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Research paper

Preliminary Design Investigation of Dual Stator HE FSM using Segmental Rotor

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Abstract

To drop the effect of air transportation on the atmosphere as well as to advance fuel productivity more-electric aircraft (MEA) architectures is a well-known approach. As the electrical machines are competent to deliver higher torque densities and are foremost for the viability of electrical driving force for aircraft applications. For these reasons a new category of machine has been familiar and published in last decade known as flux switching machine (FSM). FSMs comprises all excitation sources on stator side without winding robust rotor structure. Additionally, FSMs are classified 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. Afterwards, HE FSMs have shown higher torque to weight ratios with higher efficiency during research in the last decade. Yet, in existing structures of HE FSMs, 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 novel structure of dual stator (DS) HE FSM with segmented rotor has been proposed and analyzed. The main reason of dual stator is to make the separate flow fluxes in HE machines to avoid cancellations. The proposed novel DS HE FSM has a simple structure using dual stators to endorse separate dual excitations to be used in fault conditions. The proposed structure has been analyzed using commercial 2D FEA package, JMAG-designer. Initially, this paper presents the coil test analysis of proposed DS HE FSM to confirm the working principle. Besides, performance analysis has been carried out at no load and load conditions.

Keywords: *Aircraft Applications; Flux Switching; Hybrid Excitation; Segmental Rotor; Torque Analysis.*

1. Introduction

Aircraft transportation and airborne passenger transportation have been increasing day by day since 1960s and has make the world to face global warming problems [1]. Whereas, presently air transportation remains high-priced and accounts more than 2% of the artificial carbon di oxide (CO_2) emissions. Hence, it is the challenge for the aircraft operatives as well as the aerospace manufacturing industry to offer continuous enhancements in terms of protection, reliability, safety, and availability while dropping cost, noise, and emission of CO_2 [2]. To use these prospects, aerospace systems are undergoing a long-term shift from mechanical, hydraulic, and pneumatic power systems into globally optimized electrical systems.

Electrical motor drives are more consistent and capable of shifting electrical power to drive actuators, fuel pumps, air compressors and other subsystems at various speed ranges in conjunction with advanced power electronics and control schemes [3]. While meeting reliability requirements electric drives are able to gain overall efficiency and reducing the weight and cost. Therefore, it is the ultimate aim of the aircraft industry to achieve the "all electric aircraft" (AEA), which converts all power systems to electrical power. It is estimated that an AEA can decrease aircraft weight and fuel consumption by 10% and 9% respectively [4].

Consequently, mechanically driven actuators have been gradually switched into electronic servo valve control "electro hydraulic actuation hydraulic actuators." In the A380, electro-hydrostatic actuators have been used which provide hydraulic actuation by means of using pump and reservoir, and the operation took place by the electrical power supply. This "more electric" development has reduced the drawbacks of reduction in mechanical linkages. Currently, hydraulic power supply networks are easy and simple in terms of maintenance and less in weight than mechanical systems. Such as, electric engine has been used in fuel pumps, in place of hydraulic engine, which has been recognized to provide profits in system efficiency, weight, and size, and flexible in speed control [5]

To familiarize the conception of electric actuators for more electric aircraft (MEA), electric motor and the control electronics both are kept in to account. In point of fact, for high performances, variable speed drives, the core of MEAs, are still far away to meet the high-reliability limitations needed in harmful conditions due to the presence of complex control systems employing power electronics, and VLSI microcontrollers or ASICs [6].

While, substantial enhancements can be gained to increase the reliability and performance of motor drives for the MEA, is present multi-phase machines. Multi-phase machines are generally intended as machines with a number of phases more than three, in the case of a one-phase fault, this number expected to be the criti-

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cal threshold. In literature, a number of proposals have been found, reporting multi-phase motors nurtured by multi-phase power electronic converters, where both the motor and drive are designed to satisfy severe fault tolerant requirements [7], [8]. A fault tolerant design methodology differs from a pure redundant one in that provisions are made for planned degraded modes of 2 International Journal of Engineering & Technology operation where it is acceptable. By providing advantages for potential failures, a fault tolerant system may achieve reliability without recourse to non-optimized redundancy or oversizing [9].

