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Overview of Novel Magnetically Geared Machines with Partitioned Stators

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Abstract: This paper overviews recent development of a new class of magnetically geared machine topologies, i.e. partitioned stator (PS) machines. They are developed from magnetic gears and magnetically geared machines, as well as stator permanent magnet (PM) machines (switched flux, flux reversal and doubly saliency PM), wound field, or hybrid PM and field winding machines. Based on the operating principle, i.e. magnetic gearing effect/airgap field modulation and flux switching by the salient rotor iron poles, various PS machine topologies are developed. All have features of two stators, two airgaps, and one segmented ferromagnetic rotor identical to a magnetic gear's modulating rotor. Their inherent relationships are revealed, while their electromagnetic performance is compared. Both PM and wound field PS machines are discussed, together with hybrid excited PS PM machines and Vernier machines. It shows that all of these PS machines share the same torque production principle and the differences are mainly in PM configurations and relative positions of two stators. All PS machines have higher torque density per copper loss compared with their counterparts of single stator machines. PS switched flux PM machines can produce the highest torque density per copper loss.

I. *Introduction*

Due to high torque density and efficiency, permanent magnet (PM) machines have been used for many applications, ranging from domestic appliance, industrial automation, electric vehicle, to wind power generation etc.

Various PM machine topologies have been developed and many new and novel PM machine topologies are still emerging [1]-[5]. A particular distinction in various brushless PM machines is the positioning of the magnets in relation to the windings whether stationary or rotating [3]-[5]. This leads to two main forms of brushless PM machines: the first is the rotor PM machine, which is more conventional, with rotating PMs and wound stator, and the second is the stator PM machine with stationary PMs and wound stator, together with a form of salient rotor. This second stator PM arrangement is relatively new and shown to be capable of achieving torque density comparable to the more conventional rotor PM machines [3]-[5].

In the conventional rotor PM radial-field machines, the most popular stator winding configurations include overlapping end-winding, concentrated or distributed types, or non-overlapping end-winding, concentrated tooth-wound types, while the rotors may be equipped with surface-mounted or interior mounted PMs (SPMs or IPMs).

Switched flux, flux reversal, and doubly saliency PM machines fall into a family of stator PM machines [3]-[5]. These machines operate on the principle of flux switching that the back EMFs are generated from the variation of PM flux coupled with concentrated coils by virtue of a salient pole rotor and switching of magnetic flux paths when the rotor rotates. For these stator PM machines, the main difference is the location of PMs in the stator, being sandwiched between the teeth in switched flux PM (SFPM) machines, on the surface of stator tooth in flux reversal PM (FRPM) machines, and at the yoke in doubly saliency PM (DSPM) machines.

On the other hand, a magnetic gear [6]-[10] providing the required torque transmission magnetically is initially developed as a substitute to conventional mechanical gears, providing advantages over their mechanical counterparts such as magnetic isolation and removing the necessity for lubrication. Thus, opportunities rise for utilising the synergies of both brushless PM machines and magnetic gears, resulting in many integrated magnetically geared machines being developed and investigated from many perspectives [11]-[23].

This paper is based on the keynote speech which the author presented at the 2014 International Conference on Electrical Machines and Systems (ICEMS2014), and overviews recent development of a new class of magnetically geared machine topologies, i.e. partitioned stator (PS) machines [24][25], which are developed from magnetic gears and magnetically geared machines, as well as stator PM machines. The PS machines uniquely unify the synergies of magnetic gears and stator PM machines, and maintain the operating principles of flux switching and magnetic gearing.

The paper is organised as follows. Section II reviews the magnetic gears and magnetically geared machines. Section III describes the operating principle and magnetic gearing effect in PS machines, while Section IV reports various PS machine topologies. Section V discusses the relationships between various PS machines, together with a comparison of their electromagnetic performance. This is followed by introduction of hybrid excited PS PM machines in Section VI. The conclusions are given in section VII, with other potential PS machines also highlighted.

II. *Magnetic Gears and Magnetically Geared Machines*

A. *Magnetic Gears [6]-[10]*

A magnetic gear usually consists of three parts: a high pole field excitation element, a low pole field excitation element, and a ferromagnetic iron pole-piece ring, as proposed in [6]. Fig. 1 shows two types of magnetic gears in which the outer and inner elements are made of PMs [6]-[10]. Theoretically, all three parts may be rotating [11] although it is more common to fix one part, either one PM element or the iron pole-piece ring. The iron pieces modulate the airgap field produced by one element to make it have the same pole number and rotating speed to those of the airgap field produced by another element so as to produce constant torque [7]-[9]. Hence, an inherent relationship between the pole-pair numbers of inner and outer PM elements exists, as shown in Table 1 [7][8].

Table 1 Gear ratios for a magnetic gear

$n_i = p_1 + p_2$		
$\omega_i = 0$	$\omega_1 = 0$	$\omega_2 = 0$
$G_r = -\frac{p_1}{p_2}$	$G_r = \frac{n_i}{p_2}$	$G_r = \frac{n_i}{p_1}$

Note: G_r is the gear ratio, n_i is the number of iron pieces, p_1 is the low speed element pole pairs, p_2 is the high speed element pole pairs, ω_i is the ferromagnetic pieces' angular velocity, ω_1 is the low speed element's angular velocity, ω_2 is the high speed element's angular velocity. The negative sign indicates opposite rotating directions.

By way of example, Fig.1(a1) shows the magnetic gear with 2 rotating inner PM pole pairs, 18 stationary modulating iron poles and 16 anti-rotating outer PM pole pairs, while Fig.1(b1) shows that with 6 stationary inner PM pole pairs, 10 rotating modulating iron poles and 4 rotating outer PM pole pairs. To illustrate the generality, the inner PM field elements in these two magnetic gears have used surface-mounted PMs and interior PMs, respectively. Indeed, various PM element topologies similar to the rotor of conventional PM machines [1] can be employed.

Due to airgap field modulation, there exists a magnetic gearing effect. It can be defined by a gear ratio which may be utilised to amplify the torque production compared with that of a conventional electrical machine in which both stator and rotor produce the fields with the same pole pair numbers. Hence, a magnetic gear can have very high torque density, e.g. >100kNm/m^3 [7][8]. In addition, compared with a mechanical gear, a magnetic gear has inherent benefits, such as no need of lubrication and overload protection.

B. Magnetically Geared Machines [12]-[19]

The magnetic gears shown in Fig. 1 [6][7] use a large amount of PM materials which are expensive if rare-earth PMs are employed to produce high torque density. Further, it is simply a passive magnetic gear without electrical output or input ports. It is possible to replace a PM rotor by employing multi-phase sinusoidally excited windings to produce a rotating magnetic field [17]-[19], as those in the stators of induction machines and synchronous machines although the torque density may be sacrificed due to the replacement of PMs by coil excitation. Therefore, from the magnetic gearing principle, many magnetically geared machine topologies can be developed to convert electrical energy to mechanical energy or vice versa.

