Performance Analysis of a Modular E-Shaped Stator Hybrid Excited Flux Switching Motor With Flux Gaps

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ABSTRACT This paper proposes a new modular hybrid excited flux switching motor (MHEFSM) with flux gaps, adding the fault-tolerant capability to the proposed motor. The proposed motor uses an E-Shaped stator, as the middle teeth of E-core produce fault-tolerant capability, and in C-core, this capability is eradicated. The no-load flux linkage is calculated by the magnetic network model (MNM) to reduce time and disk storage. The drawback of the constant flux linkage of PM motors is overcome by employing field excitation (FE). The FE helps in regulation flux at higher speeds. The motor leading geometry variables are optimized by using Genetic Global Optimization (GGO). The GGO helped in refining the structure of the motor and has improved the flux linkage by 68.17%, average torque and torque density by 62.39% each, reduced torque ripples by 20.69%, and cogging torque by 18.48%. The volume of permanent magnet (PM) in the proposed MHEFSM is reduced by 36.24%, and 48.49% higher average torque and torque density is obtained compared to the state of art motor proposed in the literature. Furthermore, a 3D analysis of the proposed MHEFSM is done to further evaluate the electromagnetic performance.

INDEX TERMS Finite element analysis, flux gaps, modular stator, variable flux machine, genetic optimization.

I. INTRODUCTION

Electrical motors with PM materials play a vital role in academia and industries concerning their characteristically high torque density, power density, and efficiency. PMs are traditionally placed on the rotating part of the motor, which causes demagnetization, poses a risk of PMs breaking, and necessitates the use of mechanical supporting sleeves [1], [2]. In the conventional synchronous motor design, Field Excitation Sources (FES) are located on their rotor, which requires commutator brushes for their operation. Because of the rotor’s simple and robust structure, improved heat dissipation, greater reliability and brushless operation, transferring the excitation sources from rotor to stator have recently received considerable attention [3]. Flux Switching Motor (FSM) accommodates excitation sources (PM and field winding) along with armature winding on the static part (stator), and the rotor is free from these excitation sources, which makes the rotor robust and simple [4], [5]. Although both the Doubly Salient PM Motor (DSPMM) and the Flux Reversal PM Motor (FRPM) also have simple and robust rotor structures; however, the torque density of the PMFSM is higher due to bi-polar flux linkage, whereas the flux linkage of the DSPMM and FRPM is unipolar which causes lower torque density [6]. Additionally, FSM provides more power density, sinusoidal back electromotive force (EMF) and high...
PM gives better flux density with a limited range of flux a wide range of flux modulation capability while NdFeB materials. This investigation shows that ferrite PMFSM has also lowering the motor’s cost. The capability of HEFSM used in this design, which improves the filling factor while efficiency. Flat wires, thin PMs, and a pair of FE coils are the HEFSM design, aiming for a high filling factor and flux leakage from the stator. The authors in [20] proposed HEFSM was proposed in [19] with a flux bridge to prevent the time necessary for HEFSM design. A consequent pole network model method was proposed that greatly decreases time-consuming. In [15], a new variable structure magnetic and PM, and optimum torque of HEFSM is challenging and optimum tooth width, coupling of magnetic flux of winding scheme of the PM. Design of different parameters like torque is developed, namely the right angle chamfering on the PM positioning. Among all, the middle-PM machine principle of three different topologies was presented based [14], [15], [16], [17], [18], [19]. In [13], the flux regulation capability of an E-core modular FSM is compared with its conventional double layer counterpart, which concludes that high fault tolerance and better demagnetization withstand capability are provided by the E-core modular FSM. E-core modular structure is also compared to C-core and E-core design, where E-core still gives promising fault-tolerant capability.

In this paper, a modular stator hybrid excited flux switching motor (MHEFSM) is proposed. Concentrated type winding for both FE and armature are used, which are wound across the middle tooth of the E-shaped stator. PMs with alternating polarities are also placed at the tips of middle teeth. This paper is organized as follows, section II presents the design and operating principle of the proposed MHEFSM, section III presents the genetic optimization, FEM based performance of the proposed motor is analyzed in section IV, while the fault-tolerant capability of the proposed motor is discussed in section V. Section VI presents the comparison of proposed motor with state of the art motor and section VII concludes the paper.

II. DESIGN AND OPERATING PRINCIPLE
The proposed MHEFSM double salient structural topology is depicted in Fig. 1, where three pairs of E-shaped stator cores are placed at 120° from each other. Radially magnetized PMs with alternating polarization directions are housed at the apex of the E-shaped stator cores’ middle pole. Stator modules are alternately separated by an angular distance of 4° and 6° degrees. This separation helps to improve the fault-tolerant

FIGURE 1. Design structure of the proposed MHEFSM.
FIGURE 2. Geometry variables representation.

