IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 11 June 2022, accepted 11 July 2022, date of publication 18 July 2022, date of current version 22 July 2022.
Digital Object Identifier 10.1109/ACCESS.2022.3191797

RESEARCH ARTICLE

Split Pole Permanent Magnet Vernier Machine With Halbach Array Magnets in Stator Slot Opening and Consequent Pole Rotor

SHAHZAD KHAN, FAISAL KHAN, (Senior Member, IEEE), WASIQ ULLAH, (Graduate Student Member, IEEE), ZAHOOR AHMAD, AND BASHARAT ULLAH, (Graduate Student Member, IEEE)
Department of Electrical and Computer Engineering, COMSATS University Islamabad, Abbottabad Campus, Abbottabad 22040, Pakistan
Corresponding author: Wasiq Ullah (wasiqullah014@gmail.com)

ABSTRACT Due to simpler mechanical structure and magnetic gearing effects, Permanent Magnet Vernier Machines (PMVMs) attract researcher interest because of their higher torque density for direct drive applications. However, regular PMVMs utilize more rare earth Permanent Magnet (PM), which increases machine cost and weight. Moreover, the PMs are mounted on the rotor surface, which enhances flux leakage and flux circulation, which degrade electromagnetic performance that ultimately decreases average torque, torque density, power density and efficiency. A new Split Pole PMVM (SP-PMVM) with Halbach PM arrangement in the stator slot opening and consequent pole rotor is proposed to overcome the issues above. The proposed SP-PMVM enhanced flux modulation phenomena to improve electromagnetic performance. Comparing the proposed machine with the existing designs reveals that the proposed design reduces the PM utilization by 22.2% and improves the flux linkage by 41.3% due to suppression of leakage flux and flux circulation. Moreover, the average torque is boosted by 42.35%. Furthermore, torque and power densities are increased by 83.01% and 44.84%, respectively. In addition, in comparison with the existing conventional design, the efficiency of the proposed model is enhanced by 25.01% at the cost of 19.75% cogging torque.

INDEX TERMS Halbach array, consequent pole, permanent magnet vernier machine, split pole, magnetic gearing effects.

I. INTRODUCTION

PMVMs have gained rapid increasing consideration due to their inherent high torque and low-speed features. Many industrial applications use PMVMs on account of high torque and low speed for electric vehicles and wind power generation systems [1]–[2]. The reason for the high torque outcome of PMVMs is because of using Magnetic Gearing (MG) effect [3]. Electric Machines based on mechanical gearing are associated with larger machine size and weight and require continual maintenance to provide lubrication for safe operation. Generally, mechanical gearing based electric machines are associated with complex structures [4] and suffer from high maintenance costs and a shorter life span. To overcome the aforesaid problems concerned with the mechanical gearing system in electric machines, vernier effects in PM machines are implemented in [5]. PMVM replaces mechanical gearing with MG effects for torque production in direct drive applications with higher torque density and low speed. Moreover, PMVMs offer low torque ripples, causing low vibration and noise; therefore, they are considered the best alternative to conventional electrical machines.

However, in comparison with regular Permanent Magnet Synchronous Machines (PMSMs), PMVMs suffer from relatively low power factors due to excessive flux leakage in the air gap [6]. This undesired feature of PMVM requires a high capacity converter which increases the cost and volume of the converter. Moreover, due to higher stator slots number than stator poles, integrated slot lap windings are most frequently implemented, which improve torque density.

The associate editor coordinating the review of this manuscript and approving it for publication was Xiaodong Liang.

However, machine weight and volume increase due to the overhang effect and higher copper consumption, increasing copper losses. Therefore, alternate techniques are preferred to reduce copper consumption and improve the power factor.

The author in [7] proposes a Halbach PMVM (HPM-PMVM) for a higher power factor. However, replacing the rotor core with non-magnetic material greatly minimizes the output torque because, for any specified slot/pole structure, the rotor core still provides the main path for flux in HPM-PMVM to complete magnetic circuits. Different winding configurations are investigated to improve the torque production capability. An outer rotor PMVM with a hybrid excitation source is proposed in [8], in which a homopolar configuration is adopted and trickily combined the flux route of the PM with the electromagnet flux route to achieve a compact structure.

The author in [9] thoroughly investigates the influence of lap winding and non-overlapping winding in PMVM. This analysis reveals that in comparison with non-overlapping winding, the torque density in PMVM with lap winding is higher. However, due to overhang effects and higher copper uses, copper losses are increased. The author in [10] proposed Split Pole (SP) PMVM (SP-PMVM) and studied the influence of concentrated and distributed winding. Analysis discloses that SP-PMVM with concentrated winding offers lower torque density. The influence of concentrated winding is further studied for higher torque and efficiency in [11]. However, due to dominant leakage flux, the proposed design suffers from the issue of low power factor. Different types of faults that occur in PM machines, such as electrical fault, mechanical fault, and magnetic fault, and their diagnoses methods are overviewed and compared in [12]. Flexible flux linkage of field excitation of PM machine, which improves torque density and efficiency, is studied in [13], where various techniques for the adjustment of flux are reviewed.

