Performance comparison of initial and optimized designs of dual stator HEFSM for aerospace applications

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Abstract. For aerospace propulsion system, electrical machines are capable to deliver high torque density and are dominant for the viability of direct-drive electrical propulsion for aircraft applications. Besides light weight and high torque ability, the machines should also be inherently fault tolerant for it to be used in aircraft applications. For these reasons, a new type of machine has been introduced in last decade know as flux switching machine (FSM). FSM contains all its flux excitation sources on stator side with robust piece of rotor which is free from permanent magnets (PMs) and coils. Since, these machines have shown high torque-to-weight ratios and high efficiency during research in the last decade. Regardless of this, the task of designing a machine appropriate for aerospace application goes beyond the electromagnetic design and into the area of mechanical design much deeper than traditional designs. Therefore, in this paper, a new structure of dual stator (DS) HEFSM with segmental rotor is proposed and analysed. Moreover, the initial structure of proposed design is optimized using deterministic optimization method. Furthermore, the performance of initial and optimized designs are compared and investigated using 2D-FEA method.

Keywords: Flux switching machine, hybrid excitation segmental rotor, aircraft

1. Introduction

Electric motor drives are capable of converting electrical power to different systems such as drive actuators, pumps, compressors, and other subsystems at variable speeds used in combination with progressive power electronics and control approaches [1-2]. Electric drives are capable to offer improvements in overall efficiency while reducing weight, and cost to meeting reliability requirements. On this basis, the ultimate goal for the aircraft industry is to achieve the all-electric aircraft (AEA), transferring all power systems to electrical power. It is estimated that an AEA can reduce aircraft weight by 15% and fuel consumption by 9% [3-4]. Consequently, mechanically driven actuators have been progressively replaced by hydraulic actuators with electronic servo valve control electro hydraulic actuation. In the A380, electro-hydrostatic actuators provide hydraulic actuation from a localized pump and reservoir, allowing operation from an electrical power supply. This “more electric” progression has allowed a reduction in mechanical linkages and latterly hydraulic power supply networks, simplifying maintenance and reducing weight. For example, electric engine fuel pumps, in place of hydraulic, have been recognized to provide benefits in system efficiency, weight and size, and flexibility in speed control [5-6]
Significant enhancements to increase the reliability in motor drives for the MEA perspective can be obtained by introducing multi-phase machines. These are generally projected as machines with a number of phases greater than three, being this number assumed as the critical threshold in case of one-phase fault. Proposals reporting multi-phase motors fed by multiphase power electronic converters can be found in “literature, where both the motor and drive are designed to satisfy severe fault-tolerant requirements [7-8]. A fault-tolerant design approach differs from a pure redundant one in that provisions are made for planned degraded modes of operation where acceptable. By providing compensation for potential failures, a fault-tolerant system may achieve reliability objectives without recourse to non-optimized redundancy or over-sizing [9]. The key areas for consideration of safety-critical drives in aircraft are engine generators, flight surface actuators, flap actuators, engine fuel pumps, and landing gear nose wheel steering systems [15].

In recent, for high performance environments such as in the aerospace industry, high torque density and reliability, flux switching (FSM) with PMs have also been shown to be able to achieve high levels of torque density coupled with good fault tolerance capabilities [11-12]. FSMs consist all flux sources in the stator with the advantage of robust rotor structure, that can be used for high speed applications and total control is maintained by the field flux. They can be further classified into three groups that are (i) permanent magnet (PM) FSM, (ii) field excitation (FE) FSM, and (iii) hybrid excitation (HE) FSM. Main flux sources are only PM in PMFSM and field excitation (FE) coil in FEFS motor while HEFSM combines both PM and FE Coils [13-14].

Due to the advancement of modern high-performance rare earth magnetic materials, PMFSMs are being increasingly more popular in various applications, ranging from electric and hybrid electric vehicles, renewable energy systems including wind power generators, electric aircrafts, industrial drives, automations, to domestic appliances, etc. [15]. Nevertheless, PM machines have some drawbacks, such as high price of rare earth material, relatively lower flux-weakening capability, uncontrollable flux, demagnetization and limited working temperature [16]. Therefore, non-PM machines have become one of the most popular research topics. In [17], field excitation flux switching (FEFSM) machine has been proposed and analyzed with double stator. However, it draws more copper losses as both the armature and field windings are separately accommodated on the outer and inner stators. It also sacrifice torque density and efficiency due to less flux strengthening capabilities.

