Design and Optimization of Segmented PM Consequent Pole Hybrid Excited Flux Switching Machine for EV/HEV Application

Wasiq Ullah, Faisal Khan, Member, IEEE, and Muhammad Umair

Abstract—Hybrid Excited Flux Switching Machines (HEFSMs) unique feature of high torque density \(T_{den}\) of Permanent Magnet (PM) machines and flux regulation capability of wound field excitation machines. Due to aforesaid unique features, stator active HEFSMs are preferred for EV/HEV applications. In this paper a new Segmented PM Consequent Pole HE-FSM (SPMCPHEFSM) with flux bridge is proposed for EV/HEV. The developed SPMCPHEFSM exhibits improved flux modulation and flux regulation capability at reduced PM usage (suppressed PM volume by 46.52% and PM cost by 46.48%) and eliminating stator leakage flux. First, SPMCPHEFSM is geometric optimized (GO) for investigating influence of leading design with key performance indicators such as flux linkage \(\Phi_{pp}\), average torque \(T_{avg}\), cogging torque \(T_{cog}\), \(T_{den}\), average power \(P_{avg}\) and power density \(P_{den}\) and then proceeded optimized model to structure modification for optimal stator design and position of field excitation coils (FEC). Comprehensive performance analysis reveals that the developed SPMCPHEFSM show improved \(\Phi_{pp}\) maximum up to 9.11%, improved \(T_{avg}\) maximum up to 23.63%, truncate \(T_{cog}\) up to 18.9% whereas \(T_{den}\) and \(P_{den}\) are boost up to 23.55% and 89.72% respectively.

Index Terms—Electric Vehicle, Hybrid Electric Vehicle, Consequent Pole, Finite Element Analysis, Optimization, Segmented PM

I. INTRODUCTION

Flux Switching Machines (FSMs) are examples of stator active brushless AC machine in which all the excitations sources (Permanent Magnets, field winding slot and Armature winding slots) resides on stator leaving passive rotor made of iron only. Due to double salient structure and simple robust rotor structure, FSMs exhibits sinusoidal flux linkage and back emf therefore, applicable for brushless AC applications. FSMs are simple structure with key features of improved heat dissipation, relaxed thermal management of excitation source and mechanically robust structure. The design, structure and class of FSMs varies based on presence of the excitation sources.

Based on excitation source, FSMs are classified in to three major class i.e. Permanent Magnet (PM) excited, field excited and Hybrid excited (PM and field excited) [1]. The three major class of the FSMs becomes Permanent Magnet FSMs (PM-FSMs), Field Excited FSMs (FE-FSMs) and Hybrid Excited FSMs (HE-FSMs). Among three major FSMs categories, FE-FSM provide better flux controllability however offer low torque and power densities. PM-FSMs provides higher torque density however utilizes high PM volume and suffer from uncontrol and constant PM flux which causes issues of voltage regulation [2]. HE-FSM provide adjustable magnetic field and better flux controllability due existance of both PM and field excitation winding in stator without effecting output characteristics. This flux controllability i.e. flux-weakening and flux enhancing capability are achieved with the help of field excitation current makes HE-FSM competent candidates for variable speed applications [3, 4] especially in Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs). In addition, flux controllability provides ratio of the PM flux and field excitation winding flux which results investigation of wide constant power speed range [5, 6]. Based on the aforesaid merits of HE-FSM, this paper solely focuses on detail investigation regarding structure variations as well torque and power capability of HE-FSM for EV and HEV applications.