Dual-PM machines are gaining increasing interest because of their high torque density and simple mechanical structure [14]–[18]. In [14], a new type of vernier machine was presented, having PMs on both the rotor and the stator. The presented machine has two rotors, one for high and one for low speeds, each with a surface-mounted PM and a fixed pole piece in between. When the inner rotor rotates at high speed, the torque transmitted to the outer rotor can be enhanced by reducing its speed. Such vernier machines can produce a higher induced back EMF and more torque by decreasing the rotor's rotational speed, as is done in magnetic gears. Another vernier machine with a dual-PM stator/rotor configuration is proposed in [15]. The magnetic field is modulated by the stator and rotor teeth in the proposed machine's stator and rotor slots, both embedded with multi-pole PMs. The findings of the comparison show that the dual modulation effect can significantly increase the machine's torque density. In [16], an advanced Flux Modulation PM machine with PMs on both stator and rotor is proposed. The proposed machine achieved a higher power factor and efficiency compared to the conventional design. In addition, the effect of rotor slot number,

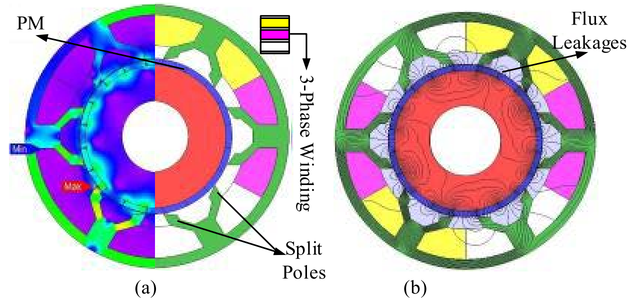

FIGURE 1. Conventional SP-PMVM (a) 2D cross sectional view (b) leakage flux.

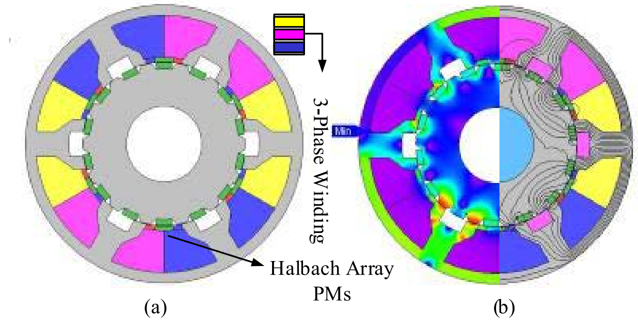

FIGURE 2. Proposed design (a) 2D Cross sectional view (b) Leakage Flux compensation.

which has a significant element influencing electromagnetic performance, has been investigated.

Leakage flux is suppressed in [18] by shifting half of the PM to the stator slot opening to provide an alternate path for the circulating flux. Such design highly improves airgap tangential magnetic flux density, which ultimately enhances torque density. However, PM usage increases which causes an increase in magnetic loading. Higher PM usage causes an increase in overall machine cost as well as magnetic saturation. In addition, cogging torque and torque ripples are further increased. In order to improve the torque density, the author proposed SP-PMVM with surface mount PMs as shown in Figure. 1 [19]. Despite the high usage of rare earth PM, this design suffers from flux leakages, flux circulation, cancellation, and saturation of the split pole tip.

To overcome the problems mentioned earlier of high PM usage, magnetic flux leakage, cogging torque, output torque, and efficiency, this paper proposed a new PMVM with Halbach PM arrangement at stator slot opening and consequent pole in the rotor as shown in Figure. 2. From Figure. 3, the flux line distribution shows that the proposed model successfully suppressed leakage flux and flux circulation, which ultimately improved average torque and reduced torque ripples and percent cogging torque. A comprehensive overview of electromagnetic performance of both conventional and proposed model are listed in the following section, and the rest of the paper is organized as Section 2 describes Design parameters and operation principle; Section 3 explain the

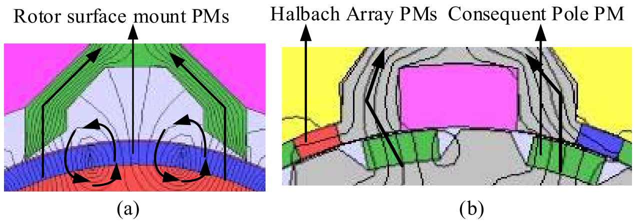

FIGURE 3. Flux line distribution (a) Conventional Design (b) Proposed Design with Halbach PM on stator slot opening and consequent pole rotor.

TABLE 1. Design parameters of conventional and proposed model.

Parameters	Conventional	Proposed
R_s (mm)	18.25	
R_{ro} (mm)	38.96	
R_{si} (mm)	39.5	
W_{PM} (mm)	7.29	
H_{PM} (mm)	3.0	
R_{sbi} (mm)	61.9	
R_{so} (mm)	67.0	
W_{st} (mm)	12.0	
H_{SP} (mm)	6.5	
W_{SP} (mm)	12.0	
V_{PM} (mm^3)	50139.6	39018

optimization technique used; Section 4 investigates the electromagnetic performance, and finally, conclusion is drawn in Section 5.

II. DESIGN PARAMETERS AND OPERATING PRINCIPLE

Both conventional and proposed models are developed based on the design parameters listed in Table 1 and shown in Figure. 4, whereas the operating principle for all PMVMs is based on Vernier effects known as magnetic gearing phenomena. Proposed design of SP-PMVM composed of radially outward magnetized PMs housed on the rotor. To reduce leakage flux due fringing effect, rotor core material attached to the PMs from asides is made chamfered. PMs Halbach array is placed in the slot opening of the coils. Halbach array creates a stronger magnetic field at the desired side and points the magnetic field in the desired direction. This is accomplished by orienting the magnets so that their poles are out of phase, typically by 90 degrees. The red PM used in the Halbach array is pointed circumferentially toward the prong of the stator tooth, and the blue PM is pointed circumferentially toward the prong of the next stator tooth. These PMs (red, blue) easily point to the magnetic flux in the stator tooth prong for better electromagnetic parameters such as torque. The middle PM is pointed upward in the same direction as rotor-mounted PM for enhancing flux.

