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# Flux Adjustable Permanent Magnet Machines: A Technology Status Review

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**Abstract:** Flux adjustable permanent magnet machines (FAPMMs) are a novel type of permanent magnet (PM) machines which are able to flexibly adjust the field excitation flux linkage and offer the distinctive advantages of high power density and high efficiency. They have attracted ever-increasing interests and are promising candidate machines for electric vehicle, machine-tool and aircraft applications. In this paper, the state-of-the-art of various FAPMMs are comprehensively reviewed according to three means of flux-adjustment, i.e. electrically adjusted by either auxiliary field windings or armature winding change, mechanically adjusted magnetic reluctances of flux paths, and memory machines by magnetizing/demagnetizing PMs. The corresponding flux-adjustable principles and electromagnetic characteristics are systematically elaborated and quantitatively compared. Their merits and demerits are highlighted, together with their recent developments.

**Keywords:** Flux-adjustable, hybrid excitation, memory machine, mechanical adjustment, permanent magnet machine, winding change.

## 1 Introduction

Due to the advent of rare-earth permanent magnet (PM) materials with high magnetic energy product, the advancement of power electronics technology and the diversification of control strategies, PM machines (PMMs) have experienced an accelerating development since they can intrinsically offer high efficiency, torque and power densities[1]. Hence, in recent decades, extensive research on PMMs have been presented and documented[2-3]. Undoubtedly, PMMs are competitive candidates for numerous applications, including vehicle propulsions, machine-tools and aircrafts. However, due to the inherent properties of PM material, it is difficult to regulate the magnetic field produced by PM. In order to extend the speed range of PMMs, negative d-axis current injection[4-6] is employed. However, this inevitably results in additional armature copper losses and increases the risk of irreversible demagnetization. Meanwhile, the maximum achievable speed is also predominantly limited by machine parameters, inverter power rating, etc. These drawbacks restrain PMMs from applications requiring excellent flux-weakening capability and high efficiency covering the entire operating range. Hence, various new flux adjustable PMMs (FAPMMs)[7-93], which enable efficient and effective field adjustment and efficiency optimization across the whole operating range have been developed and identified as a key research topic worldwide.

In this paper, these novel FAPMMs are comprehensively reviewed according to three means of flux-adjustment, i.e. electrically adjustment by auxiliary field winding, mechanical methods by varying magnetic reluctances of flux paths and memory machines by magnetizing/demagnetizing PM. Their machine topologies, flux-adjustable principles and electromagnetic characteristics will be highlighted with the challenges and opportunities for industry applications summarized.

The purpose of this paper is to present a comprehensive review of typical FAPMMs suitable for extendable speed range industrial applications while highlighting their challenges and opportunities. In Section 2, the concepts and classification of FAPMMs are introduced and the earliest developments of each type of FAPMMs briefly reviewed as well. In Section 3, the existing FAPMMs are reviewed with particular emphasis on their machine topologies, flux-adjustable principles and electromagnetic characterristics. Section 4 is devoted to the recently emerged FAPMMs which are promising for future applications. Comprehensive conclusions are drawn in Section 5 with the upcoming opportunities and challenges highlighted.

## 2 Concepts and classifications of FAPMMs

In order to provide a comprehensive insight into the operation principles of FAPMMs, a generalized equivalent magnetic circuit is employed as shown in Fig.1, where $F_{\mathrm{m}}$, $F_{\mathrm{f1}}$ and $F_{\mathrm{f2}}$ represent the flux sources of PMs and field windings connected in series and in parallel, respectively. $R_{\mathrm{m}}$, $R_{\mathrm{H}}$ and $R_{\sigma}$ are the magnetic reluctances of PMs, the main flux path and the flux leakage path, respectively. It is worth noting that $F_{\mathrm{f1}}$ and $F_{\mathrm{f2}}$ can be employed as field-controlling sources connected to PM either in series, parallel or paratactic. Based on Fig.1, all FAPMMs can be classified into three groups, namely electrically adjusted machines using auxiliary field windings[8-37, 94-100] or winding change[38-44], mechanically-adjusted ones resorting to the alteration of $R_{\mathrm{H}}$ and $R_{\sigma}$[46-55], and memory machines (MMs) by magnetizing or demagnetizing variable flux magnets[57-93].

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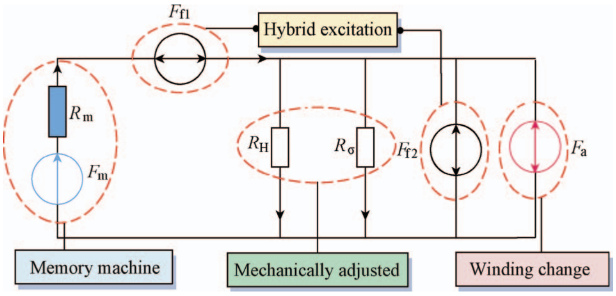


Fig.1 Illustration of flux-adjustable principle via equivalent magnetic circuit

The idea of hybridization of PM and field excitations can be traced back to 1989 when E. Spooner et al. proposed a HEM by positioning a toroidal field winding between two axially parallel machines[8].

The concept of “winding change” originates from “pole-changing” induction machines, which vary the connection of armature windings to change the machine pole number, and hence the adjustable speed operation can be achieved. Prof. E. Nipp presented a “winding change” surface-mounted PMM[38]. In this invention, he adopted various winding connected types, i.e., delta-wye or series-parallel connection, so as to change the back-EMF to realize wide speed operation.

The idea of mechanically adjusted FAPMMs was firstly implemented by T. A. Lipo et al. in 1995 utilizing three mechanical alternatives to weaken PM flux and realize the high-speed operation of PMM[51]. The concept of MM as firstly proposed by V. Ostovic by applying *d*-axis current pulse to magnetize or demagnetize aluminum-nickel-cobalt(AlNiCo) PMs in an interior PMM to achieve online flux regulation[57]. Since then, various FAPMMs have been developed and identified as a key research topic worldwide. The detailed categorization of FAPMMs is illustrated in Fig.2.

# 3 Electrically adjusted FAPMMs

## 3.1 Hybrid excitation machines

HEM is the major branch of FAPMMs. By employing both PMs and field windings, HEMs are able to tackle the limitations of the machines having either magnets or field windings only and realize either flux-enhancing or weakening without resorting to the *d*-axis armature current. Theoretically, HEMs inherit not only the merits of wound-field machines, such as easier flux adjustment, but also the advantages of PMM, such as high efficiency and large torque density. Hence, HEMs are promising candidate machines for electric vehicle propulsion[9-12].

Based on the flux path relationship between PM and field winding flux sources, HEMs can be further categorized into three groups:

### 3.1.1 Series flux-path HEM

Series flux-path HEMs(SFP-HEMs) have PM and winding excitation magnetic motive forces(MMFs) connected in series, which exhibit simple structure without significantly compromising torque capability. However, they have relatively low efficiencies since the DC winding flux inevitably passes through PMs with a low permeability. Meanwhile, this also increases the possibility of irreversible PM demagnetization.

For rotor-PM SFP-HEMs, the PMs are accommodated in the rotor as shown in Fig.3. The presented SFP-HEM shown in Fig.3(a) was developed for direct drive application and named as double-excited synchronous machines (DESM)[11]. Its field windings are also accommodated in the rotor. When applying negative field excitation, the decrease of flux density occurs in the active parts, resulting in the reduction of total iron losses (up to 10%). Hence, it demonstrates DESM can maintain high efficiency over a wide speed range. The main drawback of this machine is the existence of brushes and slip rings.

For stator-PM SFP-HEMs, the PMs are located in the stator such as doubly-salient HEMs (DS-HEMs) illustrated in Fig.3(b). By combining the concepts of stator-PM, stator-field excitation, and brushless configuration, DS-HEMs have high power density, robust rotor and excellent heat dissipation capability. The topology proposed in [12-13] is characterized by flux-concentrating and iron bridges to enhance the flux-weakening effect. The outer-rotor version of DS-HEM was developed in [14]. This machine offers high torque density due to high utilization of the stator space. The flux-weakening capability is significantly amplified by employing the iron bridges. However, DS-HEMs have high torque ripples resulted from double saliency configuration and low utilization ratio of DC-link voltage at brushless DC mode. Due to the large volume of field windings, the flexible field regulation is achieved at the expense of torque density. In order to tackle the above-mentioned problems, Prof. W. Hua proposed a SFP-HE switched flux machine, and investigated its flux regulation principle, optimal field winding arrangement, and fault-tolerant control strategy[15].

