Hybrid Excited Permanent Magnet Machines for Electric and Hybrid Electric Vehicles

Z. Q. Zhu, *Fellow, IEEE*, and S. Cai

***Abstract*—This paper reviews various hybrid excited (HE) machines from the perspective of location of PM and DC excitation, series/parallel connection of PM and DC excited magnetic fields, and 2D/3D magnetic fields, respectively. The advantages as well as drawbacks of each category are analyzed. Since an additional control degree, i.e. DC excitation, is introduced in the HE machine, the flux weakening control strategies are more complex. The flux weakening performance as well as efficiency are compared with different control strategies. Then, the potential to mitigate the risk of uncontrolled overvoltage fault at high speed operation is highlighted by controlling the field excitation. Since additional DC coils are usually required for HE machines compared with pure PM excitation, the spatial confliction inevitably results in electromagnetic performance reduction. Finally, the technique to integrate the field and armature windings with open-winding drive circuit is introduced, and novel HE machines without a DC coil are summarized.**

***Index Terms*— Electric vehicle (EV), flux weakening control, hybrid electric vehicle (HEV), hybrid excited (HE) machine, open-winding, permanent magnet (PM).**

I. INTRODUCTION

DUE to significant environmental concerns, electric vehicles and hybrid electric vehicles (EVs/HEVs) are increasingly being developed and commercialized [1] [2]. Electrical machines are a key technology for EV/HEV, and the main requirements of machines for EV/HEV include [1]-[3]:

- High torque density and high power density;
- High overload capability;
- Extensive flux-weakening region;
- High efficiency over the whole operating region;
- High reliability and fault tolerant capability;
- Low cost and low acoustic noise.

Permanent magnet (PM) machines, especially equipped with high-energy product rare-earth PM material, exhibit high torque density as well as high efficiency, and have been perceived as good candidates for EV/HEV, e.g. Toyota PRIUS, Nissan LEAF, BMW I3, etc. [4]-[6]. However, the magnetic field of PM machines is constant and a flux-weakening current component is required to operate at high speed. Consequently, the efficiency at high speed is degraded and uncontrolled overvoltage fault may damage the power inverter [7] [8].

An alternative solution is to develop hybrid excited electrical machine, with synergies of PM machine and wound field (WF) machine. The introduction of field winding can help to regulate the magnetic field and the output capability according to working condition, which is beneficial for the EV/HEV with variable speed requirements. Compared with the conventional PM machines, an extra flexibility can be utilized to adjust the flux linkage by the field excitation current. Consequently, higher torque at low speed and wider operating speed range, as well as high efficiency over a wide operating region can be obtained by employing appropriate control strategies [9] [10].

Various HE machine topologies have been reviewed in the previous publications [11]-[18]. This paper, which is extended from the keynote speech at the 14th International Conference on Ecological Vehicles and Renewable Energies, EVER19, 8-10 May 2019, Monaco, [19], emphasizes on the origination of the HE machines, either to enhance the torque density of WF machine or improve the flux weakening performance of stator/rotor PM machine. The purposes of this paper include (a) to review different HE machine topologies according to the PM and DC coil excitation location, the series/parallel hybridization and the 2D/3D magnetic fields to demonstrate the possibility to achieve hybridization from existing PM/WF machine and further enhance the electromagnetic performance for variable speed requirement of EV/HEV; (b) to compare unique control strategies for the HE machines; (c) to describe a mitigation technique for uncontrolled overvoltage fault at high speed operation; and (d) to introduce the integration concept of the field and armature windings with open-winding drive circuit to realize HE machines without a DC coil.

II. HYBRID EXCITED MACHINE TOPOLOGIES

In this section, the HE machine topologies are overviewed according to the location of PM and DC excitations.

A. Both PM and DC Coil in Rotor

Based on the classical rotor surface-mounted PM (SPM) machines, HE machines can be obtained by attaching the field winding in the rotor PM pole directly, as shown in Fig. 1 (a) with all pole PMs [20]-[22] and Fig. 1 (b) with consequent pole PMs [23], respectively. The machine topology can be perceived as the integration of a rotor SPM machine and a rotor WF machine. Since the flux path of DC excitation passes through the

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PM, the reluctance is significant and the flux regulation capability is limited. An alternate topology is to allocate the field winding and PM in different poles, as shown in Fig. 2 [24]. As a result, the flux regulation capability and demagnetization withstanding capability are enhanced.

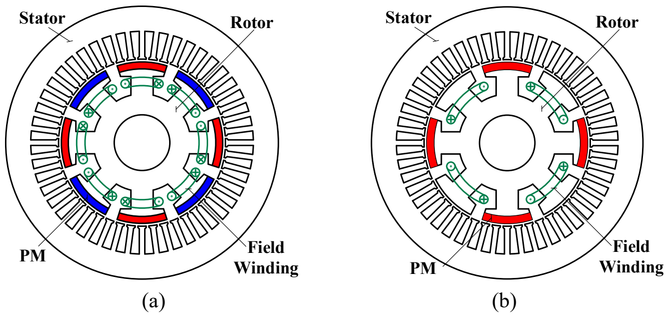


Fig. 1. HE machines with rotor surface mounted PM. (a) All pole PMs [20]-[22]. (b) Consequent pole PMs [23].

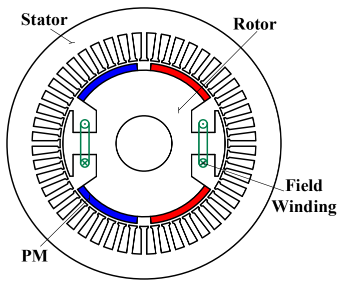


Fig. 2. HE machine with field winding and PM in different rotor poles [24].

Besides, HE machines with rotor radial and tangential interior PMs are shown in Fig. 3 (a) and (b), respectively. The machine configurations in Fig. 1 (b) and Fig. 3 (a) are similar, but the iron bridge in the IPM machine provides additional flux path for DC excitation. Therefore, the risk of irreversible demagnetization is reduced although the flux regulation capability is still limited by the saturated iron bridge.

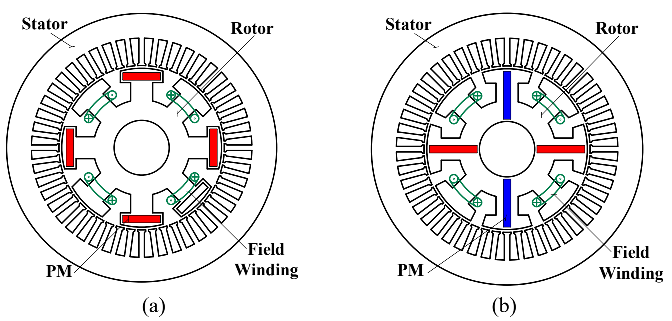


Fig. 3. HE machine with rotor interior PM [23]. (a) Radial magnetized PM. (b) Tangential magnetized PM.

Moreover, PMs can be added in the rotor slots of the rotor WF machine, as shown in Fig. 4 [25]-[28]. The PM flux is short circuited in the rotor, and therefore, negligible cogging torque and back-EMF are produced at open-circuit. With field winding excitation, the PM flux can counteract the DC flux in rotor and alleviate magnetic saturation. It is revealed that the torque density as well as efficiency can be enhanced with the assistance of PMs.

In [29] and [30], a HE machine is developed by combining the rotor PM machine and the rotor WF machine directly, as shown in Fig. 5. The proposed machine consists of a single

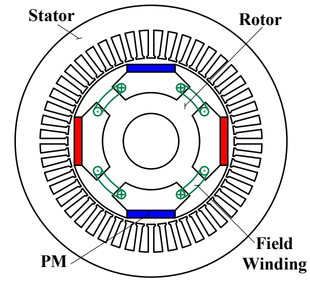


Fig. 4. HE machine with PMs in the rotor slots of field winding [25]-[28].

stator whereas the PM field rotor and the WF rotor are connected by the same shaft. The flux paths of PM excitation and field winding excitation are separated inherently and parallel hybridization with wide flux regulation range is achieved. However, additional gap between two rotors is inevitably introduced by the end-winding of field coil.

It should be noted that brushes and slip rings are required to feed DC to the rotary component for the HE machine topologies in Fig. 1-Fig. 5. The mechanical contact reduces the system reliability while increasing the cost of maintenance.

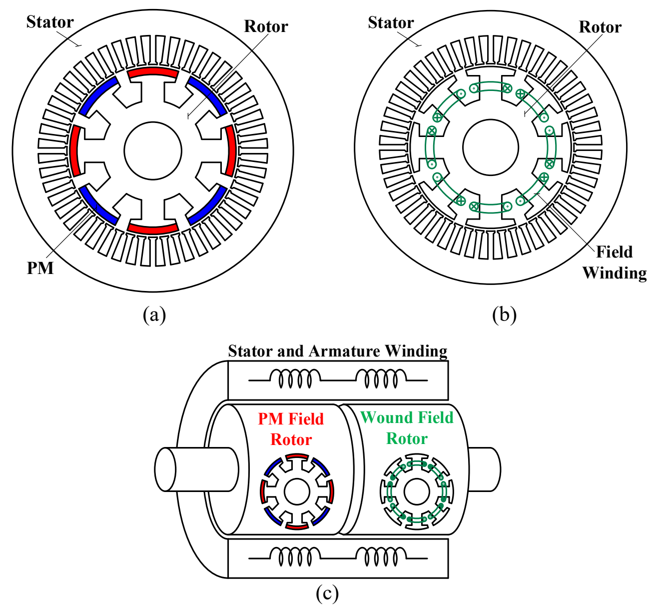


Fig. 5. HE machine with the combination of two rotors [29] [30]. (a) PM field machine. (b) WF machine. (c) HE configuration with the combination of two parts.

To remove the slip rings and brushes, a brushless rotor WF HE machine is proposed in Fig. 6 [31]-[36]. The stator accommodates armature winding, whereas the rotor is located with field and harmonic windings. An additional rectifier is attached in the rotor to supply DC to field winding through harmonic winding, and therefore, mechanical contact of brushes with slip rings is saved. The HE machines with all PM rotor poles and consequent PM poles are presented in Fig. 6 (a) and (b), respectively. The introduction of rotor PMs can improve the torque density and especially enhance the starting performance. In order to produce current in the rotor harmonic winding, various techniques have been proposed, e.g. single phase third harmonic current injection [33] [34], dual inverter to feed unequal amplitude of current [35], single inverter to feed the unequal turns of armature winding [36], as shown in Fig. 6 (c).

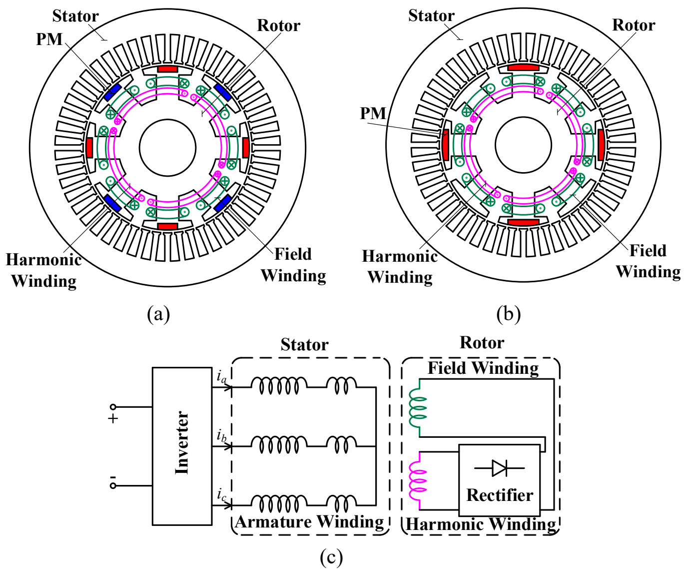


Fig. 6. Brushless rotor WF HE machines. (a) PM in all rotor poles [31]. (b) PM in consequent rotor poles [32]. (c) Single inverter to feed to unequal turns of armature winding [36].