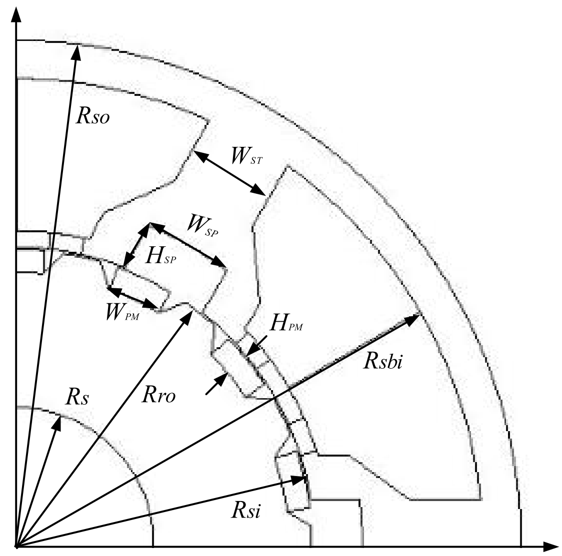

FIGURE 4. Design parameters.

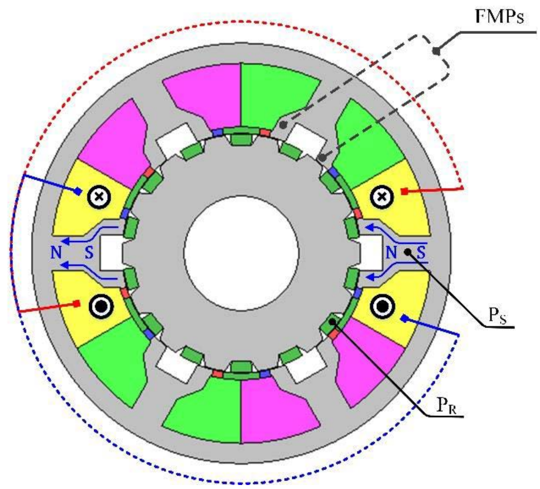

FIGURE 5. Alternating poles of the proposed PMVM.

The operating principle of the SP-PMVM is based on the flux modulation phenomena. The structure of the proposed machine shows that the proposed model utilizes a consequent pole on the rotor and a Halbach magnet array in the slot opening to give an alternate path for the flux flow through the split pole of the stator. Since the consequent pole on the rotor utilizes only the N-pole of the PMs therefore, it only produces the main flux, which flows to the stator through the split pole and avoids flux leakage and flux circulations. Moreover, the conventional design utilizes both N-pole and S-pole magnets in which N-pole produces useful flux, whereas S-pole generates leakage flux. This S-pole in the conventional design causes a serious issue of flux leakage and flux circulation, which degrade the electromagnetic performance.

Coils connections and instantaneously building of N-pole and S-pole in the stator are shown in Figure. 5. The

TABLE 2. Initial and optimized dimensions of parameters.

Parameter	Initial values (mm)	Optimized values (mm)	*TRI*
SR	0.59	0.57	37.1%
H_{RPM}	3.12	3.49	33.4%
T_{RTP}	4.8	6.4	20.1%
β	0.4958	0.6394	13.5%
SO	16.58	17.88	11.9%
H_P	6.79	7.15	11.4%
H_{TX}	8.2	9.9	7%
(T_S)	12	11	6.1%

relationship between winding pole pair (PS), rotor pole pair (PR), and flux modulating poles (FMPS) discussed in [20] is

$$P_R = FMPS + P_S \tag{1}$$

where P_R of the proposed design is 14 and FMP_S is 12. Using equation. (1), P_S of the proposed design is 2, already shown in the Figure. 5. From this, it concludes that proposed design of SP-PMVM meet the basic principle of the Vernier machine.

III. OPTIMIZATIION

In order to achieve optimum performances of the proposed SP-PMVM, the initially designed topology of SP-PMVM has been optimized by updating several parameters of the rotor, stator, Halbach array, and armature slot. Parameters like an air gap, stack length, and outer diameter are kept constant using maximum current density (Ja) and magnetic flux density (B) conditions. Using deterministic optimization analysis in JMAG Designer version 18.1, the optimum performance in terms of torque ripples of the proposed SP-PMVM is examined. Torque Ripple Index (TRI) of unoptimized SP-PMVM was 46.7% which is reduced through optimization of various parameters.