TABLE 1. Geometry variables of MHEFSM.

| Parameter               | Symbol | Value   |
|-------------------------|--------|---------|
| Stator outer radius     | \( R_o \) | 64 mm   |
| Stator yoke             | \( R_y \) | 5 mm    |
| Armature winding width  | \( D_{AW} \) | 19 mm  |
| Field winding width     | \( D_{FW} \) | 11 mm  |
| PM height               | \( h_{PM} \) | 3 mm   |
| PM width                | \( w_{PM} \) | 3 mm   |
| Rotor outer radius      | \( R_r \) | 34.5 mm |
| Rotor inner radius      | \( R_s \) | 10 mm   |
| Air gap length          | \( A_o \) | 0.5 mm  |
| Axial length            | \( L \) | 75 mm   |
| Fill factor armature    | –      | 23.8%   |
| Fill factor field       | –      | 38.4%   |

capability of the proposed MHEFSM. Armature and field winding is coiled over the E-shaped stator core’s central leg. Each armature phase is composed of two set of coils. The geometry parameters are denoted in Fig. 2 and given in Table 1.

The operating principle of proposed MHEFSM is based on no-load flux linkage, which is evaluated using magnetic network model (MNM) initially to save time of computation and disk storage. The MNM helps in finding the suitable coil combination and no-load flux linkage. Based on the flux linking path given in Fig. 3, two permeance networks are generated shown in Fig. 4. As MNM models all parts of the motor so it gives accurate no-load flux in terms of precision. The formulations of MNM are based on authors own published work [22]. After MNM, the proposed motor is design in JMAG v. 20.1 to validate the mathematical analysis via Finite Element Method (FEM). The no-load flux linkage obtained by MNM and FEM are compared in Fig. 5. The results reveal a small error between two. The time and storage comparison is made in Table 2. The MNM significantly reduces the drive storage and time as compared to FEM. Both the MNM and FEM are done using Lenovo system having 8 GB RAM, Intel(R), Core(TM) i5-8500 CPU 3.00GHz.

FIGURE 3. Operating principle (a) positive flux (b) zero flux (c) negative flux (d) zero flux.

FIGURE 4. Permeance networks of the proposed MHEFSM (a) Network-I (b) Network-II.

FIGURE 5. No-load flux linkage MNM vs FEM.

TABLE 2. MNM and FEM comparison.

| Method   | Time   | Disk Storage |
|----------|--------|--------------|
| MNM      | 4.59 s | 107 KBs      |
| FEM      | 8 min and 19 s | 353 MBs |

III. GENETIC OPTIMIZATION

The Genetic Global Optimization (GGO) method is used to optimize the various design parameters of the proposed MHEFSM. Variations in design parameters improve the performance, such as electromagnetic (EM) torque and cogging torque of the proposed design of MHEFSM. GGO improves the performance of the examined design by adjusting the size of design parameters such as the stator yoke radial length, stator pole thickness, PM dimensions, PM position, rotor tooth thickness, and so on. Some design parameters, such as stator outer diameter, air gap, stack
length, and module separator width, are kept constant in this analysis. GGO significantly improves the performance of the proposed MHEFSM by investigating the parameter’s optimum dimensions. The flow of the methodology used during GGO is depicted in Fig. 6.

GGO is accomplished by using JMAG software’s built-in genetic algorithm. The number of generations simulated are 15, which consumed 88 hours. Specification of the PC is 64-bit operating Lenovo system Intel(R), Core(TM) i5-8500 CPU with 3.00 GHz, 8 GB RAM, 3,000 Mhz.

Targets of the optimization are:

**Objective Function** (1)

\[
\text{max}(T_{\text{avg}}, T_D) \text{ and } \min(T_{\text{ripp}}, T_{\text{cog}})
\]

**Constraints** (2)

\[
\begin{align*}
T_{\text{avg}} & \geq 3.59 \text{ Nm} \\
T_D & \geq 5.348 \text{ kNm/m}^3 \\
T_{\text{ripp}} & \leq 1.45 \text{ Nm} \\
T_{\text{cog}} & \leq 2.11 \text{ Nm}
\end{align*}
\]

where

\[
\begin{align*}
T_{\text{avg}} &= T_{\text{EM}} + T_{\text{cog}} \\
T_D &= \frac{T_{\text{avg}}}{V_{\text{MHEFSM}}} \\
T_{\text{ripp}} &= T_{\text{Max}} - T_{\text{Min}}
\end{align*}
\]

In (3), \(T_{\text{avg}}\), \(T_{\text{EM}}\) and \(T_{\text{cog}}\) represents average torque, electromagnetic torque and cogging torque, respectively. In (4), \(T_D\) represent electromagnetic torque per volume of the proposed MHEFSM, whereas \(T_{\text{Max}}\) and \(T_{\text{Min}}\), used in (5) represents maximum and minimum values of the torque.

