Available online at www.sciencedirect.com
ScienceDirect
Procedia Technology 11 (2013) 572 – 579
Procedia Technology

The 4th International Conference on Electrical Engineering and Informatics (ICEEI 2013)

Investigation on Flux Characteristics of Field Excitation Flux Switching Machine with Single FEC Polarity

E.Sulaiman[a,]*, M. F. M. Teridi[a], Z. A. Husin[a], M. Z. Ahmad[a], T. Kosaka[b]

[a] *Faculty of Electrical & Electronic Eng., Universiti Tun Hussein Onn Malaysia, Bt. Pahat, 86400, Johor, MALAYSIA*
[b]*Dept. of Electrical and Computer Engineering, Nagoya Institute of Technology (NIT), Nagoya, 466-8555, JAPAN*

Abstract

Flux switching machines (FSMs) that consist of all flux sources in the stator have been developed in recent years due to their definite advantage of single piece robust rotor structure suitable for high speed applications. They can be categorized into three groups that are permanent magnet (PM) FSM, field excitation (FE) FSM, and hybrid excitation (HE) FSM. Both PMFSM and FEFSM has only PM and field excitation coil (FEC), respectively as their main flux sources, while HEFSM combines both PM and FECs. Among these FSMs, the FEFSM offers advantages of low cost, simple construction and variable flux control capabilities suitable for various performances. In this paper, design study and flux interaction analysis of 24S-10P FEFSM with single direction of FEC winding is presented. Initially, design procedures of the FEFSM including parts drawing, materials and conditions setting, and properties setting are explained. Then, coil arrangement tests are examined to confirm the machine operating principle and position of each armature coil phase. Finally, the flux interaction between DC FEC and armature coil, FEC flux capabilities at various current condition, and initial torque are also investigated.

Selection and peer-review under responsibility of the Faculty of Information Science & Technology, Universiti Kebangsaan Malaysia.

Keywords: Field excitation flux switching machine; DC filed excitation coil; single FEC polarity

1. Introduction

The first concept of flux switching machine (FSM) has been founded and published in the mid 1950s. A permanent magnet (PM) FSM i.e. permanent magnet single-phase limited angle actuator or more well-known as

* Corresponding author.
E-mail address: erwan@uthm.edu.my

Selection and peer-review under responsibility of the Faculty of Information Science & Technology, Universiti Kebangsaan Malaysia.
doi:10.1016/j.protcy.2013.12.230

Laws relay, having 4 stator slots and 4 rotor poles (4S-4P) has been developed [1], and it has been extended to a single phase generator with 4 stator slots, and 4or 6 rotor poles (4S-4/6P) [2]. Over the last ten years, many novel and new FSMs topologies have been developed for various applications, ranging from low cost domestic appliances, automotive, wind power, aerospace, and etc. Fig. 1 illustrates the classifications of FSMs which can be categorized into three groups that are permanent magnet (PM) FSMs, field excitation (FE) FSMs, and hybrid excitation (HE) FSMs.

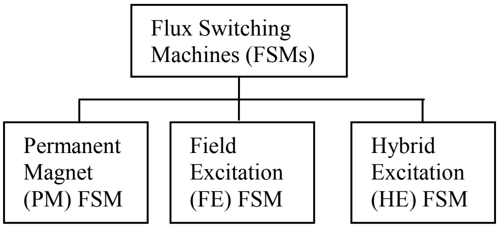


Fig. 1. Classification of flux switching machine (FSMs).

Both PMFSMs and FEFSMs have only PM and field excitation coil (FEC), respectively as their main flux sources, while HEFSMs combines both PM and FECs [3-4]. Among all FSMs, the FEFSM offers advantages of magnet-less machine, low cost, simple construction, and variable flux control capabilities suitable for various performances. Moreover, to form the FEFSMs, the PM excitation on the stator of conventional PMFSMs can be easily replaced by DC FEC as shown in Figs. 2 to 5. In other words, the FEFSMs are a form of salient-rotor reluctance machine with a novel topology, combining the principles of the inductor generator and the SRMs [5-6].

