VOL. 10, NO. 16, SEPTEMBER 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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PROTOTYPE DEVELOPMENT OF A NEW SINGLE-PHASE FEFSM SEGMENTED ROTOR FOR HIGH DENSITY AIR CONDITIONER

Mohd Fairoz Omar, Erwan Sulaiman, Faisal Khan, Mahyuzie Jenal and Gadafi M Romalan
Research Center for Applied Electromagnetics (EMC), UniversitiTun Hussein Onn Malaysia, BatuPahat, Johor, Malaysia
E-Mail: fairoz.omar@yahoo.com

ABSTRACT

Diverse topology of three-phase and single-phase Field Excitation Flux Switching Machines (FEFSMs) that have been developed recently have several advantages such as variable flux capability and the single piece structure of rotor suitable for high-speed applications. However, overlap windings between armature and FEC cause the fundamental principles of the develop machine with salient pole rotor created the problems of high end coil, increases size of motor as well as high copper losses. A new topology of single phase segmented rotor FEFSM with 12S-6P configuration is presented with the advantages of non-overlap armature and FEC windings, less weight, low copper loss and high efficiency. The design, operating principles, characteristics of torque, speed and power of this new topology is investigated by JMAG-Designer via a 2D Finite Element Analysis (2D-FEA), while Solidwork software is used in the fabrication process. The initial design enables to obtain maximum torque and power of 16.6Nm and 10.74kW, respectively suitable for High Density Air Conditioner.

Keywords: flux switching machine, single-phase winding, segmented rotor, non-overlap windings.

INTRODUCTION

Air conditioning is the process of modifying the properties of air to more comfortable conditions, typically with the target of distributing the conditioned air to an occupied space to improve comfort. In the most general sense, air conditioning can refer to any form of technology, heating, cooling, de-humidification, humidification, ventilation, or air movement that modifies the condition of air. In common use, an air conditioner is a device that lowers the air temperature. Nowadays, in most countries, the use of electrical energy used for air conditioner is about 30% to 40% of the overall electrical energy in normal usage, whereas can increase to 50% during the summer (Haitao, Yan, & Shouqian, 2006). Currently, most of the air conditioner system used induction motors (IMs) and commonly used in the compressor, blower and fan. Table-1 shows the example of single phase induction motors specifications commonly used in air conditioner systems.

Table-1. Single-phase induction motor specifications.

Items	Parameters
Voltage input (Volt)	240
Frequency (Hz)	50
Power (kW)	0.75
Torque (Nm)	2.54
Speed (rpm)	2000-3000

However, IMs has the disadvantage of active part is located on the rotor. Thus, it will affect in the cooling process and the motor not robust. To overcome the drawbacks of IMs, Field Excitation Flux Switching Motor (FEFSM) with the both FEC and armature coils placed in the stator, the motor is easy cold and the flux will always can be controlled. The flux switching motor FEFSM is combining the principles of the switched reluctance machine (SRM) and the inductor generator. The concept of FEFSM involves motion of the rotor caused by changing the polarity of the flux linking the armature winding as shown in Figure-1(Ackim Zulu, Mecrow, & Armstrong, 2010), (Erwan Sulaiman, Kosaka, & Matsui, 2011).

Considering Figure-1(a), the excitation of field and armature windings at positive current create a flux vector in the north-westerly direction and north-easterly direction, respectively. The combined flux generated by the two coils cause the flux moving vertically upwards and the rotor align himself with a pair of vertical stator. Additionally Figure-1(b) illustrates the current in armature winding is reversed, while FEC winding is continue being excited in the same direction by effect of 180° flux shifting from west-south. The result from 180° shifting makes the rotor tends to align with the stator poles based on flux movement in westerly direction through horizontal stator poles. Therefore, each reversal of current directions in the armature causes the stator flux vector to switch between the horizontal and vertical directions, hence introduces the name flux switching machine(C. Pollock & Wallace, 1999).

