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INVESTIGATIVE STUDY OF A NOVEL PERMANENT MAGNET FLUX SWITCHING MACHINE EMPLOYING ALTERNATE CIRCUMFERENTIAL AND RADIAL PERMANENT MAGNET

M. Jenal and E. Sulaiman
Research Center for Applied Electromagnetics (EMC), Universiti Tun Hussein Onn Malaysia (UTHM), Parit Raja, Batu Pahat, Johor, Malaysia
E-Mail: mahyuzie@uthm.edu.my

ABSTRACT

Flux switching machines (FSMs) which employing all flux sources in the stator body have been lately developed all over the world due to their undisputed advantage of single piece robust rotor structure suitable for high speed applications. Furthermore, they can be broken down into three clusters namely permanent magnet (PM) FSM, field excitation (FE) FSM, and hybrid excitation (HE) FSM. Both PMFSM and FEFSM has only permanent magnet (PM) and field excitation coil (FEC), respectively as their main flux sources, while HEFSM unites both PM and FECs. Among these, PMFSM presents benefits of low cost, simple construction and FEC-free winding that gains low copper losses- suitable for various performances. In this paper, design study and investigative analysis of a new alternate circumferential and radial magnetization flux (AlCiRaf) of 12S-10P PMFSM with salient rotor (SalR) is presented. The proposed design is then compared to the conventional PMFSM and segmental rotor PMFSM (SegR PMFSM). Initially, design procedures of the AlCiRaF PMFSM including topology development, materials and conditions setting and properties setting are described. Subsequently, coil arrangement tests are examined to validate machine operating principle and position of each armature coil phase. Moreover, the flux interaction between PM and armature coil, induced voltage, cogging torque at various rotor position, initial output power and torque performances are also investigated using 2D-FEA . The simulated result shows that the proposed AlCiRaF PMFSM achieves its highest output power performances of 8.1kW at maximum Ja=30Arms/mm^2 significantly 15.2% higher than that of conventional PMFSM and 12.9% better than SegR PMFSM in terms of initial output torque.

Keywords: circumferential PM, finite-element analysis (FEA), permanent magnet flux switching motor, radial PM.

INTRODUCTION

Permanent Magnet Flux Switching Machine (PMFSM) was first introduced as a single-phase alternator by (Rauch and Johnson, 1955) while the three-phase version was first reported in 1997 (Hoang *et al.* 1997). Undoubtedly, PMFSM machine inherits numerous advantages from the conventional PM brushless machines where it employs a conventional doubly salient structure, which made up of a simple passive and robust rotor but a rather complicated stator. The mechanically rugged rotor is the similar as that of a switched reluctance machine which results in fast dynamic response. Since all the excitation sources such as armature windings and PMs are housed in the salient-pole stator, majority of the heat generated by the losses in those active components during machine operation can be effectively dissipated to prevent the active components from being locally overheated, so that good thermal management such as liquid cooling can be easily installed (Thomas *et al.* 2014). Moreover, PMFSM machine also reveals rather good flux weakening capability.

The purpose of this paper is to develop a new class of Permanent Magnet Flux Switching Machine (PMFSM) using alternate circumferential and radial magnetization flux of permanent magnet in the stator with salient rotor pole so that the resulting machine not only inherit the merits of high torque density, high power density, and high reliability but also can effectively enhance the PMs usage efficiency. In further study, the conventional PMFSM, segmental rotor PMFSM (SegR PMFSM) and alternate circumferential and radial flux PMFSM (AlCiRaf PMFSM) machine topologies are investigated and their specifications are listed in detail for the comparison to be made. Finally, three topologies' corresponding electromagnetic performances, including magnetic field distribution, PM flux linkage, back EMF and torque and power performances are analyzed using finite element method (FEM).

AlCiRaf PMFSM

Machine topology

AlCiraf PMFSM is a kind of machine which solely utilize PM as magnetizing flux excitation. The goal behind using only one excitation field source is to optimize the capability of PM housed in the stator compartment. Besides, PM excitation offers an additional degree of freedom and improves energy efficiency of the traction motors which have been researched extensively over many years.