By way of example, as developed from Fig.1(a1), Fig.1(a2) has a stationary modulating iron piece ring which is placed between a 3-phase wound stator and a higher pole number PM rotor [17]-[19]. In this case, both the modulating iron piece ring and the wound stator are stationary and there is no relative mechanical motion between them. Hence, it is possible to remove the airgap between them so that only a single mechanical airgap remains while the stator has a multi-tooth structure. Consequently, the resulting machine is identical to a Vernier machine [26]-[38], Fig.1(a3). A Vernier PM machine [26] has been noted for its magnetic gearing effect [27][29] and further connected with the magnetic gearing principle from the magnetically geared machine or flux modulated machine [27]-[38].

Similarly, Fig.1(b2) can be derived from Fig.1(b1), which has a stationary inner PM rotor, a rotating modulating iron piece ring, but now the rotating outer PM pole rotor has been replaced by a stationary 3-phase wound stator [24][25]. In this case, both outer and inner elements are stationary and separated by a rotating modulating iron piece ring. Consequently, a PS-SFPM machine can be obtained [24][25], Fig.1(b2). As will be shown later in this paper, it is possible to combine two stationary elements into a single stator. Thus, only a single mechanical airgap remains, a single stator having both armature windings and PMs, while the rotor becomes a salient pole rotor, identical to that of a switched reluctance machine (SRM). The resulting machine is a SFPM machine [39]-[40], Fig.1(b3).

From above description and evolution, all these machines can be termed as magnetically geared or flux modulated machines [17]-[19], [24][25], [39]-[45]. However, it is clearly revealed graphically in Fig.1, as author presented at the keynote speech of ICEMS2014 for the first time, the inherent relationships amongst the magnetic gears, the PS-PM machines, the Vernier machines and the SFPM machines. These machines share the same torque production principle, i.e. magnetic gearing effect and airgap field modulation by the salient pole iron piece ring.

In contrast, different from the magnetically geared machines which are developed electromagnetically as described above, the magnetically geared machines can also be derived from the simple mechanical integration of a magnetic gear into the electrical machine [12]-[16]. By way of example, Fig.2a [12][13][14] shows a magnetically geared machine with 6 stator teeth, 2 inner rotating PM pole pairs, 16 stationary modulating iron poles and 18 rotating outer PM pole pairs. This arrangement includes a wound stator, a stationary modulating ring with PM rotors at both sides of the modulating ring. As can be seen, there are three airgaps and the machine mechanical structure is very complicated, which prevents it from practical applications.

Fig.2b shows another integration, so-called pseudo direct drive machines [15][16] (with 6 stator teeth, 2 rotating inner PM pole pairs, 18 rotating modulating poles and 16 outer PM pole pairs). This type of machine utilises the modulating ring as the low speed output. Both a conventional electrical machine configuration and a magnetic gear can still be clearly seen. The outer wound stator also produces a rotating magnetic field. There are two mechanically rotating elements and two airgaps, i.e. inner rotating PM rotor, and a rotating iron piece ring. One potential application of this multiple airgap magnetically geared machine is to operate as a variable speed transmission, using two of the magnetic gear rotors to transmit torque and the stator windings to vary the excitation frequency for hybrid electric vehicle and wind power application although the structure is still too complicated with two rotors and two airgaps.

Fig.2c shows so-called doubly-fed dual stator reluctance machines [20]-[23] in which the rotating magnets in a magnetic gear have been replaced by two stators wound with distributed or non-distributed windings. Two stators usually have different slot numbers and pole numbers, and both are excited by ac sources with different frequencies. This type of machines is actually a PS type of brushless doubly-fed reluctance machine. It utilises the middle modulating ring of iron pieces as the only rotor, and may be in the formats of either radial field [20][21] or axial-field [22][23]. If the two stators and the one rotor have the same pole number and the two stator windings are excited by the same frequency, it becomes a dual-stator synchronous reluctance machine.

This paper will focus on the overview of novel PS machines, Fig. 1(b2), and describe various developed PS machines in section IV.

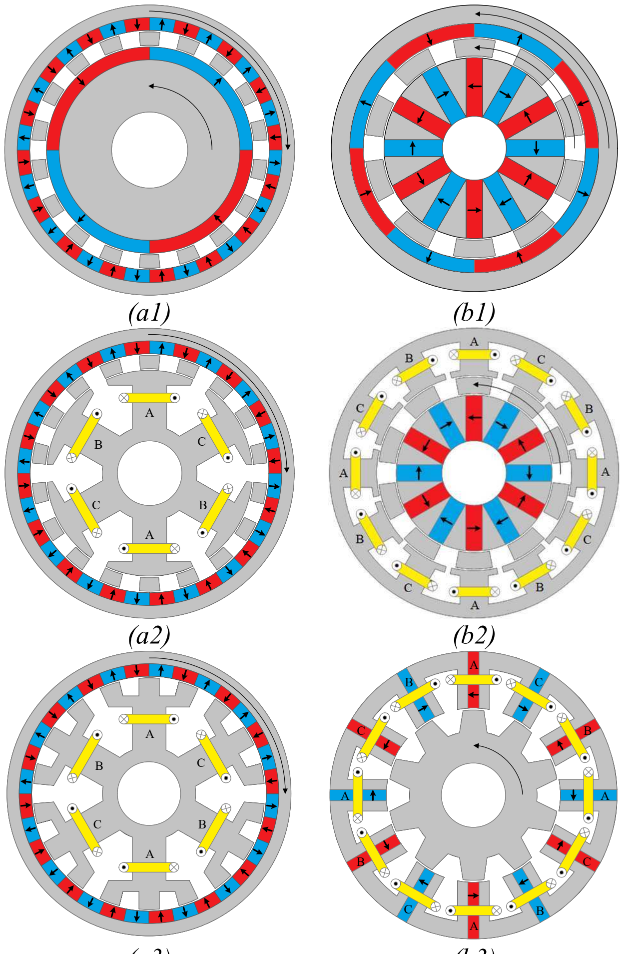
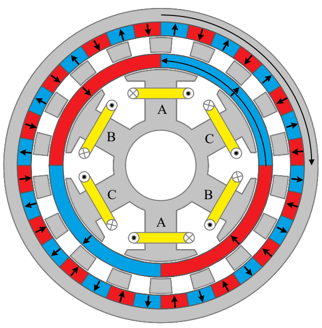
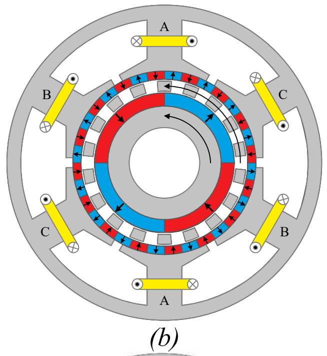
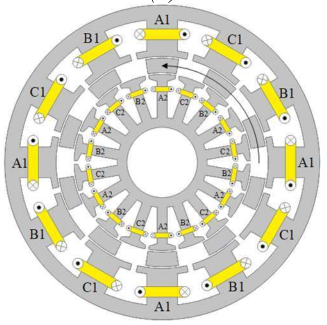