The viability of this design has been demonstrated in applications requiring high power densities and a good level of durability. The novelty of the single-phase AC motor can be realized with connects the FEC windings to DC supply and armature windings to AC supply to get the orientation of flux to allow the rotor rotation(Ackim Zulu *et al.* 2010), (H. Pollock, Pollock, Walter, & Gorti, 2003), (C. Pollock, Pollock, & Brackley, 2003), (C. Pollock, Pollock, Barron, *et al.* 2003).

In addition, based on the literature, a3-Φ 24S-10P FEFSM has been developed as illustrated in Figure-2(a) suitable for high speed applications due to its robust and single rotor structure(E Sulaiman, Teridi, Husin, Ahmad,

VOL. 10, NO. 16, SEPTEMBER 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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& Kosaka, 2013). However, the overlapped windings between armature and FEC of both single-phase and three-phase design create problem of high end coil which increase the size of the motor. To overcome the problems, three-phase 12S-8P FEFSM with segmental rotor has been design to reduce the coil end problem. It may be seen in Figure-2(b) (Ackim Zulu *et al.* 2010),(A Zulu, Mecrow, & Armstrong, 2010).

In this research, a single-phase 12S-6P FEFSM with segmental rotor using adjacent armature winding and FEC winding is introduced. The proposed motor has been successfully design and analyze using JMAG-Designer version 13. Hence, the development of prototype motor is carried out to test and validate the performances.

METHODOLOGY

This section explains the process involved in this project, as shown in Figure-3. Obviously the process is divided into 2 main parts, namely 2D Finite Element Analysis (FEA) with JMAG-Designer and3D prototype development using SOLIDWORKS. In the first part it divided into two sections.

Geometry editor is used to design each part of motor separately, such as rotor, stator, armature coil and FEC, while JMAG Designer used to set the materials, condition, circuit, mesh properties and run the simulations. The design parameters and specifications of the design and machine configuration are illustrated in Table-2 and Figure-4, respectively. From Figure-4, it clearly shows that the FEC and armature coil windings is non-overlap. Both windings are alternate with two directions, clockwise and anticlockwise.

In part 2, SOLIDWORKS used to create and assemble the 3D parts in order to show the overall form of the FEFSM prototype. This section will describes about material, dimension and construction process of FEFSM prototype. The completely 3D design transferred into Computer Numerical Control (CNC) machine for fabrication process.Specifics process will define on the next section.

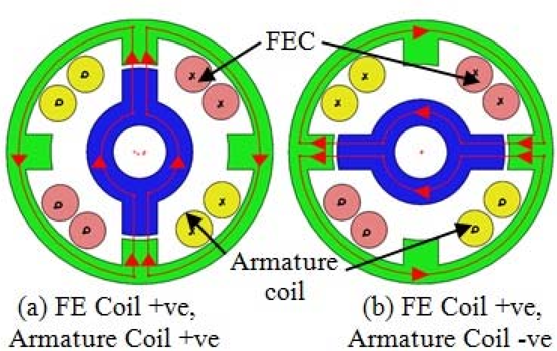

Figure-1. Basic principle of FSM.

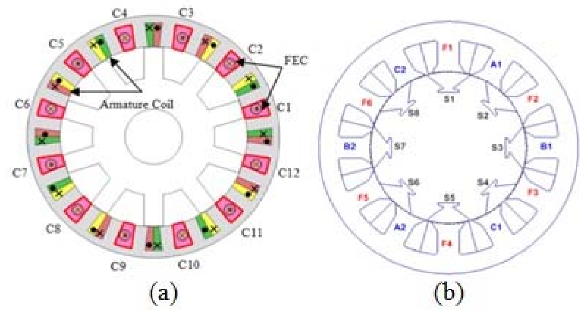

Figure-2. Examples of 3-phase FEFSMs (a) 24S-10P with salient rotor (b) 12S-8P with segmental rotor.