A comprehensive overview of HE-FSM for EV and HEVs are discussed in [7] whereas various classification of HE-FSM for EV/HEV based on position of PM and field excitation coils (FEC) reported in literature are listed in Fig. 1. Author in [8] mentioned series and parallel HE-FSM however in series HE-FSM PM permeability is same as air resulting higher excitation circuit reluctance. Flux controllability of HE-FSMs are improved utilizing iron ring at the outermost with concentrated field winding at the stator yoke in [9] whereas concept of iron flux bridge is presented in [10]. However narrow flux bridges easily saturated under loaded condition and heat up machine parts. The resultant heat causes PM demagnetization which degraded electromagnetic performance and its operation. Author in [11] developed HE-FSMs for hybrid vehicle from the existing PM-HEFSMs topologies by reducing the PM volume to reserve the space for field winding however flux regulation solely depend on PM length in axial direction. Moreover, the reverse current applied to field excitation winding causes PM demagnetization of the adjacent PMs. The flux regulation theories in HE-FSMS is investigated in [12]. Detailed analysis reveals that partial PM flux short circuited which results in decrease of the torque density. The torque production is improved in PM memory machines with novel flux regulation methodology utilizing High Coercive force (HCF) and low coercive force (LCF) PM. However, flux regulation range of memory machines are limited since flux is controllable in the maximum and minimum HCF and LCF magnetization state [13]-[15].
In order to overcome the aforesaid demerits in various HE-FSMs designs regarding flux controllability, flux regulation capability, position of armature and field winding, torque and power densities, this paper introduces a new topology of Segmented PM (SPM) Consequent Pole HE-FSM (SPMCPHEFSM) for EV and HEV as shown in Fig. 2. The developed model utilized SPM with Circumferential Magnetization PMs (CM-PMs) and Radial Magnetization PMs (RM-PMs) to reduce the overall PM volume and introduces flux bridges to improve the flux modulation phenomena. SPMCPHEFSM is constructed and investigated regarding for flux controllability, flux regulation capability, working principle and proceed to optimization, geometric modification for optimal stator structure, position of armature and field winding and comparison of various SPMCPHEFSM topologies.

It is worth mentioning that SPMCPHEFSM is extension of the previously studies of author regarding SPM Consequent Pole FSM (SPMCPFSM) with only PM excitation [29]-[31] which were proposed on [32] to reduce PM volume and curtailed flux circulation within flux bridge and flux barrier. In comparison of the aforesaid models, the proposed model greatly helps in PM volume reduction by 46.52% and suppression of circulating flux in stator core. Initially, in SPMCPFSM design, armature winding is halved and allocate it to field excitation winding and later on geometric modification is performed for optimum position and stator structure.

Main contributions of this paper include designing of a new SPMCPHEFSM for EV and HEV application at 46.52% reduced PM volume that suppress the overall PM cost by 46.48 and enhancing the flux modulation, flux controllability and power density. Furthermore, Geometric Optimization (GO) is investigated for enhancing electromagnetic performance and to achieving optimum design parameters. The optimized SPMCPHEFSM is updated for various stator structure and optimum position of field excitation winding. Comprehensive
performance analysis reveals that the developed SPMCPHEFSM show improved $\Phi_{pp}$ maximum up to 9.11%, enhanced $T_{avg}$ maximum up to 23.63% suppressed $T_{cog}$ up to 18.9%, whereas $T_{den}$ and $P_{den}$ up to 23.55% and 89.72 respectively.

In the following, SPMCPHEFSM topology and flux regulation capability are shown in section II, section III discusses geometric optimization, afterward, optimized model is proceeded to structural modification and comparison in section IV. Finally, some conclusions are drawn in section V.

II. SPMCPHEFSM TOPOLOGY AND FLUX REGULATION CAPABILITY

A. SPMCPHEFSM Topology

Design parameters of proposed SPMCPHEFSM is listed in Table I and indicated in Fig 3. Cross sectional view of SPMCPHEFSM shows that each armature winding coils are concentrated between segmented PMs with different magnetization pattern i.e. CM-PMS and RM-PMs which are enclosed between flux bridge, flux barrier and stator teeth. The flux bridge not only act as 2nd pole of the PMs but also provide magnetic path for flux distribution and linkage that ultimately helps in enhancing flux modulation phenomena and reducing the total PM usage.

B. Flux Regulation Capability

The flux controllability of the proposed SPMCPHEFSM mainly depend on the excitation current. The flux distribution under different excitation sources (only PM source and both PM and FEC) is shown in Fig. 5 whereas flux enhancing and flux weakening condition are as shown in Fig. 6. It can be clearly seen that the flux linked to armature windings are contribution of both PM flux and FEC flux. Analysis reveals that the flux linkage can be easily controlled by injecting field current with different polarities.

The flux enhancing and flux weakening capability is further investigated under various field excitation current density i.e. $J_e = 0, \pm 5, \pm 10, \pm 15 (A/mm^2)$ is shown in Fig. 7. Analysis unveils that under flux enhancing operation mode ($J_e > 0$) air-gap flux density enhanced resulting increase in the flux linkage with the increase in positive excitation current whereas under flux weakening operation mode ($J_e < 0$) air-gap flux density is