Fig. 1. *Magnetic gears and evolution of many novel machines.*
(a1) *Magnetic gear with stationary modulating iron poles,* ***(b1)*** *Magnetic gear with rotating modulating iron poles,* ***(a2)*** *Harmonic magnetically geared machine,* ***(b2)*** *PS-SFPM machine,* ***(a3)*** *Vernier machine,* ***(b3)*** *SFPM machine. (in a1, a2, a3: p_1=16, p_2=2, n_i=18, stator slot no: Q=6, and in b1, b2, b3: p_1=6, p_2=4, n_i=10, stator slot no: Q=12)*



(a)





(c)

Fig. 2. *Conventional way of integrating magnetic gear and conventional electrical machine.*
(a) *Magnetically geared machine [12][13],* ***(b)*** *Pseudo direct drive machine [15][16], (c) Doubly-fed dual stator reluctance machine [20][21]*

III. *Operating Principle and Magnetic Gearing Effect in Partitioned Stator Machines*

SFPM, FRPM, and DSPM machines are three types of stator PM machines and have been well researched in literature [3]-[5]. Compared with stator PM machines, PS PM machines [24][25] benefit from the removal of conflict between PM and armature winding spaces on the stator, allowing for increased copper and PM areas within the same machine space envelop to reduce copper loss, improve efficiency and increase torque density. While in stator PM machines the temperature rise in PMs may be managed by forced cooling, in PS PM machines the separation of PMs and armature windings allows PMs to be cooled on a stationary body which is remote from the hot copper windings. Furthermore, the interior PM stator can utilise flux focusing effect. All of the above advantages contribute to achieving maximum magnetic and electric loadings, and ultimately higher torque and torque density.

It is also worth noting that a PS PM machine may have the number of PM poles of one stator either equal or not equal to the number of teeth of another stator, as will be shown later.

To illustrate the evolution of PS PM machines from stator PM machines and also further reveal their inherent relationship, Fig.3 shows its flux paths. As can be seen, the iron rotor pole structure used in harmonic magnetic gears [6][7] is applied to stator PM machines to achieve the separation of PM and copper. For PS machines with PMs placed as shown in Fig.3(b), a second airgap must be introduced between the salient rotor poles and secondary PM stator. The structure of the rotor, which in conventional stator PM machines is very similar to that of a SRM, is now analogous to a magnetic gear's modulating rotor. To maintain the direction of flux as in a conventional switched flux machine, the flux direction of the PM associated with an individual tooth is circumferentially reversed. The structure of one armature stator is identical to that in a conventional AC machine, while the other excitation stator provides field excitation and its structure is similar to a PM rotor (or a wound field rotor) although it is now stationary.

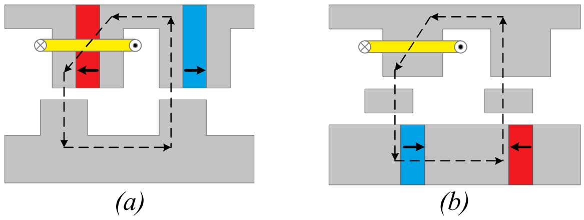


Fig. 3. *Flux paths and PM magnetisation directions in stator PM and PS PM machines.*
(a) *Single stator,* ***(b)*** *Partitioned stator*

The coil flux-linkage variation of the PS PM machine is demonstrated by considering the flux linking an individual coil in a 10 rotor pole machines. The distributions of flux through a single coil are presented in Fig.4(a)-(d), with positions A and C having maximum positive and maximum negative fluxes linking the single coil, B and D having no flux through the single coil when the iron piece or iron piece airspace is aligned with the stator tooth with coil. Thus, bi-polar flux linkage is produced as shown in Fig. 4(e).

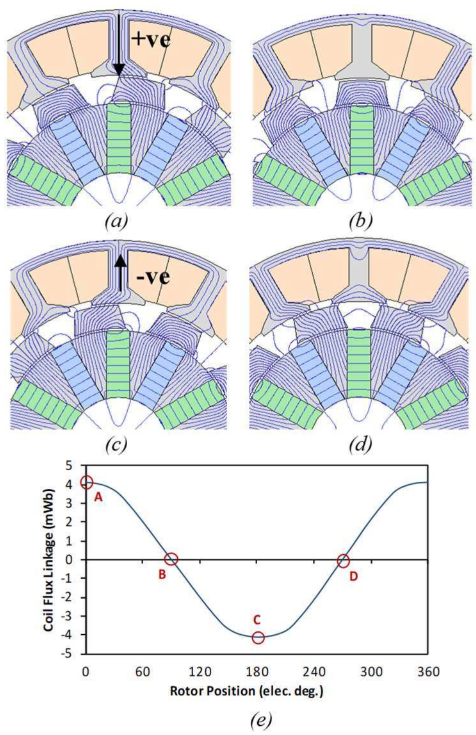


Fig. 4. *Equal potential distributions and variation of flux linkage in a single coil of PS PM machine with 10 rotor poles at different rotor positions.*
(a) *Position A,* ***(b)*** *Position B,* ***(c)*** *Position C,* ***(d)*** *Position D,* ***(e)*** *Variation of flux linkage in a single coil*

The phase flux linkage can be obtained by summation of all series coils of one phase, from which the corresponding phase back-EMF waveform can be obtained. Both are essentially sinusoidal (the back-EMF waveforms will be shown later in the paper). Consequently, by supplying multi-phase (e.g. 3-phase) sinusoidal currents, the torque can be produced as in the conventional machines.

Of course, the torque production can also be obtained numerically in an alternative way from magnetic gearing and airgap flux modulation [17]-[19], [39]-[43], [45]. Pairs of PM and armature field harmonics with the same pole pair number and rotation speed and direction through the modulation of iron pieces contribute to torque production.

The magnetic gear ratio in PS PM machines can be obtained in a similar way to that in a magnetic gear given in Table I by utilising an equivalent pole pair number of the stator armature field [45].