Overall, the HE machines discussed in Fig. 1-Fig. 6 can be perceived as the hybridization of a rotor SPM or IPM machine with a WF machine. Therefore, the machine topologies are generally simple with controllable magnetic field. However, brushes and slip rings are required to feed DC excitation to rotary part. Although brushless structure can be achieved in Fig. 6, both the machine topology and the drive circuit become complicated. Moreover, the rotor spatial confliction of PM and DC coil restricts the torque density as well as flux regulation capability.

B. PM in rotor and DC Coil in Stator

Another solution to eliminate the sliding contacts is to locate the field winding in the stationary parts, whilst PMs are still on the rotor. In [37]-[39], a consequent pole rotor PM HE machine with toroidal field winding is investigated, as shown in Fig. 7. The PM flux path circulates from PM north pole to PM south pole, whereas the DC flux path passes from one iron pole to another iron pole with reduced reluctance. Both the PM and DC excited magnetic fields have 3D flux path and the synthesized magnetic field can be regulated by the field current. Compared with the conventional rotor PM machine, a solid stator yoke core is attached outside the stator laminated core and the rotor core should also be solid iron to allow for both radial and axial fluxes.

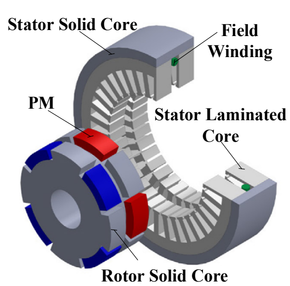


Fig. 7. Consequent pole HE machines with toroidal field winding [37]-[39].

To further enhance the HE machine performance, some improvements have been made in [40]-[43]. In [40], this concept is utilized in the axial flux PM machine to achieve hybridization. In [41], the proportion of PM to iron pole is enlarged to reduce the voltage regulation and improve the power density. In order to reduce the field winding length as well as copper loss, the toroidal field winding is moved to inner stator in [42]. In [43], the toroidal field winding is further employed for consequent pole Vernier machine to achieve hybrid excitation.

Besides, in [44]-[47], homopolar and bipolar HE machines are proposed based on the spoke type IPM machine by introducing toroidal field windings in the end plate, as shown in Fig. 8. The PM flux path is radial, whereas the DC excited magnetic field has both radial and axial flux paths. Therefore, additional solid stator yoke core, solid end plate as well as solid rotor core are required to allow for 3D magnetic flux path. The two field windings of the homopolar HE machine are of opposite direction, whereas those of the bipolar HE machine are of the same direction. In [48]-[50], an improved topology with inner stator to accommodate the field winding is proposed, which is beneficial to shorten the toroidal field winding length.

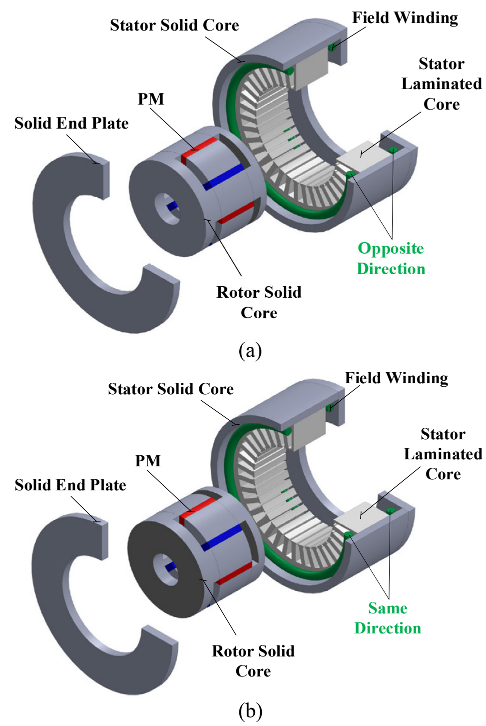
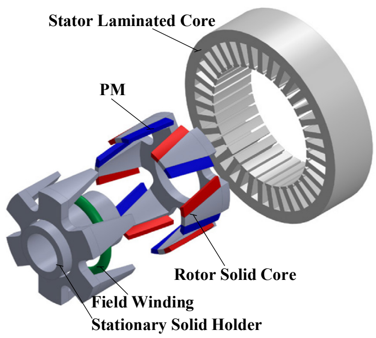


Fig. 8. Homopolar and bipolar HE machines with toroidal field winding [44]-[47]. (a) Homopolar HE machine with field windings at two edges of opposite direction. (b) Bipolar HE machine with field windings at two edges of the same directions.

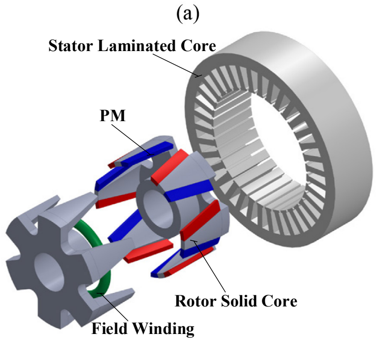
Besides, in Fig. 9, HE machines can be developed by introducing PMs in WF claw pole machines to reduce flux leakage and further improve the performance. The toroidal field winding can be wound around the inner stator [51] [52] or the rotor [53] [54], as shown in Figs. 9 (a) and (b), respectively. For the inner stator topology, brushes and slip rings to feed DC excitation can be removed. However, additional air-gap between the inner stationary holder and the rotor is inevitably introduced, which decreases the machine performance. In [55] and [56], PM is further introduced both in the rotor and the stator to improve the performance, whereas the machine configuration becomes complex.

Moreover, it can be observed that the bipolar HE machine in

Fig. 8 (b) and brushless claw pole HE machine in Fig. 9 (a) share similar machine topology and operating principle. The spoke type IPM is evolved into claw slot PM, and the field winding is moved from the outer stator to the inner stator.



(a)



(b)

Fig. 9. Claw pole HE machines with PM between rotor claws. (a) Brushless structure with inner stator accommodating toroidal field winding [51] [52]. (b) Brushes and slip rings required with rotor accommodating toroidal field winding [53] [54].

Another HE stepper machine is shown in Fig. 10 [57] [58]. The PM is sandwiched by two reluctance rotors with a half rotor pole pitch shift and the toroidal field winding is located at the stationary end plate. Since the magnetic field is controllable and the rotor is robust, the HE stepper machine is suitable for high speed application.

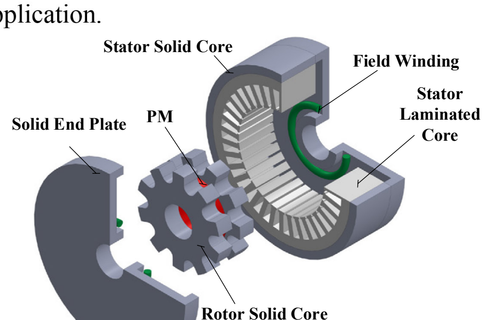


Fig. 10. HE stepper machine [57] [58].

In summary, the HE machines discussed in Fig. 7-Fig. 10 can be perceived as the introduction of a stationary toroidal field winding to the rotor PM machines. Therefore, the brushes and slip rings can be removed and mechanical contract problem is solved. Moreover, the flux path of DC excitation bypasses the PM and the demagnetization issue becomes less severe compared with flux weakening with d-axis current directly. Nevertheless, both radial and axial fluxes exist in the PM and DC excited magnetic fields. Therefore, soft magnetic composite (SMC) or solid material is required to allow for the 3D magnetic field, making the manufacturing and assembling complicated.

C. Both PM and DC Coil in Stator

Besides developing from the rotor PM machines, HE machine configurations can be achieved by attaching field coils in stator PM machines. The sliding contacts are avoided and the machine possesses good heat management since all the excitations are stationary. Generally speaking, stator PM machines can be classified according to the PM location as the doubly salient (stator yoke PM) machine, the flux reversal (stator tooth tip PM) machine, the flux switching (stator teeth sandwiched PM) machine, the stator slot PM machine, etc. [59] [60]. All the stator PM machines can be developed for hybridization as follows.

Based on the conventional doubly salient PM machine, hybrid excitation can be obtained in Fig. 11. In Fig. 11 (a), a field winding is attached in series with PM excitation [61]. The doubly salient HE machine is further improved to adopt PM in stator yoke to reduce the PM usage in Fig. 11 (b) [62]. However, the flux path of field winding passes through PM, which restricts the flux regulation capability and may potentially cause irreversible demagnetization. In [63], an additional air-gap is introduced in the field winding path to achieve parallel hybridization. Moreover, the iron bridge is introduced in [64] [65] to avoid demagnetization as shown in Fig. 11 (c). Similar concept is employed in the outer rotor HE machine in [66]. However, the magnetic field regulation is still limited since the magnetic bridge is saturated by PM flux. In [67] and [68], PM poles are replaced with field winding poles, as illustrated in Fig. 11 (d) to achieve a wide flux regulation range. In [69], the flux regulation capability of the HE doubly salient machines are compared. It is revealed that the series HE machine in Fig. 11 (a) (b) has the lowest flux regulation ratio whereas the parallel HE machine in Fig. 11 (d) possesses the best controllable flux capability.

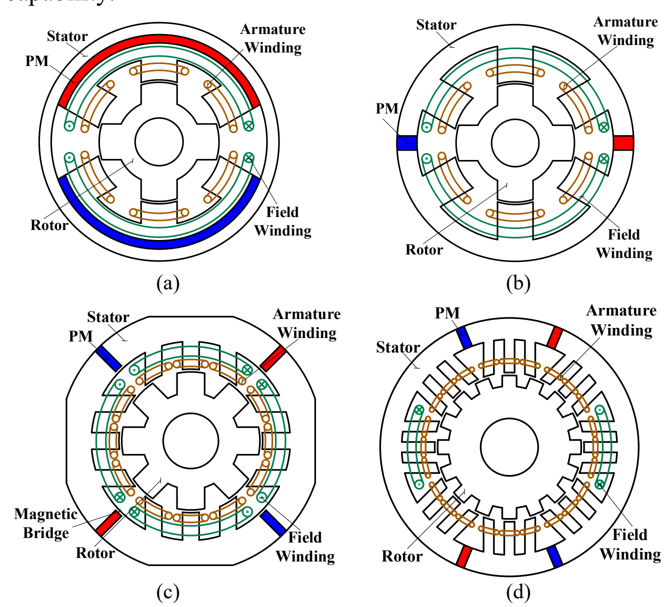


Fig. 11. Doubly salient HE machines. (a) Original topology [61]. (b) PM moved to the stator yoke [62]. (c) Parallel hybridization with iron bridge [64] [65]. (d) Parallel hybridization by replacing PM poles with field winding poles [67] [68].

Besides, other HE machines with stator yoke PMs are presented in Figs. 12 (a) and (b), with field winding coil pitch of 1 [70] and 2 [71], respectively. Compared with the conventional doubly salient machines in Fig. 11, the three phase back-EMFs of the HE machines in Fig. 12 are the same due to symmetrical structure. Similarly, iron bridge is attached not only for connection the stator segment, but also to avoid flux lines of field winding passing through PM.

