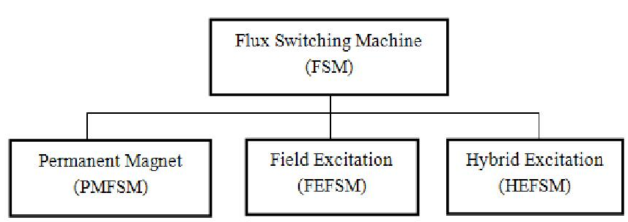


Fig. 1. Classifications of Flux Switching Machine (FSM)

advantages of this machine are easy cooling of all active parts in the stator and robust rotor structure that makes it better suitability for low-speed or high-speed application. This type of machine is classified into flux switching synchronous machines (FSSM) which is also getting more popular and popular in recent years.

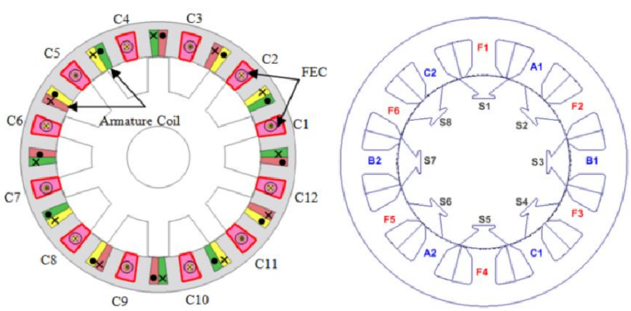
This paper compares analysis of single-phase FEFSM 12S-6P with segmental rotor and single-phase FEFSM 12S-6P non-segmental rotor and highlights the effect of non-overlap armature and field windings.

2 Design Restriction, Specifications and Procedures

The design restrictions, the target specifications and parameters of the proposed FEFSM 12S-6P with segmental and non-segmental rotor are listed in Table 1. The limit of the current density is set to the maximum $30A_{rms}/mm^2$ for armature winding and $30A/mm^2$ for FEC, respectively. The machine configuration and windings for 12S-6P FEFSM with segmental and non-segmental rotor are illustrated in Fig. 3.

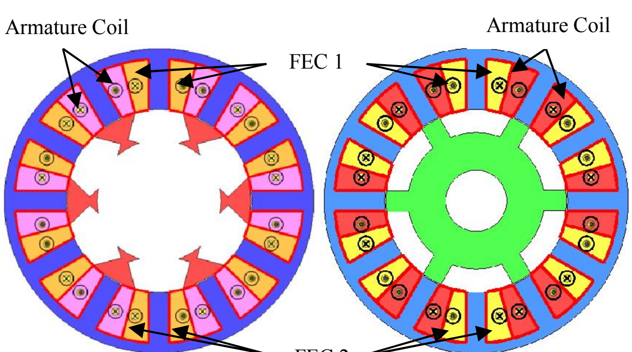
From the configurations, both FEC and armature coil is non-overlap windings. The directions of the FEC are in counter clockwise polarity, while the armature coils are placed in between of FEC. Commercial FEA package, JMAG-Designer ver. 13.0, released by the Japan Research Institute (JRI) is used as a 2D-FEA solvent for this design. Initially, the rotor, stator, armature coil and FEC of the proposed 12S-6P FEFSM is drawn by using Geometry Editor followed by the set up of materials, conditions, circuits and properties of the machine are set in JMAG Designer. The electrical steel 35H210 is used for rotor and stator body.

Furthermore, coil arrangement tests are examined to verify the operating principle of the machine and to situate the position of each armature coil phase.



(a) (b)

Fig. 2. Examples of 3-phase FEFSMs (a) 24S-10P with non-segmental rotor (b) 12S-8P segmental rotor.



(a) (b)

Fig. 3. Single-phase 12S-6P (a) FEFSM with segmental rotor (b) FEFSM non-segmental rotor

3 Result and Performances Based On 2D-Finite Element Analysis

3.1 Coil Arrangement Test

Coil arrangement tests are examined in each armature coil separately in order to verify the operating principle of the FEFSM and to set the position of each armature coil phase. Fig. 5 and Fig. 6 demonstrate the flux linkage of all armature coils. The flux produced relatively smooth as there is no distortion occurs. Flux linkage of segmental rotor approximately is five times greater than non-segmental.

Fig. 7 and Fig. 8 show the result of coil test for FEFSM with segmental rotor and FEFSM non-segmental rotor. Flux linkage at non-segmental rotor is slightly high than segmental rotor, that is non-segmental rotor produces 0.09Wb and segmental rotor produces 0.08Wb.