The development of AlCiRaF begins with evolution of conventional 12S-10P three phase PMFSM as shown in Figure-1(a), where the stator core consists of modular U-shaped laminated segments arranged next to each other with PMs slotted in between them. For flux switching operation principles, the PM magnetization

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polarity is being reversed from one magnet to another (Hoang *et al.* 1997). The stator armature winding consists of concentrated coils and each coil being wound around the stator tooth formed by two adjacent laminated segments and a magnet. Similarly, all the armature phases employ the similar winding configuration and embedded in the stator core to form 12 winding slots. In this revision, the salient pole rotor is similar to that of switch reluctant machines (SRMs), which is more robust and suitable for high speed applications. The main drawbacks of these types of motors are the magnetic flux leakage at the outmost tip of PM which limits the distribution of flux and also separated stator structure from one segment to another - that is hardly to be fabricated and assembled.

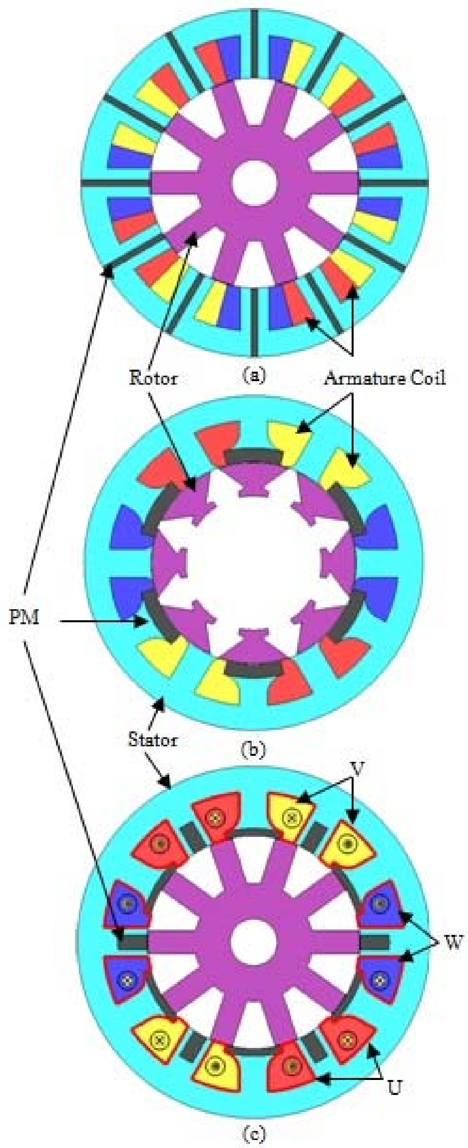

Figure-1. PMFSM topologies. (a) Typical 12S-10P PMFSM. (b) 12S-8P PMFSM with segmental rotor. (c) 12S-10P alternate circumferential and radial magnetization flux PMFSM.

(Zulu *et al.* 2012) have proposed another class of three-phase 12S-8P PMFSM employing segmental rotor type of structure as shown in Figure-1(b). Excitation sources such as armature coils and rare earth permanent magnets are located alternately on the stator teeth. The purpose of the proposed configuration is to generate the necessary unipolar excitation in the field teeth utilising PMs which act in the radial direction. However, in terms of high speed applications, this kind of motor is merely irrelevant due to its dubious rotor mechanical strength and furthermore, a lot of effort to be put pertaining to manufacturing process. A new structure of 12S-10P AlCiraF PMFSM is designed by employing 2 different shapes of PM in all stator poles as depicted in Figure-1(c). The first type of PM is configured most likely similar to the design proposed by (Zulu *et al.* 2012) where 6 PMs with radial magnetization flux are located at the stator pole tips alternately while the second PM structure is embedded inside the remaining 6 stator poles. These 6 PMs are more or less identical to the conventional type of PMFSM with circumferential magnetization flux direction but much shorter in size. The main objective is to provide uniform flux path throughout the entire stator core without any issue of leakage occurrence - the drawback suffered by the conventional PMFSM. In addition, the salient rotor pole configuration is being introduced in order to secure robust structure while rotating at high speed. Consequently, the proposed stator and rotor configurations would assure the simple and effortless manufacturing process.