The concept of the FEFSM involves changing the polarity of the flux linking with the armature coil windings, with respect to the rotor position. Early examples of single-phase 4S-2P FEFSM that employs with a DC FEC on the stator, a toothed-rotor structure and fully-pitched windings on the stator is shown in Fig. 2 [7]. From the figure, it is clear that both armature coil and FEC windings are placed in the stator which overlapped each other. The viability of this design has been demonstrated in various applications requiring high power densities with a good level of durability [8-9]. The novelty of the invention is that the single-phase ac configuration could be realized in the armature windings by deployment of DC FEC and armature winding, to give the required flux orientation for rotation. The torque is produced by the variable mutual inductance of the windings. The single-phase FEFSM is very simple machine to manufacture, coupled with a power electronic controller and it has the potential to be extremely low cost in high volume applications. Furthermore, being an electronically commutated brushless machine, it inherently offers longer life and very flexible and precise control of torque, speed, and position at no additional cost.

Another example of single-phase FEFSM is shown in Fig. 3 with eight stator slots and four rotor poles, 8S-4P FEFSM [10]. From the figure, the FEC winding in four of the slots is fed with direct current to establish four pole magnetic fields. The other four slots contain an armature winding that also pitched over two stator teeth. The direction of the current in the armature winding determines a set of four stator poles carries flux and also the position of the rotor. Since the FEC is excited by unipolar current, it can be directly connected in parallel or in series with the dc-supply of power converter which feeds the bipolar current into the armature winding. The design principle is explained in [11], and the single-phase 8S-4P FEFSM has achieved higher output power density and much higher efficiency when compared with the induction machine (IM). However, the 1-phase FEFSMs suffer with problems of low starting torque, large torque ripple, fixed rotating direction, and overlapped windings between armature coil and FEC.

To improve the performances, a 3-phase 12S-8P with segmental rotor and 24S-10P FEFSMs have been developed as shown in Figs. 4 and 5, respectively. For 12S-8P FEFSM, segmental rotor is used to provide a clear magnetic path for conveying the field flux to adjacent stator armature coil following the rotor rotation. This design gives shorter end windings than the toothed-rotor structure which is associated with overlapping coils. There are significant gains with this arrangement as it uses less conductor materials and also can improve the overall machine efficiency [12]. Furthermore, the 24S-10P FEFSM is redesigned from the 24S-10P PMFSM in which the PM is removed from the stator and half of the armature coil slots in the upper layer are placed with the FEC windings [13].

In contrast with alternate flux polarities from adjacent PM of 24S-10P PMFSM, the FEC in this machine is arranged with a sole polarity of DC current source. Since the adjacent DC FECs are isolated as shown in red circle in Fig. 5, the total flux generation is limited and thus reducing the performances.

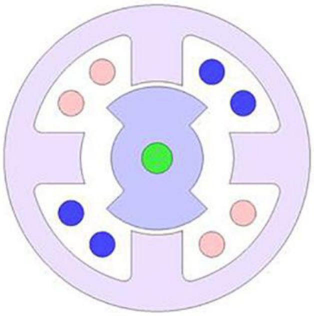


Fig. 2. 1-phase 4S-2P FEFSM

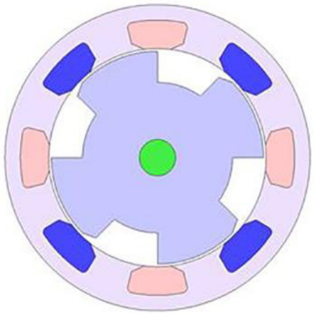


Fig. 3. 1-phase 8S-4P FEFSM.

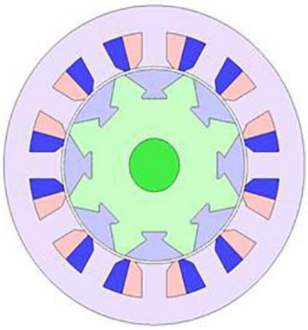


Fig. 4. 3-phase 12S-8P segmental rotor

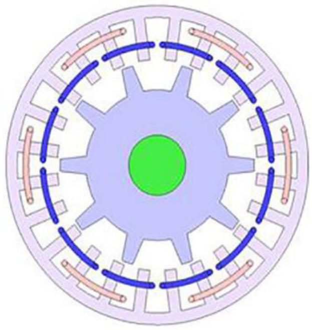


Fig. 5. 3-phase 24S-10P FEFSM

2. Design Methodology of 24S-10P FEFSM

In this paper, design study and flux interaction between FEC and armature coil of the 24S-10P FEFSM are investigated. The machine configuration and dimensions are illustrated in Fig. 6 and Table I, respectively.