Items	12S-6P FEFSM with Segmental	12S-6P FEFSM non-segmental
Number of phases	1	3
No. of slots	12	12
No. of poles	6	10
Stator outer radius (mm)	75	75
Stator inner radius (mm)	70	70
Stator back inner width (mm)	5	5
Stator tooth width (mm)	10	10
Armature coil slot area (mm^2)	251	251
FEC slot area (mm^2)	251	251
Rotor outer radius (mm)	44.5	44.5
Rotor inner radius (mm)	30	15
Rotor pole radius (mm)	33.5	33.5
Rotor tooth width (mm)	23	10
Rotor shaft	30	15
Air gap length (mm)	0.5	0.5
Number of turns per field tooth coil (FEC)	75	75
Number of turns per armature coil slot (AC)	11	11

Table 1: Design Restrictions, Specifications and Parameters for 12S-6P FEFSM

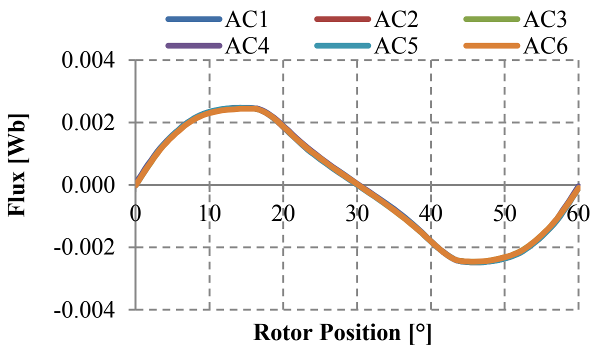


Fig. 5. Flux linkage of 12S-6P FEFSM with segmental rotor

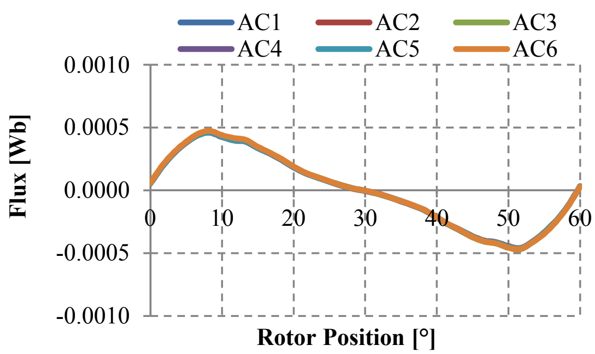


Fig. 6. Flux linkage of 12S-6P FEFSM non-segmental rotor

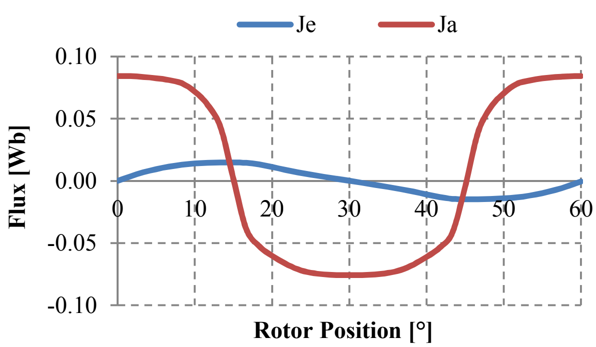


Fig. 7. Flux linkage waveform of 12S-6P FEFSM with segmental rotor

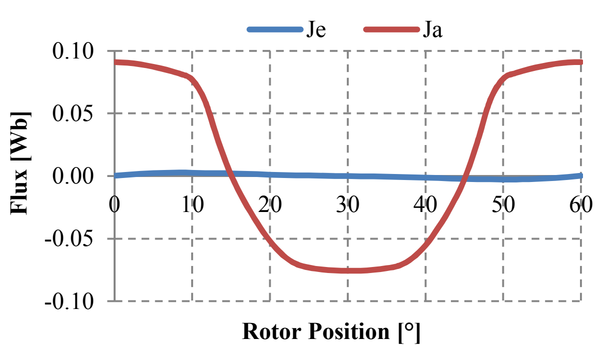


Fig. 8. Flux linkage waveform of 12S-6P FEFSM non-segmental rotor

3.2 Flux Strengthening/weakening

To examine the effect of flux strengthening and weakening, current density, J_E set to 5A/mm^2, 10A/mm^2, 15A/mm^2, 20A/mm^2, 25A/mm^2 and 30 A/mm^2. The number of turns of FEC are calculated and set by using Equation 1. Then, calculate the value of input current of FEC, A_E by using Equation 2. Table 2, shows the reading of input current of FEC and Fig. 9 shows a maximum flux at various FEC current densities, J_E. There are two causes why the flux patterns increase linearly and then become decrease. The material used for the FECs are copper and have reached the limit to produce a flux when J_E is 10A/mm^2 for segmental design and J_E is 20A/mm^2 for non-segmental design and the other reason is due to iron loss. Furthermore, inside the motor, there is some flux that flow in the opposite direction, thus it will cancel each other.