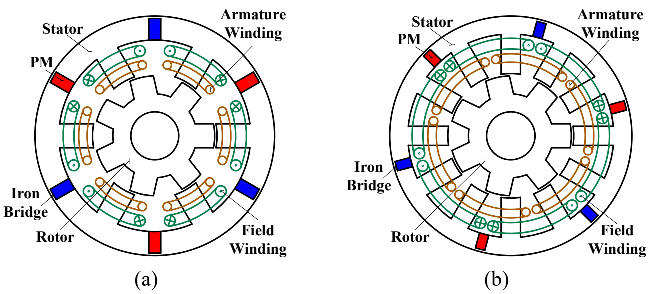


Fig. 12. Other HE machines having PMs on stator yoke. (a) Field winding coil pitch of 1 [70]. (b) Field winding coil pitch of 2 [71].

In Fig. 13, the HE machines developed from the flux reversal PM machine are presented. In [72] and [73], PMs are located at the edge and center of the stator tooth, respectively, whereas the field winding is placed in the stator slots as shown in Fig. 13 (a) and (b). Moreover, consequent pole machines with PMs alternately located at the tooth center is proposed in [74], as shown in Fig. 13 (c). The magnetic field of the DC coils is in parallel with PMs, which can ensure the flux regulation capability. It should be noted that the machines discussed in [73] and [74] are the DC-biased HE machines without field winding, and Figs. 13 (b) and (c) present the potential field winding location for comparison. The integrated field and armature windings technique will be detailed in the last section.

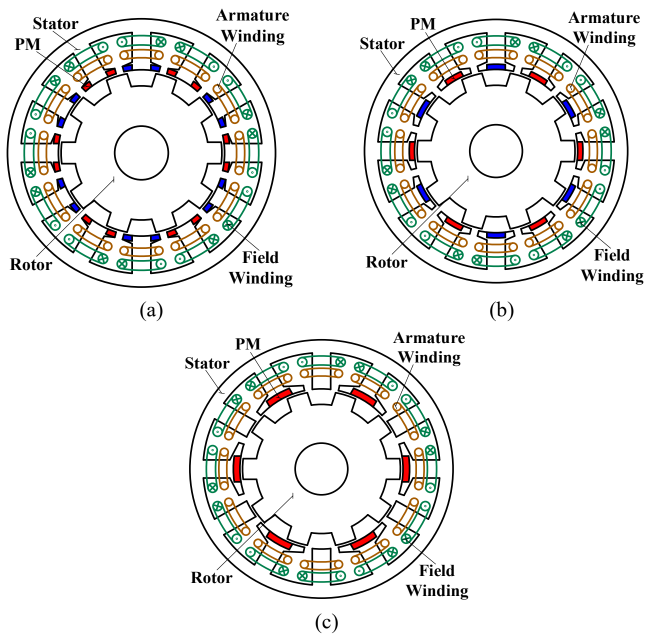


Fig. 13. Flux reversal HE machines. (a) PM sandwiching iron pole [72]. (b) Iron pole sandwiching PM [73]. (c) Consequent-pole with PMs alternately sandwiched by iron pole [74].

Flux switching PM machines utilize the flux-concentrating effect of circumferentially magnetized PMs, and possess comparable torque density as IPM machines [75]. Therefore, the HE machines developed based on flux switching PM machines are most widely investigated, as shown in Figs. 14-16.

In Fig. 14 (a), the flux switching HE machine is achieved by attaching additional stator yoke for DC excitation flux path [76]. However, the stator outer diameter is enlarged compared with the conventional flux switching PM machine. In Fig. 14 (b), a part of PM is replaced by a DC coil to achieve hybrid excitation [77]. The location, polarity, and flux regulation mechanism of the DC excitation have been investigated in [78]-[80]. To avoid the flux lines of DC excitation passing through the PM, an iron bridge has been introduced in Fig. 14 (c) [81]. In fact, the flux switching HE machines in Figs. 14 (a) and (c) share similar operating principle and topology, whereas the difference can be perceived as the thickness of iron bridge. Moreover, PM pole-pair and DC pole-pair can be allocated alternately to achieve parallel hybridization in Fig. 14 (d) [78]. In [82], a novel E-core stator is proposed for the flux switching HE machine, as shown in Fig. 14 (e). Similarly, it is extended to an axial flux E-core HE flux switching machine in [83]. In Fig. 14 (f), a field winding is introduced in the stator slots of a conventional flux switching PM machine [84]. However, only flux weakening can be achieved via magnetic saturation.

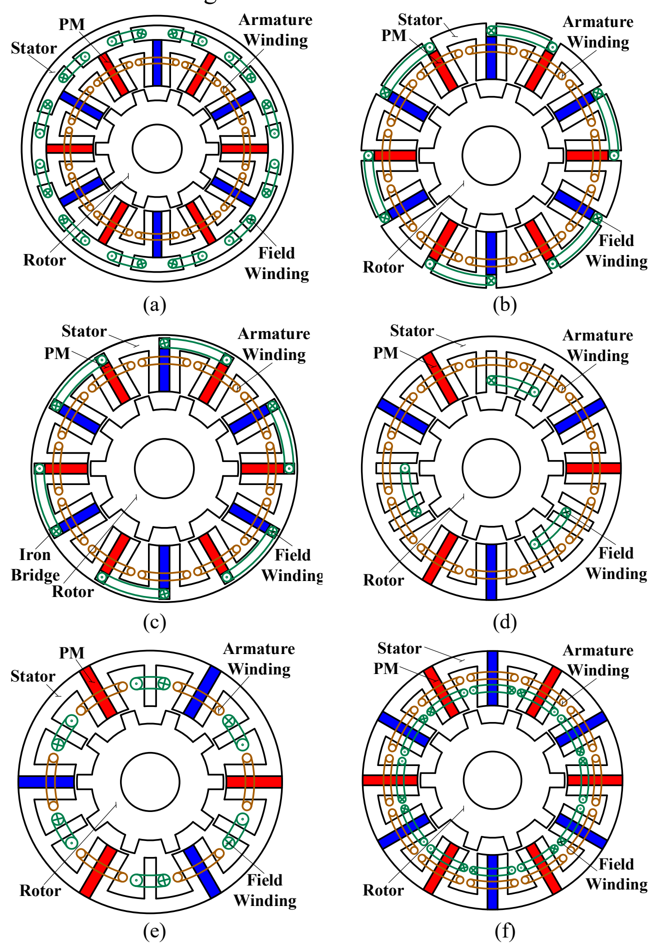


Fig. 14. Flux switching HE machines. (a) HE machine with additional stator yoke and field winding [76]. (b) HE machine with DC coil replacing part of PM [77]. (c) HE machine with iron bridge [81]. (d) HE machine with PM pole-pair and DC pole-pair locating alternately [78]. (e) HE machine with E-core segment [82]. (f) HE machine with by adding field winding in stator slots [84].

In Fig. 15, the two-part flux switching HE machine is proposed by combining a flux switching PM machine and a WF flux switching machine directly [85]. The stators are split into a PM field stator and a WF stator, as shown in Figs. 15 (a) and (b), respectively. The HE structure inherently possesses parallel hybridization and a wide flux regulation range.

In Fig. 16. HE flux switching machines with a segmental rotor have been discussed [86]. Field winding can be wound on the PM poles directly in Fig. 16 (a) or wound alternately with PM poles in Fig. 16 (b). The machine shown in Fig. 16 (a) is series hybridization whereas parallel hybridization is achieved in Fig. 16 (b).

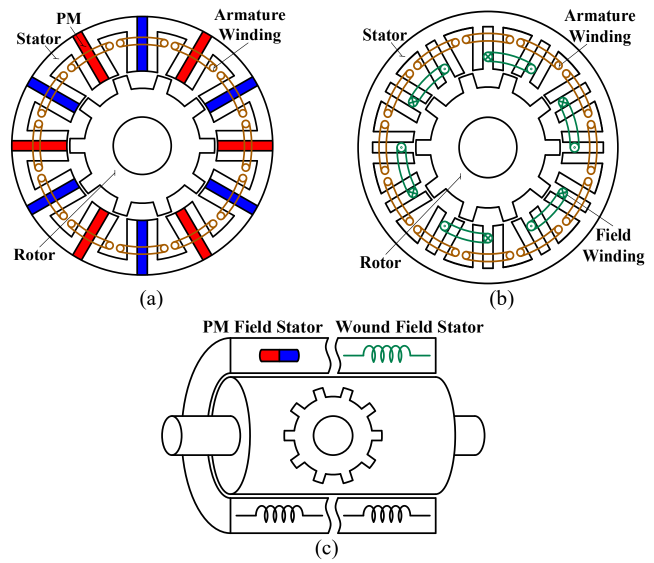


Fig. 15. HE flux switching machine with the combination of two stators [85]. (a) Flux switching PM machine. (b) Flux switching WF machine. (c) HE machine with the combination of PM field stator and WF stator.

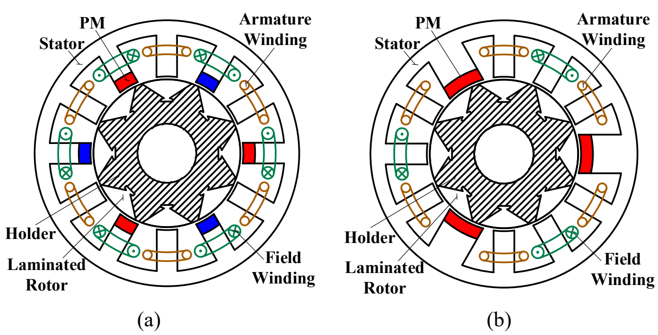


Fig. 16. HE flux switching machines with segmental rotor [86]. (a) PM and field winding in the same pole. (b) PM and field winding in alternate pole.

Besides locating PMs in the stator yoke, stator tooth tip, stator tooth center, the HE machines with stator slot PM are shown in Figs. 17 (a) and (b) [87] [88]. The PM flux is short-circuited in stator at open-circuit, and the HE machine potentially exhibits high speed fault tolerant capability. When field winding is excited, PM flux is pushed to link with air-gap, and the field excitation can regulate the magnetic field effectively. Furthermore, different stator/rotor pole combinations and overlapping windings are introduced for the HE stator slot PM machine [89].

Although the HE machines with both stator PM and stator DC coil exhibit good heat management, the stator is crowded with PM, field winding and armature winding. To solve the spatial confliction, HE machines with partitioned stator have been proposed in Fig. 18 [90]-[96]. HE machines with inner stator to

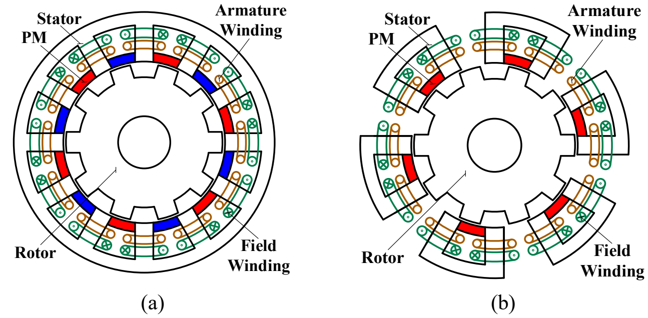


Fig. 17. HE machine having PMs in stator slots. (a) Stator slot HE machine [87]. (b) Modular stator HE machine [88].

PM are shown in Figs. 18 (a)-(c), respectively [90]-[92]. In [93],the PM is further moved from the inner stator yoke to the inner stator tooth tip to reduce the iron bridge flux leakage. Besides, the field winding poles can be employed to replace the PM South poles or a pair of PM poles as shown in Figs. 18 (d) and (e), respectively [94] [95]. It should be noted that PMs and field winding are in series hybridization in Fig. 15 (d) and parallel hybridization in Fig. 15 (e). Furthermore, PMs can be allocated in the inner stator slots of field winding to alleviate the magnetic saturation and enhance flux regulation capability [96].