Hence, the concept of hybrid excited (HE) machines, in which PM and DC excitations coexist, is proposed to combine their advantages. HE machines are excellent candidates for variable-speed applications, e.g. electric vehicle, aircraft and wind power generation etc. [18-19]. 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. However, due to flux cancellations issues between PM flux and FE flux these structures are required to improve further.

Therefore, in this research, the new structure of DS HEFSM with segmental rotor is optimized using deterministic method. Furthermore, the performance of initial and optimized designs such as magnetic flux, cogging torque, induced voltage and torque analysis are compared and investigated using 2D-FEA method.

2. Initial geometry and parameter specifications of the proposed machine

The initial design geometry, and parameter specifications of the proposed dual stator (DS) FSM with hybrid excitations are tabulated in Table I. While, the limit of both armature current density, $J_a$ and FEC current density, $J_e$ is set to 15 A/mm$^2$ maximum. Generally, the proposed machine is composed by 6 PMs which are located at the tips of inner stator along with 6 FECs distributed uniformly in the midst of each armature coil in outer stator. Whereas, armature winding coil and FEC winding coil are located on the outer stator, and robust single piece of a segmented rotor situated in between the inner and outer stators. Figure. 1 shows the cross-sectional view of the proposed dual stator HE FSM with segmental rotor.
In the proposed motor, for the motor rotation through 1/15 of a revolution, the flux linkage of armature has one periodic cycle and thus, the frequency of back-emf induced in the armature coil is ten times of the mechanical rotational frequency. In general, the relation between the mechanical rotation frequency, \( fm \) and the electrical frequency, \( fe \) for the proposed machine can be expressed as:

\[
fe = Nr \cdot fm
\]  

(1)

where \( fe \) is the electrical frequency, \( fm \) is the mechanical rotation frequency and \( Nr \) is the number of rotor poles respectively.

| Items                        | DS HEFSM with segmental rotor |
|------------------------------|-------------------------------|
| Max. DC-bus voltage inverter (V) | 650                           |
| Max. inverter current (Arms)  | 360                           |
| Max. current density in armature coil, \( Ja \) (Arms/mm\(^2\)) | 15                            |
| Max. current density in FEC, \( Je \) (A/mm\(^2\)) | 15                            |
| Outer stator diameter (mm)    | 273                           |
| Inner stator diameter (mm)    | 131                           |
| Number of rotor segments      | 15                            |
| Back iron length of outer stator (mm) | 20                       |
| Tooth width of stator (mm)    | 11                            |
| Slot area of armature (mm\(^2\)) | 526                          |
| Slot area of FEC (mm\(^2\))   | 526                           |
| Length of air gap (mm)        | 0.5                           |
| Segment span (degree)         | 30°                            |
| Number of turns per slot of FEC | 15                            |

**Figure 1.** Initial design of DS HE FSM with segmental rotor
3. Performance comparison of initial and optimisation DS he FSM designs

The initial design of DS HEFSM with 15 segments has been examined systematically where average output torque is approximately 160Nm which far from the required target. Therefore, design free parameters located in stators and rotor part were updated by using the deterministic optimization method for few cycles so optimal torque can be obtained. Fundamentally, the design parameters are divided into two categories such as those related to stators core and rotor core. On the stator core, it is subdivide into three groups which are the FEC slot shape, armature slot shape, and PM in (inner stator). The stators parameters involved are the outer stator radius (D1), inner stator radius (D2), and PM width (D3). While for the FEC slot parameters are FEC coil height and FEC coil width, (D4) and (D5) respectively. The armature coil parameters shown are armature coil height (D6) and the armature coil width (D7). Finally, the segmental rotor parameters includes, rotor radius (D8), rotor width (D9) and span angle (D10) of segment. These mentioned design free parameters, from D1 to D10 are demonstrated in Figure 2. Whereas Figure 3 shows the optimized design of DS EFSM. The comparative examination between the initial and optimized design parameters of DS HEFSM for aerospace application with segmented rotor are detailed in Table 2.

Table 2. Initial Design Parameters Of Proposed DS HEFSM

| Parameters | Descriptions | Initial DS HEFSM | Optimized DS HEFSM |
|------------|--------------|------------------|--------------------|
| D1         | Outer stator radius (mm) | 136.5            | 136.5              |
| D2         | Inner stator radius         | 65.5             | 60.6               |
| D3         | PM width (mm)              | 7.43             | 11                 |
| D4         | FEC coil height (mm)       | 30               | 33                 |
| D5         | FEC coil width (mm)        | 21.4             | 17                 |
| D6         | Armature coil height (mm)  | 30               | 32.7               |
| D7         | Armature coil width (mm)   | 21.4             | 21.7               |
| D8         | Rotor radius (mm)          | 86               | 93                 |
| D9         | Rotor width (mm)           | 15               | 21                 |
| D10        | Span angle (degree)        | 15               | 14                 |

Figure 2. Design parameters defined as D1 – D10
At open and close circuit analysis, the performance comparison of initial and optimized design is carried out using 2D FEA. The open circuit examination includes flux linkage, flux distribution, cogging torque and induced voltages while close circuit analysis consist of torque at various armature current densities and torque-power versus speed characteristics.