The major areas, which can be taken as attention of safety-critical drives for aircraft are engine generators, flight surface actuators, flap actuators, engine fuel pumps, and landing gear nose wheel steering systems [10].

In recent times, a new structure of machine named as 'flux switching machine' (FSM) has been recognized and published which consists of active flux sources on the stator. In addition, besides the benefit of the brushless machine, it contains a single piece of an iron rotor which is robust, winding less, and efficient for high-speed applications. In FSM, the flux is controlled and maintained by the field flux. Moreover, there a three groups of FSMs, which are (i) permanent magnet PM-FSM, (ii) field excitation FE-FSM and (iii) hybrid excitation HE-FSM. PMs and FECs are key active flux sources of PM-FSM and FEFSM respectively. While both PM and FECs are combined to produce flux in HE-FSM [11-12].

Presently, PM-FSMs are being gradually more popular and widely used in several applications because of the advancement of modern high-performances of rare earth magnetic materials. The applications where PM-FSMs are being widely used are electric and hybrid electric vehicles, renewable energy systems including wind power generators, industrial drives, electric aircraft, and automation, to domestic appliances [13].

Nevertheless, PM machines have some hitches, such as high cost of rare earth magnet, relatively lower flux-weakening capability, uncontrollable flux, demagnetization and limited working temperature [14]. Therefore, non-PM machines have become one of the most widespread research topics. In [15], field excitation flux switching FE-FSM machine has been proposed and analyzed with the double stator. However, it draws more copper losses as both the armature and field windings are separately housed on the outer and inner stators. It also sacrifices torque density and efficiency due to less flux strengthening capabilities.

Hence, to combine the merits of PM-FSM and FE-FSM machines the PM and FE are coexist, and the concept of hybrid excited HE machines have been proposed. HE machines are good applicants for variable speed applications, such as electric vehicle, aircraft and wind power generation [16], [17]. There are a numerous number of topologies of HE machines have been introduced and published, because of two excitation sources PM and FE can be arranged in various techniques and arrangements. Hence several numbers of new designs and structures have been proposed and investigated in the past two decades. According to the structure and construction between FE and PM fluxes, the HE machines are categorized into two different groups, which are series HE machines and parallel HE machines. For series HE machines, the flux created by the field coils would go through the PMs. Thus PM and field winding have the same flux path and on the other hand in case of parallel HE machines the fluxes of both excitations travel in separate paths hence there are rarer chances of demagnetizations and cancellation.[18].

Moreover, the series topology may lead to the demagnetization of the PMs especially for the ferrite materials with low coercive force. In parallel hybrid excitation machines, the PM is not in the magnetic circuit of the excitation coils. The excitation coils are not only used for the field-weakening but also for the field-strengthening. The excitation current is much smaller because of the magnetic reluctance is lower. [21]

Hence, in this paper, a novel structure of dual-stator (DS) HE FSM is presented. The salient advantage of this novel structure is it realizes the parallel hybrid excitation magnetic path with relatively considerable simple and compact structure. The novel HE FSM machine contains stators and one rotor in between stators.

2. Preliminary Design Geometry and specifications of the proposed machine

The design requirements, restrictions and specifications for the proposed dual stator (DS) FSM with hybrid excitations are tabulated in Table I. For the proposed design the PM weight is limits to 1.0 kg. The corresponding electrical restrictions to the inverter such as maximum DC bus voltage and maximum inverter current is set to 650 V and 360 Arms, respectively. While, the limit of both armature current density, Ja and FEC current density, Je is set to 10 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. Whereas, armature winding coil and FEC winding coil are located on the stator, and robust single piece of a segmented rotor situated in between the inner and outer rotor. Its features can be said similar to the switched reluctance motor. Figure. 1 shows the cross-sectional view of the proposed dual stator HE FSM with segmental rotor.

