Torque Ripples Reduction and Performance Analysis of Electrically Excited Flux Switching Motor

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This work was supported in part by COMSATS University Islamabad, Abbottabad Campus, and in part by the Higher Education Commission of Pakistan under Grant TDF - 03 - 067/R&D/HEC/2019.

ABSTRACT Torque ripples cause acoustic noise, fluctuation in speed, vibration, and reduce lifetime of the motor. The double salient structure of Flux Switching Motor (FSM) has a high air-gap permeance variation that produces high torque ripples. This paper presents an analytical model to reduce air-gap permeance variation and torque ripples of the proposed octane modular stator 8slots-6poles single-phase Electrically Excited (EE) FSM. Furthermore, the rotor pole shaping technique is used to minimize the air-gap permeance variation and therefore, torque ripples of the proposed design are reduced. The electromagnetic performance of EEFSM is analyzed via the Finite Element Analysis (FEA) method. For the proposed design magnetic flux harmonics are reduced by 71% and back-EMF harmonics are suppressed by 48.5%. Torque ripples of the proposed EEFSM are reduced by 20%, cogging torque is diminished by 42.7% and average torque is enhanced by 5.8%. Finally, the prototype is fabricated and tested experimentally. Calculated values and experimental results are in good agreement and the difference is 3.5%-5%.

INDEX TERMS Torque ripples reduction, flux switching motor, single phase, electrically excited, analytical model, electromagnetic performance.

I. INTRODUCTION
The focus of research activities in advanced motors is high torque density, high power density, high efficiency, robust rotor structure, low noise and low cost [1]–[3]. Flux Switching Motors (FSMs) are attractive for their exclusive features [4]–[5]. Permanent Magnet (PM) FSMs have high torque density, high efficiency, simple and heavy-duty rotor construction [6]–[8]. However, PMFSM has disadvantages, e.g. it consumes rare-earth magnets and with the passage of time PM resources are depleting [9]–[13]. Moreover, the magnetic flux of PMFSM is uncontrollable and its performance is degraded with an increase in temperature [14], [15]. The magnetic flux of PMFSM is uncontrollable and its performance is degraded with an increase in temperature [14], [15]. The magnetic flux of the Electrically Excited Flux Switching Motor (EEFSM) is controlled electronically, with an increase in temperature performance of EEFSM is not affected and its overall cost is low compared to the PMFSM. Single-phase EEFSM has many advantages i.e. its manufacturing process is simple, maintenance is easy, longer lifetime and low cost [3], [16].

Novel single-phase designs with good average torque and efficiency are presented in [16]–[18]. However, overlapped windings and segmented rotors are the drawbacks of these designs. Overlapped windings produce high copper losses and segmented rotors cannot be used for high-speed applications. In [19] all these concerns have been addressed but, the doubly salient structure of FSM is the cause of high air-gap permeance variation and torque ripples which produce acoustic noise, unwanted fluctuation in speed, vibration and reduce motor lifetime [20]. Comparative illustration of existing topologies is organized in Table 1.

In this paper, an analytical model and rotor pole shaping technique are presented for minimizing air-gap permeance variation and torque ripples of the octane modular stator EEFSM. The Copper Slot Filling Factor (CSFF) is calculated by an analytical method in [21] and octane modular stator
TABLE 1. Comparative Illustration of the Existing state of the art.

| R.no. | Torque ripple | Rotor topology | Windings end effect |
|-------|---------------|----------------|-------------------|
| [16]  | High          | Segmented      | Low               |
| [17]  | High          | Salient        | High              |
| [18]  | High          | Salient        | High              |
| [19]  | High          | Salient        | Low               |

EEFSM has 9% higher CSFF than the conventional designs. It has a salient pole rotor and can be used for high-speed applications [22]. The forward non-overlapped windings of the octane modular stator EEFSM has a low copper loss. Furthermore, it can be easily unfolded for coil placement, maintenance and transportation. For optimal performance of the proposed design, optimization is carried out. Besides, magnetic flux harmonics, back-EMF harmonics, cogging torque, torque ripples, average torque, output power, and efficiency of the proposed design are analyzed. Finally, the prototype is manufactured and tested experimentally.

II. PROPOSED TOPOLOGY AND ANALYTICAL MODEL

This section presents the proposed topology, analytical model for the reduction of permeance variation and torque ripples, and detailed discussion is included in the subsections.

A. PROPOSED TOPOLOGY

Figure 1 shows schematic of the proposed octane modular stator, rotor pole shaped rotor and forward non-overlapped windings. Fifty eight silicon steel sheets, each sheet of 0.35 mm are combined to get each T-shaped segment of octane modular stator and rotor pole shaped salient rotor.