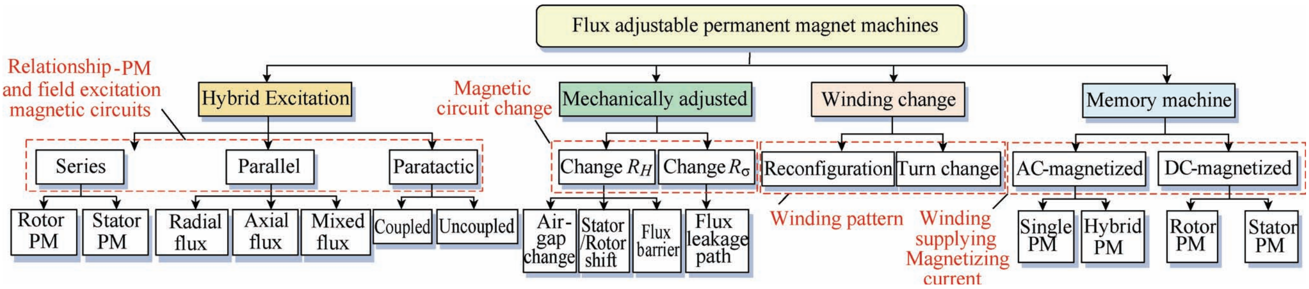
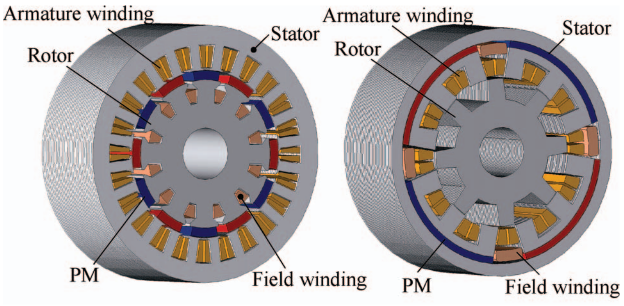


Fig.2 Categorization of FAPMMs



(a) DESM[11] (b) DS-HEM[12]

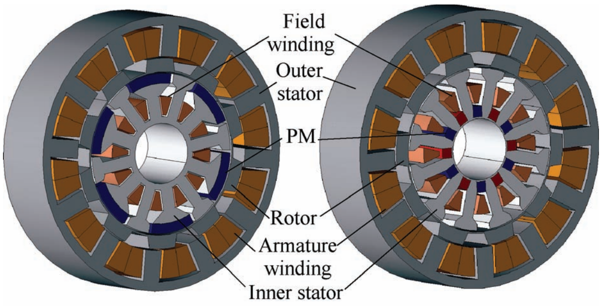
Fig.3 Typical SFP-HEM topologies

The field windings inevitably reduce the space for armature winding, and consequently compromise torque density. In order to solve this issue, Prof. Z. Q. Zhu applied the design concept of “partitioned stator (PS)” to HEM, and hence form various PS-HEMs[16-17], as shown in Fig.4. The results demonstrate that the proposed PS machines can exhibit wide flux regulation range as well as better torque density than their original counterparts. Nevertheless, the relatively complicated mechanical structure is a major concern.

### 3.1.2 Parallel flux-path HEM

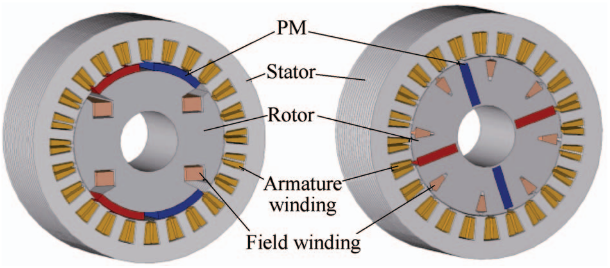
Parallel flux-path HEMs (PFP-HEMs) have the PM and field winding MMFs connected in parallel, i.e., the PMs and field windings have different flux paths. Due to the nature of parallel connection, the risk of irreversible demagnetization is minimized. Various machine topologies are available. Based on the main flux path direction, PFP-HEMs are sub-divided into three groups, i.e. radial, axial and radial/axial.

(1) Radial field topologies. In [18], a PFP-HEM, which is shown in Fig.5(a) and termed as SynPM machine, was invented based on the hybridization of a 4-pole PM synchronous machine and a 2-pole wound field synchronous machine. It purposely enables the transition between 6-pole and 2-pole modes. Due to higher power/mass ratio, SynPM machine can compete with AC induction motor drives for potential industrial applications. However, the main concerns of SynPM machines are the employment of slip rings and brushes as well as the torque ripple and acoustic noise during flux weakening operations. The spoke-type counterpart is shown in Fig.5(b) and able to obtain higher air-gap flux and torque capability[19]. For the SynPM machines, high magnetic saturation exists in the stator core region between two adjacent PM poles at flux- weakening operation, which may yield high iron loss in the stator core.



(a) Flux reversal[16] (b) Switched flux[17]

Fig.4 Typical PS-HEM topologies



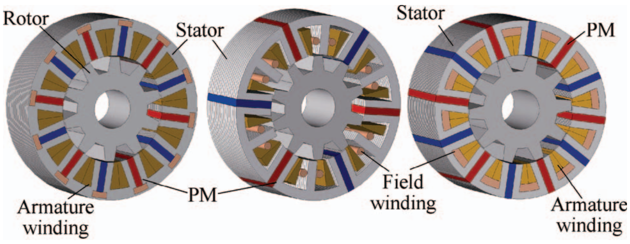
(a) Surface-mounted type[18] (b) Spoke-type[19]

Fig.5 SynPM machines

When PMs are located in the stator, the most widely investigated PFP-HEMs are hybrid excited switched-flux PMMs(HE-SFPMMs), which utilize the switched-flux principle to achieve sinusoidal flux-linkages and back-EMFs, and consequently smaller torque ripple can be obtained. By alternatively replacing magnets by field windings, two types of HE-SFPMMs shown in Fig.6 were proposed in [20-22], respectively. The machine in Fig.6(a) is equipped with flux bridges to enhance the effectiveness of field windings. However, the outer radius of the machine needs to be enlarged due to the utilization of field windings, and consequently the overall torque density is compromised by nearly 40%. The machine in Fig.6(b) represents another version of HE-SFPMMs by placing field winding in the identical slot with armature windings. However, the overall power rating and torque performance are compromised due to the reduction of armature slot area. The machine in Fig.6(c) is derived from an alternately wound E-core SFPMM. In this machine, the torque density can be improved compared to the foregoing two counterparts without passive expansion of peripheral dimension. The analysis results show that the flux-enhancing capability is better than the flux-weakening capability since the flux-weakening current increases the magnetic saturation in the stator cores.

In [23], a novel stator slot PM HEM was introduced from the design concept of inserting magnets into the stator slot. In a comparison, it is shown that the proposed machine can achieve 18% higher torque than the electrically excited counterpart for fixed copper loss.

(2) Axial field topologies. A field-controlled axial-flux PFP-HEM termed as TORUS concept machine



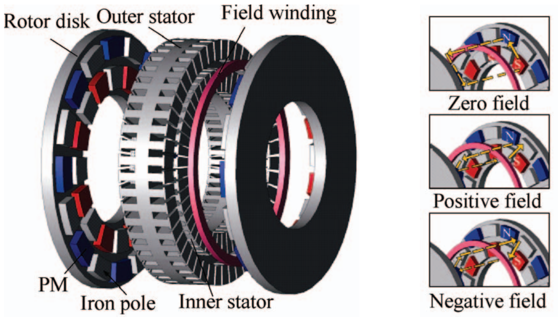
(a) iron flux bridges[20] (b) E-core stator-pole[21] (c) field windings in armature slot[22]

Fig.6 HE-SFPMM topologies

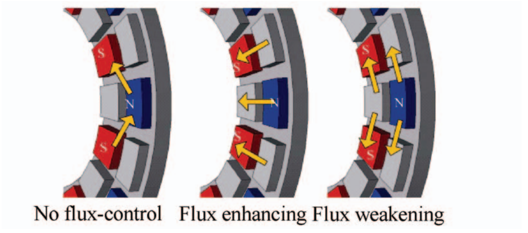
was developed in [24] shown in Fig.7(a). The rotor is formed by two circles of alternative iron- and PM-poles. Toroidal field windings are placed between the outer and inner slotted stator modules. The stator and rotor structures can be alternatively swapped to form intermediated-rotor-disk and intermediated-stator-disk while the operation principle remains the same. In addition, when the stator is sandwiched between two rotors, the polarities of magnet poles aligned in the two rotors can be assigned in two different ways, namely, N-S and N-N. Fig.7(b) shows three flux-control states corresponding to the field current excitations having zero-, positive- and negative-directions, respectively. The resultant no-load flux patterns using the principle of flux superposition with PM and field excitations are shown in Fig.7(c). It can be confirmed that the fluxes produced by positive and negative field currents passing through from stator to iron pole to offer effective air-gap flux control. However, the prototype shows some deficiencies such as fabrication difficulty and significant inter-pole flux leakages.