Figure. 6 shows different parameters of SP- PMVM that are optimized by changing its dimension. Figure. 7 show the reduction of TRI by optimizing different parameters of SP-PMVM. Table. 2 shows the initial and final optimum values of parameters that are optimized. Moreover, it shows the reduction of TRI in percent. Split Ratio (SR), which is the ratio of stator inner diameter to the stator outer diameter, is optimized by reducing the SR from 0.59 to 0.57. This optimization reduces the TRI from 46.7% to 37.1%, as shown in Figure. 6 and Table. 2. Rotor PMs height (H_{RPM}) is optimized by changing the height from 3.12 mm to 3.49 mm, which reduces TRI from 37.1% to 33.4%. The thickness of the rotor tip (T_{RTP}) is optimized by varying the dimension from 4.8 mm to 6.4 mm, which greatly reduces TRI to 20.1%. Optimizing the ratio of the length of Halbach array middle PM to the total length of Halbach array (β) reduces TRI from 20.1% to 13.5%. This is made by changing the value of β from 0.4958 to 0.6394. Length of Slot opening (SO) reduces

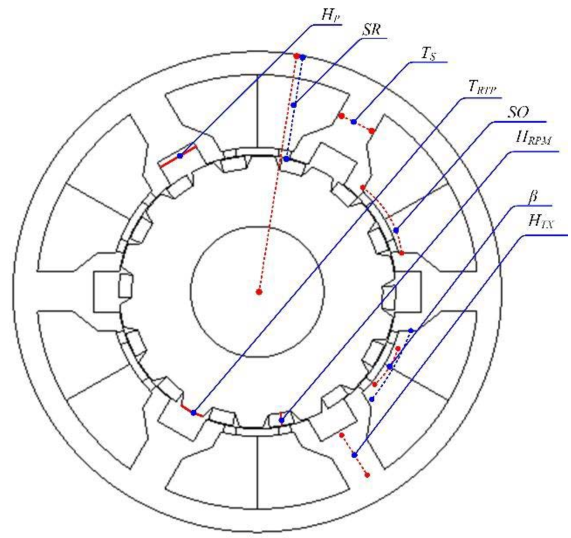

FIGURE 6. Parameters considered in optimization.

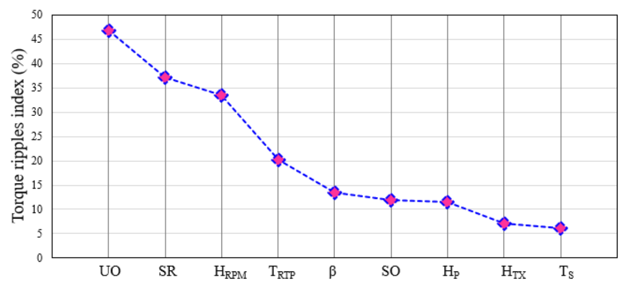

FIGURE 7. Variation of torque ripple versus optimizing variables.

TRI to 11.9% by changing its dimension from 16.58 mm to 17. 88 mm. Stator tooth prong horizontal length

(H_P) also shows an effect on TRI. By changing the dimension of HP from 6.79 mm to 7.17 mm, reduces TRI to 11.5%. Stator tooth height (horizontal distance from yoke to prong) (H_{TX}) also shows a great contribution in minimizing the TRI. Optimization of H_{TX} reduces TRI to 7% by changing its length from 8.2 mm to 9.9 mm. Stator tooth thickness at yoke (vertical distance) (T_S) reduces TRI to 6.1% by changing its dimensions from 12 mm to 11 mm. From this analysis, it is concluded that by changing the dimension of various parameters of SP-PMVM, TRI is reduced from 46.7% to 6.1%. Figure. 8 shows instantaneous torque of unoptimized and optimized proposed SP-PMVM. The blue line show torque produced by unoptimized SP-PMVM, which has high torque ripples. The black line shows instantaneous torque of optimized SP-PMVM, which indicates the least torque ripples.

IV. INVESTIGATION OF ELECTROMAGNETIC PERFORMANCE

Comprehensive electromagnetic performance of conventional and proposed designs is investigated with the key

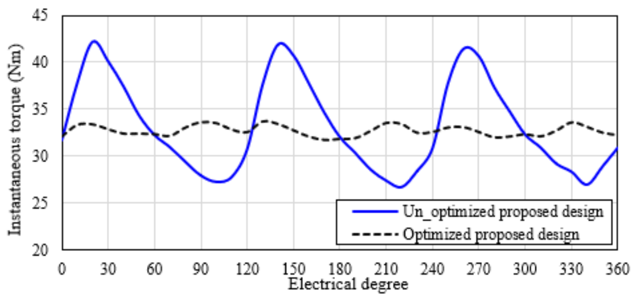

FIGURE 8. Instantaneous torque optimized and un-optimized design.

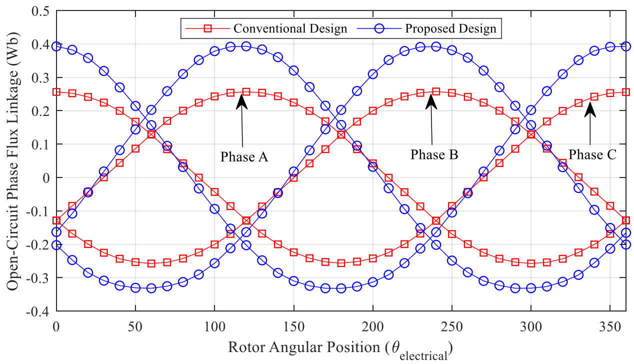

FIGURE 9. Comparison of open-circuit phase flux linkage for conventional and proposed design.

performance indicators such as peak to peak open- circuit phase flux linkage (Φp-p), Total Harmonics Distortion (THD) for open circuit flux linkage (ΦTHD), average torque (T_{avg}), Torque ripples (T_{rip}), Torque density (T_{den}), Power Density (P_{den}) and torque characteristics based on wide speed range.