| Symbol | Parameter (unit) | Value (mm) |
|--------|-----------------|-------------|
| $R_o$  | Outer radius of stator | 45          |
| $R_{sy}$ | Inner radius of stator yoke | 41.4        |
| $R_{FBH}$ | Radius of flux bridge | 37          |
| $h_{si}$ | Stator back iron height | 3.6         |
| $R_{si}$ | Stator inner radius | 27.5        |
| $R_{ri}$ | Rotor inner radius | 20.4        |
| $R_{or}$ | Rotor outer radius | 27          |
| $R_{tw}$ | Rotor tooth width | 3.6         |
| $R_{stw}$ | Stator slot width | 3.6         |
| $H_{pm}$ | CM-PM height | 8.5         |
| $W_{pm}$ | CM-PM width | 3.03        |
| $H_{fb}$ | Flux bridge height | 9.5         |
| $W_{fb}$ | Flux bridge width | 1.0         |
| $H_{rp}$ | Rotor pole height | 6.6         |
| $L$ | Axial length | 25          |
| $\sigma$ | Air gap gap length | 0.5         |

Fig. 4. Flux Modulation in SPMCPHEFSM.
ULLAH et al: DESIGN AND OPTIMIZATION OF SEGMENTED PM CONSEQUENT POLE HYBRID EXCITED FLUX SWITCHING MACHINE FOR EV/HEV APPLICATION

Fig. 5. Flux distribution with (a) PM excitation and (b) PM and FEC.

Fig. 6. Flux linkage under different excitation source. Deteriorated resulting decrease in the flux linkage with the increase in the negative excitation current. Furthermore, it can be clearly seen that under various identical field excitation current and different polarities, the flux linkage is symmetrical and sinusoidal. Overall, this verify flux enhancing and flux weakening capability of SPMCPHEFSM and confirm that flux regulation capability solely depends on excitation current.

Fig. 7. Variation of the flux linkage under flux enhancing and weakening operation mode before optimization.

III. GEOMETRIC OPTIMIZATION

Electromagnetic performance of the developed SPMCPHEFSM is enhanced utilizing Geometric Optimization (GO) with key performance indicator such as flux linkage ($\Phi_{pp}$), flux linkage Harmonic ($\Phi_{THD}$), average torque ($T_{avg}$), cogging torque ($T_{cog}$), torque ripples ($T_{rip}$), torque density ($T_{den}$), average power ($P_{avg}$), and power density ($P_{den}$). Overall, GO is implemented in multiple steps with detailed flow as shown in Fig. 8. Key performance indicators are calculated as

$$\Phi_{THD} = \sqrt{\frac{1}{N} \sum_{i=2}^{N} U_i^2}$$

$$T_{trip} = T_{max} - T_{min}$$

$$T_{den} = \frac{T_{avg}}{V_{PM}}$$

$$P_{den} = \frac{P_{avg}}{W_{PM}}$$

Where as $U_i$ is ith harmonic terms, $U_1$ is fundamental harmonic terms, $T_{max}$ is maximum torque peak, $T_{min}$ is minimum torque peak, $V_{PM}$ is PM volume and $W_{PM}$ is PM weight. Note that $V_{PM}$ and $W_{PM}$ for proposed SPMCPHEFSM is 8091.25 mm$^3$ ≈ 8.09125x10$^{-6}$ m$^3$ and 0.061 kg, respectively.

In this process, initial design parameters of SPMCPHEFSM based on their sensitivity are opted for optimization. GO is implemented such that most sensitive design parameter is optimized first and then proceed to next level with previous stage optimum design. In this process, sequentially GO optimize leading design parameters of rotor as well as stator. GO is opted based on objective function, constraint and boundary condition as

$$\begin{align*}
\text{Objective function} & \quad \max \left( T_{avg}, T_{den}, P_{avg}, T_{den} \right) \quad \text{and} \quad \min \left( T_{cog}, T_{trip} \right) \\
\text{Constraint} & \quad T_{avg} > 2.5 \text{Nm}, \quad T_{cog} < 2 \text{Nm}, \quad \Phi_{THD} \leq 2\% \\
& \quad T_{rip} < 2.5 \text{Nm}, \quad T_{den} > 310 \text{kNm/m}^2 \\
& \quad P_{den} > 12.45 \text{kW/kg} \quad \text{and} \quad P_{avg} > 760 \text{W} \\
\text{Boundary condition} & \quad 0.55 \leq \beta \leq 0.65 \\
& \quad 2.47 \leq R_{rtw} \leq 7.74 \\
& \quad 5.1 \leq H_{pm} \leq 10.1 \\
& \quad 2.5 \leq W_{pm} \leq 5.0 \\
& \quad 5.1 \leq H_{fb} \leq 10.1 \\
& \quad 0 \leq W_{fb} \leq 1.0 
\end{align*}$$

Fig. 8. Flow chart of geometric Optimization.
Note that during GO, electrical loading (number of turns and applied current), magnetic loading (PM volume), slot area, stack length and air gap length are kept constant. Influence of GO in various optimization steps on different design parameters are discussed in the proceeding sub-sections.