B. ANALYTICAL MODEL

The doubly-sloated structure and main design parameters, i.e. internal radius of the stator \((R_d)\), outer radius of the rotor \((R_m)\), air-gap \((g)\), rotor displacement angle in the air-gap \((\phi)\) and rotor pole span \((\beta)\) are given in Figure 1. The developed electromagnetic torque \((\tau)\) of EEFSM is given by [23]:

\[
\tau = i_F i_A \frac{dL_{FA}}{dt}
\]

where \(i_F\), \(i_A\), \(\theta\), \(L_{FA}\) are armature current, field current, rotor circumferenceal angle, magnetic inductance of the field and armature windings, respectively. Also we can write electromagnetic torque as follows:

\[
\tau = \tau_{avg} + \tau_{cog}
\]

here \(\tau_{avg}\) is the average torque of EEFSM and \(\tau_{cog}\) is cogging torque produced due to energy variation in the motor parts. The energy variation in the air-gap is high due to the doubly-salient structure of EEFSM. This energy variation in the air-gap is minimum when the rotor poles aligned with the stator teeth and maximum while both are not overlapped. The cogging torque caused by energy variation in the air-gap is given as follows:

\[
\tau_{cog} = \frac{\partial E_g}{\partial \theta}
\]

Similarly, in terms of EEFSM parameters, energy in the air-gap \((E_g)\) is calculated as follows [24]:

\[
E_g = \frac{g^2 I_{stack}^2}{4 \mu_0} \int_0^{2\pi} B^2(\phi, \theta) \cdot \Lambda^2(\Phi) \, d\phi
\]

where \(\mu_0\), \(I_{stack}\), \(\Lambda(\phi)\) and \(B(\phi, \theta)\) are permeability of free space, stack length of the EEFSM, permeance of air-gap and magnetic flux density, respectively. For 8s-6p EEFSM, \(B^2(\phi, \theta)\) and \(\Lambda^2(\Phi)\) fourier expansion is given as:

\[
B^2(\phi, \theta) = \sum_{k=0}^{\infty} B_k \cos kT_s(\Phi + \theta)
\]

\(T_s\) is number of stator teeth while \(B_k\) is air-gap flux density Fourier coefficient, and is given below:

\[
B_k = \frac{P_r}{\pi} \int_{-\gamma}^{\gamma} \frac{1}{\gamma} B_{max} \cos (M_L \theta) \, d\theta
\]

\[
= \frac{2P_r}{k\pi M_L} B_{max} \sin \left(\frac{kM_L \pi}{P_r} \right)
\]

where \(\gamma\) is the ratio of rotor pole span and rotor pole pitch. EEFSM air-gap permeance model is presented in Figure 2 and permeance function is given below as:

\[
\Lambda^2(\Phi) = \sum_{k=0}^{\infty} P_k \cos kP_r \Phi
\]

\(P_r\) is the number of rotor poles and \(P_k\) air-gap permeance Fourier coefficient is given as follows:

\[
P_k = \frac{P_r}{\pi} \int_{\gamma}^{\pi} \cos (kM_L \theta) \, d\theta
\]

\[
= \frac{2P_r}{\pi kM_L} \left( (-1)^{k} \frac{M_L}{P_r} \right) \sin \left( kM_L \frac{\beta}{2} \right)
\]
Putting (5) and (7) in (4), the energy in the air-gap is calculated. Further, by putting the result of (4) in (3) and by simplifying, cogging torque is formulated as:

$$\tau_{cog} = \frac{M_L \cdot \pi \cdot \frac{g^2}{4} \cdot l_{stack}}{4\mu_0} \cdot \sum_{k=1}^{\infty} kP_k B_k \sin (kM_L \theta) \quad (9)$$

From (8) and permeance model in Figure 2, it is clear that air-gap permeance variation can be reduced by increasing the rotor pole span $\beta$, hence energy variation in the air-gap and thus overall ripples in the torque will be reduced.

