Design and Investigation of a Novel Three Phase Segmented Rotor HE FSM for Aircraft Applications

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***Abstract*— To decrease the influence of air transport on the environment as well as to improve fuel efficiency more-electric aircraft (MEA) architecture is a well-known approach. Due to the fact that electrical machines are capable to provide higher torque densities and are dominant for the feasibility of direct drive electrical driving force for aircraft applications. For these reasons a new sort of machine has been acquainted and published in last decade well-known as flux switching machine (FSM). FSMs comprises all excitation sources on stator side with winding less robust rotor structure. Further FSMs are characterized into three types such as permanent magnet (PM) FSMs, field excitation (FE) FSMs and hybrid excitation (HE) FSMs. PM FSM and FE FSM use PM and FE coil for their excitation sources respectively, whereas both PM and FE coil are used in HE-FSM for excitation. Subsequently, HE FSMs have shown higher torque to weight ratios with higher efficiency during research in the last decade. Nevertheless, in existing structures of HE FSMs using segmental, there is flux cancellation between the fluxes of PMs and FE coil which causes to reduce the performance of machines. Hence, in this paper, a proposed structure of HE FSM with segmented rotor has been proposed and analyzed. The proposed HE FSM has a simple structure using three PMs and three FECs. The proposed structure has been analyzed using commercial 2D FEA package, JMAG-designer. Initially, this paper presents the coil test analysis of novel HE FSM to confirm the working principle. Besides, performance of proposed HE FSM has been analysis and comparison with existing HE FSM at no load and load conditions.**

***Index Terms*— flux switching, hybrid excitation, segmented rotor, aircraft**

I. INTRODUCTION

Recently, the use of electric machines in aircrafts have increased during the last decade. They are used in many applications such as fuel pumps for aircraft, flaps, spoilers etc. [1]. This choice is motivated by numerous benefits like, reduced weight, easier maintenance and cleaner technology with fault tolerant capabilities [2]. For high performance applications, such as in the aerospace industry high torque density and reliability of electrical machines have been always considered as two of the most significant factors to consider during the design and manufacturing of machines. Whereas, permanent magnet (PM) machines have been shown to offer better performances in terms of high torque density [3-5], whilst suitable design procedures can guarantee reliable fault tolerance capabilities [6, 7]. Flux switching (FS) motors with PMs have also been shown to be able to achieve high levels of torque density along with fault tolerance capabilities [8, 9]. The main advantage of such FS machines is that PMs and armature coil can be located on the stator, thus achieving a robust and simple rotor structure.

Furthermore, Due to increases in the commercial prices of rare-earth magnets, field excitation FE (FEFS) machines without PMs have been investigated and published [10, 11]. The advantage of the FE FSM machines is to generate flexible flux regulation with low cost of production, but sacrifice torque density and efficiency [12].

Therefore, the concept of hybrid excited (HE) machines have been introduced, in which PM and field excitations coexist as main flux sources, to combine their advantages [13, 15]. HE machines are excellent candidates for variable speed applications, e.g. electric vehicle, aircraft and wind power generation etc. [16, 17]. The topologies of HE machines are diverse, as two excitation sources can be arranged flexibly. A multitude of novel structures have been proposed and investigated in the past two decades [18].

On the other hand, recently researchers have developed the use of segmental rotor construction for different topologies of flux switching motors, which give significant advantages over other topologies. Whereas segmental rotors are used traditionally to control the saliency ratio in synchronous reluctance machines, the primary function of the segments in this design is to provide a defined magnetic path for conveying the field flux to adjacent stator armature coils as the rotor rotates. As each coil arrangement is around a single tooth, this design gives shorter end windings than the toothed rotor structure, which requires fully-pitched coils. There are

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significant advantages with this arrangement as it uses less conductor materials and may improve the overall motor efficiency. There is a choice to use either a field 3 winding or PM, or a combination of both for primary excitation Subsequently, FE FSM and PM FSM with segmented rotor have been produced, yet because of their ailment of low torque production acquire from low flux linkage, both conventional designs FE FSM and PM FSM with segmented rotor have been merged in [17] and another structure of 12S-8P hybrid excitation HE FSM is proposed as presented in Fig. 1.