A. $\beta_s$ Optimization

$\beta_s$ is the ratio of $R_{sl}$ and $R_{so}$. In this optimization step, the influence of the stator length is investigated by varying $R_{sl}$. The maximum and minimum values of $\beta_s$ is restricted to $h_{sl}/2$ and $2 \times h_{sl}$ to avoid magnetic saturation and ensure uniform magnetic field distribution. $\beta_s$ shows major influences in variation of $T_{avg}$, $T_{cog}$, $T_{den}$ and $T_{rip}$. Performance analysis with varying $\beta_s$ is shown in Fig. 9 and listed in Table II.

Performance analysis of initial developed SPMCPHEFSM, and $\beta_s$ optimizations (term as SPMCPHEFSM-1) reveals that $T_{cog}$ is reduced by 23.5%, improve $T_{avg}$ by 2.85%, suppressed $T_{rip}$ by 22.08%, enhance $T_{den}$ by 2.84%. Note that initially $\beta_s$ was 0.61 and in this stage, it is updated to 0.56.

B. $R_{rtw}$ Optimization

This step analyzed influence of $R_{rtw}$ on electromagnetic performance. $R_{rtw}$ is varied for optimal point between 2.47 mm and 7.74-mm. Detailed performance analysis with the variation of $R_{rtw}$ is shown in Fig. 10 and listed in Table III. It can be clearly seen that $R_{rtw}$ show major influence in variation of the of $T_{avg}$, $T_{cog}$, $T_{rip}$, $P_{avg}$ and $T_{den}$.

Performance analysis of SPMCPHEFSM-1, and $R_{rtw}$ optimizations (term as SPMCPHEFSM-2) reveals that $T_{avg}$ is improved by 1.4%, suppressed $\Phi_{THD}$ by 16.4%, enhance $T_{den}$ by 1.37% at the cost of 2.7% increase in $T_{cog}$. Note that initially $R_{rtw}$ was 7 mm and in this phase, it is updated to 4.86 mm.

C. $H_{pm}$ Optimization

Proposed SPMCPHEFSM design utilized SPM with CM-PMs and RM-PMs enclosed inside flux bridge and flux barrier. In this step, $H_{pm}$ of the CM-PMs is investigated. It is worth mentioning that while varying $H_{pm}$ of the CM-PMs, the respective height of the RM-PMs is varied to fix the PM volume. It is also worth mentioning that $H_{pm}$ is same as height of the flux bridge.

In this phase, CM-PMs $H_{pm}$ is varied between 8 mm to 12 mm and their corresponding electromagnetic performance are shown in Fig. 11 and listed in Table IV. Performance analysis of SPMCPHEFSM-2, and $H_{pm}$ optimizations (term as SPMCPHEFSM-3) unveil that $H_{pm}$ exhibit slight variation on electromagnetic performance. Note that initially $H_{pm}$ was 10 mm and in this stage, it is updated to 11 mm. It is worth mentioning that $H_{pm}$ is the same as $H_{fb}$.

D. $W_{fb}$ Optimization

Structure of proposed SPMCPHEFSM enclosed CM-PMs and RM-PMs in flux barrier which provide physical isolation of
both PMs and provide alternate path to working harmonics to enhanced flux modulation phenomena however it causes flux circulation which degrade electromagnetic performances. In this optimization phase, $W_{fb}$ is optimized so that ensure least possible flux circulation and flux leakage. Detailed electromagnetic performance with variation of $W_{fb}$ is shown in Fig. 12 and listed in Table V. Performance analysis of SPMCPHEFSM-3, and $W_{fb}$ optimizations (term as SPMCPHEFSM-4) reveals that $\Phi_{pp}$ is enhanced by 3.05%, enhance $T_{avg}$, $T_{den}$ by 1.37% at the cost of 3.7% increase in $\Phi_{THD}$. Note that initially $W_{fb}$ was 1 mm and in this point, it is updated to 0 mm such that the flux barrier is removed.