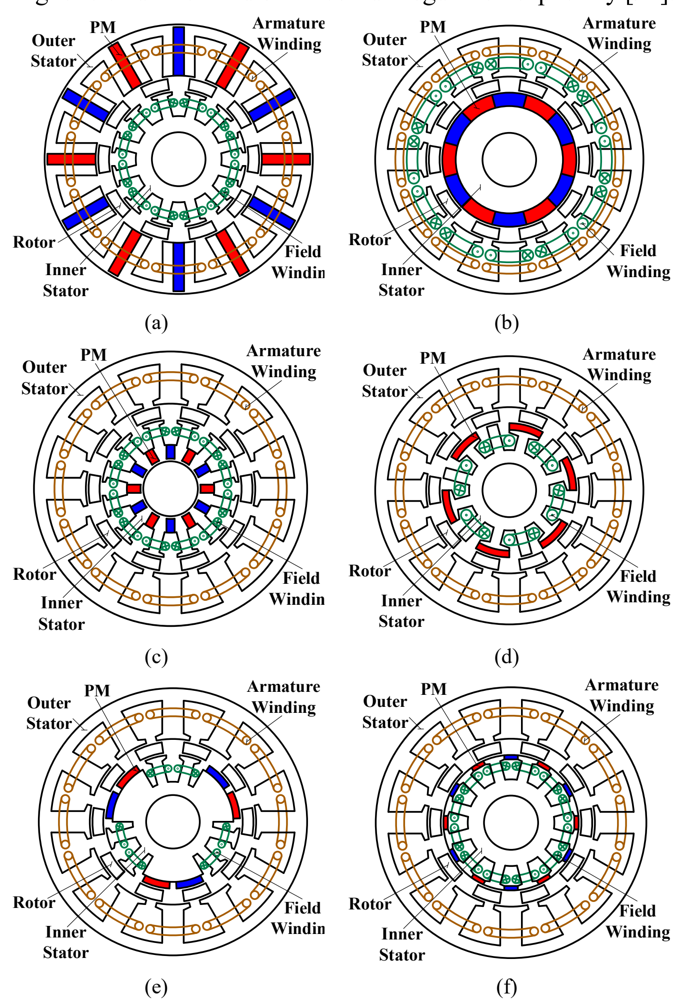


Fig. 18. HE machines having partitioned stators. (a) Inner stator accommodates field winding [90]. (b) Inner stator accommodates PMs [91]. (c) Inner stator accommodates both field winding and PMs [92]. (d) Field winding poles replacing PM South poles [94]. (e) Field winding poles replacing pairs of PM poles [95]. (f) PMs in the inner stator slots of field winding [96].

To conclude, the HE machines discussed in Fig. 11-Fig. 18 can be perceived as the combination of a stator PM machine with a stator WF machine. The machine structure is generally simple without brushes and slip rings. All the excitations are located in the stator and the heat management is efficient. However, the stator spatial confliction problem exists with the PM, field winding and armature winding. Although partition stator concept has been utilized in Fig. 18, the segmental rotor requires mechanical connection, making the manufacturing and assembling complex.

D. Others

Moreover, Vernier machine with stator and rotor PM has been widely investigated due to high torque density. HE machines based on stator and rotor PM Vernier machines are presented in Fig. 19 [97] [98]. PMs are located in stator tooth tip and rotor surface with consequent pole, whereas the field winding is placed in the stator slots. Series hybridization and parallel hybridization are presented in Figs. 19 (a) and (b), respectively.

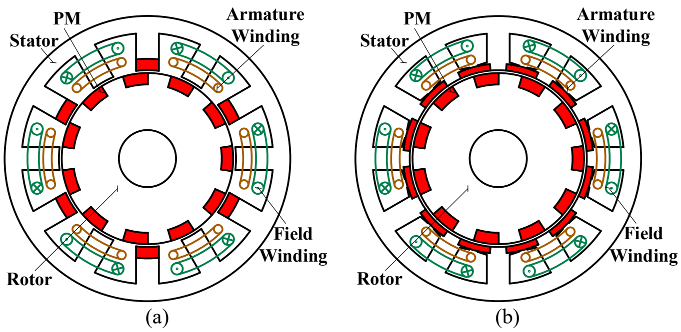


Fig. 19. HE machines based on Vernier PM machines. (a) Series hybridization of field winding and stator PMs [97]. (b) Parallel hybridization of field winding and stator PMs [98].

III. SERIES AND PARALLEL HYBRIDIZATION

According to the connection of PM and DC excited magnetic fields, HE machines can be classified as series hybridization and parallel hybridization. If the flux lines of DC excitation pass through PM, series hybrid excitation is achieved. In this section, the series and parallel hybridization characteristic of the above HE machines will be analyzed.

A. Series Hybridization

In the series HE machines, the PM and DC excitations share the same flux path, and the DC coil is simply wound around the PM pole. The series HE machines have been developed from the rotor SPM machine (Fig. 1 [20]-[23]), the stator doubly salient PM machine (Figs. 11 (a) and (b) [61] [62]), the flux switching PM machine (Fig. 14 (b) [77]-[80], Fig. 16 (a) [86]), the partitioned stator PM machine (Figs. 18 (b) (d) [91] [94]), and the Vernier machine (Fig. 19 (a) [97]) by replacing a part of PM with a DC coil, or adding a DC coil around the PM.

Generally speaking, the series HE machines possess simple structure with the combination of PM and DC excitation. However, the DC flux path is of significant reluctance and the flux regulation capability is limited. Moreover, the flux lines of DC excitation passing through the PM may potentially cause irreversible demagnetization.

B. Parallel Hybridization

Compared with series HE machine, the flux path of DC excitation in the parallel HE machine bypasses the PM. Therefore, the flux regulation capability can be enhanced and the risk of demagnetization is reduced. Therefore, the parallel HE machine is more popular considering electromagnetic performance. The parallel HE machine discussed above can be summarized as follows.

Type I: Iron bridge to provide additional flux path for DC excitation. This concept has been utilized in the IPM HE machine (Fig. 3 [23]), the doubly salient HE machine (Fig. 11 (c) [64] [65]), the flux switching HE machine (Figs. 15 (a) (c) [76] [81]), the partitioned stator HE machine (Figs. 18 (a) (c) [90] [92]). However, since the iron bridge is saturated by the PM flux, the reluctance of DC flux path is still large and the flux regulation ratio is restricted.

Type II: One pole consisting of PM and DC excitation parallel. This classification of HE machine contains the SPM HE machine (Fig. 6 [31]-[36]), the IPM HE machine (Fig. 3 (b) [23]), the flux reversal HE machine (Fig. 13 [72]-[74]), the partitioned stator HE machine [93], and the Vernier HE machine (Fig. 19 (b) [98]). Obviously, the PM should be located at the stator or rotor tooth tip, and otherwise, the PM flux short-circuits from the DC flux path as Type I.

Type III: Two-part parallel HE machine by combining a PM machine and a WF machine axially. The two-part rotor PM HE machine discussed in Fig. 5 [29] [30] shares the same stator, whereas the two-part flux switching HE machine discussed in Fig. 15 [85] shares the same rotor. Moreover, the two-part HE machine can consist of both different stators and rotors. In [99] [100], the rotor PM machine is combined with a doubly salient WF machine to achieve parallel hybridization. It should be noted an additional axial gap is introduced due to end-winding of field coils, and the axial length is increased inevitably.

Type IV: PM pole-pairs and DC pole-pairs alternately allocated. This concept has been employed in the SPM HE machine (Fig. 2 [24]), the doubly salient HE machine (Fig. 11 (d) [67] [68]), the flux switching HE machine (Fig. 14 (d) [78], Fig. 16 (b) [86]), and the partitioned stator HE machine (Fig. 18 (e) [95]).

Type VI: Slot PM HE machine with tangential magnetized PM. This classification includes the rotor slot PM HE machine (Fig. 4 [25]-[28]), the stator slot PM HE machine (Fig. 17 [87]-[89]), the partitioned stator slot PM HE machine (Fig. 18 (f) [96]), and the claw pole slot PM HE machine (Fig. 9 [51]-[54]). Since the PM flux is short-circuited without field excitation, the slot PM HE machines exhibit high fault tolerant capability.

Type V: Toroidal field winding with additional flux path. In Fig. 7-Fig.11, a stationary toroidal field winding is added for the rotor PM machine to regulate magnetic field [37]-[58]. The DC excitation has both radial and axial fluxes, and consequently, SMC or solid stator and rotor cores are required to allow for 3D flux. The benefit of this classification is better spatial utilization with separate PM and DC flux paths. However, the machine configuration is complex and manufacturing can be expensive.

Although the flux path of DC excitation bypasses the PM in the above topologies, the HE machine with iron bridge (Type I) possesses a lower flux regulation capability due to saturated iron bridge. Therefore, the HE machine with iron bridge can be classified as the third type beside series and parallel hybridizations [101].

IV. 2D and 3D Magnetic Fields

According to the magnetic fields of PM and DC excitations, HE machines can also be classified into 2D and 3D HE machines. If the PM and DC excitations have both radial and axial fluxes, it is called as a 3D HE machine.

A. 2D Magnetic Field

2D HE machine can be achieved by attaching a rotary DC coil to the rotor PM machines (Figs. 1-6 [20]-[36]), or a stationary DC coil to the stator PM machines (Figs. 11-19 [61]-[98]). The hybridization can be either in series or parallel, as illustrated in Section III.

Overall, the machine structure is simple for designing, optimizing, manufacturing, and assembling. However, since the PM and DC excitations are located in the same component (stator or rotor), the spatial confliction inevitably results in limited torque density as well as flux regulation capability.

B. 3D Magnetic Field

Compared with 2D HE machine, the 3D magnetic field structure is more complex. As shown in Figs. 7-10 [37]-[58], the HE machines with rotor PM and toroidal field winding have both radial and axial fluxes. The field excitation has separate axial flux path with PM excitation, and therefore, this classification of HE machine is generally parallel hybrid with a wide flux regulation range.

Since the toroidal field winding is located at the end or center of stator core, the spatial utilization is improved. However, SMC or solid material stator and rotor cores are required for both radial and axial fluxes, making the manufacturing and assembling complex.

V. Typical Flux Regulation Performance

In the previous sections, various HE machine topologies have been overviewed, and the benefits as well as drawbacks are demonstrated. In this section, a typical flux switching HE machine, shown in Fig. 14 (a), is chosen to illustrate the basic flux regulation of hybrid excitation.

The open-circuit field distribution of the HE machine is illustrated in Fig. 20. The DC and PM excitations are in parallel, and the field excitation can regulate the flux density effectively. Fig. 21 shows the flux linkage variation with field excitation current density. It can be observed that the field excitation can control the magnetic field as well as the flux linkage. Without PM excitation, i.e. B_r=0, the effect of positive and negative DC excitation is symmetrical. With the increase of PM remanence, the flux regulation ratio is reduced due to magnetic saturation. Overall, the DC current can regulate the flux linkage, and consequently the output capability according to the EV/HEV requirements effectively. At low speed operation, positive DC excitation can be employed to improve the starting torque. At high speed operation, negative DC excitation can be injected to weaken the magnetic field.

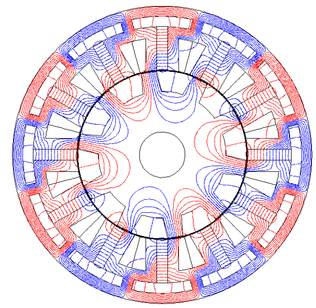


Fig. 20. Field distribution of flux switching HE machine.