Design specifications and limitations

The design specifications and limitations of the proposed AlCiRaf PMFSM with salient rotor pole are listed in Table-1 together with the typical and segmental rotor PMFSM. Pertaining to Figure-1(c), it is understandable that the designed machine is portraying 12 stator teeth, 6 armature coil slots, 10 salient rotor poles and 12 pieces of PMs in which consist of alternate radial and circumferences flux direction. Since the volume of PM is limited to maximum 0.5kg, the final machine is expected to have less weight but high performances in terms of machine efficiency. In addition, the material type used is Neomax35AH which having coercive force at 20°C and residual flux density of 932kA/m and 1.2T, while for the rotor and stator part made up of electrical steel 35H210. The fundamental rotor structure is mechanically robust to spin at high speed because it consists of only laminated electromagnetic sheets. Supposing that only a water-jacket system is applied as the cooling system of the machine, a value of $30A_{rms}/mm^2$ is set to be the limit of the armature current density.

The affiliation between rotor pole number and stator slot for the three phase structure are used to find the achievable numbers of slot and pole which can be expressed as:

$$n_r = n_s\left(1 \pm \frac{k}{2q}\right) \tag{1}$$

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Table-1. design specifications and limitations.

Parameters	Conventional PMFSM	SegR PMFSM	AlCiRaF PMFSM
No of phase	3	3	3
No of stator pole	12	12	12
No of rotor pole	10	8	10
Outside diameter of stator	150 mm	150 mm	150 mm
Width of stator tooth	12.5 mm	12.5 mm	12.5 mm
Width of rotor tooth	10 mm	40°	10 mm
Back iron depth of stator	11 mm	11 mm	11 mm
Motor stack length	70 mm	70 mm	70 mm
Length of air gap	0.3mm	0.3mm	0.3mm
Diameter of rotor	89.7 mm	89.7 mm	89.7 mm
No. of turns per armature coil slot	44	44	44
PM volume	0.5 kg	0.5 kg	0.5 kg

where n_r is the number of rotor poles, n_s is the number of stator slot , q is the number of phases and k is the natural entity. In this study, 12 and 10 has been selected as the number of stator and rotor slot correspondingly. In regards to the proposed machine, the motor rotation through $1/n_r$ of a revolution, the flux linkage of armature has one periodic cycle and thus, the frequency of back-emf induced in the armature coil is n_r times of the mechanical rotational frequency. In general, the mechanical rotation frequency, f_m and the electrical frequency, f_e for the designed motor can be uttered as:

$$f_e = n_r f_m \tag{2}$$

f_e, n_r and f_m is the is the electrical frequency, rotor pole number and mechanical rotation frequency, respectively. The number of turns of armature coil is defined from equation 3 while the filling factor of the motor, α is set at 0.5.

$$N_a = \frac{J_a \alpha S_a}{I_a} \tag{3}$$

where *N*, *J*, α, *S* and *I* are number of turns, current density, filling factor, slot area and input current, respectively. Furthermore, to ascertain no flux leakage and equal distribution of flux flow from stator to rotor, the rotor teeth width of the proposed machine is defined as:

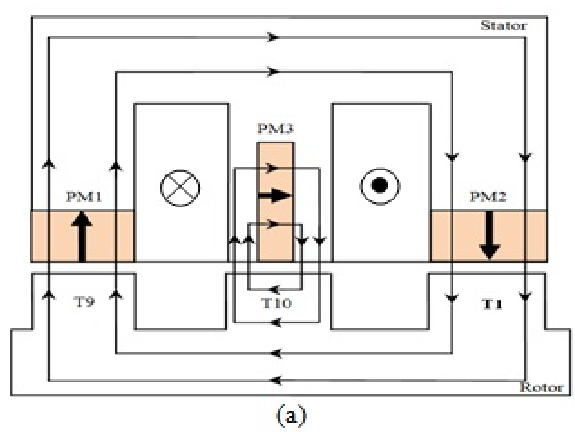
$$\Sigma \text{ Stator Tooth Width} = \Sigma \text{ Rotor Tooth Width} \tag{4}$$