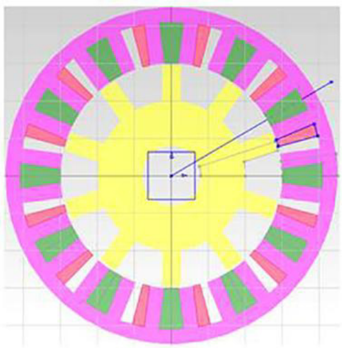


Fig. 6. Initial design of the 24S-10P FEFSM

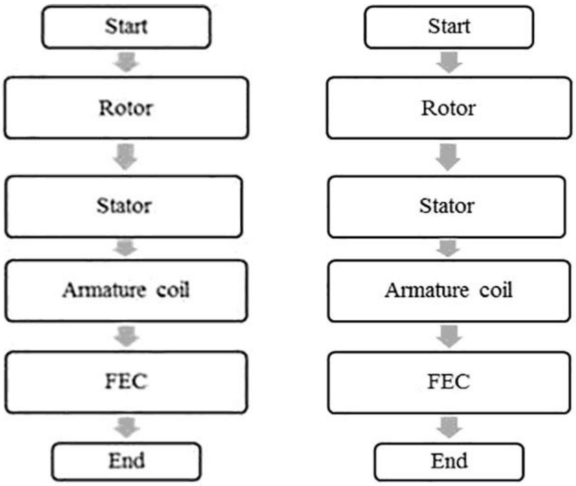
Table 1. 24S-10P FEFSM Parameters

Parameters	Quantity/Unit
Number of phase	3
Number of stator poles	12
Number of rotor poles	10
Outer radius of stator	45mm
Stack length	25mm
Air gap length	0.5mm
Inner radius of stator	29.75mm
Stator tooth top width	4.4mm
Stator tooth bottom width	4.7mm
Stator yoke thickness	3.5mm
Slot opening for armature winding	3.8mm
Slot opening for DC winding	5.0mm
Rotor tooth width	5.6mm
Number of phase turns	12
Number of DC winding turns	10

From the structure, it is clear that the FEFSM is having 24 stator teeth, 10 rotor poles, and alternate FEC and armature coil slot around the stator. The DC FEC is wound in counter-clockwise polarity, while the three phase armature coils are placed in between them. The advantages of this machine are easy manufacturing of single DC FEC windings, low copper loss due to less volume of FEC, less flux leakage when compared with dual FEC adjacent windings, and design freedom of FEC for various performances.

Commercial FEA package, JMAG-Designer ver.11.0, released by Japan Research Institute (JRI) is used as 2D-FEA solver for this design. Firstly, the rotor, stator, armature coil and FEC of the proposed 24S-10P FEFSM is draw by using JMAG Editor. Then, the materials, conditions, circuits and properties of the machine are set in JMAG Designer. The design process of both parts is demonstrated in Fig. 7. Furthermore, coil arrangement tests are examined to validate the operating principle of the machine and to set the position of each armature coil phase.

Finally, the flux interaction between DC FEC and armature coil, FEC flux capabilities at various current condition, induced voltage and initial torque are also investigated.



(a) (b)

Fig. 7. Design methodology of the proposed FEFSM (a) Parts drawing (b) Conditions setting

3. Performance Predictions of the 24S-10P FEFSM Based on 2D-FEA

3.1. Coil Arrangement Test

In order to validate the operating principle of the FEFSM and to set the position of each armature coil phase, coil arrangement tests are examined in each armature coil separately as shown in Fig. 8, where all armature coils and FEC are wounded in counter-clockwise direction. Firstly, the DC FEC current of 6A is supplied to the system and the flux linkage at each coil is observed. Then, the resulting flux linkages are compared and the armature coil phases are defined according to the conventional three-phase system.

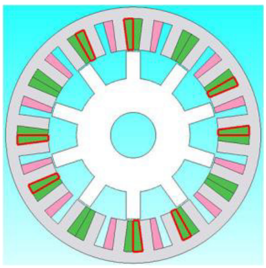


Fig. 8. Initial separate coil setting for armature coil test

Figs. 9 to 12 illustrate the flux linkage of all coils at separate phase and three-phase flux linkage defined as U, V, and W, respectively. Although all flux linkages exhibit small distortion at maximum positive and negative peak, the proof of principles to get 3-phase flux linkage of the machine have been successfully achieved. Thus, further design reconsideration to reduce the distortion will be investigated in future. The final design of the proposed 12S-10P FEFSM is depicted in Fig. 13. It is obvious that the FEC slot in the final design utilizes only half of the provided slot which proves the design flexibility of the FEC slot with various FEC current conditions.