3.1. Magnetic flux characteristics
The amplitude of magnetic flux linkage generated from both PMs and FE coils for initial and optimized design is achieved by revolving rotor at the speed of 1000 r/min while armature current density is set at 0 Arms/mm². The u-phase flux linkage of initial DS HEFSM design is shown in Fig. 4 which is raised up to 0.037 Wb. Whereas, the flux linkage of optimized DS HEFSM is raised up to 0.056 Wb which is almost 40% greater than the initial DS HEFSM. It is verified from the Figure 3, that the fluxes from both sources of PMs and FE coils are combined properly avoiding the flux cancellation and flux leakage which has huge influence of the magnetic flux linkage.

Figure 3. Optimized design of DS HE FSM with segmental rotor

Figure 4. Flux linkage of initial and optimized design of DS HE FSM
3.2. Cogging torque analysis

The cogging torque is also known as no-current torque that causes noise and vibration in machine during operation. The PM delivered cogging torque examination for one electrical cycle is delineated in Fig. 5. The cogging torque waveform of introductory and streamlined outline has 6 numbers of cycles. In initial design of DS HEFSM for the aerospace application with high crest to crest cogging torque of around 21 Nm is noticed. While optimized design of DS HEFSM has attained the peak to peak torque of around 49.2Nm which higher than the initial design. However, using different techniques further the cogging torque can be reduced.

![Cogging torque waveform](image)

Figure 5. Cogging torque of initial and optimized design of DS HE FSM

3.3. Average output torque analysis at various field and armature current densities

Torque analysis of initial and optimized DS HEFSM with segmental rotor has been conducted at various loads by applying different armature current densities from zero to 15 Arms/mm$^2$. Henceforth, at maximum field current density of 15 A/mm$^2$ the torque has been examined at different armature current densities ($J_a$) such as at 0Arms/mm$^2$, 3Arms/mm$^2$, 6 Arms/mm$^2$, 9 Arms/mm$^2$, 12 Arms/mm$^2$ and 15 Arms/mm$^2$. As a flux source, PM produces constant flux thus the field current density is varied to examine the torque behaviour at different loads. Figure 6 and Figure 7 show the comparison of torque analysis for initial and optimized design at different armature current densities for different injected current. From the figure 6, in case of initial design, it obvious that by increasing the current densities the torque value is also increasing linearly verifying that the flux produced from PMs and FECs is combined properly in both designs. Which endorse that the proposed structure is capable to produce more torque at higher loads. From figure, it can be seen that at maximum armature current density of 15Arms/mm$^2$ the torque achieved in case of initial design is approximately 158Nm. While, after optimization, the DS HEFSM has achieved average torque around 258.5Nm which almost 38.7% higher than the initial design as shown in Figure 7. This increase in torque verifies the hybrid nature of the machine in which both fluxes from PMs and FE coils are combined properly hence torque is increased more. The achieved torque is evidently appropriate for the aircraft applications under lower altitudes. For aircraft applications where it is essential for electric motors to achieve high torques especially at lower altitudes and lower speeds DS HEFSM is capable to achieve required performances. Consequently, the DS HE FSM is the appropriate structure which can be work at fault conditions due to dual excitations.
4. Conclusion
In this paper the performance comparison analysis of initial and optimized designs of proposed DS HEFSM with segmental rotor has been investigated. The performance analysis of both designs have been investigated using 2D FEA method. Moreover, due to less torque production of intimal design for required aerospace applications, the “deterministic optimization” method is used to enhance the performance of the proposed DS HEFSM structure. Furthermore, in this paper, magnetic flux analysis, cogging torque, and torque characteristics at load conditions of initial and optimized designs have been investigated and compared. In case of cogging torque, the design needs more attention on different techniques to reduce the cogging torque. While, in case of torque analysis, the optimized design achieved almost 38.7% more torque than the initial design. Which evidently appropriate for the aircraft applications under lower altitudes. Henceforth, it is apparent that the proposed design of DS HEFSM with segmental rotor is suitable candidate to be applied for the aircraft applications at different speed regions as the motor draws high torque at maximum speeds ranges.
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