

INVESTIGATION OF HYBRID EXCITATION FLUX SWITCHING MACHINE WITH MODULAR ROTOR

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Abstract

Hybrid Excitation Flux Switching Machines (HEFSMs) are extensively researched for vehicle applications due to their high torque density and controllable magnetic flux. However, the impact of rotor pole number variation in modular rotor structures remains insufficiently studied. In the 12S-10P HEFSM, improper magnetic coupling between PM and FEC causes flux cancellation during the high excitation current, which limits electromagnetic torque and weakening of flux strengthening capabilities. This paper uses Finite Element Analysis (FEA) to compare two configurations, 12S-10P and 12S-14P under identical operation condition, such as flux linkage, electromagnetic torque, output power and speed. Due to better magnetic alignment between the rotor and stator and reduced flux leakage and flux cancellation, the 12S-14P configuration is determined to provide better flux linkage, higher torque production, and enhanced output power. Compared with the 12S-10P HEFSM, the proposed 12S-14P HEFSM achieves 23.3% higher torque, 37.5% higher power, and a significantly wider operational speed range. These results demonstrate that an increased rotor pole number significantly enhances overall machine performance, making the 12S-14P topology a more appropriate candidate for electric vehicles drive systems.

1 Introduction

Researchers have recently become interested in the Flux Switching Based Machine, a novel type of machine that has the advantage of operating at high speeds while having complete control over the field flux because all flux sources are incorporated into the stator and a rotor structure, three forms of FSMs are distributed: (1) PM FSM (2)FE FSM and (3) HEFSM for FSM[1][2]. These machines typically feature a prominent rotor with PMs located in the stator part. The PM material has a high torque density and efficiency despite its high cost. Additionally, PM materials have operating temperatures that limit their usage cost and completion. Because of the fixed excitation of PM, the flux- weakening operation affects the performance of PM machines at high-speed operating regions. Therefore, to reduce high cost of Flux switching Machine[3]. However, the conventional design depicted in Figure 1 is suffering from excessive volume PM. Various PMFSM designs have been introduced since then. A basic stator tooth is alternately used in place of the stator poles to reduce PM consumption[4].

In terms of structure, DC field excitation coils (FEC) can effectively replace most of the permanent magnet (PM) excitation coils found on the stator of conventional PMFSM to create FEFSM. However, previous layouts face strict performance constrains; for instance, the isolation or

separation between adjacent DC field coils limit the overall flu generation, which severally impacts of the machine's performance[5].

The design and performance of the 12S-10P and 12S-14P HEFSM with DC FEC in radial polarity are studied. The motor's parameters and design limitations are examined. Open circuit analysis is investigated, including armature coil testing, PM flux distribution, cogging torque, and PM flux linkage with different DC FEC current density circumstances[6].

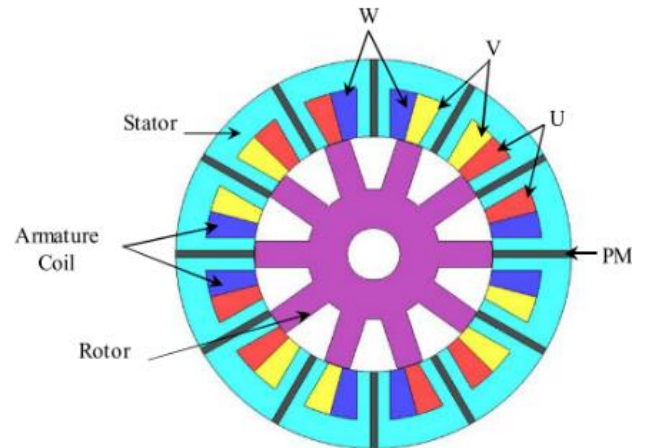


Fig. 1 12S-10P Conventional PMFSM Topologies

Hybrid energised machines use a field coil for secondary excitation in addition to permanent magnets for primary excitation. Permanent magnet machines can operate above base speed by controlling the armature winding current, although their generally poor performance in the flux weakening zone. However, using a negative d-axis current raises the possibility of magnet demagnetisation and increase copper losses. By combining the advantages of PM and wound field, hybrid excitation provides increased flux weakening and efficiency[7].