Nevertheless, in the previously proposed structure of HE FSM, there is flux cancellation occurring in between the fluxes of PMs and FE coil. Consequently, the main purpose of this paper is to design and examine a new structure of HE FSM with a segmented rotor having three FE coils and three PMs alternatively as shown in Fig. 2. Due to less FE coil slots, there is enough space on the stator side to combine fluxes of PM and FEC easily. In addition, less usage of copper and less number of PM make structure simple, lightweight and less costly. Besides this coil test has been performed to validate the working principle of motor afterward the performance has been analyzed and compared with initial existing HE FSM at load and no load conditions on the basis 2-D FEA.

II. Design Methodology And Parameter Specifications

The design measurements and parameters of a novel structure of HE FSM using a segmental construction of rotor are itemized in Table 1. By means of FEA simulation, a design of HE FSM is analyzed and conducted by means of JMAG-designer. JMAG designer makes a discourse on the qualities of design configuration in terms of the flux linkage, emf creation flux, distribution and cogging torque (unwanted torque). Initially, using JMAG Editor different parts of the motor like stator, rotor segments, armature coil and FE coils are designed. Afterward, material, conditions, circuit's settings and properties of the motor design are selected out in JMAG designer. Electromagnetic steel of 35H210 is assigned to stator core and rotor segments separately. Furthermore, coils arrangements test has been evaluated to affirm the working principle of HE FSM with a segmented rotor and to establish the proper location of individually armature coils phases. Besides, for the proposed segmented HE FSM, the probable number of rotor segments and stator slots are defined by Equation (1)

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

where Nr represented rotor segments number, Ns symbolized the number of stator slots, k is the integer from 1 to 5 and q denotes the number of phases.

By using the same parameter restriction and specification of 12slot-8 pole HE FSM, the performances are analyzed based on 2D-FEA at open circuit condition which means no current is supplied to armature coil, and at load condition with maximum armature current density and DC excitation current densities of 30Arms/mm^2 and 30A/mm to be applied respectively.

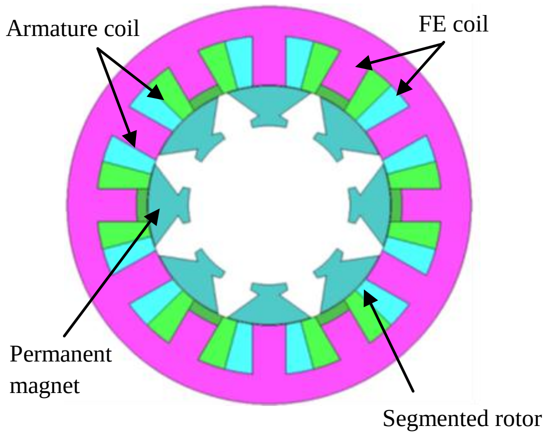


Figure 1. 12S-8P HE FSM segmented rotor

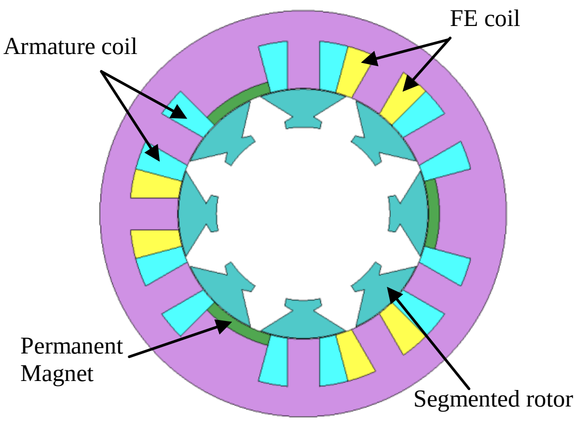


Figure 2. Novel structure of HE FSM with segmented rotor

III. Performance Analysis of Proposed HE FEFSM

In this section, the performance investigation of the proposed structure of HE FSM with segmented rotor has been presented and compared with initial HE FSM on the basis of 2D-FEA. Firstly, to verify the operating principle of HE FSM coil test analysis has been conducted at no load afterward rest analysis like torque and power have been examined at load conditions.

