Electromagnetic torque capabilities of permanent magnet flux-switching machine using modular rotor

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Abstract. The use of a segmented rotor electric motor for lightweight electric vehicle applications has gained a lot of attention since the motor must have a high output torque and output power. Segmented rotor motors have performance indices that should be taken into consideration because not every machine is effective. Recently, permanent magnet flux switching machine (PMFSM) in salient rotor has become attractive for provide high torque and power. Undesirably, salient rotor inherited high iron loss and winding loss, Furthermore, PMFSM uses high PM volume and more flux leakage resulting in poor performance. This paper deals with a novel structure of modular rotor PMFSM with non-overlapping winding with minimal iron loss, high torque and high power. 2D finite element analysis (FEA) is used to investigate the performance of proposed motor in J MAG Designer 14.1. Three-phase operation of 12S/10P modular rotor PMFSM was designed and analysed based on the cogging torque, induced back emf, output torque and output power performances. The proposed motor securing the initial torque of 33.30 Nm and power of 12Kw at maximum current density of 30Arms/mm2. From the result it is concluded that modular rotor based PMFSM motor is suitable for lightweight electric vehicles.

1. Introduction
Electric motors are essential part of both industrial and domestic appliances. Thus, most of the industrial and domestic applications demand more compact, better efficient, vigorous, light weight and low-priced electric motors. This leads a challenge for researchers to develop an advanced electric motor. Just a decade ago, Flux Switching machine (FSM) has pulled an interest of researchers because of its all excitation sources situated on the stator, come up with simple cooling systems, while the rotor comprises of single piece of iron, which is robust can be used for high speed applications. Flux switching machines are categorized into three kinds as shown in Figure 1, which are (i) field excitation (FE) FSM, (ii) permanent magnet (PM) FSM and (iii) hybrid excitation (HE) FSM. PMFSM and HEFSM both uses permanent magnet as excitation source which generates uniform magnetic flux. While in FEFSM, DC excitation has used which controls the magnet field density [1-3]. The working principle of FSM is conditioned on flux switching. For the better efficiency, easy cooling, robust rotor structure, light weight and low-priced makes FSMS most reliable and effective [4-8]. The flux switching machine (FSM) is known as one of the forms of salient rotor reluctance machine with a novel topology, merging the inductor generator principle [9, 10] and switched reluctance machine (SRM) [9].

In the flux switching machine all the active sources are placed on the stator such as both field and armature winding. Rotor consists of iron core with a simple shape and high strength. The term “flux
“switching” is to designate machines in which the stator teeth switches flux polarity resulting the motion of a salient pole rotor, and that’s basic working principle of operation [11, 12].

![Flux Switching Machine (FSM)]

**Figure 1. Categorization of FSM**

In 1955, Rauch and Johnson had innovated a single-phase alternator [9]. From that time diverse designs of PMSFM has been presented. Figure 2 describes a PMFSM conventional design with the disadvantage of high volume of PM.

![Conventional PMFSM](image)

**Figure 2. Conventional PMFSM**

In order to utilize a smaller number of PM, an E-core topology is set up which replaced the stator poles alternately by stator tooth [13, 14]. Radial and circumferential directions of PM are authorized in E-core configuration. All radial PM are set up alternately while circumferential magnets are remain identical [15, 16]. Furthermore, to increase the armature coil area the middle teeth of E-core has removed which introduces the new C-core topology [17]. Lately another design has introduced in PM with segmented rotor [18, 19]. But it carries a drawback of ambiguous operation of high-speed rotor. Moreover, distribution of flux is not uniform due to the flux leakage at the tip of the PM which decreases the efficiency of motor.

In this paper, a novel topology of PMFSM with 12S-10P modular rotor has been investigated. The main advantage of modular rotor is to reduce the iron loss with marginal reduction in output torque as shown in Figure 3. Modular rotor also known as segmented rotor, it helps to reduce the weight of rotor over salient rotor. Modular rotor firstly was introduced in reluctance machines. Due to the shortest paths produces along the iron core through modular rotor decreases iron losses. The flux flows from one rotor tooth to another rotor tooth [19, 20]. In order to avoid flux leakage through stator core an iron bridge has established. Furthermore, performance of the initial modular PMFSM design has been investigated by 2D FEA (finite element analysis). The performance of the motor is intercept specially at maximum current densities. An optimization technique will be implemented for the better performance of the motor [21].
2. Research method

The novel modular rotor PMFSM design description and limitations are shown in Table 1. Electrical restrictions associated with inverter are set in the same way. Additionally, the current density for the armature coil are varies from 0 A_{rms}/mm^2 to 30 A_{rms}/mm^2. Based on the structure of motor and current density air cooling is feasible for motor. The complete process to accomplish the objective of this paper is shown in Figure 4.

From the arrangement, armature coil is sandwiched in permanent magnets, which are non-overlapping winding. For the purpose of design and scrutiny 2D Finite Element Analysis (FEA) tool is implemented in JMAG Designer 14.1 introduced by Japan Research Institute (JRI). Firstly, the main parts such as stator, rotor, PM and armature coils of the proposed PMFSM modular rotor are built in geometry editor consequently materials, boundary conditions and machine circuitry of machine are set in JMAG designer. The material employed for stator and rotor are steel 35H210, while NEOMAX-35AH is set for the PM.