$$N_E = \frac{J_E \alpha_E S_E}{A_E} \qquad (1)$$

Where;
N_E = No. of turn of FEC
J_E = FEC current density (set to maximum of 30A/mm^2)
A_E = Input current FEC (set to maximum of 50A)
α_E = FEC filling factor (fix to 0.5)
S_E = FEC slot area (estimate the slot area from the drawing)

$$A_E = \frac{J_E \alpha_E S_E}{N_E} \qquad (2)$$

Where;
A_E = Input current FEC
J_E = FEC current density (set to maximum of 30A/mm^2)
α_E = FEC filling factor (fix to 0.5)
N_E = No. of turn of FEC
S_E = FEC slot area (estimate the slot area from the drawing)

FE Coil current density, J_E (A/mm^2)	Input current of FE Coil, A_E (A)
5	8.37
10	16.75
15	25.12
20	33.49
25	41.87
30	50.24

Table 2: Reading of input current of FE Coils, A_E

3.3 Total Flux

Fig 10 and Fig.11 show the total flux for 12S-6P FEFSM with segmental and non-segmental rotor. Maximum value at J_A of 30A/mm^2 for both designs is approximately same, but at J_E of 30A/mm^2 flux linkage at segmental rotor is three times greater than flux linkage at non-segmental rotor. From Fig. 10 the maximum flux produced is 0.08Wb when both J_E and J_A of 30A/mm^2 are applied and from Fig. 11 the maximum flux produced is 0.09Wb at J_E and J_A of 30A/mm^2.

3.4 Torque against Excitation current density, J_E at various armature current density, J_A

Fig.12 and Fig. 13 show the torque versus excitation current density, J_E at various armature current densities, J_A. Torque produced at segmental rotor is higher than the non-segmental rotor. This can be seen when J_E and J_A are set to 30A/mm^2 for segmental rotor, the torque produced is 16.6Nm. While for non-segmental rotor, the highest torque value is 5.98Nm when J_E set to 25A/mm^2 and J_A set to 30A/mm^2.