A. Three Phase Coil Test Analysis at No Load

To authenticate the functioning principle of the novel proposed structure of HE FSM with the segmented rotor, and to discover out the appropriate location of individually armature coil phase, the pre-arrangements of coil tests are performed individually at no load condition. Fig. 3 shows that at DC current of 51.27A, each armature coil and FE coil have been organized in the alternate direction to endorse the working principle of HE FSM with segmented rotor along with inward directions of PMs. using this arrangement of armature coils, three-phase sinusoidal flux linkage is defined as U, V, and W with maximum flux linkage of 0.056Wb is managed as confirmed in Fig. 4.

B. Cogging or Detent Torque Analysis at No Load Conditions

The cogging torque or it is also known as no-current torque which has been analyzed at no load condition.

Hence armature coil current density applied is zero. Comparison of no load torque analysis of three-phase initial and proposed HE FSM using segmented rotor is presented in Fig. 5. From the figure, it is understandable that proposed HE FSM with segmented rotor structure has determined acceptable cogging torque which is nearly less than initial HE FSM and achieved the value of almost 4.021Nm peak to peak with smooth graph pattern. The analysis of cogging torque results that proposed HE FSM with segmented rotor has achieved less cogging torque due to the simple structure as there are only three FECs and three PM used leaving much free space in the stator. Less cogging torque confirms that motor is able to run at high speed without vibration and acoustic noises. Henceforth, reduces the iron losses. Consequently, for aircraft applications, the proposed motor is appropriate where smoothness of system, motor with less weight and fewer vibrations are a prerequisite to achieve.

TABLE I. DESIGN SPECIFICATION AND RESTRICTIONS OF INITIAL AND PROPOSED HE FSM WITH SEGMENTED ROTOR

Items	Initial (HE FSM) with segmented rotor	Proposed(HE FSM) with segmented rotor
Slot numbers	12	12
Number of rotor segments	8	8
Number of PMs	6	3
Number of FEC slots	6	3
Length of stator outer radius of (mm)	75	75
Stator back iron length (mm)	11	11
Width of stator tooth (mm)	12.5	12.5
Area of armature coil slots (mm^2)	250	250
Area of FEC slots (mm^2)	250	250
Rotor outer radius (mm)	45	45
Rotor inner radius (mm)	30	30
Air gap length (mm)	0.3	0.3
Span angle segments (degree)	39°	40°
Number of turns per slot of FE coil	44	44
Number of turns per slot of armature coil	44	44