The convergence plot of objective function is shown in Fig. 7. The varying parameters are investigated, and their response in terms of EM torque and torque ripples are depicted in Fig. 8 and Fig. 9. Fig. 8a to 8e show the optimum value of the objective function at stator yoke of value 4.22 mm, stator middle tooth thickness of value 8.23 mm, the thickness of the end poles of the E-shaped stator core value 4.61 mm, PM position with value 1.33 mm, and PM radial length of value 7.88 mm, respectively. Similarly, the rotor of the proposed MHEFSM is also optimized through GGO, where the effect of different rotor parts dimensions is presented in the Fig. 9. Fig. 9a and Fig. 9b presents optimum values of the objective function at a rotor tooth thickness value of 6.09 mm and a shaft radius value of 14.08 mm. The ranges, initial and optimum design parameter values obtained after optimization are listed in Table 3.

To summarize, the proposed MHEFSM performance is significantly enhanced by using GGO through FEM. This analysis reveals that the EM torque response achieves a global value of 5.83 Nm, while the torque ripples are optimized to 1.15 Nm at the optimum values of the geometry varying parameters. The quantitative improvement in all performance indices is provided in Table 4.

### Table 3. Geometry variables details used in GGO.

| Variable (unit)         | Initial Value | Optimum Value | Range   |
|-------------------------|---------------|---------------|---------|
| Stator yoke (mm)        | 5             | 4.22          | [3-7]   |
| Middle tooth thickness (mm) | 6.6        | 8.23          | [6-10]  |
| End pole thickness (mm)  | 3             | 4.61          | [2.5-6] |
| PM position (mm)        | 1.5           | 1.33          | [1-2.4] |
| PM height length (mm)   | 3             | 7.88          | [2-8]   |
| Rotor tooth thickness (mm) | 5            | 6.09          | [3-6.4] |
| Rotor shaft radius (mm)  | 10            | 14.08         | [8-15]  |

![FIGURE 6. Methodology flow of GGO.](image)

![FIGURE 7. Convergence of objective function after GGO.](image)
IV. PERFORMANCE ANALYSIS USING FEM

The performance of the proposed MHEFSM is examined utilizing initial and optimum design parameters through 2D and 3D FEM. The flux lines distribution patterns due to PM, FE and overall throughout the proposed MHEFSM geometry are presented in Fig. 10. The other performance indices are explained in the following subsections.

A. NO-LOAD FLUX LINKAGE AND FLUX REGULATION

The three-phase no-load armature flux linkage over one pole pitch of the initial, optimized, and 3D topology of MHEFSM is shown in the Fig. 11a. The flux linkage is improved by 68% after optimization. The 3D analysis validates the 2D analysis. Harmonics in the flux linkage of both the initial design and optimized design of MHEFSM are illustrated in Fig. 11b. The ability to adjust the magnetic flux is an essential characteristic of the HEFSM, which reflects the influence of the field excitation on the magnetic field. The impact of field excitation on the PM flux linkage is provided in Fig. 12.
and the impact of FE on overall flux linkage is shown in Fig. 13 which reveals that the proposed motor is capable of weakening flux at higher speeds. Fig. 14 reveals that the proposed motor works as a PM motor in the absence of field excitation and achieves 5.12Nm average torque. This average torque can be decreased and increased by 34.18% and 30.86%, respectively, by changing field current.

**B. BACK-EMF**

The back-EMF of the proposed design is shown in Fig. 15 at the rated speed of 500 rpm. If the amplitude of the phase back-EMF increases, this means that the flux focusing improves. Fig. 15 depicts that after GGO, the amplitude of back-EMF has increased from 78.73V to 121.96V, which is a 54.91% increment from its initial value.

**C. COGGING TORQUE**

The cogging torque is calculated at no-load when the armature current is zero. The cogging torque causes ripples in the instantaneous torque. The cogging torque of the proposed MHEFSM is minimized after GGO. Furthermore, 3D analysis is conducted, and the response of initial, optimized and 3D cogging torque is plotted in Fig. 16.

**D. ELECTROMAGNETIC TORQUE**

The instantaneous torque is calculated under loaded conditions, i.e., when the armature current is applied. The average torque of the proposed MHEFSM is improved by 62.39% after GGO, as shown in Fig. 17. The 3D analysis is done to validate the 2D analysis. The ripples rate in the 3D analysis is a bit higher due to the end effects. In Fig. 18, the average torque with varying armature current density is observed at different field current densities.