Table 1: Design Parameters and Specifications of DS HE FSM

Items	DS HE FSM 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)	10
Max. current density in FEC, Je (A/mm^2)	10
Outer stator diameter (mm)	273
Inner stator diameter (mm)	131
Number of rotor segments	10
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	10
Number of turns per armature coil (AC) slot	10

In the proposed motor, for the motor rotation through 1/10 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;

$$fe = Nr.fm \tag{1}$$

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

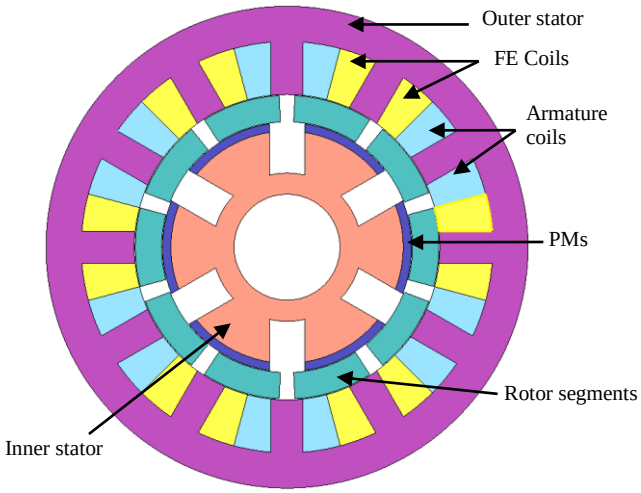


Fig.1: Initial design of proposed DS HE FSM with segmental rotor

Basically, 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. In this study, the initial design parameters of the proposed DS HE FSM with segmental rotor are depicted in Table 2.

Table 2: Initial design parameters of proposed DS HE FSM

Parameters	Descriptions	Initial design rotor
D1	Outer stator radius (mm)	136.5
D2	Max. inverter current (Arms)	360
D3	PM width (mm)	7.43
D4	FEC coil height (mm)	30
D5	FEC coil width (mm)	21.4
D6	Armature coil height (mm)	30
D7	Armature coil width (mm)	21.4
D8	Rotor radius (mm)	86
D9	Rotor width (mm)	15
D10	Span angle (degree)	526

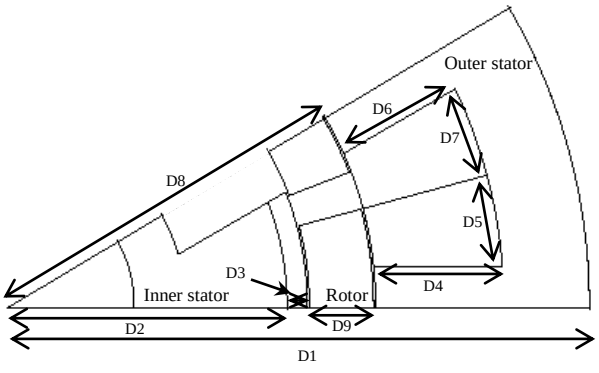


Fig. 2: Design parameters defined as D1 – D10

3. FEA-Based performance prediction of initial design DS HE FSSM

The Commercial FEA package, JMAG-Designer ver.14.0, released by Japan Research Institute is used as 2D-FEA solver for this design. The PM used is NEOMAX-35AH while the electromagnetic steel, 35H210 is used for the rotor and stators core. The necessary, slot area of armature coil (Sa) gives optimum number of turns of armature coil (Na), which is calculated using equation (2) where the limits of armature current density, Ja is set to 10 Arms/mm^2. Similarly for the slot area of FEC coil (Se) is determined by equation (3) where the maximum current density of FEC, Je is set to 10 A/mm^2. In this study the number of turns of both armature coil and FEC are set to 10 turns.