A consequent-pole HEM (CP-HEM) was firstly proposed by E. Spooner et al in 1989[8], and then intensively investigated worldwide[25]. It has two rotor sections composed of alternative PM and iron poles. The toroidal DC field windings are embedded in the middle of the stator to serve as a flux regulator. However, the torque density is compromised due to the additional volume of field winding as well as that a partial of air-gap is not involved in the effective electromechanical energy conversion. Due to the employment of solid cores, tangential and axial flux components exist, which require more material and results in additional iron loss.

Y. Amara et al made significant contributions to PFP-HEM by employing mixed flux paths using 3-D structure[26-27]. Fig.8 shows two PFP-HEMs, i.e. homopolar and bipolar hybrid excitation synchronous machines (HB-HESMs). The toroidal field windings are placed in the spare spaces between the end plates and the stator core. The solid iron cores(external yoke and end-plates) provide a low magnetic reluctance path for the field windings, and hence excellent air-gap flux control is realized. The only difference between homopolar and bipolar configurations is the arrangement of sided solid rotor cores. In order to reduce the flux leakage of the magnet, the magnetic insulation between the solid parts of rotor and laminated parts is employed by inserting PMs. However, the utilization of laminated rotor cores deteriorates the flux-adjustable efficiency due to its relatively low axial permeability for field excitation, thus a compromise between iron loss and excitation copper loss should be examined in the future. Besides, HB-HESM requires more iron materials due to the presence of sided cores and plates and hence is bulkier than conventional PMMs.

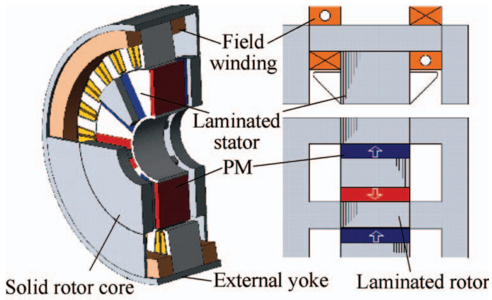


(a) 3-D cutaway view (b) Field current excitations

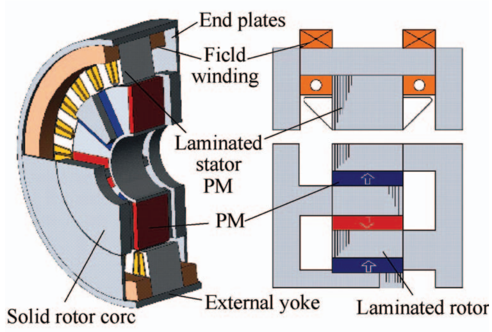


(c) Mixed radial/axial field topologies

Fig.7 Torus-concept structure[24]



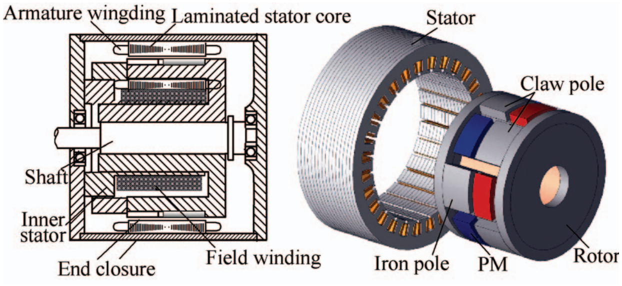
(a) Homopolar-HESMs[26]



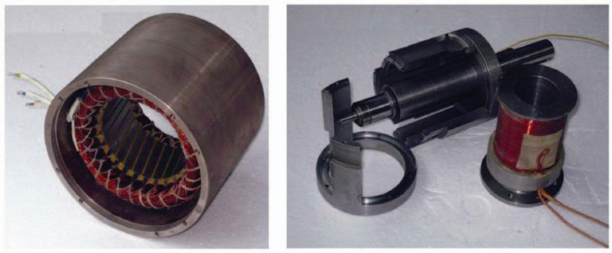
(b) Bipolar-HESMs[27]

Fig.8 PFP-HEMs

An asymmetrically stagger-HEM (AS-HEM) was proposed as shown in Fig.9[28]. The major merits of the machine are that the field windings are placed in the internal stator underneath the claw-pole rotor instead of the outer stator core. Thus, the rotor space is fully utilized and effective stator space for armature windings is not compromised by the field windings. The claw rotor consists of alternative surface-mounted magnets and iron poles, characterized by asymmetric magnet- and iron-poles. Since the magnetic saturation is heavier when the machine is under flux-enhancing operation, the flux-weakening capability is relatively higher than the flux-enhancing capability, as can be observed in the torque-current characteristics of the prototype machine in Fig.10. The main concerns of this machine are the inter-pole flux leakages and resultant low power factor, as well as the complicated structure.



(a) Cross-sectional view (b) Assembly



(c) The outer stator (d) Prototype: inner stator and claw-pole rotor

Fig.9 AS-HEPMM[28]

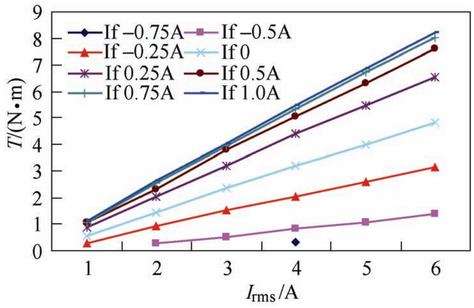


Fig.10 Measured torque versus current characteristics of the prototype AS-HEPMM under different field currents

In [29], two HEMs equipped with endplates made of powdered iron (PI) and allowing 3D magnetic flux were proposed and can be termed as PI-HEM. Fig.11 shows the PI-HEM developed from a hybrid-stepper machine. The main magnetic field is produced by the axially magnetized PM sandwiched between rotor yokes. The field windings are toroidally wound on the endplates. The field winding flux acts as not only a magnetic shield for PM flux but also an air-gap flux contributor. However, the rotor tooth-to-tooth flux leakage and long stack length are inevitable. The extremely complicated structure and relatively low reliability also reduce its feasibility for current industrial applications.

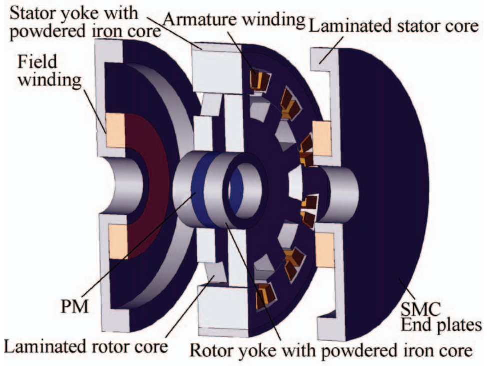


Fig.11 HEPMM equipped with powdered iron cores[29]

### 3.1.3 Paratactic flux-path HEM

The paratactic-HEM (PT-HEM)[33] can be divided into two types according to the magnetic relationship between PM and field excitation fluxes, namely, coupled and uncoupled.

B. Chalmers et al[31] have made great contributions to PT-type machines by proposing a magnetically uncoupled dual-rotor machine. The machine is comprised of a surface-mounted PM part and a reluctance part in order to allow the magnet and reluctance torque components to be designed independently. The low saliency of surface-mounted magnet part is compensated by a reluctance part, thereby pottentially obtaining wide speed operation. Upon this invention, a rotor magnet- shunting HEM characterized by two ends of rotor magnetizers was proposed[32]. The existence of axial path dramatically weakens the air-gap flux by bypassing a part of PM flux when the field windings are unpowered. Thus, the flux-weakening capability is restricted as the axial path is magnetically saturated when a negative field current is applied. In addition, another uncoupled dual-rotor HEMs (DR-HEMs) was developed to provide a completely magnetic and physical separation between PM- and field-excitation sections[33]. The flux-regulation efficiency is improved and the excitation losses are reduced due to the mechanical integrity of field- excitation.

In [34], a new type of PT-HEM named as dual-stator hybrid excited synchronous generator (DS-HESG) was proposed. As can be seen from Fig.13, this machine is an integration of a dual-stator cup-rotor PMM and a brushless claw-pole wound field machine. It is implemented as a wind power generator to realize constant voltage output even when wind speed varies randomly. As can be seen in Fig.13, the output voltage of the generator can be effectively increased by adopting a dual-stator structure. However, the complicated structure compromises the mechanical reliability. Partial air-gap is involved in the effective energy conversion and the inherently large flux leakage in the claw pole structure remains unsettled.