The 12S-10P HEFSM with modular rotor, improper magnetic coupling between PM and FEC causes flux cancellation when increases the excitation current, which limits electromagnetic torque and weakness of flux strengthening capabilities. In this study, 12S-14P HEFSM with modular rotor, to increase the rotor pole number from 10 to 14, the magnetic interaction between the stator and rotor excitation sources, which results in higher torque performance analysis of 12S-10P and 12S-14P HEFSM with modular rotor such as Flux Linkage Torque vs J_e at various J_a and Torque vs Speed vs Power are investigated by 2D- Finite Element Analysis(2D-FEA). Higher torque achieved by 12S-14P.

In this research, the influence of rotor pole configuration on the electromagnetic performance of Hybrid Excitation Flux Switching Machines (HEFSMs) employing a modular rotor structure is investigated. Although HEFSMs offer high torque density, the standard 12S-10P design often suffers from flux cancellation due to improper magnetic coupling between the permanent magnet and field excitation coil, which restricts torque and flux- strengthening capabilities. Unlike conventional HEFSM topologies using salient-pole rotors, which are highly susceptible to mutual flux cancellation and severe stator yoke saturation, this work presents a unique combination of a hybrid-excited stator and a modular (segmented) rotor structure. Although modular rotors for permanent magnet synchronous motors with a single excited rotor have been studied to reduce magnet volume, their interaction with two excitation sources (permanent magnet + DC) remains largely unexplored. The novelty of this work lies

in systematically establishing how modulation of the rotor pole configuration (in particular, changing the topology from 10P to 14P) with identical stator geometry changes the magnetic flux density distribution in the air gap and eliminates the paths of mutual flux cancellation, which makes it possible to create a model for optimized dual-excited machines with magnetic flux switching. Furthermore, The study reveals that the 12S-14P configuration provides superior magnetic alignment and minimized leakage, achieving a 23.3% increase in average torque and 37.5% increase in output power compared with the conventional 12S-10P design.

2. HEFEM Topology Design Specifications and Limitations

2.1 Machine design

The cross-sectional views of the 12S-10P and 12S-14P HEFSM with modular rotors are shown in Fig.2 (a) and (b) respectively and are listed in Table 1. It is clear from the figure that the 12S-14P HEFSM machine has 14 segmental rotor poles. 6 FE coil slots, 6 armature coil slots, and 12 stator teeth, in contrast to the 12S-10P HEFSM machine has 12 stator teeth, 6 armature coil slots, 6 DC FE coil slots and 10 Modular rotor poles. The three phase armature coils are situated between the DC FE Coil, which is coiled in an anticlockwise polarity. The armature coil and DC FE Coil have non-overlapping windings and individually wound at their respective slots. As a result, the design has significantly shorter end windings and less conductor materials, which can increase machine efficiency.

2.2 Design Simulation

The Japan Research Institute's (JRI) commercial FEA program, JMAG -Designer ver.18.1, is utilized to solve this design. First, JMAG Editor is used to sketch every part of 12S-10P and 12S-14P HEFSM machine, including the rotor, stator, armature coil, and DC FE Coil, slots. JMAG Designer is used to configure the machines, materials, conditions, circuits, and properties. Coil arrangement tests are carried out to determine the position of each armature coil phase and to confirm how the machine operates.