Figure. 9 shows that despite the 22.2% reduction in total PM volume in the proposed model in comparison with the conventional design, the proposed model offers 0.2118 Wb higher open-circuit phase flux linkage. The flux linkage is improved due to the suppression of flux leakages and circulation. Moreover, it can be seen from Figure. 10 that when the flux linkage increases, the fundamental harmonics component improves, and some of the higher-order harmonics content are curtailed.

Figure. 11 presents the average torque of the proposed and conventional design of SP-PMVM. The Blue and red lines show the average torque of the proposed and conventional design of SP-PMVM, respectively. Due to improved flux modulation phenomena, it can be clearly seen in Figure. 11 that the average torque of the proposed SP-PMVM is enhanced from 28.6 Nm in conventional design to 40.8 Nm in the proposed design. In this analysis, the current density is kept constant of magnitude 8 A/mm2, while the PM volume of the proposed design is 22.2% less than the conventional design. Cogging torque of the proposed and conventional design is shown in Figure. 12. Cogging torque of the proposed design is higher than the conventional design. This

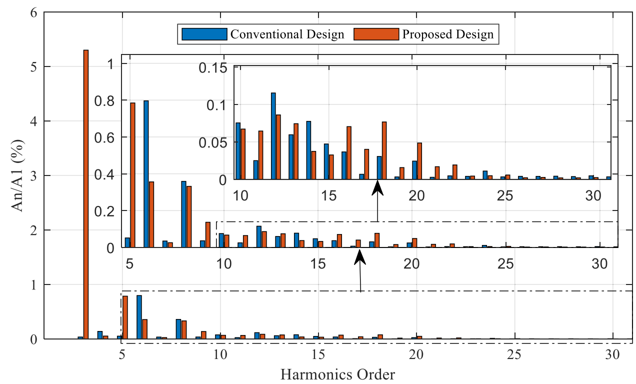

FIGURE 10. Harmonics content of open-circuit phase flux linkage for conventional and proposed design.

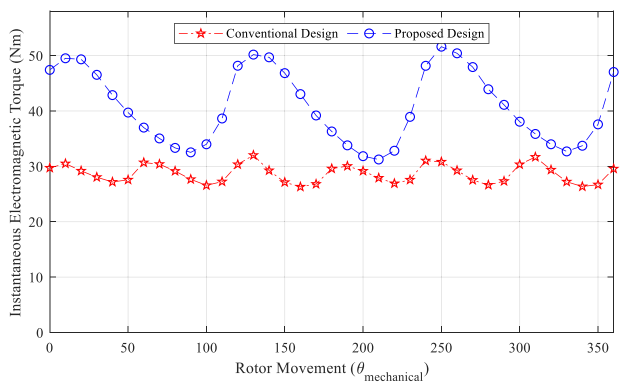

FIGURE 11. Instantaneous torque behavior of conventional and proposed design.

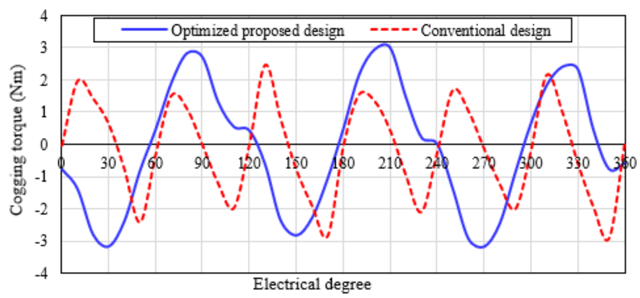

FIGURE 12. Cogging torque of optimized proposed and conventional design.

higher value of cogging torque is due to the high value of the average torque of the proposed design. The percent cogging torque of the proposed design is 18.91%, while the conventional design provides 26.91% cogging torque. From this analysis, it can be concluded that the proposed design has a small value of cogging toque in percent compared to conventional design.

Figure. 13 shows the influence of applied current densities on the conventional and proposed model. It can be seen from Figure. 13 that with the increase in applied current density average torque of the proposed model increases more in

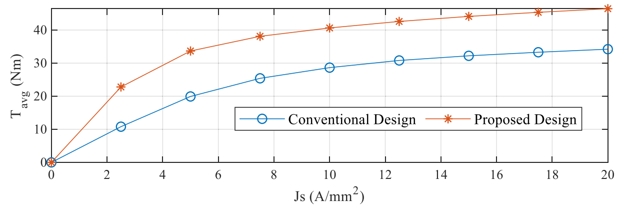

FIGURE 13. Average torque of optimized proposed and conventional design.

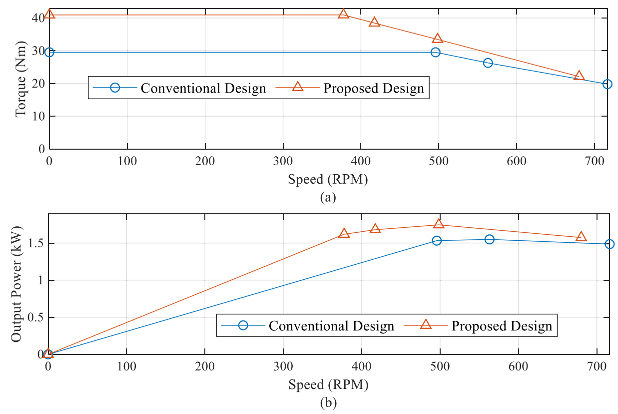

FIGURE 14. Torque-power vs speed characteristics of conventional and proposed design.