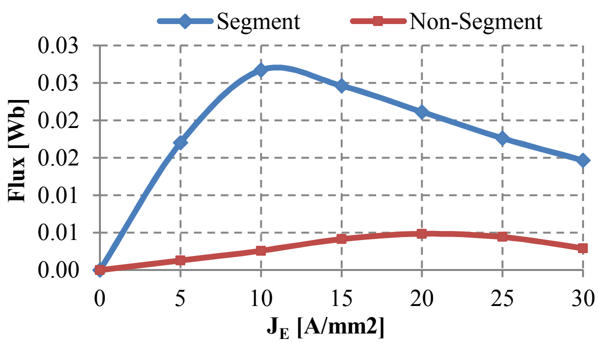


Fig.9. Flux linkage at various FEC current densities, Je

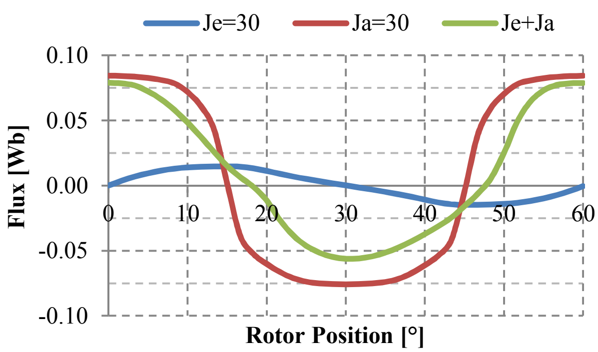


Fig. 10. Total flux for 12S-6P FEFSM with segmental rotor

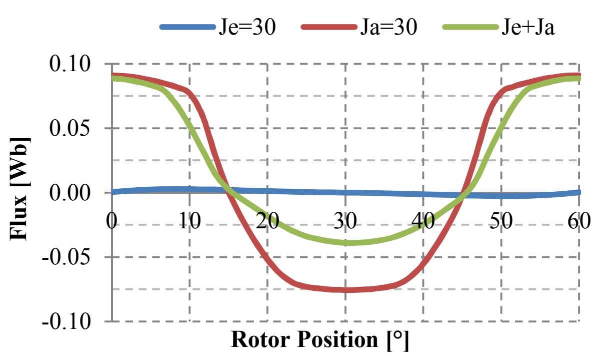


Fig. 11.Total flux for 12S-6P FEFSM with non-segmental rotor

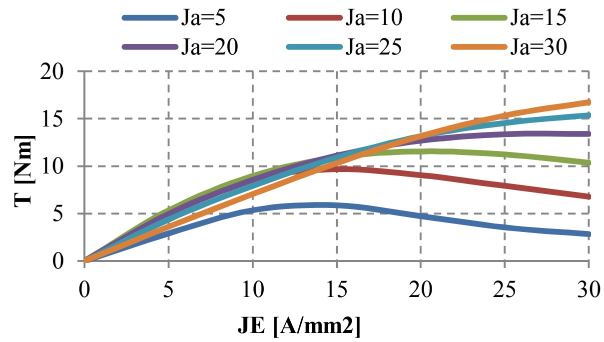


Fig. 12. Torque versus J_E at various J_A for 12S-6P FEFSM with segmental rotor

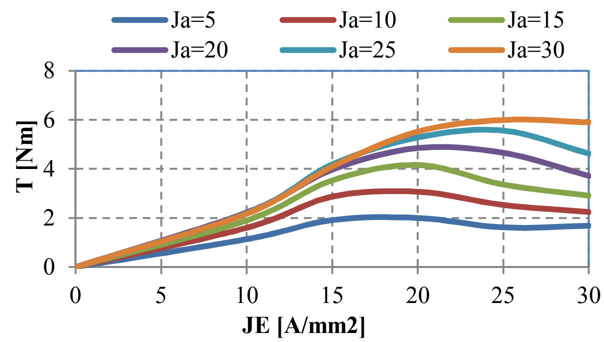


Fig.13. Torque versus J_E at various J_A for 12S-6P FEFSM non-segmental rotor

3.5 Torque and Power versus Speed

The torque and power versus speed curves of the designed motor is plotted in Fig. 14 and Fig. 15. From Fig.14, the initial speed 4977 r/min and the resulting torque is 16.6Nm, while the corresponding power reaches 8.66kW. The average power 8.17kW is achieved between 4000 - 5000r/min. From Fig. 15 at the initial speed of 5696 r/min, the resulting torque is 5.98Nm, less compared to 12S-6P FEFSM with segmental rotor and the corresponding power reaches 3.57 kW. The average power of 2.83 kW is achieved between 15000 – 17000 r/min.

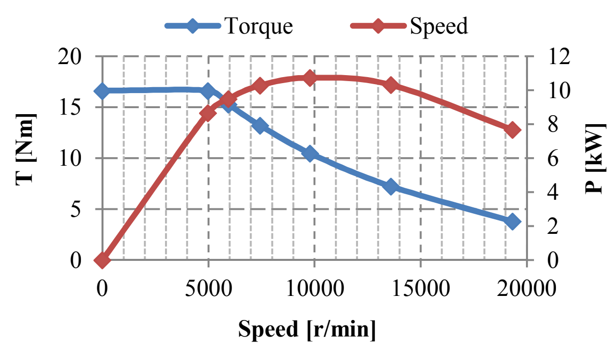


Fig. 14. Torque and power versus speed characteristics 12S-6P FEFSM with segmental rotor

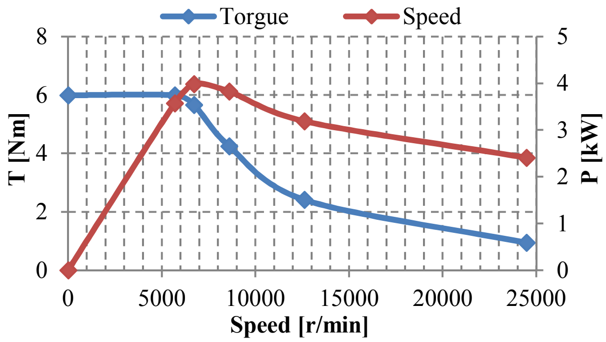


Fig. 15. Torque and power versus speed characteristics 12S-6P FEFSM non-segmental rotor

4 Conclusions

In this paper, design study of 12S-6P FEFSM with segmental and non-segmental rotor has been investigated. The procedure to design the FEFSMs has been clearly explained. The performances of the FEFSMs such as flux distribution, induced voltage, torque, speed and power characteristics have been investigated. The machines have very simple configuration yet no permanent magnet and thus, it can be expected as very low cost machine. Problem of high end coil which increase the size of the motor is solved with adjacent armature and FEC to reduce the coil end problem. The performance of 12S-6P FEFSM with segmental and non-segmental rotor are compared. Finally, 12S-6P FEFSM with segmental rotor is considered suitable to be applied for High Density Air-Conditioner. It is because 1kW power generated at 1.8Nm and the corresponding speed of 4977 r/min. To produced torque equal to 1.8 Nm, FEC current density, J_E and armature current density, J_A should be set to less then 5 A/mm^2. On the other side, for 12S-6P FEFSM non-segmental rotor, 1 kW power generated at 1.6 Nm and the corresponding speed of 5696 r/min. To produce torque equal to 1.6Nm, the current density FEC, J_E and the armature current density, J_A should be set to 20A/mm^2 and 30A/mm^2, respectively.

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