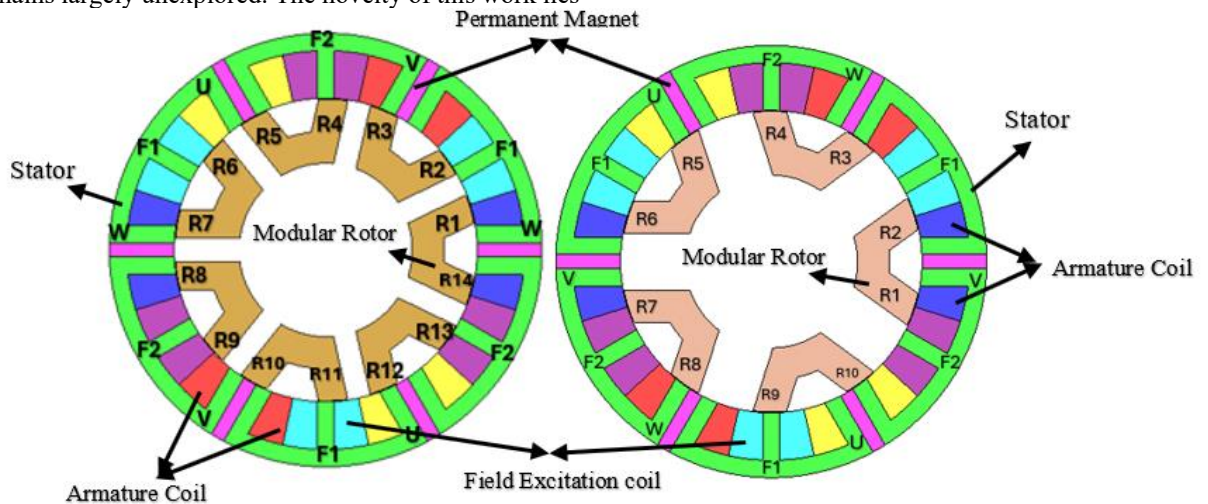


Fig. 2 HEFSM with Modular rotor (a)12S-14P (b)12S-10P

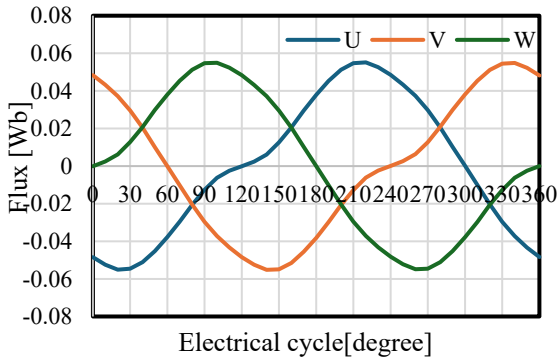
Table 1. Design specifications & limitations OF HEFSM with modular rotor

Parameter	12S-10P	12S-14P
No: of Phase	3	3
Stator poles	12	12
Rotor poles	10	14
Radius of outer stator(mm)	75	75
Radius of Inner stator(mm)	52.5	52.5
Outer radius of rotor(mm)	52.2	52.2
Inner radius of rotor(mm)	41.10	41.10
Stack length	70	70
Air gap	0.3	0.3
Shaft radius(mm)	30	30
Maximum AC density (J_a) A_{rms}/mm^2	30	30
Maximum FE density (J_e) A_{rms}/mm^2	30	30
Number of turns AC	109	109
Number of turns FE	107	107

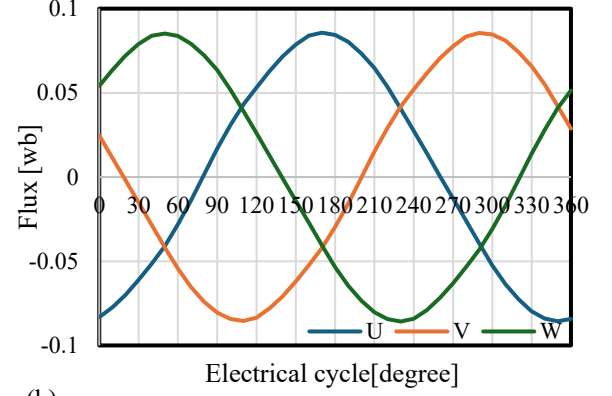
3. Results

3.1 Open circuit analysis

To verify the machine functions, coil arrangement tests are conducted for each armature coil to determine the position of each phase. The system is first fed the DC FE Coil current, and the flux linkage of each armature coil is evaluated. The resulting flux linkage are analysed, and the phases are categorized using the conventional three-phase system. For comparison, Fig. 3(a) and Fig. 3(b) demonstrate the three-phase flux linkage waveforms of the 12S-10P and 12S-14P HEFSM machines, respectively, at FE Coil current density of $30A/mm^2$. It is observed that both designs successfully executed the fundamental principles of three-phase flux linkage. However, compared to the sinusoidal flux coupling in the 12S-14P HEFSM machine, the 12S-10P design produces a large distortion. Furthermore, the 12S-14P waveform appears more symmetrical and sinusoidal, indicating a higher magnetic connection between stator and rotor. Although maintaining a smaller flux linkage magnitude, the 12S-10P arrangement still offers stable machine operation and satisfactory three-phase characteristics.