![Flow chart for design process](image)

Figure 4. Flow chart for design process

Moreover, to validate the operating principle and the positions of armature coil phase of the proposed design coil arrangement tests are conducted. After the authorisation of the operating principle and coil arrangement test, numerous characteristics of modular rotor PMFSM on no load and at load were
examined respectively. In order to inspect the numerous executions of the novel proposed motor at no-load armature current density $J_a$ was set to $0 \, \text{Am}^{-2}$. Furthermore, flux distributions lines, back emf, cogging torque and torque characteristics and efficiency were evaluated.

3. Results and discussions
The outcomes of the proposed 12S-10P modular rotor based PMFSM have been explored in this section. In order to follow through the process results are showed in figures, graphs for better understanding. Table 1 shows the design specifications, parameter requirements and electrical restrictions are provided. There are three methods being discussed in this work as follows.

| Table 1. Modular PMFSM design parameters |
|----------------------------------------|
| Items | PMFSM with Modular rotor |
|--------|--------------------------|
| Number of rotor poles | 10 |
| Stator Outer radius (mm) | 75 |
| Stator tooth width (mm) | 12.5 |
| Rotor tooth width (mm) | 10 |
| Stator back iron depth (mm) | 11 |
| Motor stack length (mm) | 70 |
| Air gap (mm) | 0.3 |
| Radius of rotor (mm) | 89.7 |
| Armature slot area (mm$^2$) | 300.8 |
| No. of turns per armature coil slot | 44 |
| PM volume (Kg) | 0.3 |

3.1. Coil arrangement test
Coil arrangement test was achieved for each coil individually to validate the armature coil location and operating principle of modular rotor PMFSM. Primarily, Coil arrangement test was achieved for each armature coil 1 to armature coil 12 individually to validate the armature coil location and operating principle of modular rotor PMFSM. The main reason for this process is to categorize the like pattern flux linkage produced in each coil. Furthermore, likewise flux linkage pattern have grouped one another. Consequently, three different phase linkage patterns established namely U, V and W phase as shown in Figure 5. From the figure, it is observed that the flux linkage is not symmetry it is due to the segmental rotor geometry and power loss in relation to stator is unaligned with flux source. Proposed design can further be improved by using optimization method.

![Figure 5. U, V and W phase Flux linkage](image-url)
3.2. Cogging torque
Cogging torque is collaboration of the armature winding and PM on the stator with rotor teeth. The performance of the motor is affected by the cogging torque if the value is higher than the acceptable value which is 10% of the average torque. The cogging torque analysis for PMFSM modular rotor is shown in Figure 6. From the plot it is obvious that modular rotor PMFSM configuration generates peak to peak cogging torque of 12Nm. It is essential to mention here that the energy variation within the motor was caused by the rotation of rotor results in the cogging torque. The shape of the cogging torque is not uniform throughout because of the odd number of rotor segments regarding the magnetic pull.

3.3. Induced or Back-EMF
The production of voltage in an armature coil at no load condition due to magnetic flux changes through it is known as induced back-emf. As usual, this is represented as a continuous wave that should be exact sine wave without harmonics. However, harmonics seems unavoidable but should present negligible distortions. For the proposed motor, at no load condition and rotating speed of 500 rev/min, 42 V induced voltage generated by the motor is plotted in Figure 7.

![Figure 6. Cogging of Modular rotor PMFSM](image1)

![Figure 7. Induced back-emf of Modular rotor PMFSM](image2)
3.4. Torque and power at various current densities \( J_a \)

The capability of an electric motor is determined by its performance under the given load condition. The plot of the output torque versus armature current density \( J_a \) for the proposed motor is shown in Figure 8. In the plot \( J_a \) is varies from 0 A\(_{\text{rms}}/\text{mm}^2\) to 30 A\(_{\text{rms}}/\text{mm}^2\) and its changes in torque are examined. It is seen from the plot that torque increased with increase in the value of \( J_a \). Thus, maximum output torque achieved is 33.30 Nm at current density of 30 A\(_{\text{rms}}/\text{mm}^2\).

![Figure 8. Torque versus armature current density (A/mm\(^2\))](image)

Furthermore, the plot of the output power versus armature current density of the proposed motor is investigated as shown in Figure 9. From the plot it is clear observed that output power raised as the current density increases. The output power of the proposed motor is observed 10.53Kw. The power of the flux switching machine can be calculated by using Equation (1).

\[
P_{\text{out}} = \frac{\text{speed} \times \text{torque}}{60} \left( \frac{2\pi}{1000} \right)
\]

Where, speed is the maximum speed of the motor after applying the load. Which can be calculated as given in Equation (2).

\[
\text{Speed} = \frac{V_{\text{max}}}{\text{flux}_{\text{max}}}
\]

Where, \( V_{\text{max}} \) is three phase maximum voltage. Power is directly proportional to the speed, as the speed of motor increases its power increases as shown in figure 10. Form the figure it is observed that after certain speed power start reducing because of the saturation point. Further improvement can be made by optimization of the motor.

![Figure 9. Power versus armature current density (A/mm\(^2\))](image)
Flux switching motor employing modular rotor has been characterised in this paper. The design considered a three-phase arrangement with permanent magnet flux excitation. In this paper a novel modular rotor PMFSM with non-overlapping winding using specification and limitations of the conventional Salient rotor PMFSM. The performance of the modular rotor PMFSM investigated in terms of induced back emf, cogging torque, and average torque and power using JMAG Designer 14.1. thus, the output torque and power of the proposed design is 33.30 Nm and 10.53 Kw respectively. Moreover, this design can be further altered using optimization technique to obtain an optimal torque. Number of PM are reduced in the proposed design which makes it a good option for light weight electric vehicles.

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