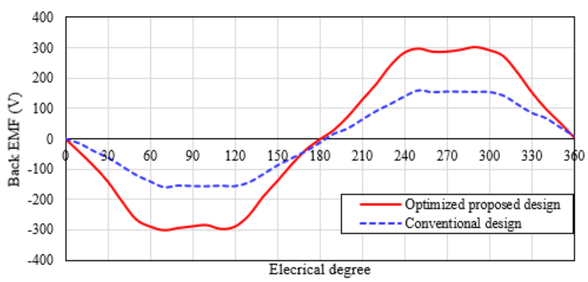

FIGURE 15. Back EMF of optimized proposed and conventional design.

comparison with the conventional design. Thus, it confirms that the torque production capability of the proposed model is higher.

Both conventional and proposed models are simulated under higher current densities and different phase angles of the applied current. It can be seen in Figure. 14 that the proposed model can be operated at a lower speed to achieve higher average torque and output power therefore considered as a suitable candidate for wind power application.

Figure. 15 is the graphical representation of the back EMF simulated results for the optimized proposed and conventional design. Back EMF of the optimized proposed design is 90% greater than the conventional design due to high flux circulation.

The average torque for different values of current densities and phase angles of conventional and proposed designs is shown in Figure. 16 and Figure. 17 respectively. It can be

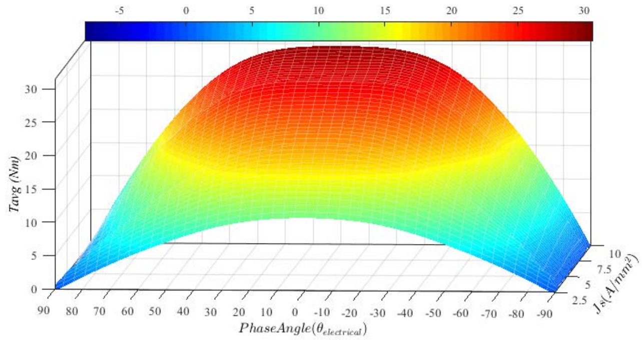

FIGURE 16. Torque behavior of conventional design with various applied current densities and phase angle.

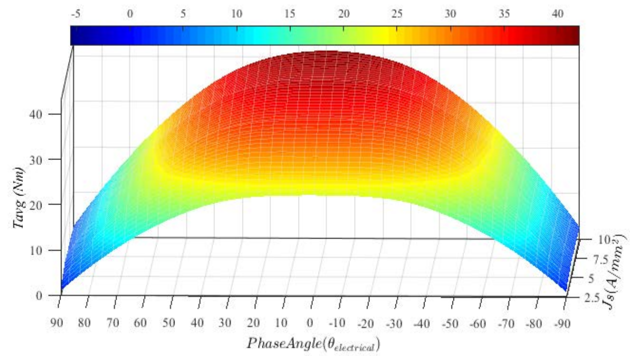

FIGURE 17. Torque behavior of proposed design with various applied current densities and phase angle.

clearly seen that both conventional and proposed designs generate higher average torque when operated in the range of 30° to −30° phase angle of the applied current. Moreover, it is also clear from the figures that the proposed design of SP-PMVM produces a high value of average torque compared to the conventional design.

The iron losses in the optimized proposed design are higher than in conventional design because the frequency of the proposed optimized design is high. Also, the size of the stator and rotor core of the proposed optimized design is larger than the conventional design. Figure. 18 shows iron losses for both optimized proposed design and conventional design. The red line shows iron losses of the proposed design for different current density values, while the blue line shows iron losses of the conventional design.

The efficiency of the proposed and conventional design for various current density values is shown in Figure. 19. This result shows the performance comparison of conventional design and optimized proposed design. Torque increases with an increase of current density, which causes copper losses to increase; hence the total efficiency is reduced.

A comprehensive quantitative electromagnetic analysis of the conventional and proposed model is listed in Table 3. This analysis reveals that the proposed model utilized 77.8% of the total PM volume to offer 41.3% higher phase flux linkage, 42.35% increased average torque, 83.01% more torque

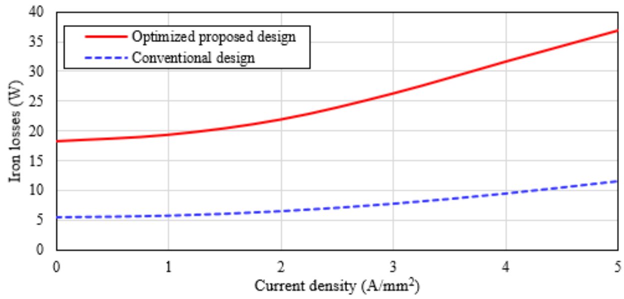

FIGURE 18. Iron losses of optimized proposed and conventional design.

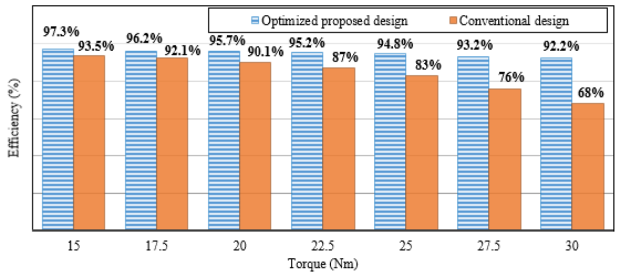

FIGURE 19. Efficiency of optimized proposed design and conventional design.