The high variation in the air-gap permeance of the FSMs due to doubly-salient structure is the reason for torque ripples. These ripples can be reduced if the variation in the air-gap with the rotor rotation is minimized [25]. From (2) it can be seen that cogging torque ($\tau_{cog}$) is the part of $\tau_{em}$, however, $\tau_{cog}$ doesn’t produce effective average torque and causes torque ripples [26]. If the variation in $\tau_{cog}$ is reduced, the overall variation in $\tau_{em}$ will be reduced. As permeance is reciprocal of reluctance, we can write $\tau_{cog}$ in terms of air-gap flux ($\phi_g$) and variation of reluctance ($R$) in magnetic circuit with the rotation of the rotor [24] as:

$$\tau_{cog} = \phi_g \frac{dR}{d\phi} \quad (10)$$

When the stator tooth and rotor poles are not overlapped, flux goes through air-gap of high reluctance, compared to stator tooth and rotor poles overlapped. In this paper, rotor pole shaping technique is used for minimizing the reluctance variation and reduces torque ripples. Rotor Pole Shoe (RPS) dimensional parameters are shown in Figure 3 while the flux paths when stator and rotor pole are not overlapped are indicated in Figure 4. As in Figure 4, for simplicity the cylindrical coordinate $\theta$ is set out in linear coordinate manner as $L$ and pole shoe height ($S_w$) is equal to pole shoe width ($S_w$). It is further assumed that flux lines are straight in air-gap region and circular elsewhere. The reluctance of the air-gap with rotor pole shoe is given as:

$$R = \frac{\pi}{2\mu_0 l_{stack}} \ln \left( \frac{\pi L + 2g + \pi S_w}{\pi L + 2g - \pi S_w} \right) \times \left( \frac{\pi L + 2g + \pi W_s + \pi S_n}{\pi L + 2g + 2\pi S_n} \right)$$

by putting $\frac{dR}{dL} = 0$

Third order equation is obtained and by solving it, value of $S_w$ is achieved in terms of $W_s$ and $g$ at any position $L$. Theoretically zero cogging torque can be calculated but practically it’s not possible because the effect of magnetic saturation and flux leakage is not considered. The magnetic flux linkage distribution of octane modular stator EEFSM in Figure 5 shows that magnetic flux leakage is highly reduced with an increase in rotor pole span. For optimal performance, the analytical value of rotor pole shoe width and other parameters are optimized by using Finite Element Analysis (FEA) method.

### III. PARAMETERS OPTIMIZATION

Deterministic Optimization (DO) is used to achieve the optimal values of RPS parameters. These parameters include Rotor Pole Shoe Width (RPSW), Rotor Pole Shoe Thickness (RPST) and Rotor Pole Shoe Height (RPSH). Magnetic Flux Harmonics ($\phi_h$), back-EMF Harmonics ($E_h$), Cogging Torque ($\tau_{cog}$), Instantaneous Torque ($\tau_{max}$ and $\tau_{min}$), Torque Ripple ($\tau_{rip}$) and Average Torque ($\tau_{avg}$) are analyzed. Figure 6 presents the optimization procedure adopted in this paper while the pseudo code is given in Algorithm 1.
The effect of each parameter variation on the performance of the proposed design is discussed in subsections.

Objective function, constraint and boundary condition are given as follows:

\[
\begin{align*}
\text{Objective function} & \quad \min (\tau_{cog}) \quad \min (\tau_{rip}) \quad \max (\tau_{avg}) \\
\text{Constraint} & \quad \tau_{rip} < 0.845 \text{ N-m} \\
& \quad \tau_{avg} > 0.48 \text{ N-m} \quad \text{and} \\
& \quad \tau_{cog} < 0.075 \text{ N-m} \\
\text{Boundary condition} & \quad 0 \leq S_w \leq 2 \\
& \quad 0.25 \leq S_t \leq 1.5 \\
& \quad 1 \leq S_h \leq 3 
\end{align*}
\]

A. EFFECT OF ROTOR POLE SHOE THICKNESS

Rotor Pole Shoe Width (RPSW) has major influence on the electromagnetic performance of the EEFSM, especially on $\phi_h$, $E_h$, $\tau_{rip}$, $\tau_{cog}$, $\tau_{max}$, $\tau_{min}$, and $\tau_{avg}$. RPSW is varied while RPST and RPSH are kept constant during the RPSW optimization. RPSW is varied 1-2mm and its effect on the key electromagnetic Performance Indicators (PIs) i.e. $\phi_h$, $E_h$, $\tau_{cog}$, $\tau_{max}$, $\tau_{min}$, $\tau_{rip}$ and $\tau_{avg}$ are organized in Table 2.
Moreover, influence of RPSW variation on cogging torque, instantaneous torque, flux harmonics and back-EMF harmonics profile is plotted in Figure 7.

After RPSW optimization, \( \phi_h \) is reduced by 66\%, \( E_h \) is minimized by 46\%, \( \tau_{cog} \) is diminished by 37\%, \( \tau_{rip} \) are reduced by 18\% and \( \tau_{avg} \) is improved by 5\%. The RPSW is updated to the optimized value of 1.5 mm.