IV. *Various Partitioned Stator Machines*

As can be seen from Fig.1(b3) to Fig.1(b2), all stator PM machines can be converted to PS PM machines. Therefore, this section will firstly describe various stator PM as well as wound field machine topologies and then give the derived equivalent PS machine topologies.

A. Stator PM and Wound Field Machines

There are three main types of stator PM machines, all developed from the switching flux principle [46]-[67], i.e. switched flux [46]-[61], Fig.5, flux reversal [62]-[65], Fig.6, and doubly salient [66]-[67], Fig.7. The distinction among these three stator PM machines is the placement of PMs. Switched flux machines sandwich the PM within each stator tooth. Flux reversal machines mount a pair of the PMs on the tooth surface adjacent to the airgap. Doubly salient machines feature PM embedded within the stator yoke between two teeth/poles or by the interval of number of phases. Stator PM machines of these types do not rely on reluctance torque to generate torque as the inductance difference between d- and q-axes is generally negligible, and the PM flux linkage variation of the stator winding due to rotor saliency dominates the torque production. In other words, the torque production in stator PM machines relies on rotor saliency, but the reluctance torque is usually negligible.

In these stator PM machines, all have a simple salient pole rotor without windings or magnets, the stators usually employ non-overlapping concentrated windings, either single layer (alternate teeth wound) or double layer (all teeth wound), although it is also possible to employ conventional distributed windings albeit with longer end-windings. There are also many possible combinations of stator and rotor teeth, the optimal rotor tooth number for maximum torque is usually close to the number of stator teeth or its multiples [53][54]. Amongst three main stator PM machines, switched flux machines can potentially achieve the highest torque density due to flux focusing albeit with a larger amount of PMs. Further, for SFPM machines, E-core type has removed the tooth PMs from the teeth without coils in the alternate teeth wound SFPM machines [55], Fig. 5(d1), while the C-core with less stator teeth and large slot openings [56] is derived by further removal of the E-core teeth that are not wound, Fig. 5(c1). Similar to E-core and C-core, multi-tooth SFPM machine configuration has also halved the number and amount of PMs, yet with potential improved torque density at lower electric loading [57]-[58]. The performance of a FRPM machine is impacted by the magnet thickness, as increased magnet thickness results in a longer effective airgap. In both SFPM and FRPM machines, the flux linkages are bipolar and the back-EMF waveforms are close to sinusoidal. In contrast, a DSPM machine exhibits unipolar flux linkage and non-sinusoidal back-EMF waveform, resulting in relatively lower torque density and higher torque ripples.

PM excitation in all PM machines can be replaced by dc-field excitation [68]-[73] (also possible by ac excitation in PS machines as mentioned earlier [20]-[23]). There are two types of stator wound field switched flux machines. One is directly converted from SFPM machines, Fig.8(a1) - wound field SF (WFSF) machines [68]-[73], and one converted from SRMs, Fig. 8(b1) – variable flux reluctance machines (VFRM) [74]-[78].

Various VFRMs can be obtained by replacing the phase winding in different SRMs with unipolar excitation by a dc coil and an ac coil with sinusoidal excitation. However, the feasible rotor tooth numbers are significantly extended. For example, in the conventional SRMs, only 6/4, 6/8, 12/8, 12/16 stator and rotor tooth numbers are feasible. For VFRMs, 6/4, 6/5, 6/7, and 6/8, … 12/8, 12/9, 12/10, 12/11, 12/13, 12/14, 12/15, and 12/16… are all possible, with potential improvement in torque density and significant reduction in acoustic noise and vibration, albeit with two sets of stator windings for field excitation and armature respectively, and thus with increased copper losses. Further, by utilising the concept of combined DC and AC excitations in one set of windings, identical to that in SRMs, the VFRMs can be excited by open-winding techniques to improve the efficiency while maintaining low noise and vibration and good torque density [79][80].

WFSF machines may have different stator coil pitches for armature and field windings [68]-[73]. Further, a segmented rotor may also be employed in WFSF machines, which were reported in [69] to have similar torque capability as the conventional SRM, but with the capability of adjusting air-gap flux density.

A review of different stator PM and WF machines has been given in [3]-[5] highlighting the features of machines which utilise switched flux principle.

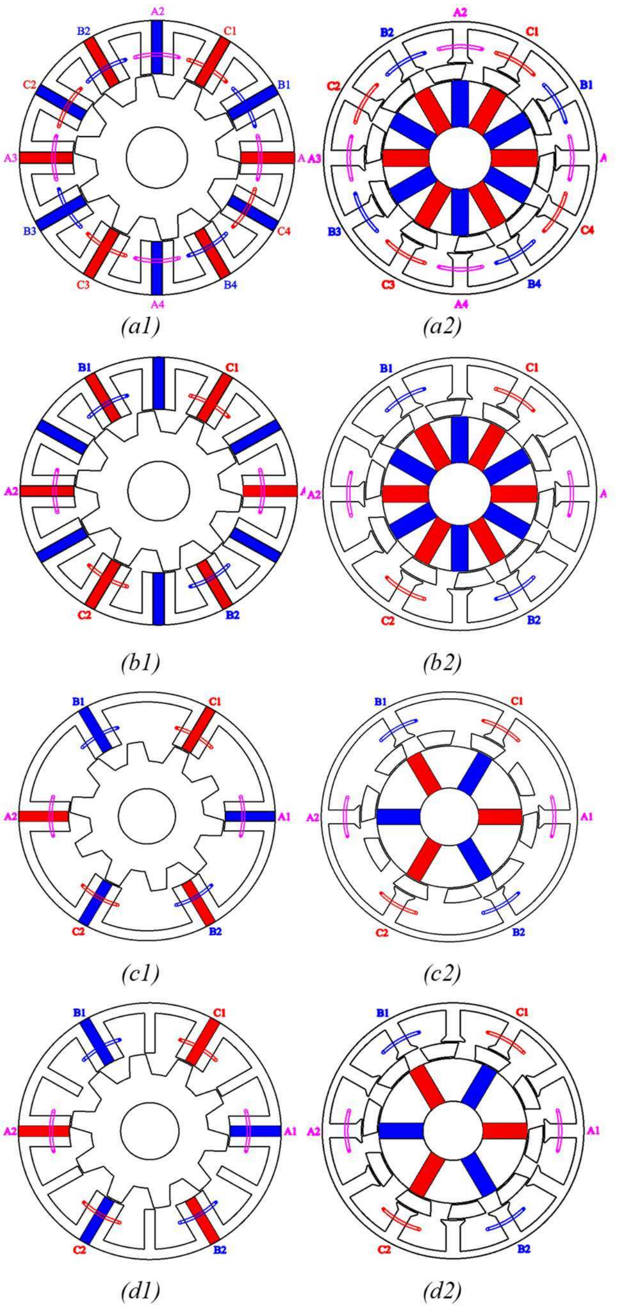


Fig. 5. *SFPM and PS-SFPM machines.*
(a1) *SFPM (all teeth wound),* ***(a2)*** *PS-SFPM (all teeth wound),* ***(b1)*** *SFPM (alternate teeth wound),* ***(b2)*** *PS-SFPM (alternate teeth wound),* ***(c1)*** *C-core SFPM,* ***(c2)*** *C-core PS-SFPM,* ***(d1)*** *E-core SFPM,* ***(d2)*** *E-core PS-SFPM*