TABLE 3. Quantitative electromagnetic performances.

Item	Unit	Conventional	Proposed
$\Phi_{p\text{-}p}$	Wb	0.5128	0.7246
T_{cog}	Nm	5.3727	6.4341
T_{avg}	Nm	28.6687	40.8115
T_{rip}	Nm	5.7120	20.3742
T_{den}	kNm/m^3	571.77	1046.4
P_{den}	MW/m^3	30.909	44.7628
η	%	72.9125	91.15
V_{PM}	m^3	5.014e-5	3.90e-5

density, 44.84% power density, and 25.01% efficiency at the cost of increased in the value cogging torque.

V. CONCLUSION

This paper proposes a reduced PM SP-PMVM with Halbach array PMs in stator slots opening and consequent pole rotor structure for enhanced flux modulation phenomena to improve electromagnetic performance. Finite element analyses are made to verify the performance of the proposed design. A deterministic optimization technique is used to improve the performance of the proposed SP-PMVM in terms of torque ripple reduction. The proposed machine is compared with the existing state-of-the-art designs. Analysis reveals that the proposed design reduces the PM utilization by 22.2% and improves the flux linkage by 41.3% due to suppression of leakage flux and flux circulation. Moreover, the average torque is boosted by 42.35% and torque and power densities by 83.01% and 44.84%, respectively. In addition, in comparison with the existing conventional design, the efficiency of the proposed model is enhanced by 25.01%. The percent cogging torque is also reduced.

REFERENCES

[1] S. Jiang, G. Liu, W. Zhao, L. Xu, and Q. Chen, "Modeling and analysis of spoke-type permanent magnet Vernier machine based on equivalent magnetic network method," *Chin. J. Electr. Eng.*, vol. 4, no. 2, pp. 96–103, 2018.

[2] Y. Wang, W. N. Fu, S. Niu, and X. Li, "A novel stator and rotor dual PM flux modulated machine," *Chin. J. Elect. Eng.*, vol. 3, no. 1, pp. 10–15, 2017.

[3] W. Li, T. W. Ching, and K. T. Chau, "Design and analysis of an outer-rotor parallel-hybrid-excited Vernier machine," *Chin. J. Elect. Eng.*, vol. 3, no. 1, pp. 27–32, 2017.

[4] L. Jian, K. T. Chau, and J. Z. Jiang, "A magnetic-geared outer-rotor permanent-magnet brushless machine for wind power generation," *IEEE Trans. Ind. Appl.*, vol. 45, no. 3, pp. 954–962, May/Jun. 2009.

[5] J. Li and K. T. Chau, "Design and analysis of a HTS Vernier PM machine," *IEEE Trans. Appl. Supercond.*, vol. 20, no. 3, pp. 1055–1059, Jun. 2010.

[6] B. Kim, "Characteristic analysis of a Vernier PM motor considering adjustable speed control," in *Proc. IEEE Transp. Electrific. Conf. Expo, Asia–Pacific (ITEC Asia-Pacific)*, Busan, South Korea, Jun. 2016, pp. 671–676.

[7] Y. Kataoka, M. Takayama, Y. Matsushima, and Y. Anazawa, "Comparison of three magnet array-type rotors in surface permanent magnet-type Vernier motor," in *Proc. 15th Int. Conf. Elect. Mach. Syst. (ICEMS)*, Sapporo, Japan, Oct. 2012, 1-6.

[8] C. Lee, M. Angle, K. Bhalla, M. Qasim, J. Mei, S. Mohammadi, K. Iyer, J. Sinkular, and J. Kirtley, "Quantitative comparison of Vernier permanent-magnet motors with interior permanent-magnet motor for hybrid electric vehicles," *Energies*, vol. 11, no. 10, p. 2546, Sep. 2018.

[9] T. Zou, D. Li, R. Qu, D. Jiang, and J. Li, "Advanced high torque density PM Vernier machine with multiple working harmonics," *IEEE Trans. Ind. Appl.*, vol. 53, no. 6, pp. 5295–5304, Nov./Dec. 2017.

[10] G. Xu, L. Jian, W. Gong, and W. Zhao, "Quantitative comparison of flux-modulated interior permanent magnet machines with distributed windings and concentrated windings," *Prog. Electromagn. Res.*, vol. 129, pp. 23–109, 2012.

[11] J. Li, K. T. Chau, J. Z. Jiang, C. Liu, and W. Li, "A new efficient permanent-magnet Vernier machine for wind power generation," *IEEE Trans. Magn.*, vol. 46, no. 6, pp. 1475–1478, Jun. 2010.

[12] M. Cheng, J. Hang, and J. Zhang, "Overview of fault diagnosis theory and method for permanent magnet machine," *Chin. J. Elect. Eng.*, vol. 1, no. 1, pp. 21–36, Dec. 2015.

[13] H. Yang, Z. Q. Zhu, H. Lin, and W. Chu, "Flux adjustable permanent magnet machines: A technology status review," *Chin. J. Elect. Eng.*, vol. 2, no. 2, pp. 14–30, Dec. 2016.