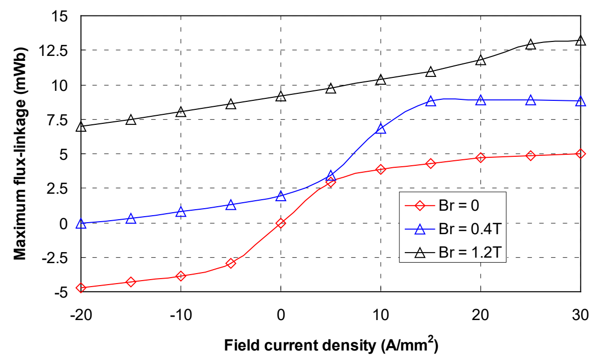


Fig. 21. Flux linkage variation with field excitation for the flux switching HE machine.

VI. Flux Weakening Control Strategies

An important issue for EV/HEV is wide constant power speed region (CPSR) and potential to operate at deep flux weakening region [102] [103]. Different from conventional PM machines, both the field excitation current and the *d*-axis current can be utilized to adjust the magnetic field in the HE machines, which provides more flexible control parameters for flux-weakening operation [104]. It has been revealed that better flux weakening performance can be expected for HE machine compared with conventional PM machine in [105]. In [106], a novel flux weakening control strategy is discussed for the HE machine by utilizing double excitations to enhance the flux weakening performance.

Therefore, three control strategies can be employed during flux weakening control, i.e. (1) utilization of field excitation current only, (2) utilization of armature current only, and (3) utilization of both field and armature current, as listed in Table I.

Table I
Flux Weakening Control Strategies for HE Machines

	Method I	Method II	Method III
I_f	Varying	Constant	Varying
I_d	Constant	Varying	Varying
I_q	Varying	Varying	Varying

In [107], the three flux weakening control strategies are conducted on a stator slot PM HE machine shown in Fig. 17 (a). The measured torque, power and efficiency map with three flux weakening strategies are compared in Fig. 22. The efficiency is relatively low due to the experiments on a small motor with only 90mm outer diameter and 25mm axial length and thus the mechanical loss is a major portion. At constant torque region, all three methods can achieve the same output torque due to the same flux-enhancing field excitation currents. In the flux weakening region, the torque of Method-I deteriorates significantly and the operating speed range is also limited by weakening field excitation current only. Based on the utilization of the optimal field excitation and d-axis armature currents, Method-III can obtain a wider speed region compared with Method-I, and achieve higher efficiency in the flux weakening region compared to Method-II.

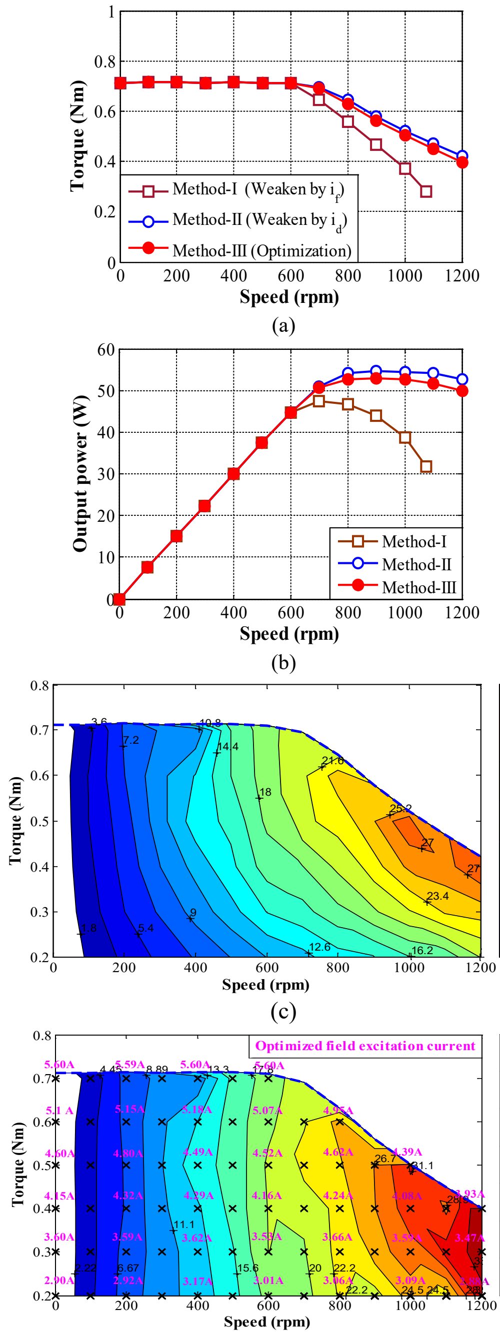


Fig. 22. Measured torque, power, and efficiency maps with different flux weakening strategies [107]. (a) Torque-speed envelope. (b) Power-speed envelope. (c) Efficiency map by regulating d-axis current only with constant maximum field excitation (Method II). (d) Efficiency map by regulating both field and d-axis currents (Method III).

Moreover, a self-optimization method of field current based on variable step size search theory is proposed in [108]. In [109], the minimum copper loss and maximum torque control strategies under flux weakening region are investigated. In [110], an optimized maximum torque per copper loss control strategy is investigated for HE machine. In [111], an improved control strategy for maximum output power is presented with the consideration of winding resistance and magnetic saturation.

VII. Recent Development

A. *Fault Tolerant Hybrid Excited Machine*

The PM machines have been popular due to high torque density and efficiency. However, some parasitic effect exists in the PM machines inevitably, such as cogging torque and potential uncontrolled overvoltage fault at high speed operation. Recently, the slot PM HE machines have been investigated and are shown to exhibit high fault tolerant capability. The slot PM HE machine can be classified into the rotor slot PM HE machine (Fig. 4 [25]-[28]), the stator slot PM HE machine (the single stator in Fig. 17 [87]-[89] and the partitioned stator in Fig. 18 (f) [96]), and the claw pole slot PM HE machine (Fig. 9 [51]-[54]). All the slot PM HE machines share similar operating principle and characteristic.

The stator slot PM HE machine in Fig. 17 (a) is taken as an example, and the flux paths with/without field excitation are illustrated in Fig. 23. Without field excitation, the PM flux is short-circuited in the stator and hardly link with the rotor. When the field current is employed, the PM flux is pushed to link with the rotor and air-gap flux density is produced. As salient rotor moves, the flux variation will produce back-EMF in the armature winding. Fig. 24 shows the open-circuit back-EMF with different DC excitations for the stator slot PM HE machine. The back-EMF is almost 0 without DC excitation and the amplitude can be regulated by the field current, verifying the theoretical analysis.

Compared with the stator WF machine, the introduction of PM alleviates the magnetic saturation and further improves the torque density. Compared with other PM machine, the PM flux hardly links with rotor without DC excitation, and the cogging torque is negligible. Furthermore, the open-circuit back-EMF caused by PM only is almost 0. Therefore, the slot PM HE machines exhibit high fault tolerant capability considering high speed operation (see next sub-section), which is critical for EV/HEV. It has been revealed in [112] that the torque density of variable flux reluctance machine is slightly lower than the IPM machine. The allocation of stator slot PM can further enhance the output capability, and the torque density of the slot PM HE machine can be comparable with the IPM machine.

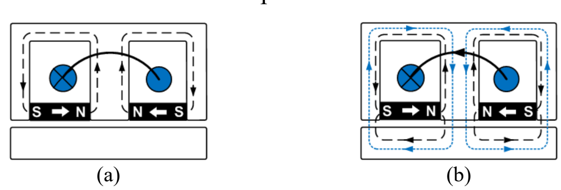


Fig. 23. Schematic of PM and DC flux paths for stator slot PM HE machine at open-circuit. (a) Without field excitation. (b) With field excitation.

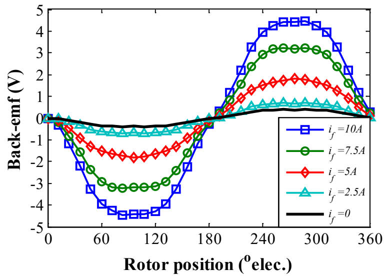


Fig. 24. Open-circuit back-EMF corresponding to the DC excitation current for the stator slot PM HE machine.

B. Uncontrolled Overvoltage Fault Mitigation

For the EV/HEV with high requirements of safe operation and fault tolerance in extreme environments, reliability of the machine system must be considered [113] [114]. Among the various machine fault types, the uncontrolled generator fault (UCGF) at high speed is one of the most serious faults that could damage the drive system [115] [116]. It occurs when the gating control signals of the inverter switches are suddenly removed during operation. This damage can be more severe for the PM machines since the magnetic field is hard to regulate and the back-EMF can be several times higher than the rated supply voltage at high speed.

In order to extend the operating region within the current and voltage limits, flux-weakening control is demanded for PM machines [102] [103]. Should the flux-weakening control signals unexpectedly disappear during high speed operation, the winding with high back-EMF would instantaneously become a large voltage source, and deliver regenerated current back to the DC-link through the free-wheeling diodes of the inverter switches, as shown in Fig. 25. If the DC-link capacitor cannot absorb the abruptly regenerative energy, both the capacitor and inverter switches may be damaged as the result of overvoltage. Therefore, a trade-off between healthy operating performance and fault tolerance capability is required during optimization for PM machines [117].

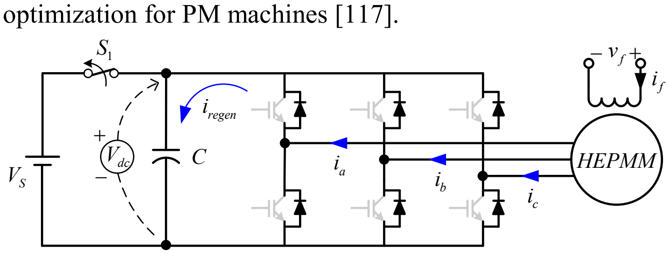


Fig. 25. Uncontrolled generator fault due to the remove of gate signals.

For HE machines with the combination of PM and WF magnetic fields, the magnetic field can still be weakened by field excitation at the UCGF. In [118], a field excitation control strategy with fault protection is proposed as shown in Fig. 26. In normal operation, the maximum flux-enhancing field excitation current is employed to achieve the highest torque. When the UCGF occurs, the DC-link capacitor is rapidly charged by the regenerated current. Therefore, the DC-link voltage can be measured as the detection of UCGF, and consequently the field excitation current can be diminished to protect the inverter from overvoltage damage.

The UCGF experiment is conducted on a stator slot PM HE machine shown in Fig. 17 (a) and the test results are presented in Fig. 27. The field current is maximized to achieve high output capability at healthy operation. When the UCGF occurs, the DC-link capacitor is rapidly charged, which potentially damages the inverter. However, the overvoltage problem in the DC-link capacitor can be eliminated by removing the field excitation. The regenerated current as well as power storage in capacitor can be sharply reduced to zero by controlling DC excitation, which is beneficial to protect the capacitors and inverter switches.

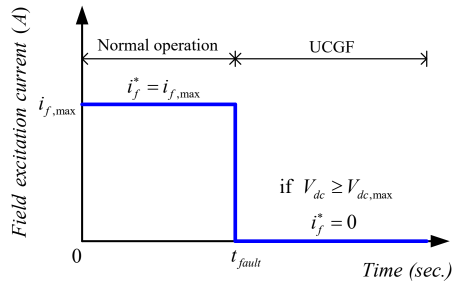


Fig. 26. Field excitation control strategy with fault protection [118].