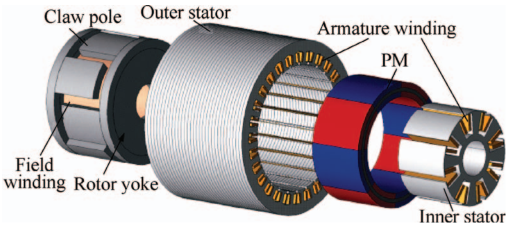


Fig.12 Exploded view of DS-HESG[34]

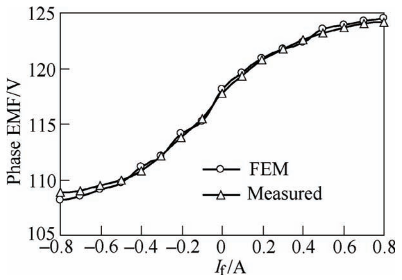


Fig.13 Measured output voltage versus field currents of DS-HESG[34]

Two twisted-rotor PT-HEMs were proposed in [35]. The wound dual-rotor HEM (WDR-HEM) combines a wound field rotor and a radially magnetized PM machine while keeping them spatially and magnetically independent. It was experimentally confirmed that a wide range of air-gap flux can be achieved by a small field current. However, slip rings and brushes required for the field windings degrade the overall mechanical reliability. Therefore, another HEM type based on integrating electrical excitation and PM machine having doubly salient structures was developed and named as PDS- HEM[36]. The axial magnetic coupling between the rotors is eliminated and wide-range voltage regulation is also obtained. However, the power density is inherently poor and the torque ripple is naturally high due to the double saliency structure. In [37], a paratactic switched-flux HEM (PSF-HEM) is proposed by combining a SFPMM and a wound field SF machine. The axial lengths of two parts can be designed independently to meet specific industrial requirements. However, the demerit of low torque density in field excitation part and high fabrication cost of this machine still exists.

### 3.1.4 Comparison and summary

In order to evaluate the aforementioned HEMs for various industrial demands, all of them are comprehensively compared in Table 1. It can be seen that the radial- and axial-field HEMs, especially DS-, SF-, PSF- and TORUS-structures, are relatively easier to be manufactured. They also have simple structure and high field regulation efficiency. In terms of performance, although the torque densities of SynPM machine and DESM are relatively high, they have poor mechanical reliability, acoustic noise and low efficiency due to slip rings and brushes. SynPM machines also produce rich flux harmonics and high torque ripple AS-, PI-HEM, DS-HESG and HB-HESMs suffer from high fabrication cost as well as relatively poor power density.

Overall, the series-flux path HEMs embrace such merits as simple mechanical structures and less periphery restrictions. However, they inevitably take the risk of PM irreversible demagnetization, and suffer from poor flux-adjustable efficiency due to the large magnetic reluctance; The parallel-flux path HEMs have acceptable flux-adjustable capability with the elimination of slip/brushes and risk of PM demagnetization, but the relatively low torque density due to peripheral enlargement and high mechanical complexity are major concerns. Paratactic-flux path HEMs can offer wide flux-adjustable range without any coupling between PM and electrically excited fields. However, high manufacturing cost restricts its industrial applicability.

## 3.2 Winding change

Since Prof. E. Nipp presented a viable electronic mechanism for speed range extension of SPM machines[38], many researchers have growing interests on the winding change method for PMMs. [39-41] reported a dual speed rearrangement for an induction machine. In low-speed region, the series winding connection is employed to offer high torque output, while for the high-speed case, the parallel winding type is utilized to extend the speed range.

Prof. T. A. Lipo innovatively proposed a winding-switching concept for SPM machine using open-winding configuration[42]. The low-speed and high-speed winding connections are illustrated in Fig.14. In low-speed operation, the two sets of sub windings share the neutral point, and their current flowing directions are identical. In this case, the machine behaves as a conventional dual-three phase one to provide the high torque output. Whereas, when the machine operates at high speeds, the open-winding mode is enabled to cancel the EMF of the two sub windings. Thus, a 13:1 speed range can be obtained. However, this winding topology involves a high number of power devices, which is relatively electronically sophiscated.

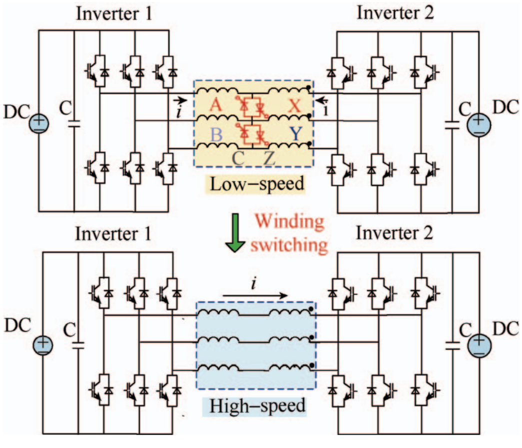


Fig.14 Winding change principle of SPM machine using open-winding topology[42]

**Table 1 Performance Comparison of HEMs**

| Item | Series | | Parallel | | | | | Paratactic | |
|---|---|---|---|---|---|---|---|---|---|
| Machine types | DESM | DS- | SynPM- | SF- | TORUS-/CP-/PI- | AS- | HB- | DS-HESG | PDS-/PSF- |
| Torque density | ++ | + | ++ | ++ | ++ | + | – | ++ | ++ |
| Topological complexity | – | + | ++ | + | + | ++ | ++ | ++ | + |
| Fabrication cost | + | - | + | – | ++ | + | ++ | ++ | ++ |
| Flux leakage | – | - | – | – | + | ++ | + | - | - |
| Brush requirement | Y | N | Y | N | N | N | N | N | N |
| Flux-weakening ability | – | + | ++ | ++ | + | ++ | + | + | ++ |
| Field excitation efficiency | – | + | ++ | ++ | + | + | ++ | + | ++ |
| PM demagnetization risk | Y | Y | N | N | N | N | N | N | N |
| Air-gap affixation | – | ++ | – | – | + | ++ | ++ | + | - |

Symbol notation: "++": good; "+": fair; "−": bad.

In [44], a winding switching scheme was presented to deal with the relatively limited flux adjustable capability of a proposed consequent magnet pole SF memory machine. The magnetizing coils will alternatively serve as the secondary armature winding after the reversal of magnetization directions of low-coercive force magnets, thus resulting in the flux linkage cancelation within the same phase. As a result, the speed range can be further extended via this control scheme. In [44], a novel circuit topology was introduced for the proposed matrix motor via winding reconfiguration and switching method to suppress the surge voltage without the snubber circuit. It is confirmed that proposed circuit topology can change winding connections without the surge voltage.

In [45], a split-winding DSPMM was presented. The winding turn number can be changed online via switchers. In this way, the winding turns can be reduced in high-speed region so as to obtain wide speed range.

## 4 Mechanically adjusted FAPMMs

Mechanically-adjusted FAPMMs, which are identified as a multidisciplinary coupling between mechanics, hydromechanics and electromagnetics, utilize unique mechanical means to achieve air-gap flux adjustment without using armature or field current. Thus, the efficiency can be improved due to the absence of relevant copper losses for flux- adjusting. It should also be mentioned that the mechanical solution can work well in surface-mounted PMMs which fail to maintain extended speed range due to low phase inductance. Based on the essence of magnetic reluctance variation, mechanically-adjusted FAPMMs can be further divided into two groups.

### 4.1 Adjustment towards $R_H$

In order to alter $R_H$, the cross-section area of the main flux path can be reduced or enlarged. A brushless SPM machine proposed in [46] and shown in Fig.15, has an axially displaceable rotor to control the aligned area between the stator and the rotor. The effective PM flux can then be controlled.

In [47], a rotor-twistable SPM machine was developed and shown in Fig.16. The rotor is consisted by two axial parts. One part is fixed to the shaft; the other part is installed on a screw thread shaft and rotatable circumferentially. By changing the circumferential angle of the rotatable part, the PM flux can be varied smoothly from the maximum to zero regardless of machine speed and rotation direction.

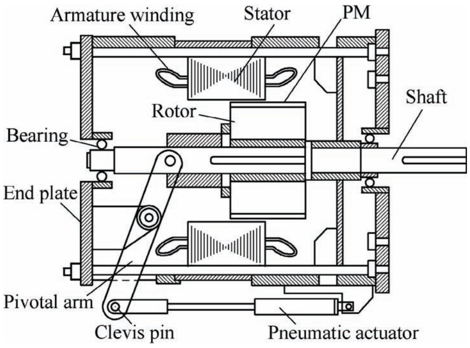
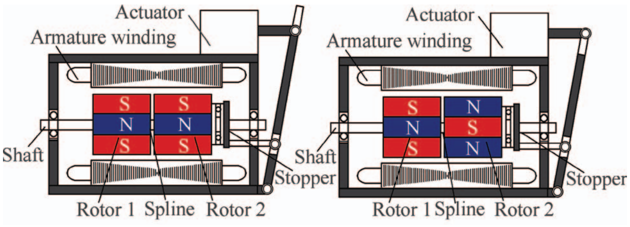


Fig.15 Cross-sectional view of SPM machine equipped with displaceable rotor part[46]



(a) Maximum effective flux (b) Zero effective flux

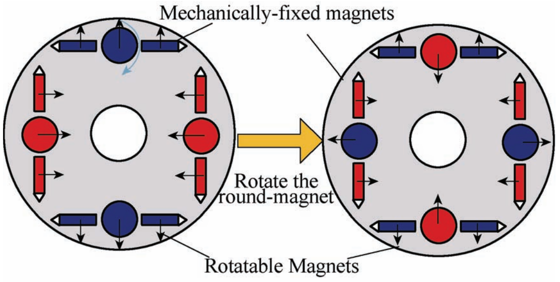
Fig.16 Cross-sectional layout of twisted SPM machine equipped with one rotatable rotor[42]

As shown in Fig.17, another mechanically-adjusted IPM was proposed by employing rotatable magnet bars[48]. The rotatable cylindrical magnets are placed between the two rectangle magnets to serve as a flux regulator. The air-gap flux is the maximum when the polarities of cylindrical magnets is the same with that the rectangle PMs. The air-gap flux density is the minimum when the cylindrical magnets have the opposite polarities to the rectangle PMs. However, the electromagnetic performance when the cylindrical magnets are at locations other than the aligned- or opposite-positions should be further investigated.