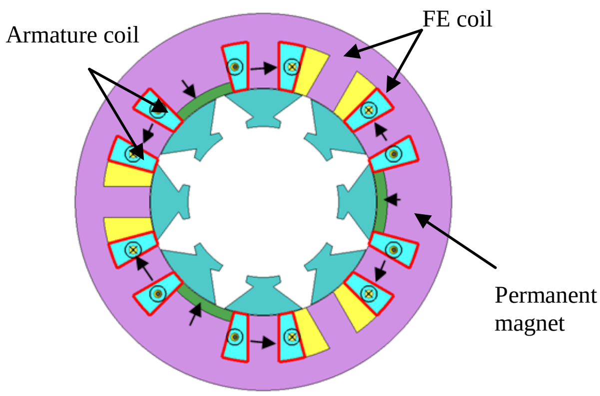


Figure 3. Armature and FEC coil arrangements of proposed HE FSM segmented rotor

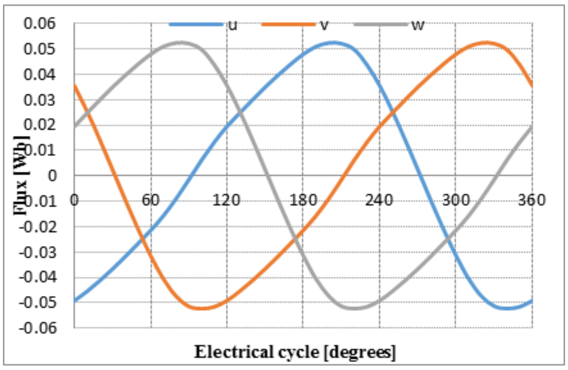


Figure 4. Three Phase flux linkage of proposed HE FSM in terms of U, V, W phases

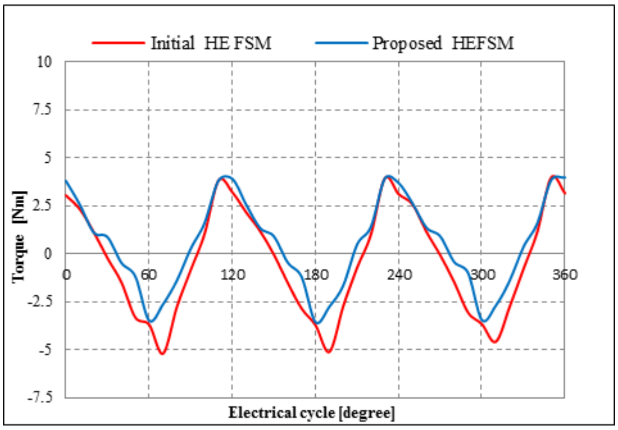


Figure 5. Cogging torque Comparison of initial and proposed HE FSM with segmental rotor

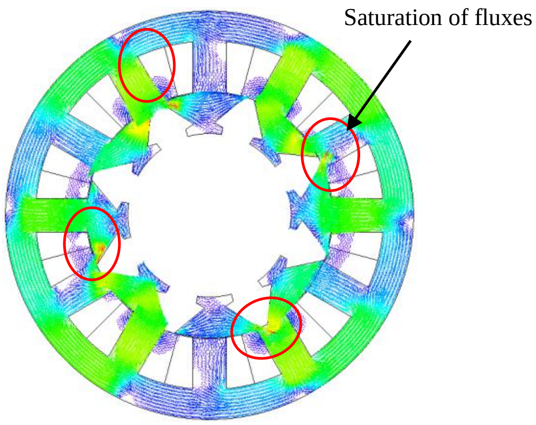
C. *Magnetic Flux Distribution and Flux Lines*

The comparison of magnetic flux distribution and magnetic flux lines of initial and proposed HE FSM have been analyzed and conducted at no load condition. While keeping field current density maximum at $30A/mm^2$ to check the pattern of flux lines and directions. On the other hand, PM is producing constant flux linkages. Moreover, magnetic flux distribution and magnetic flux lines of initial and proposed HE FSM are illustrated in Fig. 6 and Fig. 7 respectively. It is obvious from the Fig. 6, that flux is distributed smoothly and properly over the stator and the rotor segments of proposed HE FSM as compared to initial HE FSM due to enough space between stator slots. On the other hand in case of initial HE FSM, which shows flux saturation at the tips of stator slots and producing long cycles of flux lines as shown in fig6(a) and 7(a). These long flux lines cycles can cause the reduction in the flux strengthening. Furthermore, proposed segmented HE FSM confirms the shortest flux path between one stator slots to another slot as shown in red circle in fig. 7(b).

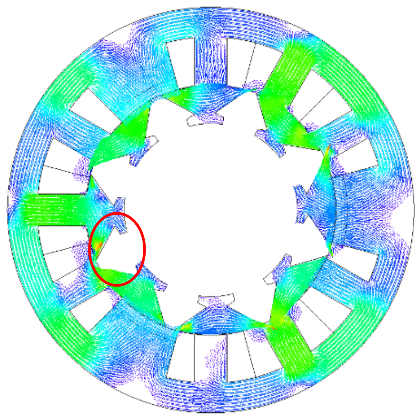
Moreover, from fig.7, the magnetic flux lines are properly and continuously flowing through stator to the rotor segments without cancellation. Hence making proper and short completed cycles. By using only three PMs and three FECs, stator iron core gets much free space which gives the advantage of full utilization of flux linkages over the stator and reducing the saturation and flux cancellation between fluxes generated from both sources.