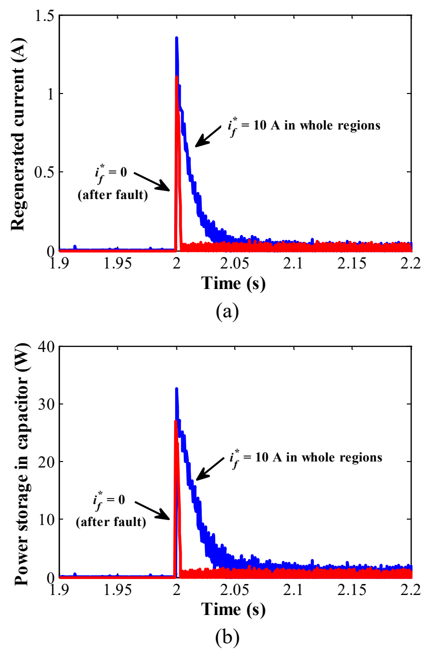


Fig. 27. Measured regenerated current and power storage in capacitor of the proposed fault protection method (i_f^*= 0) compared to the method that utilising the maximum field excitation current in whole regions (i_f^*= 10 A) [118]. (a) Regenerated current, (b) Measured power storage in capacitor.

C. Integrated Hybrid Excitation with Open-Winding

Since the HE machine contains PM, field and armature windings, the spatial confliction inevitably restricts the torque density as well as flux regulation capability. In [119], the field and armature windings are integrated with open-winding inverter shown in Fig. 28. Different from conventional machines, the neutral point of three-phase armature winding is released. The terminals of each phase winding are connected to two inverters at the same time, so that zero-sequence, i.e. DC excitation, can flow in the winding. Since the field winding is removed with open-winding, in the integrated HE machine it is DC coil free [120].

Besides, the conductor area for DC and AC excitation is enlarged with integrated winding, and consequently, the copper loss can be reduced and the operating range can be extended. Furthermore, Fig. 29 shows the measured operating envelopes with separate as well as integrated DC and AC winding. The operating range is extended and efficiency is improved due to the reduction of winding resistance. Moreover, the voltage utilization ratio is increased with open-winding drive circuit, which is beneficial to the low voltage battery supplied EV/HEV.

The concept to integrate field and armature winding using open-winding technique is firstly introduced in the variable flux reluctance machine in [119]. Then, it is further extended to the flux reversal HE machine (Fig. 13 [73] [74]), the flux modulated HE machine (Fig. 18 (b) [91]), and the Vernier HE machine (Fig. 19 [121]). In fact, the integrated field and armature winding technique is suitable for all the HE machines with DC and AC coils in the same slots to further enhance the performances.

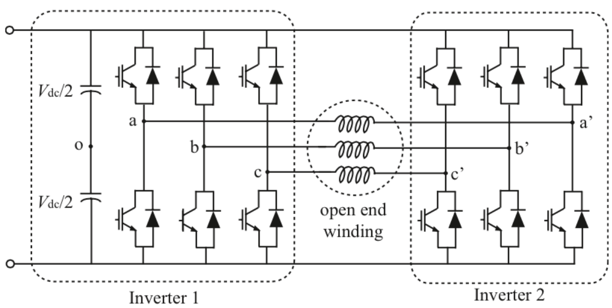
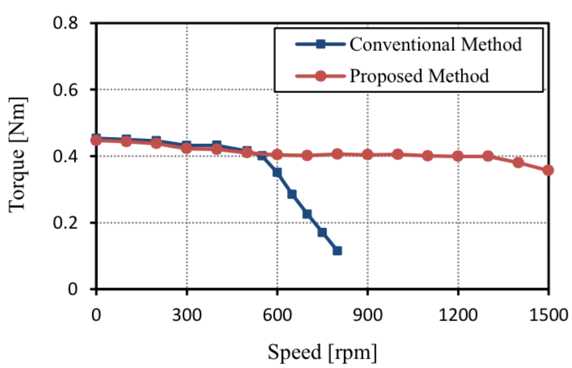
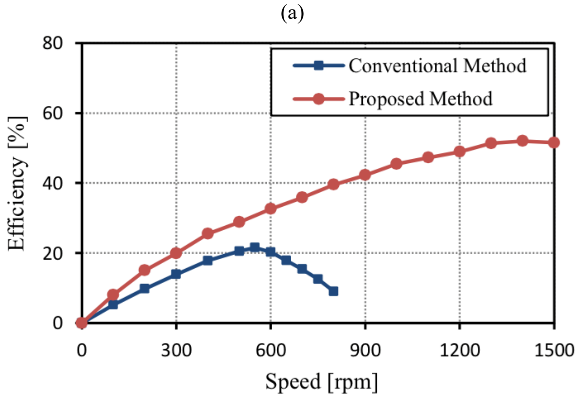


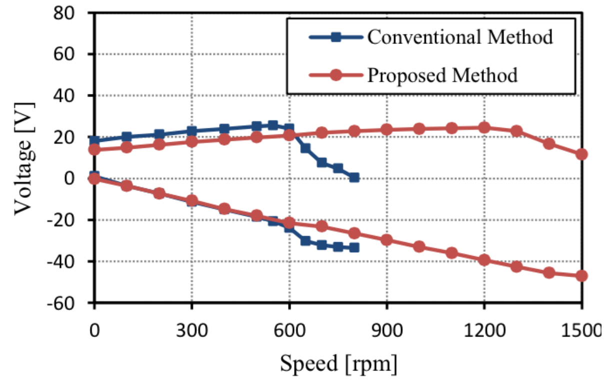
Fig. 28. Open-winding inverter with single voltage source.



(a)



(b)



(c)

Fig. 29. Measured operating envelopes with separate field and armature winding (conventional method) as well as integrated field and armature winding (proposed method with open-winding technique) [119]. (a) Torque-speed curves. (b) Efficiency-speed curves. (c) Voltage-speed curves.

VIII. Conclusion

Various HE machine topologies have been reviewed according to the allocation of PM and field winding excitations, the series and parallel hybridization, as well as 2D and 3D magnetic fields together with the flux regulation capability. Since an extra flexibility is introduced by field winding, different flux weakening control strategies of HE machines were discussed. Thanks to the controllable magnetic field, the HE machines can potentially mitigate the generator fault caused by overvoltage at high speed by regulating the field excitation. Finally, the integrated field and armature winding technique using open-winding is introduced for HE machine to solve the spatial confliction of PM, field and armature windings.

References

[1] Z. Q. Zhu and D. Howe, "Electrical machines and drives for electric, hybrid, and fuel cell vehicles," in *Proceedings of the IEEE*, vol. 95, no. 4, pp. 746-765, April 2007.

[2] C. C. Chan, "The state of the art of electric, hybrid, and fuel cell vehicles," in *Proceedings of the IEEE*, vol. 95, no. 4, pp. 704-718, April 2007.

[3] N. Bianchi, S. Bolognani, E. Carraro, M. Castiello and E. Fornasiero, "Electric vehicle traction based on synchronous reluctance motors," *IEEE Trans. Ind. Appl.*, vol. 52, no. 6, pp. 4762-4769, Nov.-Dec. 2016.

[4] M. Kamiya, "Development of traction drive motors for the Toyota hybrid system," *IEEJ Trans. on Ind. Appl.,* vol. 126, pp. 473-479, 2006.

[5] Y. Sato, S. Ishikawa, T. Okubo, M. Abe, and K. Tamai, "Development of high response motor and inverter system for the Nissan LEAF electric vehicle," *SAE Technical Paper*, 0148-7191, 2011.

[6] R. Wilden and S. P. Gudergan, "The impact of dynamic capabilities on operational marketing and technological capabilities: investigating the role of environmental turbulence," *Journal of the Academy of Marketing Science,* vol. 43, pp. 181-199, 2015.

[7] W. L. Soong and N. Ertugrul, "Field-weakening performance of interior permanent-magnet motors," *IEEE Trans. Ind. Appl.*, vol. 38, no. 5, pp. 1251-1258, Sept.-Oct. 2002.

[8] T. Raminosoa, C. Gerada and M. Galea, "Design considerations for a fault-tolerant flux-switching permanent-magnet machine," *IEEE Trans. Ind. Electron.*, vol. 58, no. 7, pp. 2818-2825, July 2011.

[9] Y. Wang and Z. Deng, "Hybrid excitation topologies and control strategies of stator permanent magnet machines for DC power system," *IEEE Trans. Ind. Electron.*, vol. 59, no. 12, pp. 4601-4616, Dec. 2012.

[10] J. F. Gieras, "PM synchronous generators with hybrid excitation systems and voltage control Capabilities: A review," in *Proc. 2012 XXth*

International Conference on Electrical Machines, Marseille, 2012, pp. 2573-2579.

[11] C. H. Zhao and Y. G. Yan, "A review of development of hybrid excitation synchronous machine," in *Proceedings of the IEEE International Symposium on Industrial Electronics, 2005. ISIE 2005*, Dubrovnik, Croatia, 2005, pp. 857-862 vol. 2.

[12] X. Y. Zhu, M. Cheng, W. X. Zhao, J. Z. Zhang and W. Hua, "An overview of hybrid excited electric machine capable of field control," *Transactions of China Electrotechnical Society,* vol. 23, pp. 30-39, 2008.

[13] R. Owen, Z. Q. Zhu, J. B. Wang, D. A. Stone and I. Urquhart, "Review of variable-flux permanent magnet machines," in *Proc. 2011 International Conference on Electrical Machines and Systems*, Beijing, 2011, pp. 1-6.

[14] J. Huang, X. J. Wang and Z. C. Sun, "Variable flux memory motors: A review," in *Proc. 2014 IEEE Conference and Expo Transportation Electrification Asia-Pacific (ITEC Asia-Pacific)*, Beijing, 2014, pp. 1-6.

[15] Q. Wang and S. Niu, "Overview of flux-controllable machines: Electrically excited machines, hybrid excited machines and memory machines," *Renewable and Sustainable Energy Reviews,* vol. 68, pp. 475-491, 2017.

[16] Y. Amara, S. Hlioui, R. Belfkira, G. Barakat and M. Gabsi, "Comparison of open circuit flux control capability of a series double excitation machine and a parallel double excitation machine," *IEEE Trans. Veh. Technol.*, vol. 60, no. 9, pp. 4194-4207, Nov. 2011.

[17] Y. Amara, L. Vido, M. Gabsi, E. Hoang, A. H. Ben Ahmed and M. Lecrivain, "Hybrid excitation synchronous machines: energy-efficient solution for vehicles propulsion," *IEEE Trans. Veh. Technol.*, vol. 58, no. 5, pp. 2137-2149, Jun 2009

[18] S. Hlioui, Y. Amara, E. Hoang, M. Lecrivain and M. Gabsi, "Overview of hybrid excitation synchronous machines technology," in *Proc. 2013 International Conference on Electrical Engineering and Software Applications*, Hammamet, 2013, pp. 1-10.

[19] Z. Q. Zhu and S. Cai, "Overview of hybrid excited machines for electric vehicles," in *Proc. Keynote Speech at 2019 Eleventh International Conference on Ecological Vehicles and Renewable Energies (EVER)*, Monte Carlo, 2019.

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

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

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

[23] A. D. Akemakou and S. K. Phounsombat, “Electrical machine with double excitation, especially a motor vehicle alternator,” U.S. Patent 6 147 429, Nov. 14, 2000.

[24] X. Luo and T. A. Lipo, “A synchronous/permanent magnet hybrid AC machine,” *IEEE Trans. Energy Convers.*, vol. 15, no. 2, pp. 203–210, Jun. 2000.

[25] T. Fukami, Yasuhiro Matsui, Takahito Hayamizu, K. Shima, R. Hanaoka and S. Takata, "Steady-state analysis of a permanent-magnet-assisted salient-pole synchronous generator," in *Proc. 2008 18th International Conference on Electrical Machines*, Vilamoura, 2008, pp. 1-6.

[26] K. Yamazaki, S. Tamiya, K. Shima, T. Fukami, and K. Shirai, “Modeling of salient-pole synchronous machines assisted by permanent magnets,” *IEEE Trans. Magn.*, vol. 47, no. 10, pp. 3028–3031, Oct. 2011.