(a)



(b)

Fig. 3 HEFSM motor with Modular rotor (a) 12S-10P (b) 12S-14P

3.2 Cogging Torque

Cogging torque, also known as detent torque, is investigated using finite element analysis (FEA). The field excitation current density (J_e) remains constant at maximum under no load conditions of $30 A_{rms}/mm^2$. In electric motors, cogging torque can result in vibration and acoustic noise, when its peak-to-peak value exceeds 10% of the average torque during its operation. Furthermore, a high cogging torque will enhance the motor's resonance and ripples, which could damage the motor's structure. Figure 4 illustrates an analysis of the three-phase HEFSM with Modular rotor at no load or open circuit. The initial proposed 12S-10P HEFSM with modular rotor design achieved an appropriate cogging torque about 21Nm peak to peak, as can be seen from the figure. It is shown by the figure that initial proposed 12S-10P HEFSM with modular rotor. However, initially look at graph, the graph shape initially seems unsmooth. However, due to better electromagnetic connection among the stator and rotor poles, the 12S-10P design demonstrates enhanced torque performance. Therefore, the 12S-14P arrangement offers better torque performance while the reduced flux linkage magnitude.

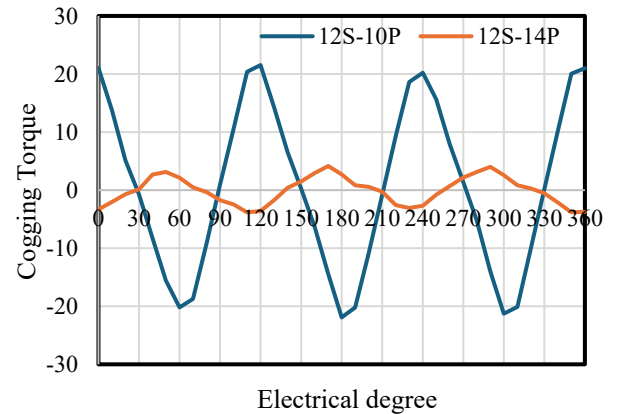


Fig. 4 Cogging torque of HEFSM motor with Modular rotor

3.3 Induced back EMF of 12S-10P and 12S-14P HEFSM with Modular Rotor

The voltage generated by both the Permanent Magnet and FE in a hybrid excitation flux switching machine is represented by the induced voltage at $J_a=0$ and $J_e=30\text{A/mm}^2$. Figure 5 illustrate the fundamental induced voltages for 12S-10P and 12S-14P configuration under open-circuit conditions at a rotor speed of 500r/min. The 12S-14P configuration produces a higher fundamental induced voltage together with a smoother waveform. This improvement is attributed to the increased rotor pole number, which enhances magnetic coupling between the stator and rotor, improves flux linkage and reduces magnetic flux leakage. Furthermore, the 12S-14P HEFSM modular rotor design demonstrates improved electromagnetic performance, thereby enhancing its suitability for electric vehicles applications.

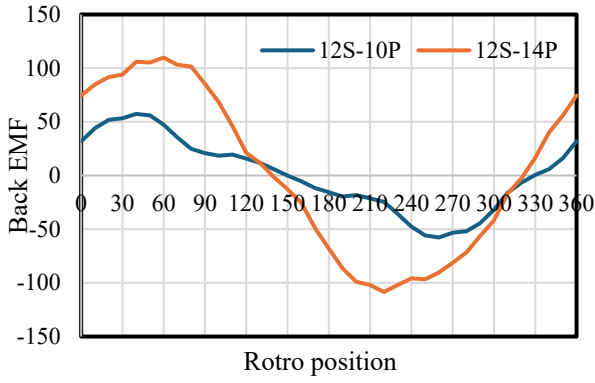
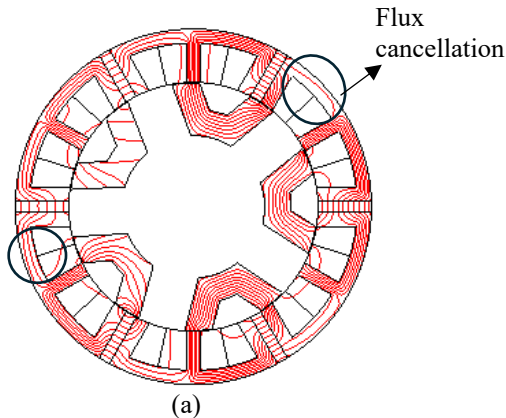