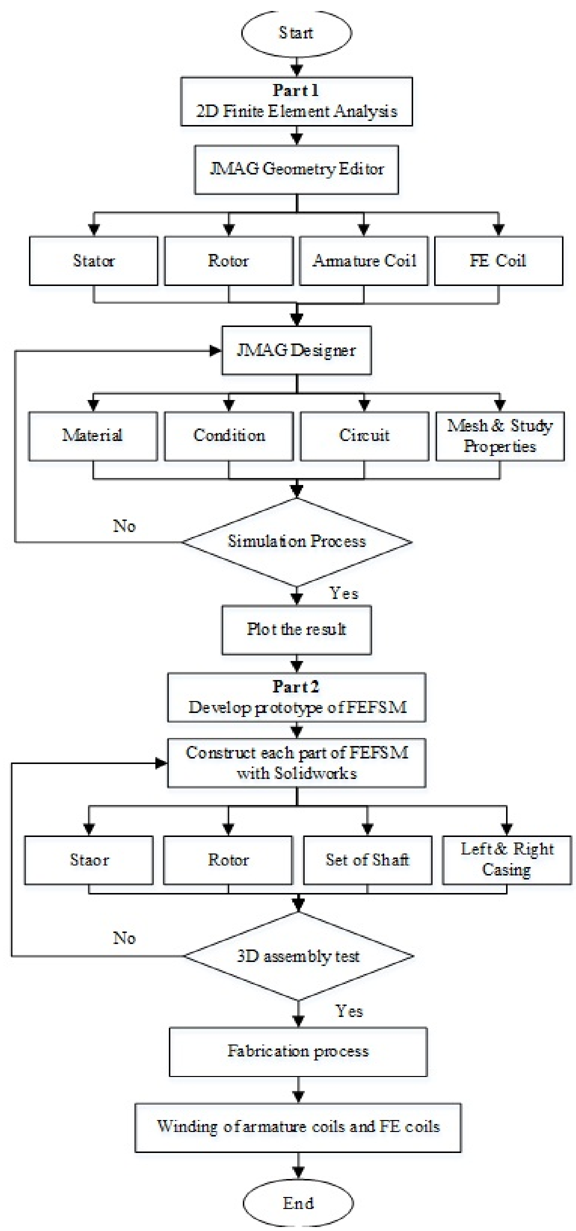

Figure-3. Working flow for the entire work.

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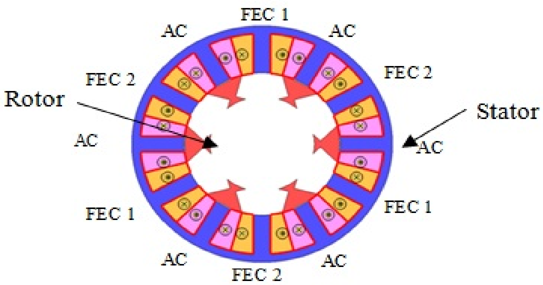

Figure-4. 1-Φ 12S-6P FEFSM segmented rotor.

RESULT AND PERFORMANCE BASED ON 2D-FINITE ELEMENT ANALYSIS (2D-FEA)

Coil Arrangement Test

To verify the operation principle of12S-6P FEFSM with segmental rotor and set the position of each phase of the armature coil, the coil arrangement is tested on each armature coils separately. Figure-5 demonstrates the flux linkage of all armature coils. The highest flux achieve is 0.0025Wb and the sinusoidal flux produced relatively smooth as there is no distortion occurs.

Figure-6 shows the result of coil test for 12S-6P FEFSM with segmental rotor. Armature coil current density, $J_A$and FEC current density, J_E is set to the maximum of 30A_{rms}/mm^{2}and 30A/mm^2, respectively. Thus, the flux linkage produces at armature coil and FEC are 0.15Wb and 0.084Wb, respectively. From this analysis, the flux linkage at maximum armature current density, J_A is 44% highest from flux linkage at maximum J_E. The flux linkage at armature coils lead 90°of flux linkage at FECs and it shows that the motor operate correctly. While, the flux total produced is 0.08Wb and this obviously shows that the reaction occurs between the fluxes produced at armature coil and FEC.