A mechanical approach to vary axial rotor alignment by an actuator to offer PM flux regulation is shown in Fig.18[49]. By introducing a displacement between the two rotor discs, the effective flux linkage can be changed accordingly. Another axial-flux type PMM being capable of air-gap length adjustment was proposed in [50]. The air-gap length is tunable by means of mechanical devices.

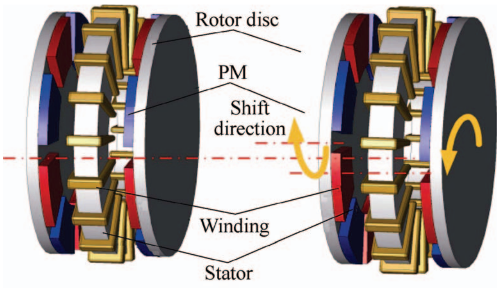
### 4.2 Adjustment towards $R_\sigma$

The principle of this type of FAPMM is intended to alter the leakage flux reluctance to provide a short-



(a) Maximum effective flux (b) Minimal effective flux

Fig.17 IPM with integrated magnet adjustable bar[43]



(a) Flux-enhancing (b) Flux-weakening

Fig.18 Mechanically-adjusted axial-flux PMM with displaceable rotor section[44] circuit path for PM magnetic flux. The related studies mainly focus on IPMM, owing to more flexible design space than SPM counterparts.

T. A. Lipo et al[51-52] proposed three DSPMMs equipped with mechanical devices to alternate by-pass PM flux-leakage. As shown in Fig.19, the first one employs circular ring constituted by alternative magnetic/non-magnetic segments to provide by-pass flux path for PM. Secondly, the flux-weakening effect is implemented by actuators to axially pulling out PMs. The third scheme realizes flux-weakening by controlling the radial position of ferromagnetic segments.

The IPM machine was introduced in [53] utilizing movable endplates. For normal operation, the plates are held far from the rotor by springs to prevent leakage. When flux weakening is required, the endplates can be pushed towards the rotor by actuators to reduce the PM flux. An IPM machine carrying axially moveable flux-shortening iron pieces was proposed in [54]. The iron pieces are inserted into the flux barriers by utilizing the centrifugal force when the speed is above the base speed. For low-speed operation, the iron pieces are out of service so that the machine is the same as conventional IPM machine.

In [55-56], a novel mechanically-adjustable SFPMM was proposed by employing flexibly moveable short-circuit iron pieces. The cross-sections when the effective PM flux is at the minimum and maximum are shown in Figs.20(a) and (b), respectively. The concept is experimentally validated by a simplified test on the prototype machine.

### 4.3 Summary

Mechanically adjusted FAPMMs offer merits of simple and straight manipulation for field regulation instead of complicated current control. The machine efficiency tends to be improved due to the elimination of copper loss for flux-adjustment. However, for all the mechanically-adjusted FAPMMs, they require external actuators. The actuators are mechanically complicated and bulky. They also need a controller and maintenance as well as consume power. Hence, the system torque density, efficiency, and reliability are compromised and increases system cost.

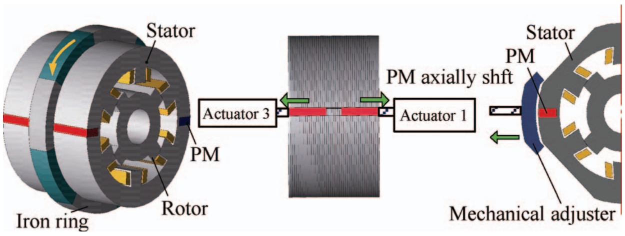
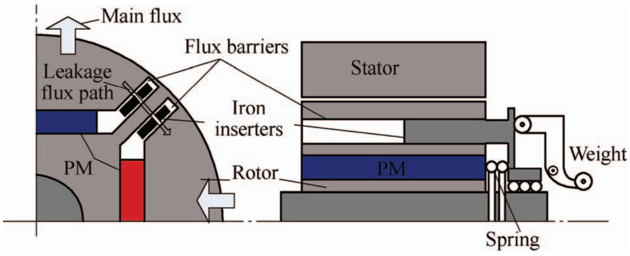


Fig.19 Cross-sectional view of SPM machine equipped with displaceable rotor part[51-52]



(a) Cross-section view (b) Longitudinal view

Fig.20 Mechanically-adjusted IPM machine with axially moveable iron pieces[55]

## 5 Variable PM flux FAPMMs-memory machines

MM is a newly emerged category of FAPMMs, which adopts the PM with low coercive force and changeable remanence, such as AlNiCo and SmCo. The concept of “flux-memory” is derived from the nature of AlNiCo PM which shows significantly non-linear hysteresis characteristic as the demagnetizing curves never superpose on the recoil curves. The first implementation of MM was by V. Ostovic in 2001 using *d*-axis current pulse to magnetize or demagnetize AlNiCo PMs in an IPMM to achieve online flux regulation[57]. Since then, various MMs have been developed.

### 5.1 Description of flux memory physics

In order to illustrate the “flux-memory” feature intuitively, Fig.21 shows the hysteresis loops of AlNiCo, where $B_r$ and $H_c$ are the residual flux density and coercive force. The working point of the PM is initiated at $P_0$, which is the cross between the load line and the demagnetizing curve. When applying a demagnetizing current pulse, the working point will descend to $Q_0$. After the withdrawal of the current pulse, the working point of the PM will move along a new recoil line ($Q_0R_1$) and stabilize at new working point $P_1$. Similarly, when another demagnetizing current pulse is imposed, the PM working point will move along $P_1Q_0Q_1P_2$ and settle at $P_2$. On the other hand, when a magnetizing current pulse is applied, the PM working point follows the trajectory of $P_2R_2R_1P_1$ and return to $P_1$. Thus, the magnetization level of AlNiCo magnets can be tuned and memorized by applying current pulses.

### 5.2 AC-demagnetized memory machines

AC-magnetized MMs utilize the *d*-axis current pulse produced by the armature windings for magnetizing/demagnetizing the low coercivity magnets. The benefits of using armature windings are simpler structure, less components and cost. However, the

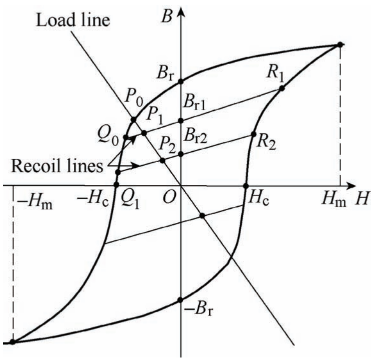
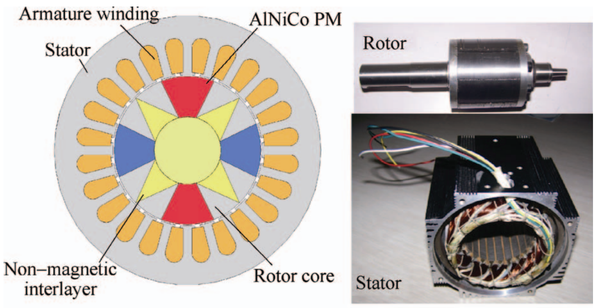


Fig.21 Hysteresis model of AlNiCo PM

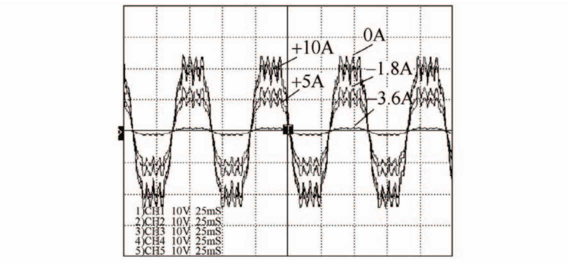
drawbacks are high requirements on armature windings and inverters.