Fig. 5 Induced back EMF of HEFSM with Modular Rotor

3.4 Flux Line 12S-10P and 12S-14P HEFSM

Figure 6(a) and 6(b) illustrate the flux lines for HEFSM machines. The 12S-14P design is generally considered to be better as the larger pole number induces a shorter magnetic pole pitch, which enhances the interaction between the rotor saliency and the stator excitation flux. Changing the number of rotor poles from 10 to 14 reduces the mechanical pole pitch. The smaller pitch allows each isolated modular segment to connect the stator excitation teeth at a smaller spatial distance, reducing the overall circuit resistance and concentrating the magnetic field within the stator teeth. In this case, electromagnetic torque capability is increased as the magnetic field becomes more concentrated around the stator teeth.



After optimization improvement to the cancellation and saturation. On other contrast, in HEFSM machines, the 12S-10P configuration results in smoother and more distributed flux path, which reduces torque ripple and harmonic distortion but usually in lower density and weaker flux-switching efficiency.

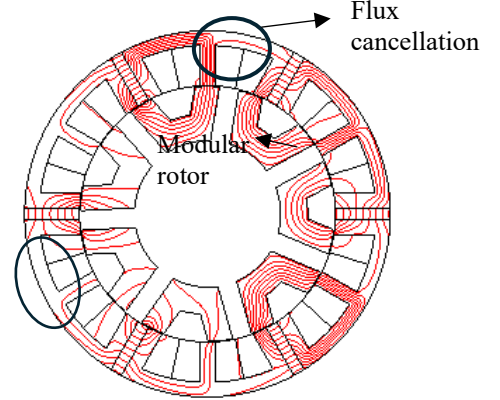


Fig. 6 Flux line at zero position (a) 12S-10P (b) 12S-14P

3.5 Flux Distribution 12S-10P and 12S-14P HEFSM

According to the findings, shown in Figure 7(a) the 12S-10P topology has a larger peak flux density of approximately 2.66T, which suggests that the stator teeth and yoke regions have higher flux densities. The electromagnetic interaction between the stator and rotor is improved by this enhanced flux concentration, which raises the average torque production. However, certain areas also exhibit limited magnetic saturation. The 12S-10P arrangement, on the other hand, exhibits a more uniform flux distribution with a lower peak flux density of about 2.25T, which results in lower core losses and less magnetic saturation. The 12S-14P arrangement shown in Figure 7(b) delivers better torque performance because of its greater pole count and stronger air-gap flux interaction, even if the 12S-10P structure offers better magnetic consumption.

3.6 Torque vs J_e at various J_a

At the short circuit, characteristics are explained in Figure 8(a) 12S-10P. The torque characteristics of initial 12S-10P HEFSM and 12S-14P HEFSM have been observed at different magnetic armature current densities (J_a) while the field current density (J_e) remains constant at $30\text{A}_{\text{rms}}/\text{mm}^2$, as shown in figure, initial 12S-10P HEFSM achieved value approximately 30Nm at a maximum current density (J_e) at $30\text{A}_{\text{rms}}/\text{mm}^2$. The FEC and PM fluxes are in opposing directions, which results in a very small increment. Due to this reason, the fluxes produced both sources cancellation to each other instead of combining as the field current density increases. On other hand, Figure 8(b) depicts torque vs FEC densities J_e for various armature current densities J_a with modular rotor.

Furthermore, the torque gradually increases up to a maximum 36.99 Nm as the current density (J_e) is raised to $30\text{A}_{\text{rms}}/\text{mm}^2$. The torque graph's growth and the direct proportionality between torque and (J_e) show the magnetic flux of FEC is properly linked to the magnetic flux of PM and has enhanced with respect to (J_e). Additionally, the 12S-14P configuration

achieved approximately 23.33% torque greater than 12S-10P configuration due to the reason its 14-pole modular rotor provides a more effective magnetic flux path and improved stator the rotor. Physically, this flux cancellation in the 12S-

10P topology occurs due to poor magnetic coupling and core saturation under high excitation current, which limits its flux-strengthening capability.