**E. $W_{pm}$ Optimization**

In final phase of GO, $W_{pm}$ of CM-PM is optimized to ensure least possible slotting effects. In this stage, $W_{pm}$ of CM-PM is varied between 3.9 mm to 1.71 mm. In order to keep the PM volume constant, span of the RM-PMs is varied to ensure fix magnetic loading. $W_{pm}$ shows major influences in variation of $T_{avg}$, $P_{avg}$, $T_{den}$ and $P_{den}$. Performance analysis with variation of $W_{pm}$ is shown in Fig. 13 and listed in Table VI. Electromagnetic performance comparison of SPMCPHEFSM-4, and $W_{pm}$ optimizations (term as SPMCPHEFSM-5) reveals that $T_{avg}$ is enhance by 2.89%, whereas $T_{den}$ is improved by 2.65% at the cost of 1.2% increase in $T_{avg}$. Note that initially $W_{pm}$ was 3.03 mm and in this stage, it is updated to 2.59 mm.

**TABLE VI**

| Performance indicator (unit) | SPMCPHEFSM-4 | SPMCPHEFSM-5 |
|------------------------------|--------------|--------------|
| $\Phi_{pp}$ (Wb)             | 0.0694038    | 0.0695326    |
| $\Phi_{THD}$ (%)             | 1.2871991    | 2.010235     |
| $T_{cog}$ (Nm)               | 1.5844472    | 1.67184445   |
| $T_{avg}$ (Nm)               | 2.6877762    | 2.7577553    |
| $T_{rip}$ (Nm)               | 2.2986872    | 2.2515639    |
| $T_{den}$ (kNm/m³)           | 332.18306    | 340.8318     |
| $P_{cog}$ (W)                | 779.19051    | 781.33921    |
| $P_{den}$ (kW/kg)            | 12.77361     | 12.80883     |

The overall GO process sequentially optimized rotor and stator. Table VII shows initial and optimized design parameters of SPMCPHEFSM. Fig. 14 shows cross sectional view of initial and optimized design whereas electromagnetic performance of initial and optimized designed are compared in Table VIII.

**TABLE VII**

| Parameter          | Initial value | Optimized value |
|--------------------|---------------|-----------------|
| $\beta_s$          | 0.61          | 0.58            |
| $H_{pm}$           | 10            | 11              |
| $W_{pm}$           | 3.05          | 2.59            |
| $W_{fb}$           | 1             | 0               |
| $R_{rip}$          | 7             | 4.86            |

**Fig. 11.** Effect of $H_{pm}$ optimization on (a) Flux linkage (b) Cogging Torque (c) Instantaneous torque (d) Power.

**Fig. 12.** Effect of $W_{fb}$ optimization on (a) Flux linkage (b) Cogging Torque (c) Instantaneous torque (d) Power.

**Fig. 13.** Effect of $W_{pm}$ optimization on (a) Flux linkage (b) Cogging Torque (c) Instantaneous torque (d) Power.
capability is achieved whereas after optimization, 13.35% flux enhancing capability and 32.89% flux weakening capability is achieved. It is the evidence that after optimization flux regulation capability is slightly reduces.

### Table VIII

| Performance indicator (unit) | Initial design | Optimized design (Model-1) |
|-----------------------------|----------------|---------------------------|
| $\Phi_{pp}$ (Wb)            | 0.0702896      | 0.0695326                 |
| $\Phi_{avg}$ (%)            | 1.2694068      | 2.0101235                 |
| $T_{avg}$ (Nm)              | 1.9126697      | 1.6718445                 |
| $T_{trp}$ (Nm)              | 2.5092076      | 2.7577553                 |
| $T_{den}$ (kN/m)            | 2.7329393      | 2.2515639                 |
| $P_{avg}$ (W)               | 762.7645       | 781.33921                 |
| $P_{den}$ (kW/kg)           | 12.50433       | 12.80883                  |

### IV. STRUCTURAL MODIFICATION AND COMPARISON

In this section, the optimized model (term as Model-1) is investigated for alternate position of the FEC and modified stator structure for improved electromagnetic performance. In this regard, initially position of the FEC are shifted to reserved space between PMs and the updated model (term as Model-2) is shown in Fig. 16(a). Furthermore, the model is reduced to E-Core and C-core as shown in Fig. 16(b) and Fig. 16(c) which are term as Model-3 and Model-4 respectively. Detailed quantitative electromagnetic performance of aforesaid topologies is listed in Table IX.