The operating principle of the AlRaCif motor with salient rotor is depicted in Figure-2 where PM1, PM2 and PM3 are the permanent magnet, T1, T2 and T3 are the rotor pole tooth while armature fluxes are represented by cross and dot symbols respectively. Apparently, the fluxes of PM circulating between stator and rotor segments generate a complete flux cycle at three typical rotor positions under one electric cycle. The term ‘‘flux switching’’ is used to explain a machine in which the stator tooth flux switches polarity following the motion of a salient pole rotor. The description of this orientation is demonstrated in Figure-2. In Figure-2(a), (1) circumferential fluxes of PM1 flow upward from rotor to stator and travel along the stator before return back to rotor through PM2 while (2) PM3 supplies radial fluxes from left to the right of stator tooth, in between of armature coils. Under this condition, it is obvious that rotor tooth T1 receives fluxes from stator. Meanwhile, in Figure-2(b), as the rotor moves to the left side which approximately half of electric cycles, rotor tooth T1 starts to circulate fluxes from PM3 within the small region of rotor tooth tip and bring them back to stator to complete one flux cycle. Finally, Figure-2(c) depicts the condition where rotor pole T1 is moved to face PM1 position and hence passing fluxes upward to stator. Throughout this process, the fluxes within T1 has changed their direction from downward to upward at three different cycles.

OPEN CIRCUIT ANALYSIS

a) Armature coil test

In order to validate the three phase operating principle of each studied PMFSM and to determine the position of armature coil phase individually, coil arrangement tests are carried out in each armature coil where all armature coils are wounded in counter-clockwise direction. The resulting flux linkages are evaluated and compared where the armature coils are classified according to conventional three phase system. Figure-3(a), 3(b) and 3(c) demonstrate the three phase flux linkage of 12S-10P conventional PMFSM, 12S-8P SegR PMFSM and 12S-10P AlCiRaf PMFSM respectively as for comparison. It is obvious that all the examined machines are achieving a successfull fundamental principles of the three phase flux linkage. Nevertheless, the proposed AlCiRaf PMFSM exhibits merely swelled waveform as compared to the rest of machine topologies thus affecting the performances of its amplitude as illustrates in Figure-4. The comparison signifies that conventional PMFSM contributes the most highest flux amplitude approximately marked at 95.4mWb followed by SegR PMFSM and AlCiRaF PMFSM which only 16mWb maximum has been achieved.



(a)