$$S_a = \frac{I_a N_a}{\alpha_f J_a} \tag{2}$$

$$S_e = \frac{I_e N_e}{\alpha_f J_e} \tag{3}$$

From (2) and (3), α is the filling factor, while Ia and Ie are rated armature and FEC currents, respectively.
Initially, performances of the proposed DS HEFSM with segmental rotor at open circuit condition such as the flux linkage, back-emf, and cogging torque are analysed. Firstly, the investigation of the flux linkage is conducted to validate the magnetic flux generated by PM and FEC to be in the same phase. Figure 3 displays the flux linkage at various conditions of PM and FEC current density. As an example, the lowest amplitude of magnetic flux generated is when the proposed machine is set at without PM and maximum FEC current density, Je of 10 A/mm^2 is injected in the field. The maximum amplitude of flux linkage is found when the proposed machine is set with 1.0 kg of PM and maximum field current density, Je of 10 A/mm^2 is applied in the coil. Afterward, when only 1.0Kg of PM is used at 0 A/mm^2 current density, the amount of flux density obtained is moderate. Which shows clearly that the both sources (PM plus FEC) after combining producing more flux linkage and validate that the both fluxes are added properly.

3.1. Three phase coil test analysis of proposed DS HE FSM at no load.

Coil test is performed at no load condition to verify the operating principle of a proposed machine and the arrangement of armature coils in their specific slots. Firstly, six coil analysis is performed separately for each armature coil to obtain six coils sinusoidal patterns. From these six patterns, two will give identical patterns. After successful arrangement of armature coil directions and FECs direction along with radially inserted PMs, the proposed design has achieved a sinusoidal three phase waveform of U, V and W, as shown in figure 4. From figure it is obvious to notice that achieved flux linkage of DS HE FSM is approximately 0.034Wb with sinusoidal pattern, which validate the operation principle of proposed DS HEFSM.

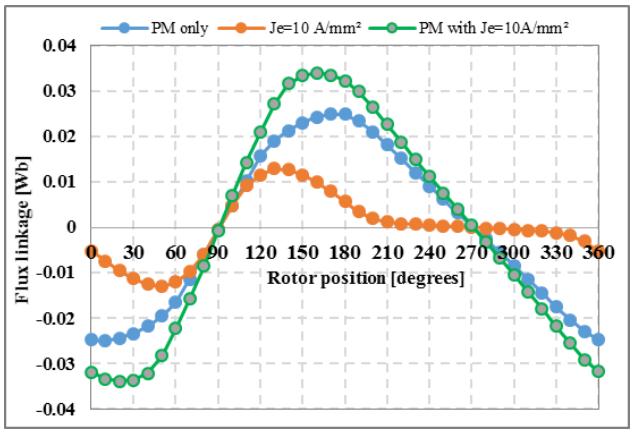


Fig. 3: Finite-element-predicted of phase flux linkage at various conditions PM and FEC current density