Detailed performance of all models (Model-1 to Model-4) are shown in Fig. 17 to Fig. 20. Comparison of Model-1 with Model-2 shows that, structural modification in Model-2 exhibits 9.11% higher $\Phi_{pp}$, 8.1% however reduces $P_{den}$ by 47.29% and offer lower $T_{avg}$, $T_{trp}$, $T_{den}$, $P_{avg}$. In addition, comparison with Model-3 reveals that Model-3 exhibits 23.63% higher $T_{avg}$, 23.55% higher $T_{den}$ by 13.34% and lower $P_{den}$ by 11.87%. Moreover, comparison with Model-4 reveals that Model-4 exhibits 13.45% higher $T_{avg}$, 13.18% and 5.49% lower $T_{trp}$.

To sum up, it is noted that proposed SPMCPHEFSM show improved $\Phi_{pp}$ maximum up to 9.11%, enhanced $T_{avg}$ maximum up to 23.63%, suppressed $T_{trp}$ up to 18.9%, whereas improves $T_{den}$ up to 23.55% and $P_{den}$ up to 89.72%.
ULLAH et al: DESIGN AND OPTIMIZATION OF SEGMENTED PM CONSEQUENT POLE HYBRID EXCITED FLUX SWITCHING MACHINE FOR EV/HEV APPLICATION

Fig. 17. Comparison of flux linkage.

Fig. 18. Cogging torque comparison.

Fig. 19. Instantaneous torque of all models.

Fig. 20. Power capability of all models.

V. CONCLUSION

This paper proposed and investigates a new SPMCPHEFSM with flux bridge for EV/HEV application. Proposed SPMCPHEFSM exhibits enhanced flux modulation and flux regulation capability at reduced PM usage utilizing CM-PMs and RM-PMs that suppressed PM volume by 46.52% and PM cost by 46.48% and eliminating stator leakage flux. Furthermore, influence of leading design parameters is investigated utilizing geometric optimization and proceeded to structure modification for optimal stator design and position of excitation winding. Analysis reveals that proposed SPMCPHEFSM show improved $\Phi_{pp}$ maximum up to 9.11%, improved $T_{avg}$ maximum up to 23.63%, truncate $T_{avg}$ up to 18.9% whereas $T_{den}$ and $P_{den}$ are boost up to 23.55%.

REFERENCES

[1] Ullah, Wasiq; Khan, Faisal; Umair, Muhammad, “Sub-Domain Modelling and Multi-Variable Optimization of Partitioned PM Consequent Pole Flux Switching Machines”, IET Electric Power Applications, vol. 14, no. 8, pp. 1360-1369, 2020.

[2] K. T. Chau, C. C. Chan and C. Liu, “Overview of Permanent-Magnet Brushless Drives for Electric and Hybrid Electric Vehicles,” in IEEE Transactions on Industrial Electronics, vol. 55, no. 6, pp. 2246-2257, June 2008

[3] J. T. Chen, Z. Q. Zhu, S. Iwasaki, and R. P. Deodhar, “A novel hybrid excited switched-flux brushless AC machine for EV/HEV applications,” IEEE Trans. Veh. Technol., vol. 60, no. 4, pp. 1365–1373, May 2011.

[4] B. Gaussens, E. Hoang, M. Lecrivain, P. Manfe, and M. Gabsi, “A hybrid-excited flux-switching machine for high-speed DC-alternator applications,” IEEE Trans. Ind. Electron., vol. 61, no. 6, pp. 2976–2989, Jun. 2014.

[5] Y. Amara, L. Vido, M. Gabsi, E. Hoang, A. H. B. Ahmed, and M. Lecrivain, “Hybrid excitation synchronous machines: Energy efficient solution for vehicles propulsion,” IEEE Trans. Veh. Technol., vol. 58, no. 5, pp. 2137–2149, Jun. 2009.

[6] F. G. Capponi, G. Borocci, G. De Donato, and F. Caricchi, “Flux regulation strategies for hybrid excitation synchronous machines,” IEEE Trans. Ind. Appl., vol. 51, no. 5, pp. 3838–3847, Sep./Oct. 2015.

[7] Z. Q. Zhu and S. Cai, “Hybrid excited permanent magnet machines for electric and hybrid electric vehicles,” in CES Transactions on Electrical Machines and Systems, vol. 3, no. 3, pp. 233–247, Sept. 2019.

[8] X. Zhu, Z. Xiang, C. Zhang, L. Quan, Y. Du, and W. Gu, “Co-reduction of torque ripple for outer rotor flux-switching PM motor using systematic multi-level design and control schemes,” IEEE Trans. Ind. Electron., vol. 64, no. 2, pp. 1102-1112, Feb. 2017.