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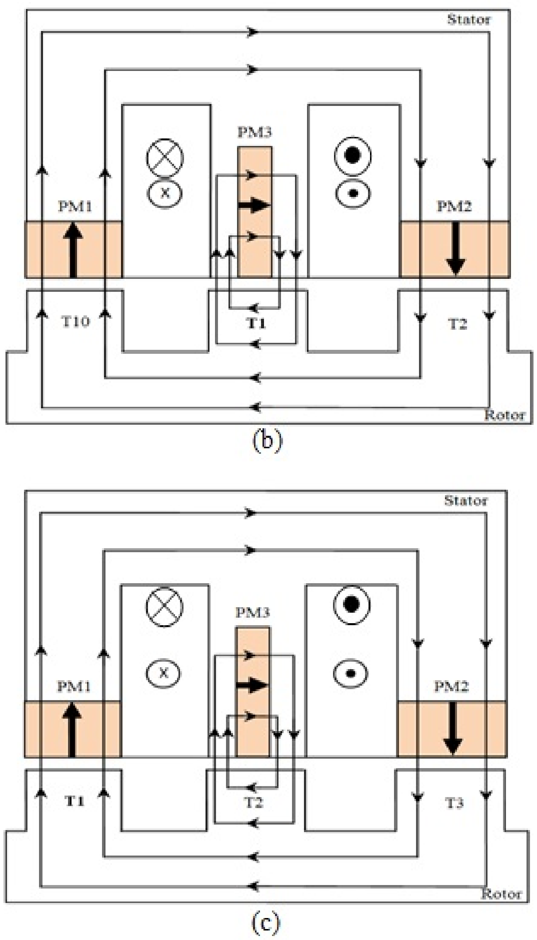
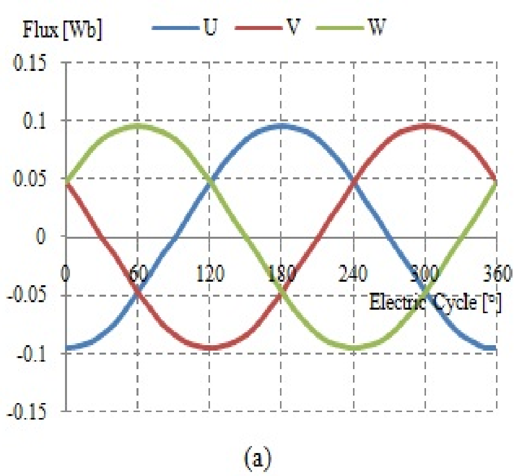
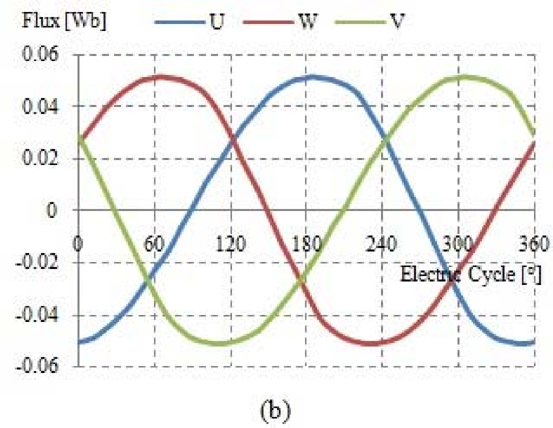


Figure-2. Principle operation of the proposed AlCiRaF 12S-10P PMFSM. (a) rotor tooth T1 receives flux from stator via PM2. (b) flux from stator via PM3 to rotor toot h T1 fed back to stator. (c) flux from rotor tooth T1 leaves rotor to stator via PM1.





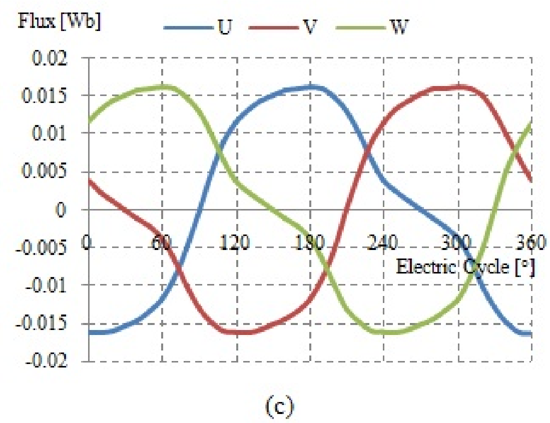


Figure-3. Three-phase flux linkage. (a) Conventional 12S-10P PMFSM. (b) SegR 12S-8P PMFSM. (c) AlCiRaF 12S-10P PMFSM.

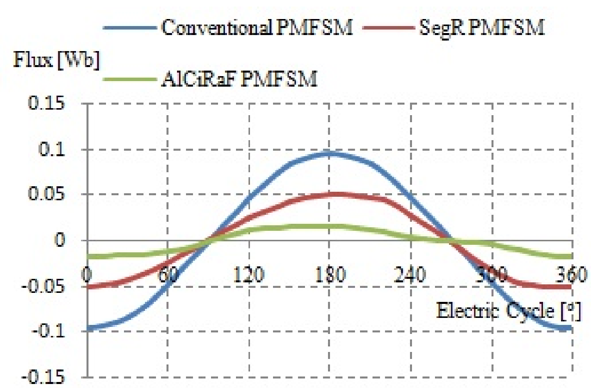


Figure-4. U flux comparison.

b) PM flux path

The analysis of flux path and distribution are examined under open circuit condition where all the three machine topologies are compared at zero degree rotor position as illustrated in Figure-5(a), 5(b) and 5(c) respectively. Apparently, the most uniform and thorough distribution of flux lines surfaced from the proposed AlCiRaf PMFSM as the flux flows from stator to rotor and return through adjacent rotor teeth result in a complete flux cycles of PM. The maximum flux density at this point is read at 2.5T. Hence, this proposed topology is supposedly to produce a better flux linkage performances after certain design reconsiderations. Meanwhile, for 12S-10P conventional and 12S-8P SegR PMFSM, both topologies has induced less flux lines orientation especially in stator part.