The very first MM was invented by incorporating the principle of online written-pole resembling sound recorders into the conventional PMM[57]. It is termed as variable flux memory motor (VFMM) and shown in Fig.22. The circumferentially magnetized and trapezoid shaped AlNiCo PMs are sandwiched between non-magnetic interlayers and iron cores. The $d$-axis current pulse produced by the armature windings is employed to magnetize/demagnetize the rotor-PMs, and then regulate the air-gap flux. The triangle non-magnetic interlayer increases the $q$-axis reluctance to protect AlNiCo from $q$-axis armature reaction. In addition, due to the trapezoid shape, the thinner magnets below will be easier remagnetized or demagnetized, and the reversely polarized magnet part will magnetically short-circuit the upper part to weaken the air-gap flux density.

In [58-61], VFMMs are further investigated to identify the flux-adjustable physics and the PM shape optimization. It was experimentally confirmed by the measured back-EMFs shown in Fig.22(c) that the remagnetization is harder than demagnetization, which agrees well with the hysteresis characteristic of AlNiCo. In [62-64], a new structure of MM was developed by employing flux-adjustable magnet material SmCo in a flux-intensifying interior-PM machine (FI-IPMM) featuring “$L_d > L_q$”. Proposed FI-IPMM topologies are shown in Fig.23. The reversed saliency can permit the maintaining of magnetization state of low-coercivity magnet when a positive $I_d$ is applied under load conditions to produce positive reluctance torque at the same time. Similarly, the FI-IPMM having spoke-type PM and various $q$-axis flux barriers was investigated by Prof. P. Pillay[65]. It was found that the torque density of this machine can be comparable with that of conventional SPM machines. Then, the rotor structure optimization is investigated by Prof. R. Qu [66], which intends to obtain the reduction of maximum magnetization current. Overall, the inherently low torque density of the FI-IPMM and the complicated online current control restrain FI-IPMMs from industry applications.

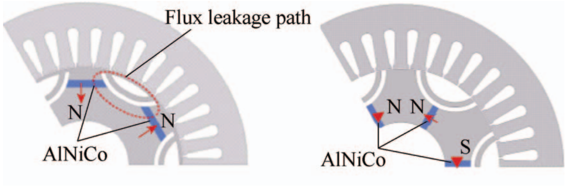


(a) Topology (b) Prototype



(c) Measured back-EMF waveforms under different magnetizing/demagnetizing currents (10V/div)

Fig.22 The origin VFMM[57]



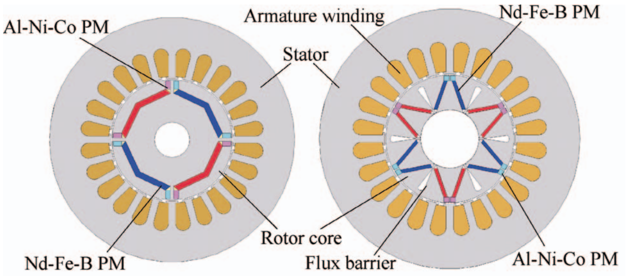
(a) Radially magnetized magnets and surface iron bridge (b) Circumferentially magnetized magnets

Fig.23 FI-IPMMs[62-64] equipped with radially and Circumferentially magnetized magnets

In order to overcome the low torque density resulted from low-coercivity PM material in the above-mentioned MMs, many MM topologies are proposed by hybridizing NdFeB with AlNiCo to obtain higher air-gap flux density and larger torque as shown in Fig.4~ Fig.6[67-70].

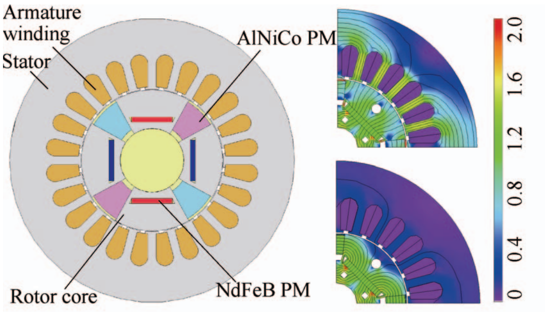
A dual-magnet VFMM (DM-VFMM) was further developed from the original VFMM in [67]. The AlNiCo magnets in original VFMM have been partially replaced by rectangle NdFeB magnets to improve the torque density. In [68], two DM-VFMMs shown in Fig.24 were developed from IPMM. The open-circuit magnetic flux is mainly contributed by NdFeB PM. It should be noted that the cancelation between of NdFeB and AlNiCo magnets having opposite polarities will result in flux-weakening effect.

In a similar way, another type of DM-VFMM called hybrid variable-magnetic-force motor was proposed by K. Sakai et al[69]. and shown in Fig.25(a). The radially magnetized NdFeB PMs act as a major



(a) Four-pole (b) Six-pole

Fig.24 DM-VFMMs[68]



(a) Topology (b) Magnetic field contours under positive- and negative magnetization states

Fig.25 Hybrid variable-magnetic-force motor[69]

MMF source whilst the tangentially magnetized AlNiCo PMs serve as a flux regulator. However, DM-VFMMs require a large magnetizing current and hence large inverter capability. Fig.25(b) shows the corresponding magnetic field contours versus positive- and negative-magnetization states of AlNiCo, which verify the flux-adjustable capability of hybrid variable-magnetic-force motor.

A fractional-slot concentrated-winding MM equipped with low-coercivity SmCo magnet was proposed and has been commercialized in TOSHIBA drum-type washing machines[70]. Two machine configurations, e.g. 48-slot/36-pole and 36-slot/24-pole, are investigated and quantitatively compared. It shows that the 48-slot/36-pole arrangement has higher magnetizing efficiency due to shorter magnetizing path. Due to alternately arranged magnet poles constituted by SmCo and NdFeB magnets in series, SmCo magnet can be maintained magnetically stable assisted by NdFeB PMs, and consequently the electrically remagnetizing demand can be released. The fractional-slot concentrated-winding design can improve the power/torque density and ease the manufacturing. However, the fractional-slot MM requires a complicated design for variable-flux magnet property and inverter parameters, since SmCo magnet must be able to withstand the demagnetizing fields produced by either $q$-axis current or NdFeB.

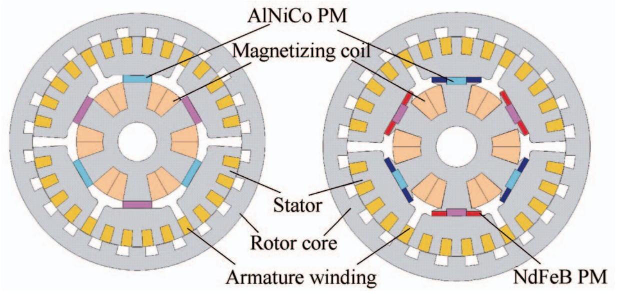
## 5.3 DC-Demagnetized memory machines

DC-magnetized MMs employ additional magnetizing coils to magnetize/demagnetize the low coercivity magnets using DC current. The benefit of this configuration is that the armature and magnetizing windings can be controlled independently. The requirements on armature windings and converter can be greatly reduced. However, additional windings and converter are required and the machines are generally more complicated.

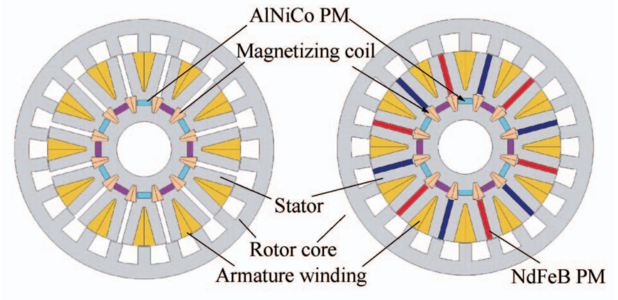
### 5.3.1 Stator LCF PM memory machines

A DC-magnetized MM called doubly-salient(DS) MM was proposed by incorporating the concept of "flux-memory" into a stator-PM machine having DS and outer-rotor configuration[71-77]. The topologies using single-PM and dual-PM are illustrated in Fig.26(a) and (b), respectively. It can be seen that DSMMs have a double-layer stator with 5-phase armature windings located in the outer layer and the magnetizing coils wound on the inner stator. The AlNiCo magnets are embedded between the two layers and can be protected from unintentional irreversible demagnetization.

In [73], a novel dual-mode operation was proposed: DSPM mode when PMs are normally magnetized and switched-reluctance(SR) mode when PMs are totally demagnetized. A new algorithm by combining Preisach theory and time-stepping finite-element-method(TS-FEM) was developed to rapidly and accurately predict the electromagnetic performance of DSMM. A phase-transformed design of stator windings to minimize the torque ripple of DS-machines was also proposed. The suitability for ISG and the optimization of the magnet proportions of DM-DSMM is analyzed.