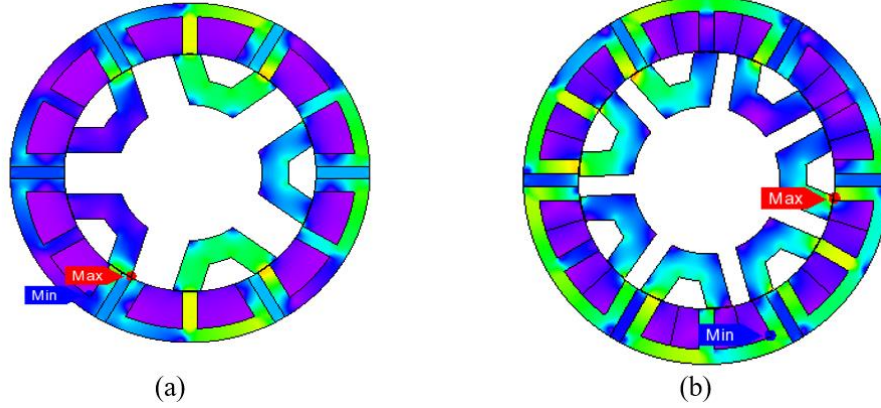


Fig. 7 Flux Distribution (a) 12S-10P (b) 12S-14P

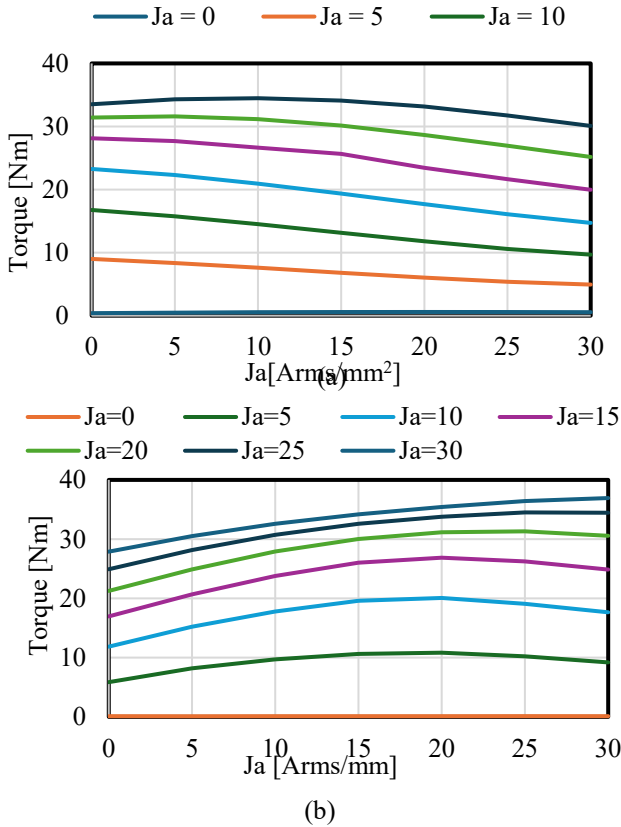


Fig. 8 Torque vs Je at various Ja (a) 12S-10P HEFSM (b)12S-14P HEFSM modular rotor

Conversely, the 12S-14P topology utilizes its 14-pole modular rotor structure to achieves better stator to rotor alignment, which minimizes flux leakage and allows the torque to rise linearly up to 36.99 approximately 37Nm.

3.7 Torque vs speed vs power

The torque and speed data can be manipulated to calculate the output power. Equation (1) defines the rotational power (P) on a given axis as the product of torque (τ) and angular velocity (ω). Equations (2) and (3), were then used to convert the measured rotational speed into angular velocity and express the output power in kilowatts(kW).