Flux Strengthening

To examine the effect of flux strengthening and weakening, the armature coil current density, $J_A$is set to 0A_{rms}/mm^2, while the FEC current density, $J_E$set from 0A/mm^{2}to 30A/mm^2. The number of turns of FEC and the value of input current of FEC are calculated by using Equation 1 and Equation 2, respectively. Table-3, shows the reading of input current of FEC and Figure-7 shows a maximum flux at various FEC current densities, J_E. From the pattern plot, the flux shapes increase linearly and then constantly decrease at FEC current density, $J_E$at 10A/mm^2 due to some flux that flow in the opposite direction inside the motor make flux cancels each other.

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

Where;
A_E = Input current FEC (Max. 50A)
J_E = FEC current density (Max. 30A/mm^2)
α_E = FEC filling factor (set to 0.5)
N_E = FE Coil turn
S_E =Slot area of FEC

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

Where;
A_E = Input current FEC
J_E = FEC current density (Max. 30A/mm^2)
α_E = FE coil filling factor (set to 0.5)
N_E =FE coil turn
S_E = Slot area of FEC

Torque versus FE Current Density, J_E at Various Armature Current Density, J_A

Figure-8 shows the torque versus FEC current density, J_E at various armature current densities, J_A. Increasing of armature current density, J_A and FEC current density, J_E the torque will increase. However, at armature current density, J_A is 5A_{rms}/mm^2 and 10A_{rms}/mm^2 torque start to decrease when FEC current density, J_E higher than 10A_{rms}/mm^2 because FEC current density, J_E cancel the total flux as proven by flux strengthening test. At armature current density, J_A is 30A_{rms}/mm^2, torque increase linearly with increasing FEC current density, J_E until maximum torque 16.6Nm is achieved.

Torque and Power versus Speed

Figure-9 shows torque and power against speed characteristic curve of the 12S-6P FEFSM with segmental rotor. At base speed of 4977r/min, where the torque is 16.6Nm, the corresponding power reaches up to 8.66kW. The maximum power of 10.74kW is obtain at speed 9782 r/min. At base speed the torque is high and start to decrease approximately at speed of 5000r/min. From the figure, power is increased directly as the speed is increased and started to reduce approximately at speed of 10000r/min.

Table-2. Parameters and specifications for 12S-6P FEFSM with segmental rotor.

Items	12S-6P FEFSM with Segmental Rotor
Number of phase	1
No. of slots	12
No. of poles	6
Outer radius of stator (mm)	75
Inner radius of stator (mm)	70
Back inner width of stator (mm)	5
Tooth width of stator (mm)	10
Armature coil slot area (mm^2)	251
FEC slot area (mm^2)	251
Outer radius of rotor (mm)	44.5
Inner radius of rotor (mm)	30
Radius of rotor pole (mm)	33.5
Width of rotor tooth (mm)	20
Shaft of rotor (mm)	30
Air gap space (mm)	0.5
Number of turns FE Coil	75
Number of turns Armature Coil	11

VOL. 10, NO. 16, SEPTEMBER 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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Table-3. Reading of input current of FE Coils, A_E.

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

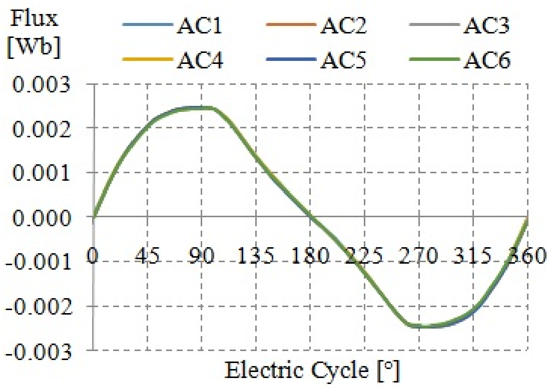

Figure-5. Flux linkage at armature coil.