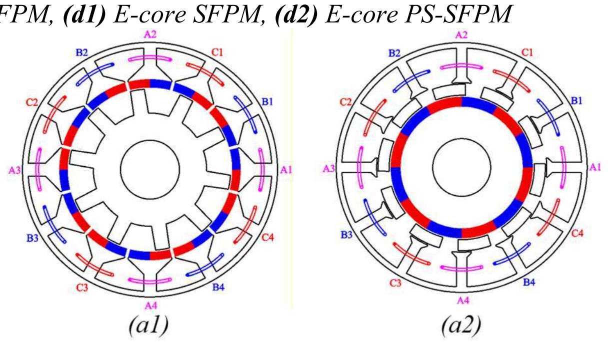


Fig.6. *Flux reversal PM (FRPM) and PS-FRPM machines.*
(a1) *FRPM,* ***(a2)*** *PS-FRPM*

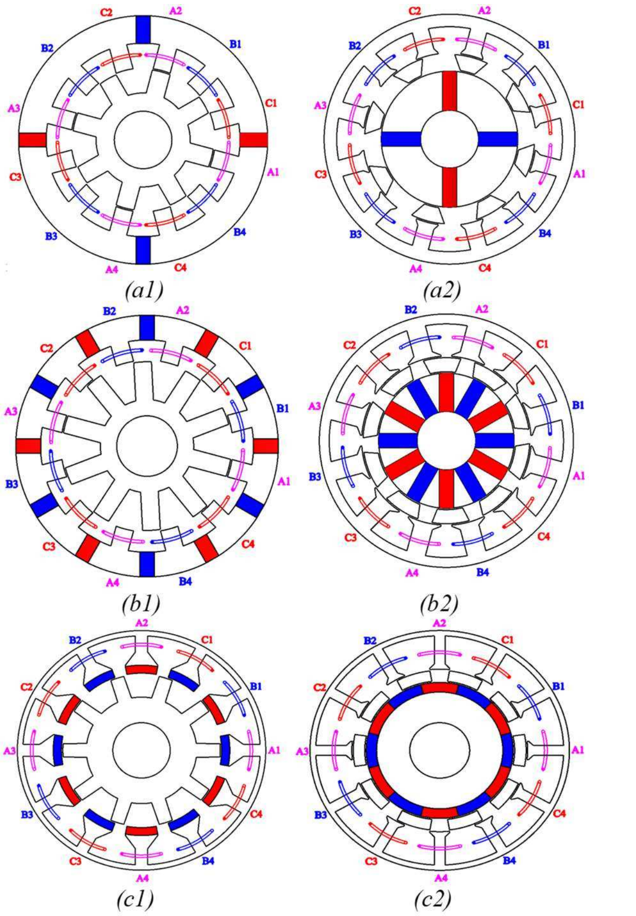


Fig. 7. *Doubly saliency PM (DSPM) and PS-DSPM machines.*
(a1) *DSPM1,* ***(a2)*** *PS-DSPM1,* ***(b1)*** *DSPM2,* ***(b2)*** *PS-DSPM2,* ***(c1)*** *DSPM3,* ***(c2)*** *PS-DSPM3*

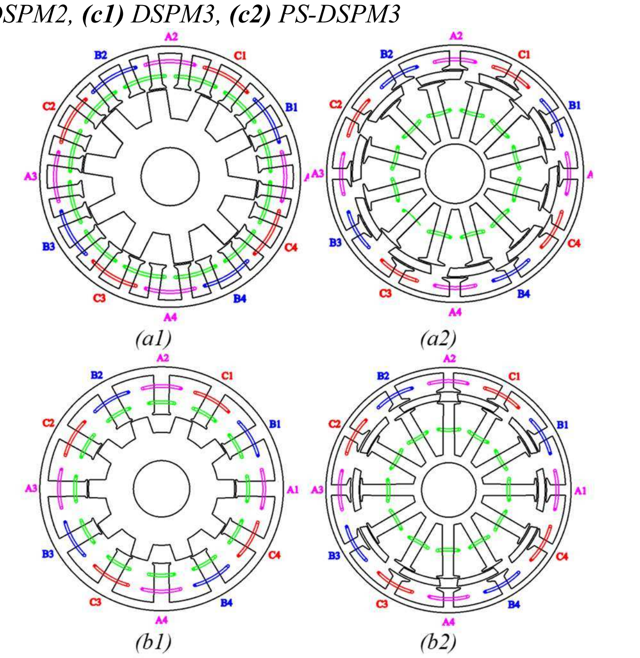


Fig. 8. *Typical partitioned stator machines and the original switched flux PM and wound field machines.*
(a1) *WFSF,* ***(a2)*** *PS-WFSF,* ***(b1)*** *VFRM,* ***(b2)*** *PS-VFRM*

B. Partitioned Stator Switched Flux Machines

Based on the foregoing evolution from stator PM and wound field machines to PS-SF machine, Fig.1 and Fig.3, various PS-SF machine configurations can be developed [24][25][81]-[97].

Figs.4-8 illustrate some typical PS-SF machine topologies associated with DS [88]-[89], FR [81] [90]-[95], and SF [25][80]-[87] machines, with either PM or wound field excitation [96][97]. Different numbers of rotor poles and stator winding configurations are also possible [85][91]. The main difference is that in the original SF machines, armature windings and PM or dc coil excitations are placed on one stator, whilst in the PS-SF machines, they are now placed in two separated stators. Of course, according to PS concept, it is also possible to partially allocate armature windings and PM or dc coil excitations on two stators.

V. *Comparison of Various PS Machine Topologies and Electromagnetic Performance*

A. Relationships between Various PS Machines

From various PS machine topologies developed from SF, FR, and DS machines, many important inherent relationships amongst alternate machines can be easily revealed graphically and summarised as follows.

(a) SFPM vs. FRPM machines. From Figs. 5(a2) and 6(a2), it is shown that SFPM and FRPM machines are the same in principle when they are converted into PS-SFPM and PS-FRPM machines, as they only differ in the PM excitation stators, having IPM and SPM respectively.