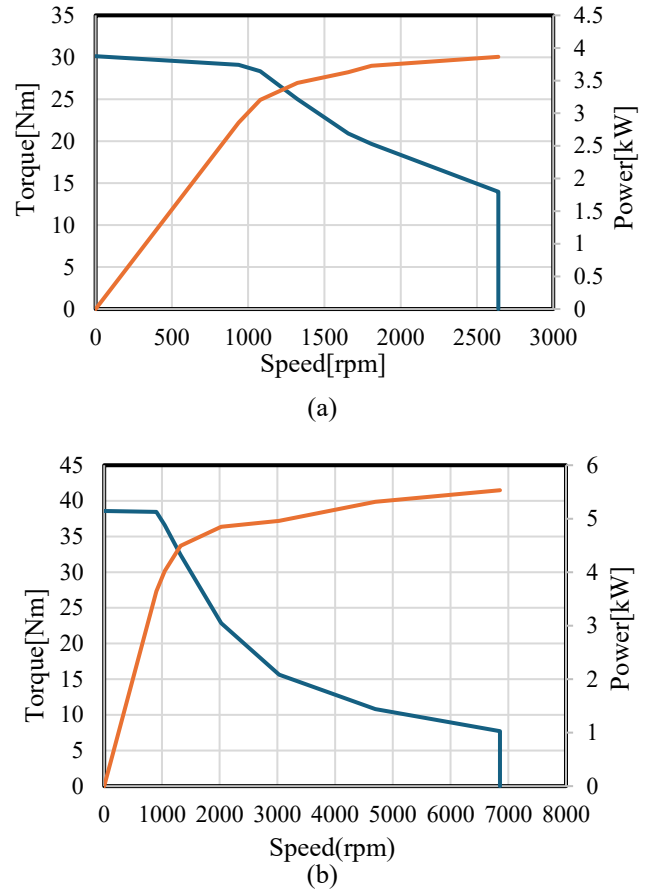


Fig. 9 Torque and Power Vs Speed (a)12S-10PHEFSM and (b) 12S-14P HEFSM

$$\begin{aligned} P &= \tau \omega & (1) \\ \omega &= 2\pi S/60 & (2) \\ P &= \tau (2\pi S/60) & (3) \end{aligned}$$

Where τ is torque in Newton meter (Nm), P is power in kilowatt (Kw), and S is speed in revolution per minute (r/min).

Figure: 9(a) illustration the torque -speed and power-speed characteristics of the 12S-10P HEFSM. At low speeds, the machine generates an initial torque of approximately 30Nm which it maintained up to around 1000 rpm. As the speed exceed this threshold, the torque gradually decreases as speed increases, dropping to 14 Nm at the maximum operating speed of 2600 rpm. However, the output power rises steadily with speed, reaching a maximum value of around 4Kw. These findings indicate the 12S-10P HEFSM can operates continuously at low speeds. Figure 9(b) shows the torque -speed and power-speed characteristics of the 12S-14P HEFSM with modular rotor. Compared to the 12S-10P configuration, this machine exhibits a significantly higher initial torque of about 39 Nm. The torque gradually drops with increasing speed, reaching around 8 Nm at the maximum speed of 7000 rpm. Despite the drop in torque, the output power keeps increasing and reaching a maximum value about 5.5 Kw. This is because the increase in speed is greater than the torque reduction, as define in equation (1). This improved performance is mainly attributed to the higher number of rotor poles in the 12s-14P modular rotor, which enhances stator to rotor magnetic coupling, improves distribution, and reduces flux leakage. These factors contribute to higher torque generation and allow the machine to maintain operation over a wider speed range.

4. Conclusion

In this research, a comprehensive 2D finite element analysis was conducted to evaluate the electromagnetic performance of 12S-10P and 12S-14P HEFSM configurations utilizing modular rotor technology. The findings indicates that the 12S-14P topology, exhibiting a 23.3% higher torque and a 37.5% increase output power. Furthermore, the 12S-14P configuration provides a wider operational speed range, which is essential for traction applications. These performance

improvements are mainly more efficient magnetic flux path, minimized leakage flux, and improved stator and rotor components. Consequently, challenging requirements for high torque density and extended constant power speed range in modern electric vehicles, the 12S-14P modular rotor topology is identified as the most suitable choice for these electric vehicle drive systems. Due to its superior electromagnetic characteristics.

5 Acknowledgements

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