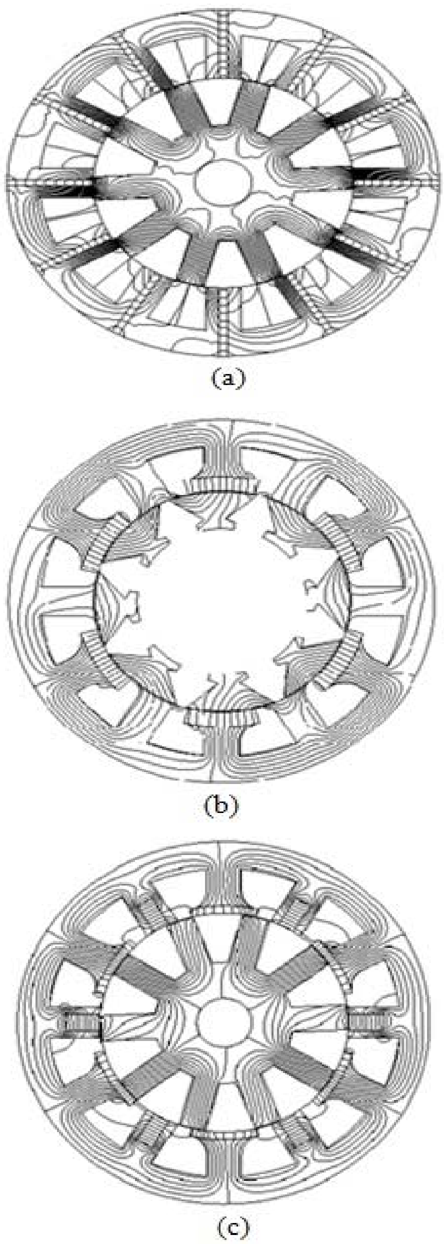


Figure-5. Flux lines. (a) Conventional 12S-10P PMFSM. (b) SegR 12S-8P PMFSM. (c) AlCiRaF 12S-10P PMFSM.

c) Induced voltage

By rotating the rotor at the rated speed of 500r/min, the no-load back electromotive force (emf) of the 3 PMFSM configurations with different motor structures are illustrated in Figure-6. It is well noticeable that the 12S-10P conventional PMFSM results in the highest amplitude of approximately 92.9V whereas the proposed 12S-10P AlCiRaF PMFSM computes the least result which is only peaked at 24V. Nevertheless, all the generated waveforms exhibit a favorable sinusoidal feature with most distorted one come from the proposed topology itself.

d) Cogging torque analysis

Figure-7 illustrates the comparison of cogging torque over the examined PMFSMs. Conventional and SegR PMFSM design has displayed the most distorted and severe ripples waveform but lower peak to peak cogging torque compared with the proposed AlCiRaf PMFSM. Nevertheless, the high cogging torque drawback is expectedly to be decreased after further design refinement and optimization.

e) Torque and power analysis

In accordance to Figure-8 and Figure-9, the output torque and power of the conventional, SegR and AlCiRaF PMFSM are analyzed under the same armature current density up to maximum J_a of 30Arms/mm^2, respectively. Significantly, the conventional PMFSM has produced the highest torque among the examined machine topologies which gauged at approximately 44.2Nm which is 42.4% higher than the proposed AlCiRaF PMFSM while SegR PMFSM generates the lowest torque at 22.62Nm. Meanwhile, as for power simulation, the results obtained in Figure-9 shows different observation where AlCiRaF PMFSM emerges as the highest machine capability instead of conventional type when it peaks at 8.1kW at maximum Ja of 30Arms/mm^2. On the other hand, higher losses are expected to occur in conventional PMFSM as the current density was injected above 10Arms/mm^2, the resulting power decreases from 9.05kW to only 7.04kW whenever maximum Ja is reached.