(b) SFPM vs. DSPM machines. From Figs. 5(a2) and 7(b2), it can be seen that DSPM and SFPM machines are equivalent, and also share identical operating principle. The major difference is that in PS-SFPM machines, the outer stator teeth align with the inner stator PMs, but in PS-DSPM2 machines the outer stator slots align with the inner stator PMs.

(c) *Two DSPM machines*. From Figs. 7(b2) and 7(c2), it can be seen that the only difference between PS-DSPM2 and PS-DSPM3 machines is that the inner stators are IPM and SPM in PS-DSPM2 and PS-DSPM3 machines, respectively.

(d) SFWF vs. VFRM machines. PS-SFWF and PS-VFRM machines are equivalent and share identical operating principle, as shown in Figs.8(a2) and 8(b2), the difference being that in PS-SFWF machine, two stator teeth are unaligned, i.e. stator teeth of one stator align with slots of another stator, while in PS-VFRM, two stator teeth are aligned.

It is worthy mentioning that for all PM stators, in addition to SPMs and IPMs, it is possible to employ consequent pole PMs [84], Halbach PMs [94], as well as a variety of IPMs, including V-shaped IPMs and multi-layer IPMs etc. [82]. In addition to rare-earth magnets, e.g. NdFeB, cheap ferrite magnets may be used, particularly when the interior PMs are used [83]. Since the stators equipped with armature windings are identical to the stators of any conventional induction machines and synchronous machines, there are a large number of stator winding topologies [91]. In addition, the inner and outer stators may be exchanged. Further, from Figs. 5(b2), 5(d2), 7(a2), and 7(b2), it is not necessary for PS machines to have the same number of PMs in one stator with the number of coils/teeth in another stator [85].

B. Comparison of Electromagnetic Performance of Selected PS Machines

In this section, some typical PS machines and their origins, including SFPM machines, FRPM machines, WFSF machines, VFRMs, etc. are globally optimised using genetic algorithm for maximum torque at fixed copper loss of 20W, and their electromagnetic performance is compared, Table 2. The outside diameter and axial length of all machines are the same, i.e. 90mm and 25mm, respectively. Hence, comparison of produced torque is also equivalent to that of torque density, i.e. torque per overall machine volume. Fig. 9 compares the back-EMF waveforms, static torque waveforms with rotor position, and average torque with copper loss of PS-SFPM machines with all stator teeth wound and different number of rotor teeth. It shows that the back-EMF waveforms are essentially sinusoidal, and 12-stator teeth/11-rotor teeth (12/11-tooth) and 12/13-tooth machines exhibit larger EMF and also average torque, but less torque ripple, albeit with potential unbalanced magnetic force due to odd number of rotor teeth. The power factors for 12/10, 12/11, 12/13, 12/14 PS-SFPM machines are 0.96, 0.96, 0.94 and 0.91, respectively.

Fig. 10 compares average torque against copper loss. It should be noted that PM machines are optimized with copper loss of 20W, and WF machines are optimized with total copper loss of 60W and armature winding loss of 30W. It is clearly shown from Fig.10 and Table 2 that all PS machines can produce higher torque or torque density/copper loss compared with their origins, due to increased slot area for armature windings and/or field windings, as well as the conventional magnetically geared machine with a single element of PMs. PM machines always produce higher torque or torque density per copper loss compared with wound field machines. IPM stator type PS machines produce higher torque or torque density than SPM stator type PS machines. PS-SFPM machines produce the highest torque or torque density per copper loss due to flux focusing of PMs. In addition, WFSF and PS-WFSF machines produce higher torque or torque density than VFRM and PS-VFRM machines. The above discussions and conclusions are also applicable to relatively large size PS machines with NdFeB or ferrite magnets, as shown in [83].

For simplicity, only the relative capability of torque per copper loss of selected machines is compared since it reflects the actual torque capability at low speed operation, where the iron loss and PM eddy current loss are relatively small but should be considered at higher speed in order to compare their efficiencies [83]. It is worth noting that as mentioned above, due to the same overall space envelop used for all machines, comparison of torque is equivalent to that of torque density in Figs. 9c and 10. However, the above comparison is still only indicative since the selection of a machine topology is much more complex than merely maximizing the torque or torque density at a fixed copper loss but also involves the usage of materials, the iron loss and PM eddy current loss computation, the mechanical and thermal analyses, as well as manufacturing. By way of example, compared with the conventional machines, the mechanical structure of a cupped-type rotor in the PS machines presents a major challenge although it is already much simpler than the conventional magnetically geared machines shown in Figs.2(a) and (b) in which there are two rotors. Nevertheless, the mechanical stress and rotor dynamic analyses are required [83]. Further, the PS machines exhibit significantly different thermal conditions from the conventional machines with all PMs and windings on a single stator, so do the wound field machines and PM machines. Therefore, future work is required for more fair comparison.

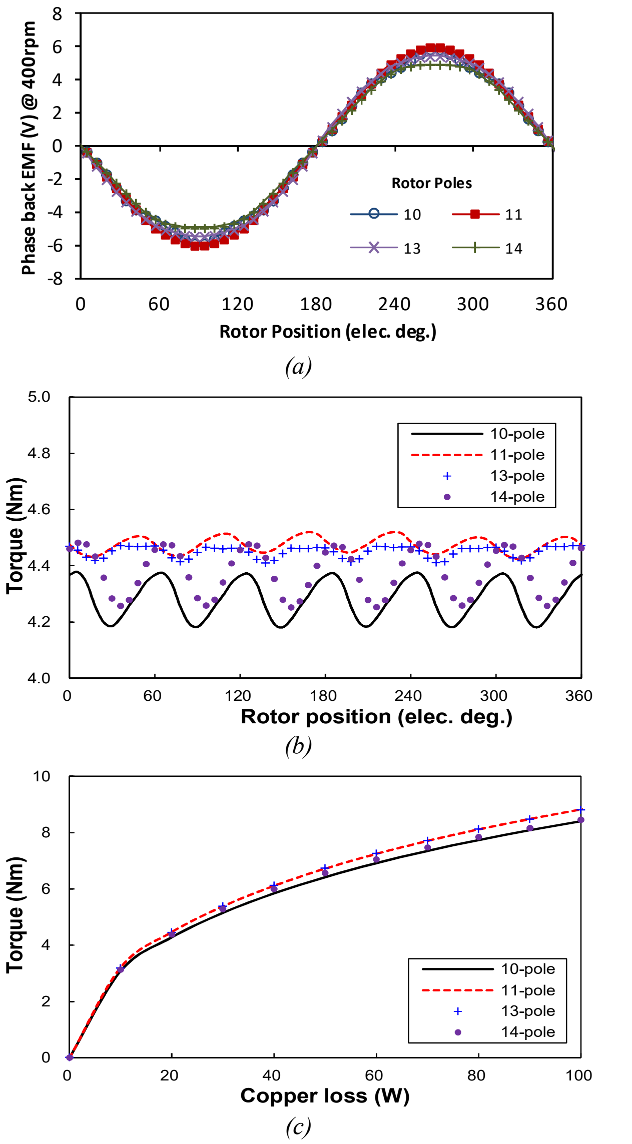


***Fig. 9**. PS-SFPM machines with all teeth wound and different rotor teeth.*
***(a)** Back-EMF waveforms at 400rpm, **(b)** Static torque waveforms at 20W copper losses, **(c)** Average torque against copper loss*