### B. EFFECT OF ROTOR POLE SHOE THICKNESS

In this subsection, the effect of Rotor Pole Shoe Thickness (RPST) variation on the electromagnetic performance of the EEFSM is analyzed. RPST is varied from 0.25 mm to 1.5 mm and its influence on PIs; \( \phi_h \), \( E_h \), \( \tau_{cog} \), \( \tau_{max} \), \( \tau_{min} \), \( \tau_{rip} \) and \( \tau_{avg} \) are arranged in Table 3. Further, effect of RPST variation on cogging torque, instantaneous torque, flux harmonics and back-EMF harmonics profile is presented in Figure 8.

With RPST optimization, \( \phi_h \) decreased by 15\%, \( E_h \) reduced by 3.6\%, \( \tau_{cog} \) minimized by 9\%, \( \tau_{avg} \) dropped by 1\% and \( \tau_{rip} \) reduced 2\%. The RPST is updated from initial value 0.5 mm to optimized value 1 mm.

### C. EFFECT OF ROTOR POLE SHOE HEIGHT

The influence of Rotor Pole Shoe Height (RPSH) on the electromagnetic performance of the EEFSM is investigated in this sub-section. RPSH is varied from 1 mm to 3 mm and its effect on \( \phi_h \), \( E_h \), \( \tau_{cog} \) and \( \tau_{ins} \) is shown in Figure 9.
As RPSH is varied above and below the initial value of 1 mm, increase in magnetic flux harmonics, back-EMF harmonics, cogging torque and torque ripples is observed. Therefore, RPSH is kept unchanged and 1 mm is taken as the optimal value.

IV. DISCUSSION

In this section, electromagnetic performance comparison is presented for the optimized design and conventional design. Further, $\varphi_h$, $E_h$, $\tau_{cog}$, $\tau_{max}$, $\tau_{min}$, $\tau_{rip}$ and $\tau_{avg}$ are analyzed in the subsections.

A. MAGNETIC FLUX AND BACK-EMF HARMONICS ANALYSIS

The most important performance indicators magnetic flux and back-EMF are analyzed in this subsection. Magnetic flux and back-EMF harmonics of the conventional design and proposed design are plotted in Figure 10 and organized in Table 4. With overall optimization, magnetic flux harmonics for the proposed design are reduced by 71% and back-EMF harmonics are minimized by 48.5%.

B. COGGING TORQUE AND TORQUE RIPPLES ANALYSIS

Cogging torque is the cause of torque ripples, acoustic noise, vibration, unwanted fluctuation in speed and reduced lifetime

TABLE 3. Effect of RPST optimization on electromagnetic performance.

| PIs     | Unit | Initial Design | Optimized Design |
|---------|------|----------------|------------------|
| $\varphi_h$ | %   | 5.021          | 4.272            |
| $E_h$    | %   | 31.928         | 30.794           |
| $\tau_{cog}$ | N-m | 0.047          | 0.043            |
| $\tau_{max}$ | N-m | 0.85           | 0.848            |
| $\tau_{min}$ | N-m | 0.157          | 0.1635           |
| $\tau_{rip}$ | N-m | 0.693          | 0.6815           |
| $\tau_{avg}$ | N-m | 0.514          | 0.512            |

FIGURE 8. Effect of RPST on (a) Cogging torque (b) Torque (c) Magnetic flux harmonics (d) Back-EMF harmonics.
FIGURE 9. Effect of RPSH on (a) Cogging torque (b) Torque (c) Magnetic flux harmonics (d) Back-EMF harmonics.

TABLE 4. Electromagnetic performance comparison.

| Pls       | Unit | Conventional Design | Proposed Design |
|-----------|------|---------------------|-----------------|
| $\varphi_0$ | %    | 14.781              | 4.271           |
| $E_0$     | %    | 59.848              | 30.794          |
| $\tau_{cog}$ | N-m  | 0.075               | 0.043           |
| $\tau_{\max}$ | N-m  | 0.88                | 0.848           |
| $\tau_{\min}$ | N-m  | 0.035               | 0.1635          |
| $\tau_{ripp}$ | N-m  | 0.845               | 0.6815          |
| $\tau_{avg}$ | N-m  | 0.48                | 0.512           |

of EEFSM [20]. Cogging torque for the proposed design and conventional design is plotted in Figure 11 (a) and arranged in Table 4. After RPS optimization, cogging torque for the proposed design is reduced by 42%.

Moreover, instantaneous torque plots for the proposed design and conventional design are given in Figure 11 (b).

The maximum and minimum values are organized in Table 4. On the overall implementation of optimization process, the torque ripples of the proposed design are reduced by 20%.