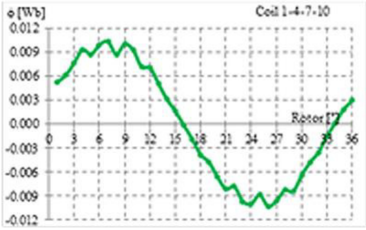


Fig. 9. Flux linkage of coil 1, 4, 7 and 10

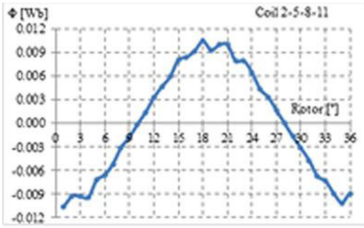


Fig. 10. Flux linkage of coil 2, 5, 8 and 11

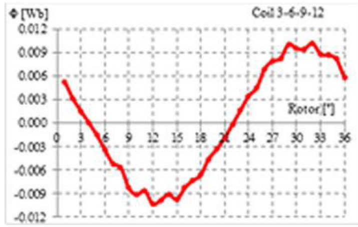


Fig. 11. Flux linkage of coil 3, 6, 9 and 12

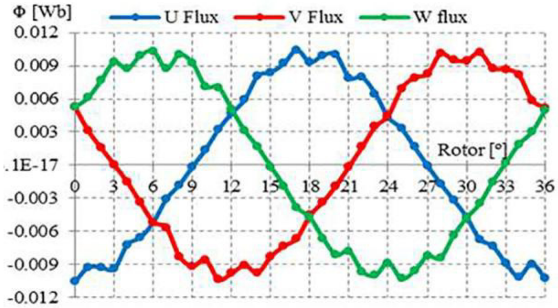


Fig. 12. Flux linkage of phase U, V and W

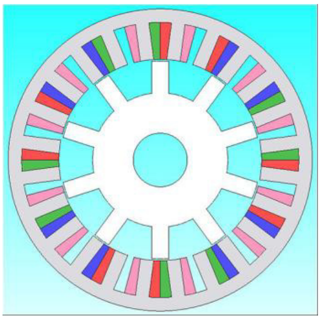


Fig. 13. The final design of 24S-10P FEFSM with three phase armature coil configurations and DC FEC

3.2. FEC Flux Linkages at Various FEC Current

The FEC flux linkage at various FEC currents is also investigated to check the flux characteristics when the current is varied. In this design, the FEC current is varied from 1A to 6A and the FEC flux linkage at U phase versus rotor position is plotted as demonstrates in Fig. 14. From the graph, it is clear that the FEC flux linkage is increased with the increase of FEC current. In addition, a linear increment of the FEC flux linkage with increasing FEC current makes the machine possible to be applied for high current density condition, without reducing the performances. This is a great advantage of the FEFSM with variable flux capabilities suitable for various applications. In addition, the open circuit field distribution of FEC at 0° and 18° rotor position is also investigated at the speed of 1200r/min as shown in Fig. 15. It is obvious that at 0° rotor position, the flux at rotor pole 1 flows from the stator to the rotor, while at 18° rotor position the flux starts to change its polarity realizing the flux switching concept.

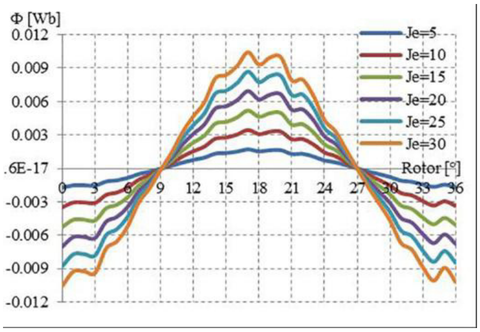
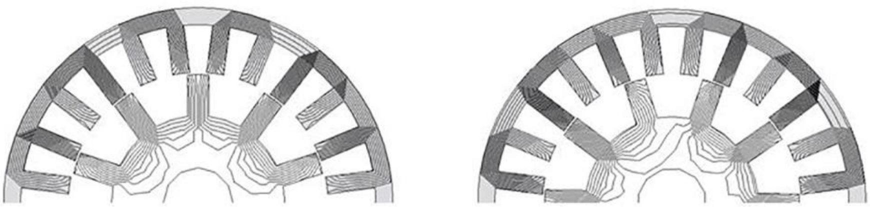


Fig. 14. U phase flux linkage at various FEC current



(a) (b)

Fig. 15. Open circuit field distribution of the proposed FEFSM (a) 0° rotor position (b) 18° rotor position

3.3. Instantaneous Torque Characteristic

The instantaneous torque versus rotor position characteristic of the proposed FEFSM at FEC and armature coil current of 6A and $6A_{rms}$, respectively is depicted in Fig. 16. The average torque and corresponding power obtained at the speed of 1200r/min are 1.72Nm and 216.14W, respectively.