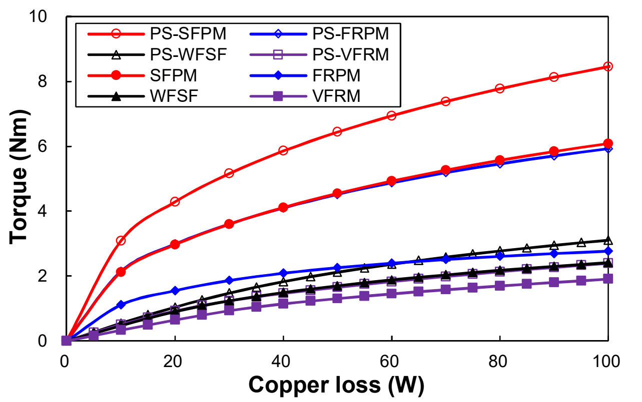


***Fig. 10.** Comparison of torque against copper loss in various switched flux PM and WF machines and corresponding PS machines. (12 stator teeth, 10 rotor teeth. PS-SF and SF are all poles wound).*

Table 2 Comparison of SFPM, FRPM, WFSF, VFRM machines and corresponding PS machines

Item	CMGM	SFPM	PS-SFPM	FRPM	PS-FRPM	WFSF	PS-WFSF	VFRM	PS-VFRM
Machine active volume, mm^3	159043	159043	159043	159043	159043	159043	159043	159043	159043
Mass of laminations, kg	0.641	0.672	0.527	0.558	0.563	0.671	0.501	0.629	0.501
Mass of windings, kg	0.531	0.316	0.498	0.446	0.590	0.434	0.731	0.543	0.731
Mass of PMs (remanence=1.2T), kg	0.100	0.140	0.182	0.100	0.100	0	0	0	0
Mass of machine without frame and shaft, kg	1.272	1.128	1.207	1.104	1.252	1.105	1.232	1.172	1.232
Torque, Nm	2.340	2.966	4.284	1.550	2.985	1.881	2.366	1.450	1.828
Rated speed, r/min	400	400	400	400	400	400	400	400	400
Power, W	98	124	179	65	125	79	99	61	77
Torque per machine volume, 10^{-6} Nm/mm^3	14.71	18.65	26.94	9.74	18.77	11.82	14.87	9.12	11.49
Torque per mass, Nm/kg	1.84	2.63	3.55	1.40	2.38	1.70	1.92	1.24	1.48
Power per volume, 10^{-6} W/mm^3	616	781	1125	408	786	495	623	382	481
Power per mass, W/kg	77	110	149	59	100	71	80	52	62
PM volume, mm^3	13414	18893	24499	13414	13414	0	0	0	0
Torque per PM volume, 10^{-6} Nm/mm^3	174	157	175	116	223				
Power per PM volume, 10^{-6} W/mm^3	7306	6577	7325	4838	9321				

Note: CMGM=conventional magnetically geared machine with single element of PMs, Fig.1(a2) with outer stator and inner PM rotor. For all machines, outer radius=45mm, stack length=25mm, airgap=0.5mm, outer element stator slot no=12, stator winding equivalent pole-pair no=4, iron piece no=10 except for CMGM=26, inner element pole-pair no=6 except for CMGM=22.

VI. *Hybrid Excited PS-PM Machines*

Hybrid excited (HE) machines, which combine high torque density of PM machines and excellent flux controllability of field winding (FW) electrical-excited machines, are of great interest in variable-speed electric drive systems [98]-[101]. An additional degree of freedom, i.e. the ratio between PM and FW flux, is obtained. In low-speed operation, the positive field current can be used to enhance the air-gap field, which contributes to higher torque output. Alternatively, the negative field current is employed to realize the flux-weakening in high-speed operation. Among a variety of HE machine topologies, the stator-excited configurations employing both PMs and FWs on the stator are attracting increasing attention [102][103]. This is due to the elimination of sliding contacts for supplying the excitation and complicated structures for three-dimensional flux. Nevertheless, the stator-excited HE machines suffer from the sacrificed performance due to space conflict, with the stator accommodating all PMs, FWs, and armature windings.

The HE concept and the PS configuration can be integrated with the synergy of the stator-excited HE machines without the space conflict. The cross sections of several typical PSHE machine topologies are illustrated in Fig. 11, in which the concentrated non-overlapping armature windings and FWs are always wound around the salient teeth in outer stator and inner stator respectively, and meanwhile, an iron-piece-rotor is sandwiched between the two stators. As shown in Fig. 11(a), the tangentially magnetized PMs are inserted in the slot-openings of the inner stator [104]. Consequently, the PM flux tends to short-circuit via the inner stator yoke without field current, and hence the back-EMF is almost negligible. However, by injecting a positive field current to counter against the PM flux, the PM flux is forced to flow through the air-gap, resulting in an induced back-EMF. Alternatively, the tangentially magnetized PMs can also be located on the yoke of the inner stator [105]. The PM flux and FW flux would contribute to the air-gap field together, and the accumulated field is regulated by different field currents. Furthermore, the radially magnetized PMs can be surface-mounted on the inner stator teeth. With the alternately arranged PM poles and FW poles, the series connection between PM flux and FW flux can be obtained, Fig. 11(c) [106]. It can be seen that the consequent pole configuration is employed to reduce the reluctance of FW flux. In Fig. 11(d), PM pole-pairs and FW pole-pairs are alternately placed, and thus their fluxes are magnetically connected in parallel [107]. Further, hybrid series and parallel [108] connections between the PMs and FWs are also possible. In fact, the PMs can also be allocated in the outer stator to share the space with armature windings, Fig. 11(e), in which the inner stator is occupied by FWs [109].