[9] E. Hoang, M. Lecrivain, and M. Gabsi, “A new structure of a switching flux synchronous polyphased machine with hybrid excitation,” in Proc. Eur. Conf. Power Electron. Appl. (EPE), Sep. 2007, pp. 1–8

[10] R. L. Owen, Z. Q. Zhu, G. W. Jewell, “Hybrid excite flux-switching permanent-magnet machines with iron flux bridges,” IEEE Trans. Magn., vol. 46, no. 6, pp. 1726-1729, 2010.

[Table IX]

| Performance (unit) | Model-2 | Model-3 | Model-4 |
|-------------------|---------|---------|---------|
| $\Phi_{pp}$ (Wb)  | 0.07587 | 0.05460 | 0.06683 |
| $\Phi_{trip}$ (%) | 5.82401 | 24.7840 | 23.4950 |
| $T_{avg}$ (Nm)    | 1.83841 | 1.79742 | 1.63534 |
| $T_{trip}$ (Nm)   | 2.52567 | 3.40733 | 3.12143 |
| $T_{den}$ (kNm/m³) | 312.149 | 421.113 | 385.779 |
| $P_{avg}$ (W)     | 411.824 | 688.563 | 738.442 |
| $P_{den}$ (kW/kg) | 312.149 | 421.113 | 385.779 |
W. Hua, M. Cheng and G. Zhang, "A novel hybrid excitation flux-switching motor for hybrid vehicles", *IEEE Trans. Magn.*, vol. 45, no. 10, pp. 4728-4731, Dec. 2009.

W. Hua, G. Zhang, and M. Cheng, "Flux-regulation theories and principles of hybrid-excited flux-switching machines," *IEEE Trans. Ind. Electron.*, vol. 62, no. 9, pp. 5359-5369, Sep. 2015.

X. Zhu, Z. Xiang, L. Quan, W. Wu, and Y. Du, "Multimode optimization design methodology for a flux-controllable stator permanent magnet motor considering driving cycles," *IEEE Trans. Ind. Electron.*, vol. 65, no. 7, pp. 5353-5366, Jul. 2018.

H. Yang et al., "Hybrid-excited switched-flux hybrid permanent magnet machines," *IEEE Trans. Magn.*, vol. 52, no. 6, pp. 1-15, Jun. 2016.

F. Li, K. T. Chau, C. Liu, J. Z. Jiang, and W. Y. Wang, "Design and analysis of magnet proportioning for dual-memory machines," *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, Jun. 2012.

H. Hua and Z. Q. Zhu, "Novel Hybrid-Excited Switched-Flux Machine Having Separate Field Winding Stator," in *IEEE Transactions on Magnetics*, vol. 52, no. 7, pp. 1-4, July 2016.

G. Henneberger, J. R. Hadji-Minaglou, and R. C. Ciorda, "Design and test of permanent magnet synchronous motor with auxiliary excitation winding for electric vehicle application," in *Proc. Eur. Power Electron. Symp.*, Oct. 1994, pp. 645-649.

D. Fodorean, A. Djerdj, I. Viorel and A. Miraoui, "A double excited synchronous machine for direct drive application—design and prototype tests," *IEEE Trans. Energy Convers.*, vol. 22, no. 3, pp. 656-665, Sept. 2007.

N. Lin, D. Wang, Y. Shen and K. Wei, "Investigation on hybrid ratio between PM and current excitation sources for high-speed synchronous generator," in *Proc. 2014 17th International Conference on Electrical Machines and Systems (ICEMS), Hangzhou*, 2014, pp. 505-508.

A. D. Akemakou and S. K. Phoumsombat, "Electrical machine with double excitation, especially a motor vehicle alternator," U.S. Patent 6,147,429, Nov. 14, 2000.

C. Syverson, and W. Francis, "Hybrid alternator," US Patent 5,774,909 B1/5 May 1998.

N. Naoe and T. Fukami, "Trial production of a hybrid excitation type synchronous machine," in *Proc. IEMDC 2001. IEEE International Electric Machines and Drives Conference (Cat. No.01EX485)*, Cambridge, MA, USA, 2001, pp. 545-549.

Q. Ali, S. Atiq, T. A. Lipo, and B. I. Kwon, "PM assisted, brushless wound rotor synchronous machine," *J. Magn.*, vol. 21, no. 3, pp. 399-404, Nov. 2016.

A. Hussain, S. Atiq and B. Kwon, "Consequent-pole hybrid brushless wound-rotor synchronous machine," *IEEE Trans. Magn.*, vol. 54, no. 11, pp. 1-5, Nov. 2018.