[27] S. Hwang, J. Sim, J. Hong and J. Lee, "Torque improvement of wound field synchronous motor for electric vehicle by PM-assist," *IEEE Trans. Ind. Appl.*, vol. 54, no. 4, pp. 3252-3259, July-Aug. 2018.

[28] L. R. Huang, Z. Q. Zhu, and W. Q. Chu, "Optimization of electrically excited synchronous machine for electrical vehicle applications," in *Power Electronics, Machines and Drives (PEMD 2016), 8th IET International Conference on*, 2016, pp. 1-6.

[29] C. Syverson, and W. Francis, “Hybrid alternator”, US Patent 5747909 B1/5 may 1998.

[30] N. Naoe and T. Fukami, "Trial production of a hybrid excitation type synchronous machine," in *Proc. IEMDC 2001. IEEE International Electric Machines and Drives Conference (Cat. No.01EX485)*, Cambridge, MA, USA, 2001, pp. 545-547.

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

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

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

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

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

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

[37] F. B. McCarty, “Hybrid excited generator with flux control of consequent-pole rotor,” U.S. Patent No. 4656379, Apr. 04, 1987.

[38] E. Spooner, S. A. W. Khatab and N. G. Nicolaou, "Hybrid excitation of AC and DC machines," in *Proc. 1989 Fourth International Conference on Electrical Machines and Drives Conf.*, London, UK, 1989, pp. 48-52.

[39] J. A. Tapia, F. Leonardi and T. A. Lipo, "Consequent-pole permanent-magnet machine with extended field-weakening capability," *IEEE Trans. Ind. Appl.*, vol. 39, no. 6, pp. 1704-1709, Nov.-Dec. 2003.

[40] M. Aydin, Surong Huang and T. A. Lipo, "A new axial flux surface mounted permanent magnet machine capable of field control," in *Proc. Conference Record of the 2002 IEEE Industry Applications Conference. 37th IAS Annual Meeting (Cat. No.02CH37344)*, Pittsburgh, PA, USA, 2002, pp. 1250-1257 vol.2.

[41] H. Wang, Z. An, R. Tang and Y. Niu, "Design of a hybrid excitation permanent magnet synchronous with low voltage regulation," in *Proc. 2005 International Conference on Electrical Machines and Systems*, Nanjing, 2005, pp. 480-483 Vol. 1.

[42] C. Yang, H. Lin, J. Guo and Z. Q. Zhu, "Design and analysis of a novel hybrid excitation synchronous machine with asymmetrically stagger permanent magnet," *IEEE Trans. Magn.*, vol. 44, no. 11, pp. 4353-4356, Nov. 2008.

[43] W. Li, T. W. Ching and K. T. Chau, "A new high-temperature superconducting Vernier permanent-magnet machine for wind turbines," *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, pp. 1-5, June 2017.

[44] L. Vido, M. Gabsi, M. Lecrivain, Y. Amara and F. Chabot, "Homopolar and bipolar hybrid excitation synchronous machines," in *Proc. IEEE International Conference on Electric Machines and Drives, 2005.*, San Antonio, TX, 2005, pp. 1212-1218.

[45] L. Vido, Y. Amara, M. Gabsi, M. Lecrivain and F. Chabot, "Compared performances of homopolar and bipolar hybrid excitation synchronous machines," in *Proc. Fourtieth IAS Annual Meeting. Conference Record of the 2005 Industry Applications Conference, 2005*, Kowloon, Hong Kong, 2005, pp. 1555-1560 vol. 3.

[46] S. Hlioui, L. Vido, Y. Amara, M. Gabsi, M. Lecrivain and A. Miraoui, "PM and hybrid excitation synchronous machines: performances comparison," in *Proc. 2008 18th International Conference on Electrical Machines*, Vilamoura, 2008, pp. 1-6.

[47] B. Nedjar, S. Hlioui, Y. Amara, L. Vido, M. Gabsi and M. Lecrivain, "A new parallel double excitation synchronous machine," *IEEE Trans. Magn.*, vol. 47, no. 9, pp. 2252-2260, Sept. 2011.

[48] Z. Zhang, Y. Yan, S. Yang and Z. Bo, "Principle of operation and feature investigation of a new topology of hybrid excitation synchronous machine," *IEEE Trans. Magn.*, vol. 44, no. 9, pp. 2174-2180, Sept. 2008.

[49] J. Han, Z. Zhang and S. M. Jiangsu, "Investigation of field regulation performance of a new hybrid excitation synchronous machine with dual-direction magnetic shunt rotor," in *Proc. 2011 International Conference on Electrical Machines and Systems*, Beijing, 2011, pp. 1-5.

[50] Y. Liu, Z. Zhang and X. Zhang, "Design and optimization of hybrid excitation synchronous machines with magnetic shunting rotor for electric vehicle traction applications," *IEEE Trans. Ind. Appl.*, vol. 53, no.

6, pp. 5252-5261, Nov.-Dec. 2017.

[51] C. C. Chan, K. T. Chau, J. Z. Jiang, W. Xia, M. Zhu and R. Zhang, "Novel permanent magnet motor drives for electric vehicles," *IEEE Trans. Ind. Electron.*, vol. 43, no. 2, pp. 331-339, April 1996.

[52] C. C. Chan, R. Zhang, K. T. Chau and J. Z. Jiang, "Optimal efficiency control of PM hybrid motor drives for electrical vehicles," in *Proc. PESC97. Record 28th Annual IEEE Power Electronics Specialists Conference. Formerly Power Conditioning Specialists Conference 1970-71. Power Processing and Electronic Specialists Conference 1972*, Saint Louis, MO, USA, 1997, pp. 363-368 vol.1.

[53] G. Henneberger and S. Küppers, "Improvement of the output performance of claw-pole alternators by additional permanent-magnets," *in Proc. ICEM*, Paris, France, 1994, pp. 472–476.

[54] H. Ishikawa, "AC generator for vehicle having combined structure of field coil and permanent magnet," U.S. Patent 5 825 116, Oct. 31, 1996.

[55] R. Rebhi, A. Ibala and A. Masmoudi, "An attempt to improve the generating capabilities of a hybrid claw pole machine," in *Proc. 2011 International Conference on Electrical Machines and Systems*, Beijing, 2011, pp. 1-5.

[56] R. Rebhi, A. Ibala and A. Masmoudi, "Hybrid excited claw pole alternators: Attempt to satisfy the increasing power need on board," in *Proc. 2014 17th International Conference on Electrical Machines and Systems (ICEMS)*, Hangzhou, 2014, pp. 3510-3514.

[57] T. Kosaka, Y. Kano, N. Matsui, and C. Pollock, "A novel multi-pole permanent magnet synchronous machine with SMC bypass core for magnet flux and SMC field-pole core with toroidal coil for independent field strengthening/weakening," in *Proc. 11th Eur. Conf. Power Electron. Appl.*, 2005, 10 pp

[58] T. Kosaka, M. Sridharbabu, M. Yamamoto and N. Matsui, "Design studies on hybrid excitation motor for main spindle drive in machine tools," *IEEE Trans. Ind. Electron.*, vol. 57, no. 11, pp. 3807-3813, Nov. 2010.

[59] M. Cheng, W. Hua, J. Zhang and W. Zhao, "Overview of stator-permanent magnet brushless machines," *IEEE Trans. Ind. Electron.*, vol. 58, no. 11, pp. 5087-5101, Nov. 2011.

[60] Z. Q. Zhu, "Switched flux permanent magnet machines — Innovation continues," in *Proc. 2011 International Conference on Electrical Machines and Systems*, Beijing, 2011, pp. 1-10.

[61] Yue Li and T. A. Lipo, "A doubly salient permanent magnet motor capable of field weakening," in *Proc. of PESC '95. Power Electronics Specialist Conference*, Atlanta, GA, USA, 1995, pp. 565-571 vol.1.

[62] K. T. Chau, Ming Cheng and C. C. Chan, "Nonlinear magnetic circuit analysis for a novel stator doubly fed doubly salient machine," *IEEE Trans. Magn.*, vol. 38, no. 5, pp. 2382-2384, Sept. 2002.

[63] K. T. Chau, J. Z. Jiang and Y. Wang, "A novel stator doubly fed doubly salient permanent magnet brushless machine," *IEEE Trans. Magn.*, vol. 39, no. 5, pp. 3001-3003, Sept. 2003.

[64] X. Y. Zhu and M. Cheng, "A novel stator hybrid excited doubly salient permanent magnet brushless machine for electric vehicles," in *Proc. 2005 International Conference on Electrical Machines and Systems*, Nanjing, 2005, pp. 412-415 vol. 1.

[65] X. Zhu, M. Cheng, W. Hua, J. Zhang and W. Zhao, "Design and analysis of a new hybrid excited doubly salient machine capable of field control," in *Proc. Conference Record of the 2006 IEEE Industry Applications Conference Forty-First IAS Annual Meeting*, Tampa, FL, 2006, pp. 2382-2389.

[66] C. Liu, K. T. Chau and J. Z. Jiang, "A permanent-magnet hybrid brushless integrated starter–generator for hybrid electric vehicles," *IEEE Trans. Ind. Electron.*, vol. 57, no. 12, pp. 4055-4064, Dec. 2010.

[67] Z. H. Chen, N. Zhou and X. L. Meng, "Analysis on a novel doubly salient machine," in *Proc. 2008 International Conference on Electrical Machines and Systems*, Wuhan, 2008, pp. 3522-3525.

[68] Z. Zhang, Y. Tao and Y. Yan, "Investigation of a new topology of hybrid excitation doubly salient brushless DC generator," *IEEE Trans. Ind. Electron.*, vol. 59, no. 6, pp. 2550-2556, June 2012.

[69] Z. Chen, B. Wang, Z. Chen and Y. Yan, "Comparison of flux regulation ability of the hybrid excitation doubly salient machines," *IEEE Trans. Ind. Electron.*, vol. 61, no. 7, pp. 3155-3166, July 2014.

[70] W. Xu and M. He, "Novel 6/7 stator/rotor hybrid excitation doubly salient permanent magnet machine," *IEEE Trans. Magn.*, vol. 52, no. 7, pp. 1-5, July 2016.

[71] M. J. He, W. Xu, C. Y. Ye, and W. Hua, "Design of hybrid excited asymmetric stator pole doubly salient machine," in *Proc. The XIX International Conference on Electrical Machines - ICEM 2018*, Greece, 2018.

[72] Y. Gao, D. Li, R. Qu, X. Fan, J. Li and H. Ding, "A novel hybrid excitation flux reversal machine for electric vehicle propulsion," *IEEE Trans. Veh. Technol.*, vol. 67, no. 1, pp. 171-182, Jan. 2018.

[73] S. Jia, R. Qu, J. Li, D. Li and H. Fang, "Hybrid excited Vernier PM machines with novel DC-biased sinusoidal armature current," *2016 IEEE Energy Conversion Congress and Exposition (ECCE)*, Milwaukee, WI, 2016, pp. 1-8.

[74] S. Jia, R. Qu, J. Li, D. Li and W. Kong, "A stator-PM consequent-pole vernier machine with hybrid excitation and dc-biased sinusoidal current," *IEEE Trans. Magn.*, vol. 53, no. 6, pp. 1-4, June 2017.

[75] A. Fasolo, L. Alberti and N. Bianchi, "Performance comparison between switching-flux and IPM machines with rare-earth and ferrite PMs," *IEEE Trans. Ind. Appl.*, vol. 50, no. 6, pp. 3708-3716, Nov.-Dec. 2014.