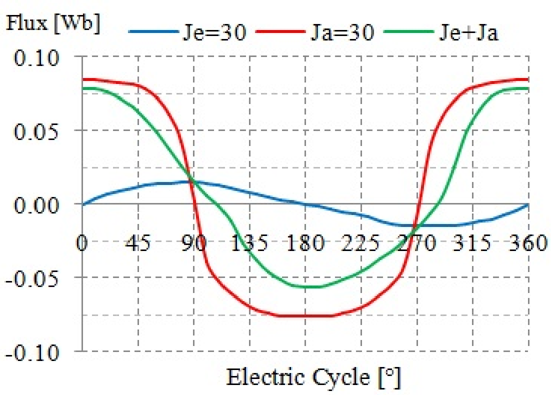

Figure-6. Flux linkage of coil test.

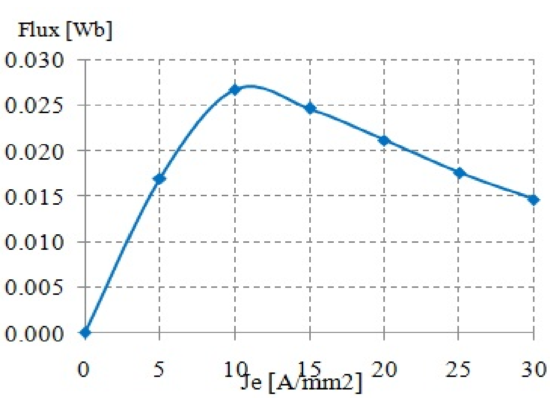

Figure-7. Flux strengthening and weakening.

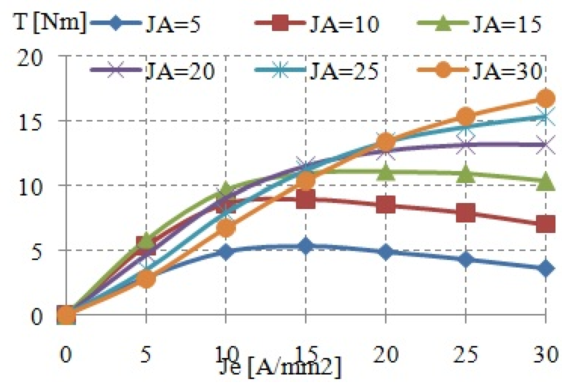

Figure-8. Torque vs. J_E at various J_A.

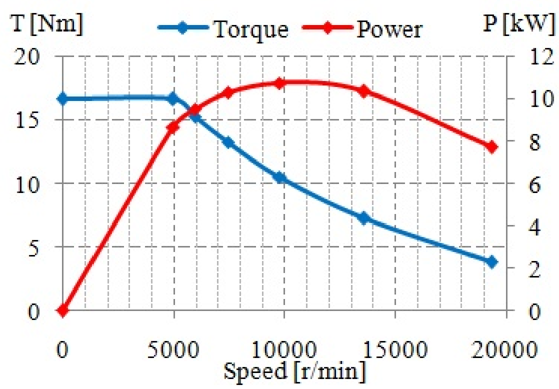

Figure-9. Torque and power versus speed characteristics.

Performances of single-phase 12S-6P FEFSM with segmental rotor based on 2D-FEA considered suitable used for air-conditioner because 1kW power generated at 1.8Nm and the corresponding speed reaches 4977r/min. To produced torque 1.8Nm, FE current density, J_E and armature current density, J_A should be set to less than $5A_{rms}/mm^2$ and $5A/mm^2$, respectively. The maximum power is 10.74kW at speed 9782r/min.

The Prototype Development of 12s-6p FEFSM with Segmental Rotor

This section show up the 3D designs and progress of each part that used in the prototype FEFSM. Table-4 shows the parts, quantity and materials of FEFSM prototype, respectively. There are4processes in order to develop the prototype, constructions of each part of the prototype with SOLIDWORK, fabrication process, coil winding and assembling process.

SOLIDWORKS used to create and assemble the 3D parts, so it will show the overall form of the prototypes. This is to avoid the prototype from mismatch between each part during the merger process after fabrication process is completed. The completely 3D design will transfer into Computer Numerical Control (CNC) machine for fabrication process. There have two CNC machines used in fabrication which are wire electrical discharge machine (WEDM) and milling machine. The CAM program used in both CNC machines to design the cutting path blueprint before cutting process is carried out.