(a) DSMM (single-magnet)[71] (b) DSMM (dual-magnet)[74]

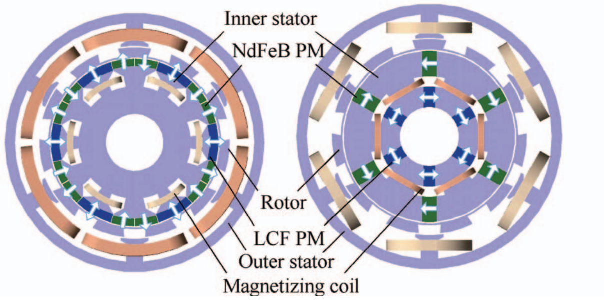


(c) SFMM (single-magnet)[78] (d) SFMM (dual-magnet)[82]

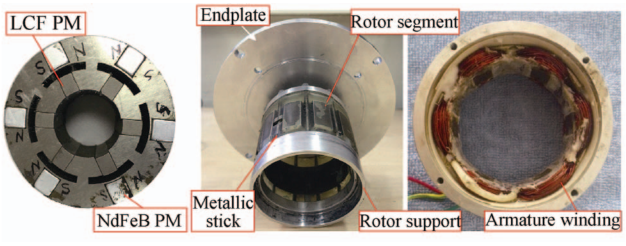
Fig.26 Stator-PM MM topologies

MMs based on switched flux (SF) machines were proposed in [78-90]. The magnetizing coil is located in the stator. Figs.26(c) and (d) reveal two external-rotor switched-flux MMs (SFMMs) developed in [87] with either single AlNiCo or DM arrangement. Compared to the single-AlNiCo structure, flux-focusing NdFeB PMs are better suited in DM machine topology to improve torque density.

More recently, as shown in Fig.27, two novel partitioned stator memory machines (PSMMs) based on flux-reversal(FR) and switched-flux(SF) topologies were presented. The proposed machines geometrically feature two separate stators with armature winding and hybrid PM excitations, i.e., NdFeB and LCF PMs. The PSMMs exhibit the merits of the alleviation of the



(a) SPM (b) IPM



(c) IPM prototype

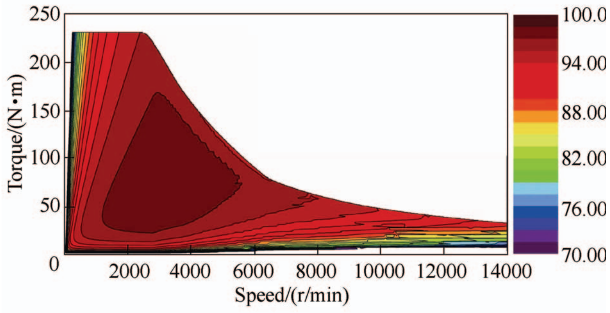
Fig.27 Topologies of the proposed PSMMs

space conflicts between PMs and armature windings from the PS design. Meanwhile, the increased available inner stator space for hybrid PM is beneficial to the torque improvement. Besides, the excellent air-gap flux regulation capability can be realized with the negligible excitation loss, which is desirable for wide-speed-range applications.

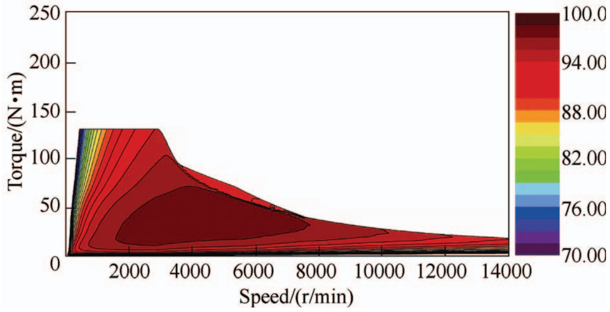
Fig.28 and Fig.29 show the simulated efficiency maps and measured torque-speed curves of the PS-SFMM, respectively. It can be seen that the high efficiency operation can be maintained over a wide operating range via the PM magnetization control. Meanwhile, the test results demonstrate that excellent flux-weakening performance can be obtained in the proposed PSMM as well.

It should be emphasized that for the online magnetization of DC-magnetized MM, the continuous flux adjustment is not essential. Flux regulations can be stepped in a similar way to mechanical gears to meet the specific performance requirement[79]. Thus, the corresponding control strategy can be greatly simplified.

Similar to those PSMMs, some researchers have applied the concept of “flux-modulated” to MM structures, thus forming various flux-modulated MMs[80-89]. Those machines can not only achieve high torque density at low speeds, but also realize energy-efficient high-speed flux weakening. As shown in Fig.30, a typical case-dual-consequent-pole vernier memory machine (DCP-VMM) having alternatively arranged NdFeB and LCF magnet poles on the rotating and stationary sides was proposed by the authors[90]. However, the major concerns for this type of MM are the relatively low power factor and high-frequency iron loss.



(a) Flux-enhanced state



(b) Flux-weakened state(DC-link voltage=650V, $I_{\max}$=414Arms)

Fig.28 Efficiency map of IPM-PSMM

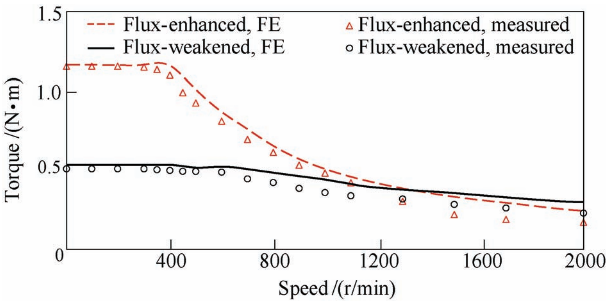
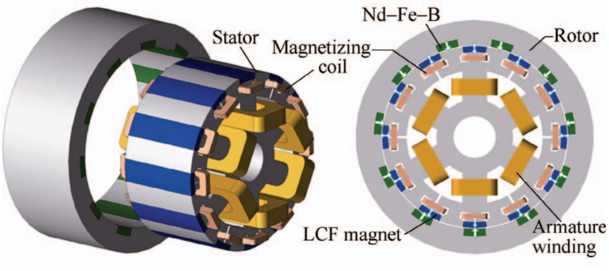


Fig.29 Measured and FE-predicted torque-speed curves

### 5.3.2 Rotor LCF PM memory machines

As shown in Fig.31, a mixed radial/axial field MM was developed by sandwiching variable flux material-AlNiCo between two twistable surface-mounted PMMs having NdFeB magnets [88]. The DC-magnetizing coils are embedded on stator. However, this machine is extremely complicated for manufacturing. The long magnetic flux path and low axial magnetic permeability result in bulky DC-magnetized coil. Prof. L. Jian proposed a novel claw-pole MM[92], where the stationary magnetizing windings are wound on the bracket, similar to the conventional electrically excited claw-pole machine. The AlNiCo PMs are embedded between the brackets to enable flexible air-gap flux adjustment.

Generally, all DC-magnetized stator-PM MMs can readily perform online magnetization with the aid of magnetizing coils. The highly robust structure and mechanical reliability are obtained. In addition, the torque is mainly due to PM torque instead of reluctance torque. The torque density is comparable to that of IPM MM, in which the reluctance torque is significantly compromised especially under high-load operation. AlNiCo magnets are protected from armature reaction. Furthermore, as opposed to DSMM which has high torque ripple and low torque density, SFMMs exhibit sinusoidal symmetrical phase back-EMFs and low torque ripples and higher torque densities. The radial/axial mixed field MM is mechanically complicated and requires expensive soft magnetic composite (SMC) to allow 3D magnetic path, which is currently not suitable for industrial applications.



(a) Exploded view (b) Cross-section

Fig.30 Proposed DCP-VMM[90]

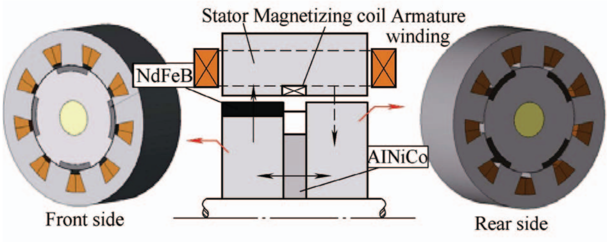


Fig.31 Radial/axial mixed field MM configuration[88]

### 5.4 Summary

MM can operate with high efficiency over a wide range of power, which enables the variation of magnetic flux of magnet using a short duration of current excitation. Thus, it is highly desirable for electric vehicle and domestic appliance applications. AC-magnetized MM involves both energy conversion and magnetization control in armature windings, which reduces the machine size and manufacturing cost, but requires relatively complicated current vector decoupling control and the power rating requirement for inverters is increased; DC-magnetized ones ease the online magnetization control due to the auxiliary magnetizing coils. The stator permanent magnet MMs especially SF can offer comparable torque density to that of IPM counterpart due to the negligible reluctance torque. However, the machine structure is relatively complex, and an integration control system involving drive and magnetization control will be required in the future work.