[76] E. Hoang, M. Lecrivain and M. Gabsi, "A new structure of a switching flux synchronous polyphased machine with hybrid excitation," in *Proc. 2007 European Conference on Power Electronics and Applications*, Aalborg, 2007, pp. 1-8.

[77] W. Hua, M. Cheng and G. Zhang, "A novel hybrid excitation flux-switching motor for hybrid vehicles," *IEEE Trans. Magn.*, vol. 45, no. 10, pp. 4728-4731, Oct. 2009.

[78] R. L. Owen, Z. Q. Zhu and G. W. Jewell, "Hybrid excited flux-switching permanent magnet machines," in *Proc. 2009 13th European Conference on Power Electronics and Applications*, Barcelona, 2009, pp. 1-10.

[79] G. Zhang, W. Hua, M. Cheng, J. Liao, K. Wang and J. Zhang, "Investigation of an improved hybrid-excitation flux-switching brushless machine for HEV/EV applications," *IEEE Trans. Ind. Appl.*, vol. 51, no. 5, pp. 3791-3799, Sept.-Oct. 2015.

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

[81] R. L. Owen, Z. Q. Zhu and G. W. Jewell, "Hybrid-excited flux-switching permanent-magnet machines with iron flux bridges," *IEEE Trans. Magn.*, vol. 46, no. 6, pp. 1726-1729, June 2010.

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

[83] W. Zhang, X. Liang, M. Lin, L. Hao and N. Li, "Design and analysis of novel hybrid-excited axial field flux-switching permanent magnet machines," *IEEE Trans. Appl. Supercond.*, vol. 26, no. 4, pp. 1-5, June 2016.

[84] B. Gaussens, E. Hoang, M. Lécrivain, P. Manfe and M. Gabsi, "A hybrid-excited flux-switching machine for high-speed DC-alternator applications," *IEEE Trans. Ind. Electron.*, vol. 61, no. 6, pp. 2976-2989, June 2014.

[85] H. Liu, Y. Wang, Z. Deng and L. Song, "Comparative study of the parallel hybrid excited flux-switching machine topology for aerospace generator system," in *Proc. 2014 IEEE Conference and Expo Transportation Electrification Asia-Pacific (ITEC Asia-Pacific)*, Beijing, 2014, pp. 1-6.

[86] H. Ali, E. bin Sulaiman, M. Jenal and M. F. Omar, "Three phase segmental rotor hybrid excitation flux switching motors for various applications," in *Proc. 2015 IEEE Student Conference on Research and Development (SCOReD)*, Kuala Lumpur, 2015, pp. 373-377.

[87] I. A. A. Afinowi, Z. Q. Zhu, Y. Guan, J. C. Mipo and P. Farah, "Hybrid-excited doubly salient synchronous machine with permanent magnets between adjacent salient stator poles," *IEEE Trans. Magn.*, vol. 51, no. 10, pp. 1-9, Oct. 2015.

[88] M. Zheng, Z. Q. Zhu, S. Cai and S. S. Xue, "A novel modular stator hybrid-excited doubly salient synchronous machine with stator slot permanent magnets," *IEEE Trans. Magn.*, early access.

[89] Z. Q. Zhu, H. Yang, S. Cai, H. Y. Li, Y. Liu, J. C. Mipo, S. Personnaz, "Hybrid excited stator slot PM machines with overlapping windings," in *Proc. 2018 XIII International Conference on Electrical Machines (ICEM)*, Alexandroupoli, 2018, pp. 2185-2191.

[90] H. Hua and Z. Q. Zhu, "Novel hybrid-excited switched-flux machine having separate field winding stator," *IEEE Trans. Magn.*, vol. 52, no. 7,

pp. 1-4, July 2016.

[91] S. Jia, R. Qu, D. Li, J. Li and W. Kong, "Improved torque capacity for flux modulated machines by injecting DC currents into the armature windings," *IEEE Trans. Magn.*, vol. 53, no. 6, pp. 1-5, June 2017.

[92] H. Hua and Z. Q. Zhu, "Novel partitioned stator hybrid excited switched flux machines," *IEEE Trans. Energy Convers.*, vol. 32, no. 2, pp. 495-504, June 2017.

[93] Z. Z. Wu and Z. Q. Zhu, 'Design and analysis of a novel partitioned stator hybrid excitation machine', *Proc. Chin. Soc. Electr. Eng.*, vol. 37, no. 22, pp. 6543–6556, 2017.

[94] H. Hua, Z. Q. Zhu and H. L. Zhan, "Novel consequent-pole hybrid excited machine with separated excitation stator," *IEEE Trans. Ind. Electron.*, vol. 63, no. 8, pp. 4718-4728, Aug. 2016.

[95] H. Hua and Z. Q. Zhu, "Novel parallel hybrid excited machines with separate stators," *IEEE Trans. Energy Convers.*, vol. 31, no. 3, pp. 1212-1220, Sept. 2016.

[96] H. Hua and Z. Q. Zhu, 'Novel partitioned stator hybrid excited machines with magnets on slot-openings'. in *Proc. Int. Conf. Power Electric Machines and Drives (PEMD)*, Liverpool, UK, April 2018

[97] Q. Wang and S. Niu, "A novel hybrid-excited dual-PM machine with bidirectional flux modulation," *IEEE Trans. Energy Convers.*, vol. 32, no. 2, pp. 424-435, June 2017.

[98] X. Zhao, S. Niu and W. Fu, "Design of a novel parallel-hybrid-excited dual-PM machine based on armature harmonics diversity for electric vehicle propulsion," *IEEE Trans. Ind. Electron*., 2018.

[99] W. Geng, Z. Zhang, K. Jiang and Y. Yan, "A new parallel hybrid excitation machine: permanent-magnet/variable-reluctance machine with bidirectional field-regulating capability," *IEEE Trans. Ind. Electron.*, vol. 62, no. 3, pp. 1372-1381, March 2015.

[100] Y. Wu, L. Sun, Z. Zhang, Z. Miao and C. Liu, "Analysis of torque characteristics of parallel hybrid excitation machine drives with sinusoidal and rectangular current excitations," *IEEE Trans. Magn.*, vol. 54, no. 11, pp. 1-5, Nov. 2018, Art no. 8207205.

[101] Y. Wang and Z. Deng, "Hybrid excitation topologies and control strategies of stator permanent magnet machines for DC power system," *IEEE Trans. Ind. Electron.*, vol. 59, no. 12, pp. 4601-4616, Dec. 2012.

[102] W. L. Soong and N. Ertugrul, "Field-weakening performance of interior permanent-magnet motors," *IEEE Trans. Ind. Appl.*, vol. 38, no. 5, pp. 1251-1258, Sept.-Oct. 2002.

[103] A. M. EL-Refaie and T. M. Jahns, "Optimal flux weakening in surface PM machines using fractional-slot concentrated windings," *IEEE Trans. Ind. Appl.*, vol. 41, no. 3, pp. 790-800, May-June 2005.

[104] W. Q. Chu, Z. Q. Zhu, J. Zhang, X. Liu, D. A. Stone and M. P. Foster, "Investigation on operational envelops and efficiency maps of electrically excited machines for electrical vehicle applications," *IEEE Trans. Magn.*, vol. 51, no. 4, pp. 1-10, April 2015.

[105] J. Zhao, M. Lin, D. Xu, L. Hao and W. Zhang, "Vector control of a hybrid axial field flux-switching permanent magnet machine based on particle swarm optimization," *IEEE Trans. Magn.*, vol. 51, no. 11, pp. 1-4, Nov. 2015, Art no. 8204004.

[106] L. Kefsi, Y. Touzani and M. Gabsi, "Hybrid excitation synchronous motor control with a new flux weakening strategy," *2010 IEEE Vehicle Power and Propulsion Conference*, Lille, 2010, pp. 1-5.

[107] N. Pothi, Z.Q. Zhu, and Yuan Ren, "Comparison of flux-weakening control strategies of novel hybrid-excited permanent magnet machines," *IEEE Trans. Ind. Appl.*, vol.55, no.4, pp. 3589-3597, 2019.

[108] Wenjia Wang and Z. Zhang, "Maximum torque control of hybrid excitation synchronous machine drives based on field current self-optimizing method," in *Proc. IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society*, Vienna, 2013, pp. 2977-2982.

[109] S. Shinnaka and T. Sagawa, "New optimal current control methods for energy-efficient and wide speed-range operation of hybrid-field synchronous motor," *IEEE Trans. Ind. Electron.*, vol. 54, no. 5, pp. 2443-2450, Oct. 2007.

[110] W. Ding and S. Li, "Maximum ratio of torque to copper loss control for hybrid excited flux-switching machine in whole speed range," *IEEE Trans. Ind. Electron.*, vol. 66, no. 2, pp. 932-943, Feb. 2019.

[111] X. Liu, Z. W. Yuan, S. H. Li and Z. Q. Zhu, "Field excitation optimization in hybrid excited switched flux permanent magnet machine for maximum output power," in *Proc. 2019 22th International Conference on Electrical Machines and Systems (ICEMS)*, Harbin, 2019, pp. 1-6.

[112] X. Liu, Z. Q. Zhu and D. Wu, "Evaluation of efficiency optimized variable flux reluctance machine for EVs/HEVs by comparing with interior PM machine," in *Proc. 2014 17th International Conference on Electrical Machines and Systems (ICEMS)*, Hangzhou, 2014, pp. 2648-2654.

[113] B. A. Welchko, T. A. Lipo, T. M. Jahn, and S. E. Schulz, "Fault tolerant three-phase AC motor drive topologies: A comparison of features, cost, and limitations," *IEEE Trans. Power Electron*., vol. 19 no. 4, pp. 1108-1116, Jul. 2004.

[114] C. Liu, K. T. Chau, and W. Li, "Comparison of fault-tolerant operations for permanent-magnet hybrid brushless motor drive," *IEEE Trans. Magn*., vol. 46, no. 6, pp. 1378–1381, Jun. 2010.

[115] T. M. Jahns and V. Caliskan, "Uncontrolled generator operation of interior PM synchronous machines following high speed inverter shutdown," *IEEE Trans. Ind. Appl*., vol. 35, no. 6, pp. 1347–1357, Nov./Dec. 1999.

[116] C. Z. Liaw, W. L. Soong, B. A. Welchko, and N. Ertugrul, "Uncontrolled generation in interior permanent-magnet machines," *IEEE Trans. Ind. Appl*., vol. 41, no. 4, pp. 945–954, Jul./Aug. 2005.

[117] G. Pellegrino, A. Vagati, and P. Guglielmi, "Design tradeoffs between constant power speed range, uncontrolled generator operation, and rated current of IPM motor drives," *IEEE Trans. Ind. Appl*., vol. 47, no. 5, pp. 1995–2003, Sep./Oct. 2011.

[118] Z. Q. Zhu, N. Pothi, Peilin Xu, Yuan Ren, "Uncontrolled generator fault protection of novel hybrid-excited permanent magnet machines utilizing field excitation current control," *IEEE Trans. Ind. Appl.*, vol.55, no.4, pp. 3598-3606, 2019.

[119] Z. Q. Zhu, B. Lee and X. Liu, "Integrated field and armature current control strategy for variable flux reluctance machine using open winding," *IEEE Trans. Ind. Appl.*, vol. 52, no. 2, pp. 1519-1529, March-April 2016.

[120] Q. Wang, X. Zhang and S. Niu, "Design of dual-electrical-port DC-coil-free hybrid-excited machines," *IEEE Trans. Energy Convers.*, early access.

[121] Q. Wang, S. Niu and X. Luo, "A novel hybrid dual-PM machine excited by AC with DC bias for electric vehicle propulsion," *IEEE Trans. Ind. Electron.*, vol. 64, no. 9, pp. 6908-6919, Sept. 2017.

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