IV. Torque Vs Je, at Various Armature Current Densities of Ja

Torque vs. FE current densities Je, at several armature coils current densities Ja, for initial and proposed HE FSM with the segmented rotor are shown in Fig. 8 and Fig. 9 respectively. To achieve the highest value of torque, this analysis has been carried out at load condition while applying various values of armature current densities Ja by injecting several field currents densities. From figure 8, it is obvious that the initial HE FSM has achieved maximum torque of 17.5Nm. There is very less increment in torque values as field current densities are increased due to the cancellations of fluxes occurring, hence not producing enough torque. While, in case of proposed HE FSM, from figure 9, it is clear that the value of torque is increased in each case of field current density Je. While reaches up to the maximum value of around 38Nm at maximum armature current density of 30Arms/mm^2. From the figure, it is noticeable that at zero field current density the torque achieved is approximately 22.5 Nm at maximum Ja. Furthermore, as field current density is injected to field coils the torque starts increasing more linearly with the increase of field current. Which implies that both fluxes from PM and FE are properly combined by avoiding cancellations. Being a small size, the proposed structure of HE FSM with segmented rotor has accomplished the maximum value of torque almost 54% greater than the initial designs of HE FSM due to enough space in the stator with a smooth distribution of fluxes. Hence, the proposed structure is reliable for aircrafts at lesser altitudes which require more torque at less speeds. Besides, the proposed structure is fault tolerant because both sources can produce separate fluxes to produce torque at different conditions. Hence, the motor continues generating flux fault condition at any source of excitation. Furthermore, the linearity of torque graph shows that torque can be further increased by design modification and optimization.

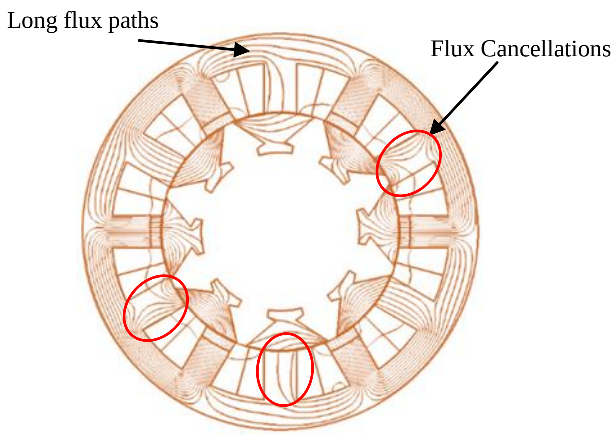


(a)

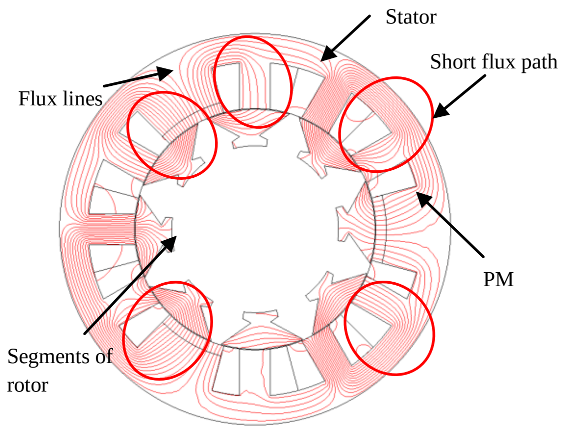


(b)

Figure 6. Magnetic flux distribution of (a) initial HE FSM and (b) proposed HE FSM with segmented rotor



(a)



(b)

Figure 7. Magnetic Flux lines of (a) initial HE FSM and (b) proposed HE FSM

V. Power vs Speed Characteristics

Power vs speed characteristics of initial HEFSM, and proposed HEFSM are illustrated in Figure 10. It is noticeable from the figure that maximum value of power achieved by initial HE FSM is 3.6KW, at speed of

2,033rpm and suddenly begins to reduce as the speed is increased and reaches up to a minimum level at maximum speed of 3400rpm. While, the figure 10, demonstrates that the maximum power achieved by proposed HE FSM is almost 9KW at speed of 2830rpm, which is approximately 61% greater than the initial HE FSM at higher speed ranges. Nevertheless, the value of power starts to decrease when speed is more than 2,830rpm due to iron and copper losses at maximum speed ranges. In addition, the maximum value of power attained at maximum torque of 38Nm is almost 8.3KW when the speed is 2,095rpm. It is clear from the figure that at lower speed ranges the power graph increased linearly and reached until maximum value at base speeds. This pattern verifies that the proposed HE FSM is reliable and suitable for aircraft applications where at lower speed power is required is necessary to be at maximum.