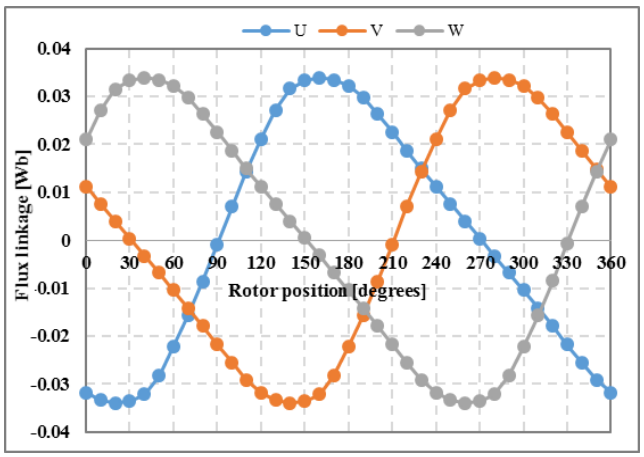


Fig. 4: Three phase U, V and W flux in armature coil

3.2. Detent torque analysis of DS HE FSM at no load conditions

The detent torque or commonly known as cogging torque which is examined at no load condition and field excitation current density Je is kept at maximum of 10 A/mm^2 by applying current in FEC. Detent torque is unwanted torque, its peak-to-peak value should be below 10% of the average torque, otherwise the motor will start creating vibration, acoustic noise, possible resonances, and speed ripples that may cause noise and structure damage. No load torque analysis of three-phase DS HE FSM using segmented rotor is presented in Figure. 5. From the figure, it is understandable that initial DS HE FSM with segmented rotor structure has determined acceptable cogging torque which is almost 12.43Nm peak to peak. Although, the graph pattern of initial design seems unsmooth initially, however, the amount obtained is sustainable. Furthermore, after design improvements and by using different optimization techniques it is expectable that cogging torque can be reduced until optimum performances. Even though, the less cogging torque value 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.

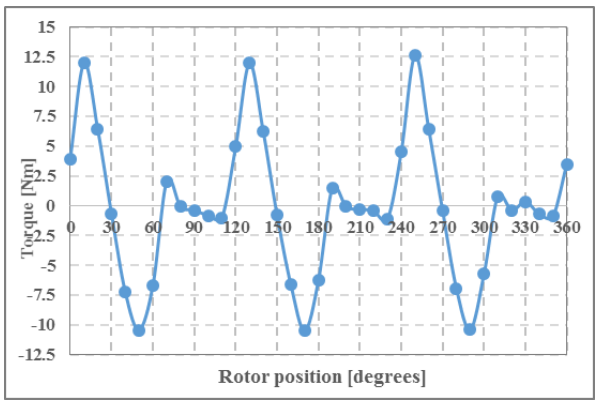


Fig. 5: Detent torque of proposed DS HE FSM with segmental rotor

3.3. Induced EMF of proposed DS HE FSM

Induced EMF or back EMF of initial DS HEFSM has been investigated at no load by applying maximum field current density of Je of 10 A/mm^2, and is illustrated in Figure 6. From the figure, it is obvious that proposed DS HEFSM has achieved maximum back EMF voltage of approximately 38V at maximum speed of 500rpm with sinusoidal waveform. The sinusoidal waveform of initial structure validate the smoothness of the motor performance. There are some variations in the waveform caused by the harmonics occurred. The amount of back EMF achieved shows that the motor will work in safe regions as the induced voltage is less than the applied voltage. However, still back EMF can be reduced more by using optimization techniques. The output of back EMF validate the fact that DS HE FSM is the suitable motor drive for aircraft applications where smoothness of system is main object to be fulfilled. Hence, after further design enhancement and improvements DS HE FSM structure will be the appropriate for aircraft applications.

3.4. Magnetic flux lines distribution

Magnetic flux lines of initial design of proposed DS HE FSM is carried out at no load to analyse the pattern and flow of the flux lines over stators and rotor. Figure 7 illustrates the flux lines of proposed design at zero load and maximum field current density of 10 A/mm^2. From figure.7, it is obvious the magnetic flux lines are properly and continuously flowing through stators to the rotor segments without much cancellation as well leakage. Hence making proper and short completed cycles. From figure it is also noticeable that the flux produced by both the sources is fully distributed over the inner stator whereas for outer stator there are some empty spaces at back iron length. However, overall flux distribution is adequate to produce higher torque performances. Furthermore, for aircraft applications DS HE FSM structure seems to be the best design to achieve higher torque performances with less flux leakage and saturations. Additionally, flux lines analysis validate that the flux cancellations are also negligible which can be favourable for high speed applications.