[14] D. K. Jang and J. H. Chang, "Design of a Vernier machine with PM on both sides of rotor and stator," *IEEE Trans. Magn.*, vol. 50, no. 2, pp. 877–880, Feb. 2014.

[15] S. Niu, S. L. Ho, and W. N. Fu, "A novel stator and rotor dual PM Vernier motor with space vector pulse width modulation," *IEEE Trans. Magn.*, vol. 50, no. 2, pp. 805–808, Feb. 2014.

[16] Y. Gao, M. Doppelbauer, R. Qu, D. Li, and H. Ding, "Synthesis of a flux modulation machine with permanent magnets on both stator and rotor," *IEEE Trans. Ind. Appl.*, vol. 57, no. 1, pp. 294–305, Jan. 2021.

[17] F. Wang, L. Zhou, J. Wang, Y. Xiao, J. Zhou, and L. Shentu, "A novel dual-stator permanent magnet Vernier machine with magnets in rotor and both stators," in *Proc. 21st Int. Conf. Electr. Mach. Syst. (ICEMS)*, Oct. 2018, pp. 197–201.

[18] K. Xie, D. Li, R. Qu, and Y. Gao, "A novel permanent magnet Vernier machine with Halbach array magnets in stator slot opening," *IEEE Trans. Magn.*, vol. 53, no. 6, pp. 1–5, Jun. 2017.

[19] K. Xie, D. Li, R. Qu, X. Ren, M. R. Shah, and Y. Pan, "A new perspective on the PM Vernier machine mechanism," *IEEE Trans. Ind. Appl.*, vol. 55, no. 2, pp. 1420–1429, Mar./Apr. 2019.
[20] Z. Song, C. Liu, F. Chai, and H. Zhao, "Modular design of an efficient permanent magnet Vernier machine," *IEEE Trans. Magn.*, vol. 56, no. 2, pp. 1–6, Feb. 2020.

SHAHZAD KHAN was born in Khyber Pakhtunkhwa, Pakistan, in 1993. He received the B.S. and M.S. degrees in electrical engineering from COMSATS University Islamabad, Attock Campus, in 2016 and 2020, respectively. He has been a member of the Electric Machine Design Research Laboratory, since 2018. His research interest includes design, optimization, and analysis of vernier machines.

FAISAL KHAN (Senior Member, IEEE) was born in Charsada, Khyber Pakhtunkhwa, Pakistan, in 1986. He received the B.S. degree in electronics engineering and the M.S. degree in electrical engineering from COMSATS University Islamabad, Abbottabad Campus, Pakistan, in 2009 and 2012, respectively, and the Ph.D. degree in electrical engineering from Universiti Tun Hussein Onn Malaysia, Malaysia, in 2017. From 2010 to 2012, he was a Lecturer at the University of Engineering and Technology Peshawar, Abbottabad Campus. Since 2017, he has been an Assistant Professor with the Department of Electrical Engineering, COMSATS University Islamabad, Abbottabad Campus. He is the author of more than 150 publications, two patents, and has received multiple research awards. His research interests include design of flux-switching, synchronous, and DC machines. Furthermore, he is a Senior Member of the IEEE Industrial Electronics Society and a member of IEEE-IES Electrical Machines Technical Committee.

WASIQ ULLAH (Graduate Student Member, IEEE) was born in Peshawar, Khyber Pakhtunkhwa, Pakistan, in 1995. He received the B.S. and M.S. degrees in electrical (power) engineering from COMSATS University Islamabad (Abbottabad Campus), Abbottabad, Pakistan, in 2018 and 2020, respectively, where he is currently pursuing the Ph.D. degree in electrical (power) engineering.

Since 2018, he has been a Research Associate with the Electric Machine Design Research Laboratory. His research interests include analytical modeling, design analysis and optimization of permanent magnet flux switching machines, linear flux switching machines, hybrid excited flux switching machines, novel consequent pole flux switching machines for high-speed brushless AC applications, and flux switching generators for counter-rotating wind turbines applications.

Mr. Ullah is a member of the IEEE-IES Electrical Machines Technical Committee and the Pakistan Engineering Council. He serves as a Reviewer for IEEE ACCESS, *IET Electric Power Application*, and 2022 IEEE Energy Conversion Congress and Exposition (ECCE 2022).

ZAHOOR AHMAD was born in Khyber Pakhtunkhwa, Pakistan, in 1993. He received the M.S. degree in electrical engineering from COMATS University Islamabad, Abbottabad Campus, Pakistan. He is currently pursuing the Ph.D. degree with the School of Electrical Engineering, Southeast University, Nanjing, China. He worked on research exchange program at the GIK Institute for one plus year with the Electrical Machine and Drive Laboratory. His research interest include design of linear oscillating actuator for refrigeration systems.

BASHARAT ULLAH (Graduate Student Member, IEEE) was born in Karak, Khyber Pakhtunkhwa, Pakistan, in 1993. He received the B.S. degree in electronics engineering from the University of Engineering and Technology (UET), Peshawar, Pakistan, in 2015, and the M.S. degree in electrical engineering from the National University of Sciences and Technology (NUST), Islamabad, Pakistan, in 2017. He is currently pursuing the Ph.D. degree in electrical engineering with COMSATS University Islamabad. Since 2019, he has been a Research Associate with the Research in Design of Electric Machines (RiDEM) Laboratory. His research interests include design, optimization, and analysis of rotary and linear hybrid excited flux-switching machines, linear actuators, and polyphase machines and their drives.