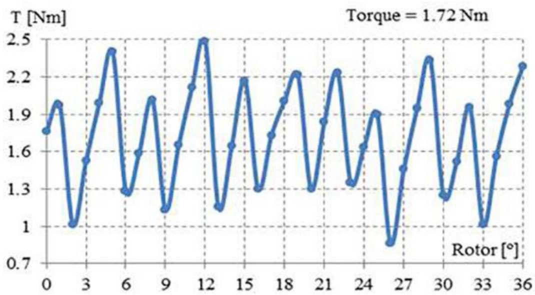


Fig. 16. Instantaneous torque characteristics.

4. Conclusion

In this paper, design study and investigation of 24S-10P FEFSM with single DC FEC polarity has been investigated. The machine has very simple configuration as well as no permanent magnet and thus, it can be expected as very low cost machine. The procedure to design the FEFSM 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 the FEFSM such as flux capability and initial torque have been investigated. The machine has the advantages of easy manufacturing, low copper loss due to less FEC, less flux leakage when compared with alternate FEC polarity of adjacent windings, and design freedom of FEC for various performances. Finally, the proposed FEFSM is suitable for various applications with various performances.

References

[1] Laws AE. An electromechanical transducer with permanent magnet polarization, Technical Note No.G.W.202, Royal Aircraft Establishment, Farnborough, UK, 1952.
[2] Rauch SE, Johnson LJ. Design principles of flux-switching alternators, *AIEE Trans*., vol.74, no.3, pp.1261-1268, Jan 1955.
[3] Sulaiman E, Kosaka, T, Matsui N. High power density design of 6slot-8pole hybrid excitation flux switching machine for hybrid electric vehicles, *IEEE Trans. on Magn.,* vol.47, no.10 pp. 4453-4456, Oct. 2011.
[4] Sulaiman E, Kosaka T, Matsui N. 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, pp.211-218, 2012.
[5] Walker JH. The theory of the inductor alternator, *J. IEE*, vol.89, no.9, pp.227–241, June 1942.
[6] Miller TJE. Switched Reluctance Machines and Their Control, Hillsboro, OH: Magna Physics, 1993.
[7] Pollock C, Wallace M. The flux switching motor, a DC motor without magnets or brushes, *Proc. Conf. Rec. IEEE IAS Annual Meeting*, vol.3, pp.1980–1987, 1999.
[8] Pollock H, Pollock C, Walter RT, Gorti BV. Low cost, high power density, flux switching machines and drives for power tools, *Proc. Conf. Rec. IEEE IAS Annual Meeting*, pp.1451–1457, 2003.
[9] Pollock C, Pollock H, Brackley M. Electronically controlled flux switching motors: A comparison with an induction motor driving an axial fan, *Proc. Conf. Rec. IEEE IAS Annual Meeting*, pp.2465–2470, 2003.
[10] Pollock C, Pollock H, Barron R, Coles JR, Moule D, Court A, Sutton R. Flux-switching motors for automotive applications, *IEEE Trans. Ind. Appl*., vol.42, no.5, pp.1177–1184, Sep./Oct. 2006.
[11] Bangura JF. Design of high-power density and relatively high efficiency flux-switching motor, *IEEE Trans. Energy Convers*., vol.21, no.2, pp.416–424, June 2006.
[12] Zulu A, Mecrow B, Armstrong A. A wound-field three-phase flux-switching synchronous motor with all excitation sources on the stator, *IEEE Trans. Ind. Appl.*, vol.46, pp.2363-2371, Nov. 2010.
[13] Chen JT, Zhu ZQ, Iwasaki S, Deodhar R. Low cost flux-switching brushless AC machines, *Proc. IEEE Vehicle Power and Propulsion Conf*., VPPC 2010, Lille, France, Sept. 2010.