F. Yao, Q. An, X. Gao, L. Sun and T. A. Lipo, "Principle of operation and performance of a synchronous machine employing a new harmonic excitation scheme," *IEEE Trans. Ind. Appl.*, vol. 51, no. 5, pp. 3890-3898, Sept.-Oct. 2015.

G. Jawad, Q. Ali, T. A. Lipo and B. Kwon, "Novel brushless wound rotor synchronous machine with zero-sequence third-harmonic field excitation," *IEEE Trans. Magn.*, vol. 52, no. 7, pp. 1-4, July 2016.

Q. Ali, T. A. Lipo and B. Kwon, "Design and analysis of a novel brushless wound rotor synchronous machine," *IEEE Trans. Magn.*, vol. 51, no. 11, pp. 1-4, Nov. 2015.

A. Hussain and B.-I. Kwon, "A new brushless wound rotor synchronous machine using a special stator winding arrangement," *Elect. Eng.*, pp. 1–8, Nov. 2017.

W. Ullah, F. Khan, N. Ullah, M. Umair, B. Khan and H. A. Khan, "Comparative Study Between C-Core/E-Core SFPPM with Consequent Pole SFPM," *2019 International Symposium on Recent Advances in Electrical Engineering (RAEE)*, Islamabad, Pakistan, 2019, pp. 1-6.

W. Ullah, F. Khan, E. Sulaiman, M. Umair, N. Ullah and B. Khan, "Influence of Various Rotor Pole on Electromagnetic Performance of Consequent Pole Switched Flux Permanent Magnet Machine," *2019 International Conference on Electrical, Communication, and Computer Engineering (ICECCE)*, Swat, Pakistan, 2019, pp. 1-6.

Ullah, Wasiq; Khan, Faisal; Sulaiman, Erwan; Umair, Muhammad, Ullah, Noman; Khan, Bakhtiar; "Analytical validation of novel consequent pole E-core stator permanent magnet flux switching machine", *IET Electric Power Applications*, 2020, 14, (5), p. 789-790, DOI: 10.1049/iet-epa.2019.0257.

Y. Gao, D. Li, R. Qu, H. Fang, H. Ding and L. Jing, "Analysis of a Novel Consequent-Pole Flux Switching Permanent Magnet Machine with Flux Bridges in Stator Core," *in IEEE Transactions on Energy Conversion*, vol. 33, no. 4, pp. 2153-2162, Dec. 2018.

Wasiq Ullah is basically from Afghanistan and was born in District Peshawar, Khyber Pakhtunkhwa, Pakistan in 1995. He received his B.S. and master’s degree degrees in electrical (power) engineering from COMSATS University Islamabad (Abbottabad Campus), Abbottabad, Pakistan in 2018 and 2020 respectively. He is currently working as a research associate in COMSATS University Islamabad (Abbottabad Campus), Abbottabad, Pakistan for analytical modelling of electric machines in electric machine design research lab. His research interests include analytical modelling, design analysis and optimization of Permanent Magnet Flux Switching Machines, Linear Flux Switching Machines, Hybrid Excited Flux Switching Machines and segmented permanent magnet Consequent Pole Flux Switching Machines for high speed brushless AC applications.

Faisal Khan was born in District Charsadda, Khyber Pakhtunkhwa, Pakistan in 1986. He received his B.S. degree in electronics engineering from COMSATS University Islamabad (Abbottabad Campus), Pakistan in 2009 and M.S. degree in electrical engineering from COMSATS University Islamabad (Abbottabad Campus), Pakistan in 2012. He received Ph.D. degree in electrical engineering from Universiti Tun Hussein Onn Malaysia, Malaysia in 2017. From 2010 to 2012, he was a Lecturer at University of Engineering & Technology, Abbottabad, Pakistan. Since 2017, he has been Assistant Professor with the Electrical Engineering Department, COMSATS University Islamabad (Abbottabad Campus), Pakistan. He is author of more than seventy publications, one patent, and received multiple research awards. His research interests include design and analysis of flux-switching machines, synchronous machines, and DC machines.

Muhammad Umair was born in District Peshawar, Khyber Pakhtunkhwa, Pakistan in 1995. He received his B.S. degrees in electrical (power) engineering from COMSATS University Islamabad (Abbottabad Campus), Abbottabad, Pakistan in 2018. He is currently pursuing M.S degree in Electrical (Power) Engineering at COMSATS University Islamabad (Abbottabad Campus). His research interests include design, analysis, optimization and experimental validation of flux-switching machines.