C. TORQUE SPEED CHARACTERISTICS, OUTPUT POWER, LosSES AND EFFICIENCY ANALYSIS

In this subsection, average torque, output power, iron loss, copper loss and efficiency are analyzed. Average torque and Output Power ($P_o$) versus speed are plotted in Figure 12 (a) while $P_o$, iron loss ($P_i$), copper loss ($P_c$) and efficiency are given in Figure 12 (b). Iron loss increased with increase in speed and at maximum speed of 14942.7 rpm, $P_i$ is 8.89 Watts. Similarly, increase in armature current raised the copper loss and at $J_a = 15 \text{ A/mm}^2$, $P_c$ is recorded as 21.6 Watts. For the proposed octane modular stator EEFSM design, an average efficiency ($\eta$) of 89.5% is attained. An output power of 230 Watts under 0.512 N-m average torque and 4273 rpm medium speed at $J_e = 15\text{ A/mm}^2$ & $J_a = 15\text{ A/mm}^2$ is achieved, which is more suitable for
V. PROTOTYPE AND EXPERIMENTAL RESULTS

The manufactured octane modular stator EEFSM prototype main parts are presented in Figure 13. Figure 13 (a), (b), (c) and (d) show unfolded stator, folded stator with non-overlapped windings, rotor with RPS and complete motor assembly, respectively. For validation the basic principle of proposed design, the prototype is tested experimentally. Figure 14 shows the experimental test setup. This setup includes a test-bench, DC power source, AC power source, servo-motor, speed transducer, torque transducer, couplers, speed meter, torque meter, oscilloscope and digital multimeter.

To detect the presence of magnetic flux in the windings, no-load back-EMF test is performed at fixed speed of 500 rpm and various field current densities. The experimental no-load back-EMF results at various $J_e$ are plotted in Figure 15(a). The no-load back-EMF profile follows a sinusoidal pattern and proved the basic principle of FSM. Moreover, at fixed $J_e = 15$ A/mm² the variation of no-load back-emf with the increase in speed is tested and presented in Figure 15(b). At low speed 500 rpm, peak value of back-emf is 11.96 V and

| PIs (Unit) | SegRN Design [16] | SalRN Design [19] | Proposed Design |
|------------|-------------------|-------------------|-----------------|
| $\phi_p$ (Wb) | 0.026             | 0.0308            | 0.0310          |
| $E_h$ (%)   | -                 | 59.848            | 30.794          |
| $\tau_{avg}$ (N$m$) | 0.30             | 0.48              | 0.512           |
| $\tau_{rip}$ (N$m$) | -               | 0.845             | 0.6815          |
| $P_{out}$ (Watts) | 220              | 225               | 230             |
| $\eta$ (%) | 73.5              | 91                | 89.5            |
at high speed of 3000 rpm it is recorded as 71.77 V which is less than the supply voltage 220 volts and verifies motor principle.

The effect of field current density \( J_e \) and armature current density \( J_a \) on average torque for the proposed octane
modular stator EEFSM is tested and plotted in Figure 16. As the current density of the field windings and armature windings is increased, a proportional change in average torque is observed. At $J_e = 15$ A/mm$^2$ and $J_a = 15$ A/mm$^2$, an average of 0.482 N-m is recorded.

The experimental results are different from the calculated values. The cause of this variation is the copper wire tensile strength loss due to the manual motor windings process and ripples from DC power source [16].

VI. CONCLUSION
High torque ripples cause acoustic noise, unwanted fluctuation in speed, vibration and reduced lifetime of FSMs. Torque ripples are produced due to high air-gap permeance variation in the doubly-slotted geometry of FSMs. In this paper, analytical model was presented for the proposed octane modular stator EEFSM design to minimize air-gap permeance variation and therefore, reduce the torque ripples. Furthermore, the rotor pole shaping technique minimized the air-gap permeance variation and torque ripples. Moreover, the copper slot filling factor of the proposed design is higher than the conventional design and the copper losses are reduced by forward non-overlapped windings. For high speed cost sensitive applications its rotor is made salient pole. Besides, it can be unfolded for easy coil placement, maintenance and transportation. The magnetic flux harmonics of the proposed design are reduced by 71%, back-EMF harmonics are minimized by 48.5%. Similarly, cogging torque is diminished by 42%, torque ripples are reduced by 20% and average torque is improved by 5%. The average power of 230 Watts under 0.51 N-m is achieved. The proposed design has attained 89.5% average efficiency. The experimental results of the prototype have resemblance with the simulation results and difference is up to 5%.

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