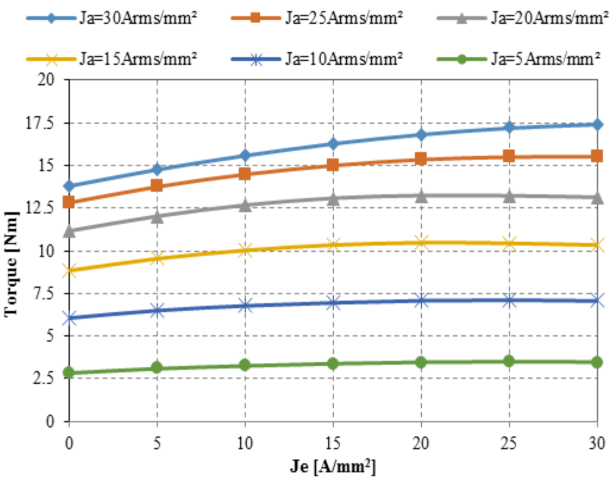


Figure 8. Torque vs Je of initial HE FSM with segmented rotor

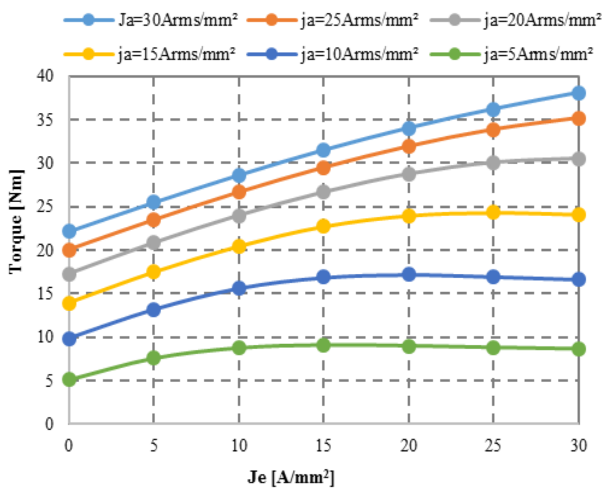


Figure 9. Torque vs Je of proposed HE FSM with segmented rotor

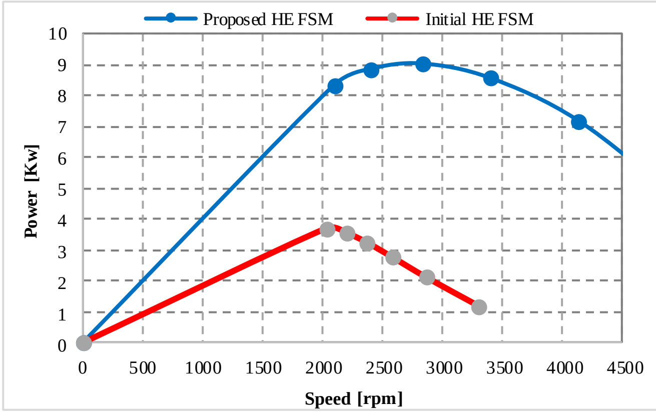


Figure 10. Power vs speed of initial and proposed HE FSM with segmental rotor

VI. Conclusion

The design, performance analysis and the comparison of the initial and proposed structures of HE FSM using segmented rotor have presented in this paper. The proposed design has simple structure promising the less cost and less weight due to the reason that less number of FE coils and less number of PMs are used on the stator side leaving enough free space and robust rotor structure. Armature coils and FE coils have been arranged alternatively to obtain sinusoidal three-phase waveform with inward PMs directions. At first, the coil test analysis of proposed HE FSM has been inspected based on 2-D FEA. The new structure uses only three FE coils and three PMs to confirm the simple structure and smooth flow of magnetic fluxes from the stator to rotor segments. Furthermore, at no load condition cogging torque, flux distribution and flux lines of initial and proposed designs have been compared and analyzed. While, at load conditions torque and power characteristics of both structures have been compared and investigated. Furthermore, the proposed HE FSM has achieved 54% and 61% more torque and power than initial HE FSM. All the analysis of the initial and proposed HE FSM endorsed that the proposed HE FSM structure is a reliable candidate for small-scale aircraft applications in terms of high torque, less cost, less weight and smooth operation with less vibrations at low to high speeds.