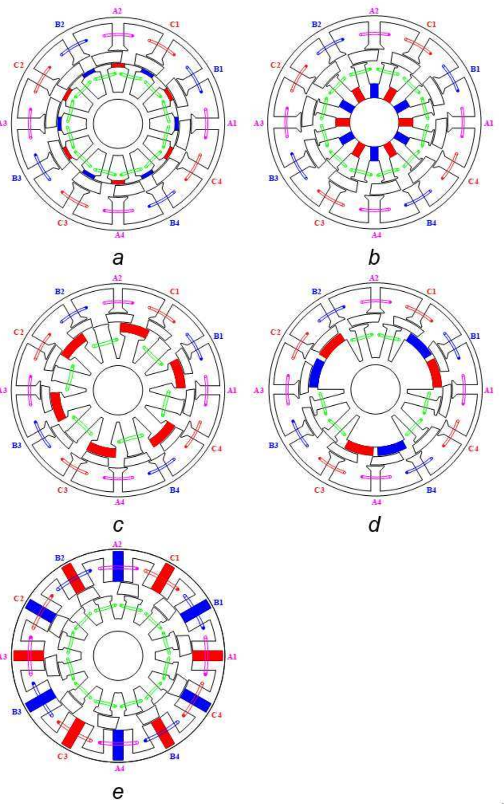
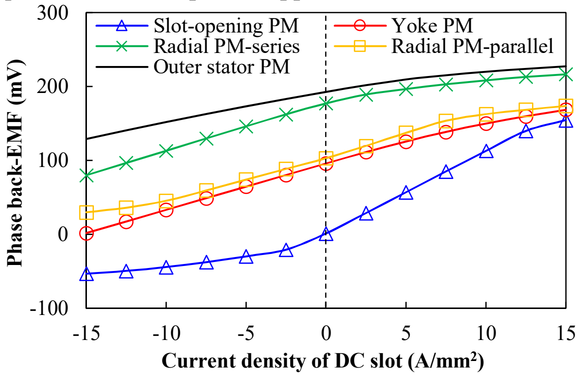
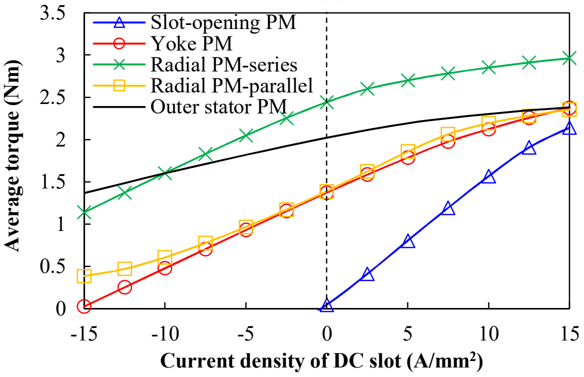


Fig. 11. *Cross sections of different 12-stator-slot/10-rotor-pole PSHE machine topologies.*
(a) *Tangnetial PM in slot-opening,* ***(b)*** *Tangential PM in yoke,* ***(c)*** *Radial PM in series connection,* ***(d)*** *Radial PM in parallel connection,* ***(e)*** *Tangential PM in outer stator*

The proposed PSHE machines can exhibit not only high torque density but also wide flux regulation range thanks to the flexible combination of PMs and FWs. The phase back-EMFs and average torques versus different field currents of the five PSHE machines are compared in Figs. 12(a) and (b) respectively. Moreover, their characteristics are summarized in Fig. 13. It can be observed that the PSHE machines with slot-opening-based and yoke-based PMs tend to have better flux regulation capability but compromised torque, compared with the counterparts. The PSHE machine with radial PMs in series exhibits the highest torque. The PSHE machine with radially magnetized PMs in parallel benefits from excellent flux controllability but it has a relatively lower torque and more harmonics. Therefore, it can be stated that the design of the PSHE machines is quite flexible and depends on the requirements for a specific application.



(a)



(b)

Fig. 12. *Comparison of phase back-EMFs and average torques with different field currents in five developed PSHE machines.*
(a) *Phase back-EMFs at 400 rpm,* ***(b)*** *Average torque with 20W copper losses and zero d-axis current*

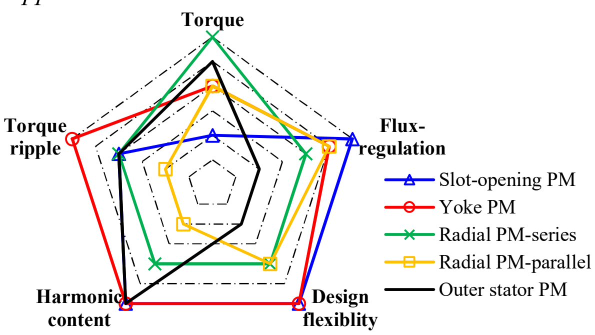


Fig. 13. *Characteristics of five developed PSHE machines.*

VII. *Conclusions*

Novel magnetically geared machines with partitioned stators have been overviewed in this paper. They combine the synergies of two distinct types of PM machines, i.e. magnetically geared machines and switched flux machines.

Various partitioned stator machines can be developed based on the concept of partitioned stators. All have features of two stators, two airgaps, and one segmented ferromagnetic rotor identical to a magnetic gear's modulating rotor. One armature stator is identical to that in conventional AC machines, while the other excitation stator provides field excitation by PMs or field windings. In addition, it is also possible to employ hybrid excited PM and field winding excitation with improved flux regulation capability and torque density.

Many inherent relationships amongst SFPM, FRPM and DSPM machines have been revealed based on the PS machine platform via graphical topology derivations. For example, it has been revealed that (1) SFPM and FRPM machines are the same in principle when they are converted into PS-SFPM and PS-FRPM machines, with excitation stators having IPMs and SPMs respectively, and this is equally applicable to two types of DSPM machines; (2) PS-SFWF and PS-VFRM machines are equivalent and share identical operating principle, the difference being in the alignment of two stators, and this is also true for SFPM machines and some DSPM machines.

It has been highlighted that all partitioned stator machines can produce higher torque and torque density/copper loss compared with their origins, due to increased slot area for armature windings and/or field windings as well as better space utilisation. PM machines always produce higher torque and torque density per copper loss compared with the wound field machines, while PS-SFPM machines produce the highest torque and torque density per copper loss due to flux focusing of PMs.

Based on the concept of partitioned stators, numerous other types of PS machines can be developed, e.g. doubly-fed dual-stator reluctance and induction machines as mentioned in section II [20]-[23], linear/tubular [110][111] and axial-field [112]-[115] PS machines, as well as PS memory machines [116] based on the concept of on-line magnetising and demagnetising PMs [117]-[120]. However, due to space limit, they are not be reviewed in this paper. It is also worth noting that many PS machines were prototyped and tested to validate the theoretical analyses. There exhibit excellent agreements between the predicted and measured results which can be found in [25], [81]-[97], [104]-[109], [116], and will not be duplicated in this paper.

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