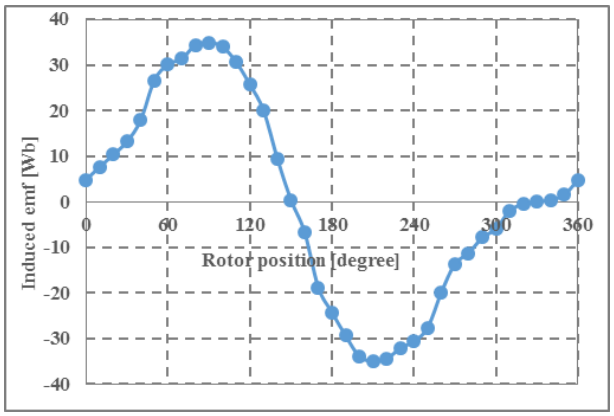


Fig. 6: Induced EMF against rotor position

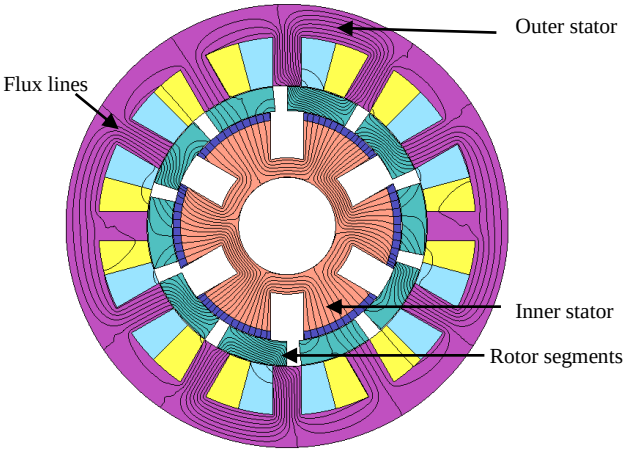


Fig. 7: Magnetic flux lines distribution of DS HE FSM

4. Torque analysis at maximum field current density (Je) of 10A/mm^2

Torque analysis of DS HE FSM with segmental rotor has been conducted at various loads. Henceforth, at maximum field current density of 10 A/mm^2 the torque has been examined at different armature current densities (Ja) such as at 1Arms/mm^2, 3Arms/mm^2, 5 Arms/mm^2, 7 Arms/mm^2 and 10 Arms/mm^2. As a flux source, PM produces constant flux thus the field current density is also kept constant at 10A/mm^2 to examine the torque behavior at different loads. Figure 8 shows the torque analysis at different armature current densities. From figure it is obvious that at constant flux (from PM and FEC) the proposed DS HE FSM has achieved the linear pattern of the torque as the armature current densities are increased. 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 10Arms/mm^2 the torque achieved is approximately 115Nm which evidently appropriate for the aircraft applications. Whereas minimum torque achieved is at minimum armature current density of 1Arms/mm^2. Furthermore, linear pattern of torque shows that DS HE FSM structure has still tendency to withstand the more flux without saturation and cancellations of fluxes as seen in figure 7. For aircraft applications where it is essential for electric motors to achieve high torques especially at lower altitudes and lower speeds. Consequently, the DS HE FSM is the appropriate structure which can be used work at fault conditions due to dual excitations.

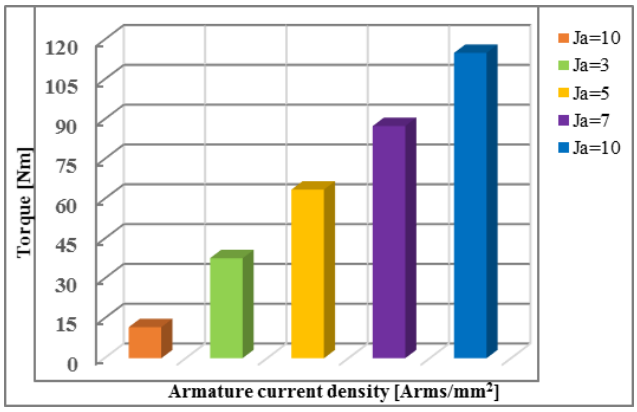


Fig. 8: Torque analysis at different armature current densities (Ja)

5. Conclusion

In this paper, preliminary study on the design principles of DS HE FSM with segmental rotor has been presented. The initial design performances demonstrate that the proposed design has achieved adequate results in terms of flux production, smooth flux lines and higher torque performance. Which is appropriate candidate for the aircraft applications at different speed regions. However, for further improvements design refinement is required to achieve the better performances. The predicted magnetic flux and torque analysis shows that the proposed DS HEFSM structure has viability to be further improved and can be applied for different aircraft applications.

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