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References

[1] G. J. Atkinson, J. W. Bennett, B. C. Mecrow, D. J. Atkinson, A. G. Jack, and V. Pickert, "Fault tolerant drives for aerospace applications," in *Proc. 2010 6th International Conference on Integrated Power Electronics Systems (CIPS)*, 2010, pp. 1-7.

[2] D. Mami, “Definition, design and experiments of innovative electromechanical actuator structures including by design safety features and operating safety,” *Ph.D. dissertation, National Polytechnic Institute of Toulouse*, 2010.

[3] C. Gerada and K. J. Bradley, "Integrated PM machine design for an aircraft EMA," *IEEE Transactions on Industrial Electronics*, vol. 55, pp. 3300-3306, 2008.

[4] T. Raminosoa, T. Hamiti, M. Galea, and C. Gerada, "Feasibility and electromagnetic design of direct drive wheel actuator for green taxiing," *IEEE Exposition in Energy Conversion Congress and (ECCE)*, 2011, pp. 2798-2804.

[5] M. Galea, C. Gerada, T. Raminosoa, and P. Wheeler, "Design of a high force density tubular permanent magnet motor," *XIX International Conference in Electrical Machines (ICEM)*, 2010, pp. 1-6.

[6] N. Bianchi, S. Bolognani, and M. D. Pre, "Design and tests of a fault-tolerant five-phase permanent magnet motor," *IEEE Electronics in Power Specialists Conference*, 2006. (PESC), 2006, pp. 1-8.

[7] T. Raminosoa, C. Gerada, and N. Othman, "Rating issues in fault tolerant PMSM," *IEEE International Conference in Electric Machines and Drives*, 2009. (IEMDC), 2009, pp. 1592-1599.

[8] T. Raminosoa and C. Gerada, "A comparative study of permanent magnet - synchronous and permanent magnet - flux switching machines for fault tolerant drive systems," *IEEE Energy Conversion Congress and Exposition* (ECCE), 2010, pp. 2471-2478.

[9] T. Raminosoa, C. Gerada, and M. Galea, "Design considerations for a fault-tolerant flux-switching permanent-magnet machine," *IEEE Transactions on Industrial Electronics*, vol. 58, pp. 2818-2825, 2011.

[10] A. Zulu, B. Mecrow, and M. Armstrong, "A wound-field three phase flux-switching synchronous motor with all excitation sources on the stator," *IEEE Energy Conversion Congress and Exposition*, 2009, pp. 1502-1509.

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

[12] A. Zulu, "Flux switching machines using segmental rotors," *PhD Thesis, School of Electrical, Electronic, and Computer Engineering*, Newcastle, UK, 2010.

[13] B. M. Frederick, “Hybrid excited generator with flux control of consequent-pole rotor,” *U.S. Patent 46* 563 797, Apr. 1987.

[14] E. Spooner, S. Khatab, and N. Nicolaou, “Hybrid excitation of AC and DC machines,” in *Proc. Inter. Elect. Mach. Drives Conf*, pp. 48–52. Sep, 1989.

[15] F. Capponi, G. Borocci, G. Donato, and F. Caricchi, “Flux regulation strategies for hybrid excitation synchronous machines,” *IEEE Trans. Ind. Appl*, vol. 51, no. 5, pp. 3838–3847, Sep./Oct. 2015.

[16] Y. Amara, L. Vido, M. Gabsi, E. Hoang, A. Ahmed, and M. Lecrivain, “Hybrid excitation synchronous machines: energy efficient solution for vehicles propulsion,” *IEEE Trans. Veh. Technol*, vol. 58, no. 5, pp. 2137– 2149, Jun. 2009.

[17] H. A. Soomro, E. Sulaiman, M. F. Omar, “Performance Comparison and analysis of (HEFSM) and (FEFSM) using Segmental rotor Structure. *Applied Mechanics and Materials*, Vol.695, pp.778-782, 2015.

[18] B. C. Mecrow, E. A. El-Kharashi, J. W. Finch, and A. G. Jack, "Segmental rotor switched reluctance motors with single-tooth windings," *IEE Proceedings on Electric Power Applications*, vol. 150, pp. 591-599, 2003.

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