**E. TORQUE AND POWER VERSUS SPEED CURVES**

The torque-speed and power-speed characteristics plots are shown in Fig. 19. The proposed MHEFSM maintains a constant torque region up to the speed of 784.49 rpm and achieves a maximum power of 565.28W. At speed beyond
784.49 rpm, the torque decreases to maintain constant power operation. The efficiency of the proposed MHEFSM at different regions under torque-speed curve is calculated and is shown in Fig. 20. It can be observed that the proposed motor has better efficiency of 82.38% in region II which is its feasible region of operation.

V. FAULT TOLERANCE

Fault tolerance of an electric machine is evaluated in terms of self-inductance and mutual inductance of the armature coil with itself and other adjacent phase coils. A high fault-tolerant machine must have magnetic, thermal, and physical separation between phase coils [24]. Due to the magnetic isolation of the coils, the healthy component of the motor remains independent from magnetic coupling with the faulty component. This section examines the self and mutual inductance of the proposed MHEFSM’s armature coils.

A. INDUCTANCE COMPUTATION IN STATOR PART

Magnetic coupling between two phases of armature coils is reduced by inserting non-magnetic materials in the middle of E-shaped stator core parts modules. After linkage of the flux from the rotor component, stator flux remains inside the stator module due to the isolation of the stator module by a non-magnetic part. Inductance is calculated by following two steps; unsaturated case and saturated case. PM and FE coils portions are made air at unsaturated conditions, and DC with appropriate current density \( J_c \) is injected into armature coils. At saturated condition, \( J_c \) is injected to both armature and FE coil. In addition, PMs are also made active with appropriate direction. Basic relations for calculating self-inductance and mutual-inductance used in [22] and [25] are

\[
L_A = \frac{\Psi_A}{i} = \frac{\Psi_A}{J_A s_{slot} s_f} = \frac{N^2 \phi_A}{J_c s_{slot} s_f} \quad (6)
\]

\[
L_{AB} = \frac{\Psi_B}{i} = \frac{\Psi_B}{J_B s_{slot} s_f} = \frac{N^2 \phi_B}{J_c s_{slot} s_f} \quad (7)
\]

where \( L_A \) represents self-inductance of phase A coil, \( \Psi_A \) is linkage flux of phase A coil, \( s_{slot} \) is the area of armature coil slot, \( N \) is the number of turns of armature coil, \( \phi_A \) is the A-phase coil flux and \( s_f \) is the coil filling factor. In (7), \( L_{AB} \) represents mutual inductance in coil B due to coil A, \( \Psi_B \) is flux linkage in coil B, and \( \phi_B \) is the coil B flux. The same relations are used for calculating the self-inductance of B and C phase coils. In addition, \( L_{BC} \) and \( L_{AC} \) are calculated using (7).

Since the A-phase contains two coils, their inductance is calculated using the sum of the self-inductance of the individual coil.

\[
L_A = L_{A1} + L_{A2} \quad (8)
\]

Similarly, the cumulative inductance of B-phase and C-phase coil sets are taken into count. At saturated conditions,
The average value of mutual-inductance under unsaturated condition is shown in Fig. 22. The excitation conditions of the proposed motor are used the same as the state-of-the-art model. An E-core stator is used compared to the C-core of the conventional topology. Furthermore, the best utilization of PM helps in achieving high torque and power density.

VII. CONCLUSION

A three-phase MHEFSM is proposed with flux gaps in the stator, which helps in flux focusing and fault-tolerant capability. The MNM reduces time and disk storage in the initial analysis of the proposed motor. GEM is used to globally optimize the geometry parameters of the proposed motor and achieve an optimal value of the objective function. Performance analysis unveils that the proposed design achieves higher torque and power density under the same dimensions and excitation conditions.

VI. COMPARISON WITH STATE-OF-THE-ART DESIGN

After the complete analysis of the proposed motor, the comparison is made with the state of art topology. The leading dimension of both the topologies and magnetic material type is kept the same. The excitation conditions of the proposed motor are compared with the state-of-the-art topology. Furthermore, the best utilization of PM helps in achieving high torque and power density.

TABLE 5. Comparison with state of the art motor.

| Parameter                  | Proposed [3] |
|----------------------------|--------------|
| Stator outer diameter (mm) | 128          |
| Axial length (mm)          | 75           |
| Air gap (mm)               | 0.5          |
| PM type                    | NdFeB30      |
| Speed (rpm)                | 500          |
| Field current density (A/mm²) | 7.4       |
| Armature current density (A/mm²) | 7.9        |
| $T_{avg}$ (Nm)             | 6.7          |
| $T_D$ (Nm/Kg)              | 1.766        |
| Power density (kW/Kg)      | 0.145        |

Comparison with state of the art motor. The comparison unveils that the proposed design achieves higher torque and power density under the same dimensions and excitation conditions.

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