The stator and rotor part will be made by using a (WEDM). Set of shaft, ring lock and left and right casing (LR casing) produced by using a milling machine. Set of shaft consists of shaft stick, ring shaft and shaft lock. While, the 3D printer used to fabricate the coil separator. Then the next process is make the armature and FEC windings on the stator. Figure-10 shows the stator and rotor sheets was fabricated and the thickness of each slice is 0.35mm.Figure-11(a) and Figure-11(b) illustrate the internal and external 3D view of 12S-6P FEFSM with segmental rotor after completing fabrication and assembling process.

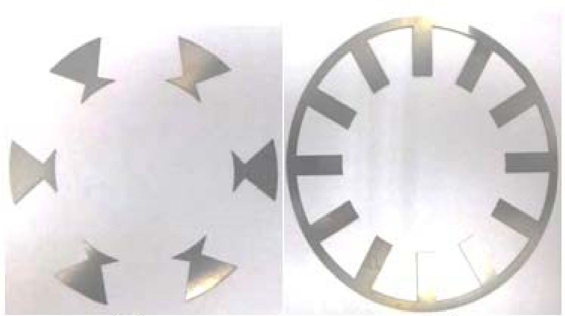

Figure-10. A piece of (a) Rotor and (b) Stator.

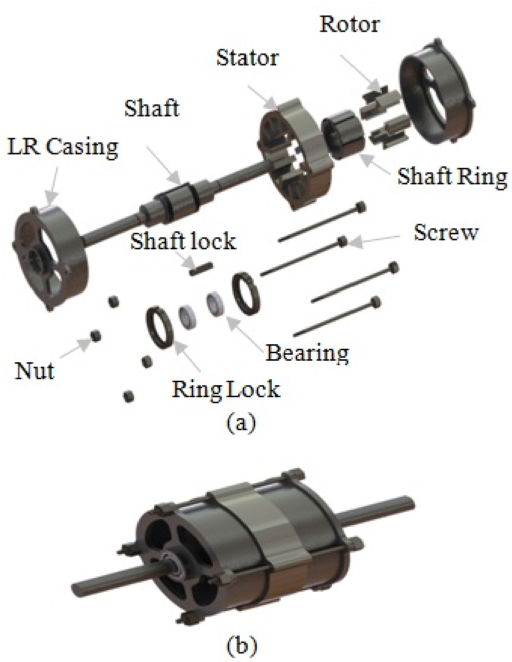

Figure-11. The (a) Internal and (b) External 3D view of 12S-6P FEFSM with segmental rotor prototype.

Table-4. Prototype details.

No.	Part	Quantity	Type of Materials
1	Stator	0.35mm x 100	Nippon Steel 35A250
2	Rotor	0.35mm x 100	
3	Armature Coil	11 Turns	Copper
4	FE Coil	75 Turns	
4	Coil Separator	12 Pcs	ABS Plastic
5	Bearing	2 set	SKF
6	Shaft Ring	1 set	Aluminium
7	Shaft Stick	1 set	
8	Shaft Lock	1 set	
9	Ring Lock	1 set	
10	LR Casing	2 set	
11	Retaining Clip	2 set	
12	Ring Lock	2 set	
13	Screw and nut	4 set	

CONCLUSIONS

In this paper, procedure to design and prototype development of single-phase FEFSM has been clearly discussed. The machine has very simple configuration due to non-overlap windings and no permanent magnet, thus it can be expected as low cost motor. The performances of the FEFSMs such as flux linkage, coil test, flux strengthening, torque and power versus speed characteristics have been investigated by using 2D-finite element analysis and 3D design of develop prototype of FEFSM has been successfully using SOLIDWORKS. The fabrication process has reached 40% of the whole development. While, the motor torque measurement systems is to be established to conduct the prototype test experimentally.

ACKNOWLEDGEMENTS

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

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