CONCLUSIONS

In this paper, design study and investigation of the proposed alternate circumferential and radial PM flux of 12S-10P PMFSM with salient rotor pole has been examined and compared with the conventional and SegR PMFSM. The proposed machine which made up of very straightforward configuration as well as no DC FEC coil can be described as having very low copper losses and effortless in manufacturing process. The procedure to design the AlCiRaF PMFSM has been clearly clarified. The armature coil arrangement has been tested to validate each armature coil phase and to testify the operating principle of the proposed machine. Moreover, the performances of PMFSMs namely flux capability, initial power and torque have been briefly investigated. Consequently, based on the overall analysis, it is

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suggested that the proposed AlCiRaF PMFSM is computing better performances with 25.54Nm output torque rather than SegR PMFSM and promising high possibility to substitute the conventional PMFSM after further design refinements and optimizations thus offering a convenience applications with various performances.

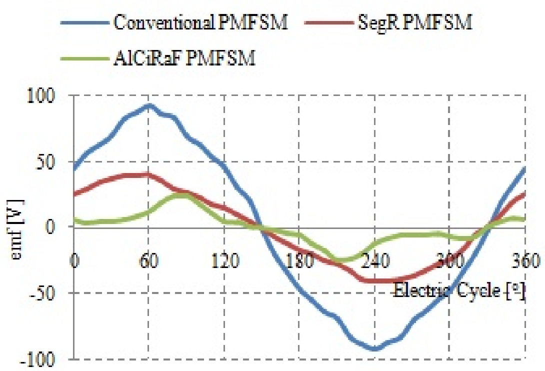

Figure-6. Back-emf comparison at speed of 500 r/min.

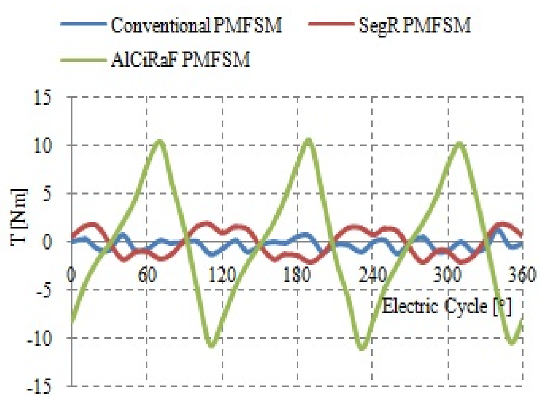

Figure-7. Cogging torque comparison.

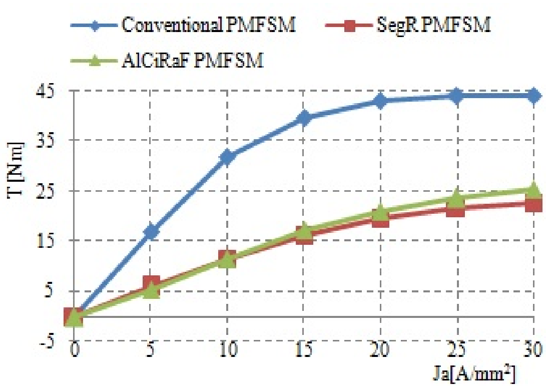

Figure-8. Comparison of output torque vs Ja.

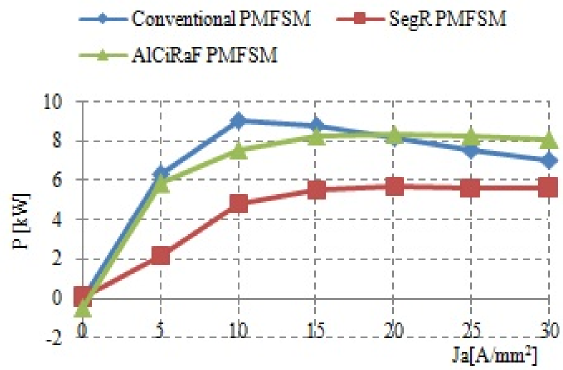

Figure-9. Comparison of output power vs Ja.

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