## 6 Advanced control strategies for FAPMM

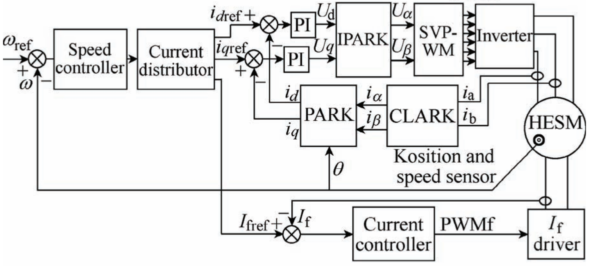
Theoretically, the control strategies of HEMs and MMs may be derived from the conventional PM motor drives. Generally, the control system of HEM is equivalent to that of a conventional PMM plus an additional field current control module. However, traditional control strategy cannot be directly applied to HEMs due to the significant nonlinear coupling between armature *d/q*-axis, field currents and torque capability. Therefore, it is of great importance to optimize the proportion of armature and field currents so as to satisfy the randomly varied operating requirement over a wide range of speed and torque. In addition, there are many challenges of controlling MMs such as coordinating control for AC-magnetized MMs and power converter integration and simplification for DC-magnetized ones.

### 6.1 Control methods for HEMs

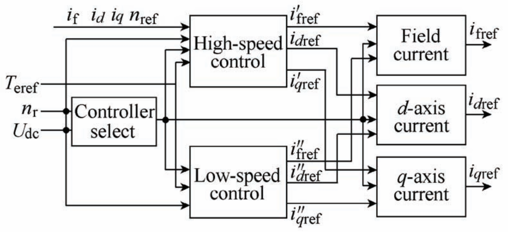
Due to the existence of dual excitation sources, HEM is referred as a multi-variable, nonlinear and highly coupled system. Thus the determination of the electromagnetic parameters inevitably becomes complicated. Hence the key issues of control algorithms for HEMs are dynamics and mathematical modeling, and optimization of the armature and field currents. Furthermore, the significant nonlinear relationship between the current and the torque leads to various control methods for HEM, all of which claim that the overall efficiency is improved.

In [94], the flux-weakening control of HEM was investigated which aimed for constant armature current, maximum torque or optimized efficiency. It is confirmed that HEM is suitable for wide-range constant-power operation. In [95], a fuzzy control scheme for HEM was proposed by introducing a fuzzy controller into the vector controller to regulate the armature and field currents appropriately. Thus, the efficiency and drive performance of HEM are maximized. In [96], a dynamic vector-control model for a non-salient HEM was developed and the effectiveness of the control mode on copper loss minimization was experimentally validated. By considering the importance of $i_d$ on flux weakening and the influence of loads on the inductances, a fuzzy control method was proposed in [97] integrating particle swarm optimization (PSO) algorithm to optimize the field current and $i_d$ for flux weakening control of HEM. As can be seen from Fig.32, the proposed HEM drive system has two additional functional modules when compared with the conventional vector control system of PMM: current distributor and field current driver. When the speed is high, the fuzzy control method combining with PSO algorithm optimize the field, *d*-axis and *q*-axis currents and hence minimize the copper losses. The variation of total copper losses during the PSO stage is shown in Fig.33. By doing so, the copper loss can be decreased by 22%.

In [98], a novel control method without the requirement of machine parameters was developed for a HESFPM machines equipped with iron bridges, which can inherently short-circuit the PM flux to release the requirement on negative field current, hence enhancing the operating efficiency as well as the fault tolerance capability. The control diagram is illustrated in Fig.34. The voltage error regulation is utilized to modify the field excitation current reference with $i_d$=0 so as to offer a smooth speed transition from flux-enhancing mode to flux-weakening mode, thus the systematic robustness and dynamic performance are improved.



(a) Overall block diagram



(b) PSO-current distributor

Fig.32 Schematic of HEPMM drive system[97]

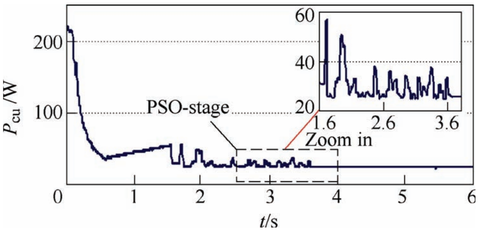
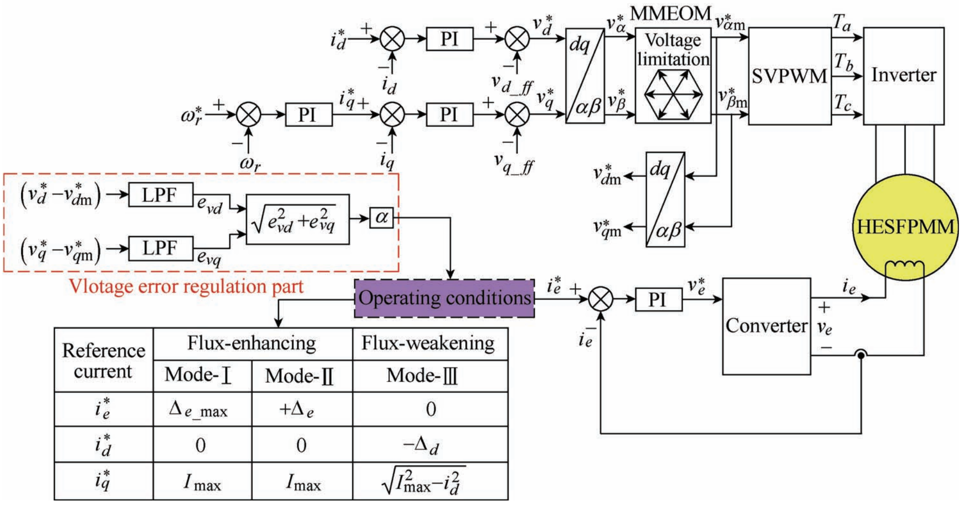


Fig.33 Total copper loss assessment subjected to PSO algorithm



| Reference current | Flux-enhancing | | Flux-weakening |
|---|---|---|---|
| | Mode-Ⅰ | Mode-Ⅱ | Mode-Ⅲ |
| $i_e^*$ | $\Delta_{e\_max}$ | $+\Delta_e$ | 0 |
| $i_d^*$ | 0 | 0 | $-\Delta_d$ |
| $i_q^*$ | $I_{max}$ | $I_{max}$ | $\sqrt{I_{max}^2-i_d^2}$ |

Fig.34 Block diagram of novel control strategy towards HESFPM machine[98]

In [99], the suitability of HEMs acting as a stand-alone DC generator for aircraft power system is investigated and verified. An improved direct-torque-control strategy combining SVPWM is adopted for HE-SFPMMs in [100] by linearly regulating the sine value of the torque angle to enhance the dynamic performance with satisfactory torque ripples and low current THD.

### 6.2 Control methods for memory machines

The vector control of MMs is basically similar to that of conventional PMMs. The major difference is that MM requires a coordinative control between normal drive and online flux regulation.

For AC-magnetized MMs, many researchers including the inventor V. Ostovic, adopted control algorithms based on the flux-orientation control [57], viz., the conventional $i_d$=0 control is employed under normal operations. The flux regulation mode can be switched on briefly, only when the armature winding is aligned with the $d$-axis. It should be noted that such a mode transition rarely affects the machine performance under open-circuit operation. However, the influence of pulsed currents on transient performance is significant when the machine is under load operation, which makes the coordinative control more difficult.

In [70], an optimal control method of online magnetization for a DM-MM equipped with fractional-slot concentrated windings is proposed, viz. only half of variable-flux magnets(sintered SmCo) are magnetized at the first stroke of magnetization control, afterwards the remaining half magnets are magnetized in order to align the magnetization states of SmCo magnets. The control diagram is shown in Fig.34, a combination of feedback control for $i_q$ and feed-forward control for $i_d$ is utilized during the magnetization. After the magnetizing current pulse is withdrawn, $i_d$ control returns to feedback control. As a result, high-efficiency high-speed magnetization control and torque ripple minimization are realized. It is worth mentioning that this type of machine has been implemented as a drive motor in TOSHIBA washing machines to achieve large torque at low-speed washing mode and to extend constant-power range at high-speed spin-drying process.

For DC-magnetized MMs, it is possible to independently control the armature and magnetizing current, which greatly simplifies the control. Fig.36 shows a typical schematic of flux control diagram for DC-magnetized MMs[71]. It is a controllable voltage source having an H-bridge converter and a Buck converter. The H-bridge converter determines the direction of pulse currents and the energizing sequence of magnetizing coils whilst the Buck converter decides the magnitude of the current pulses.

For SFMM, a coordinated control strategy was proposed to effectively extend constant power speed range (CSPR)[93]. In order to avoid the frequent adjustment of the PM flux linkage with current pulse and further extend the CPSR with minimized required

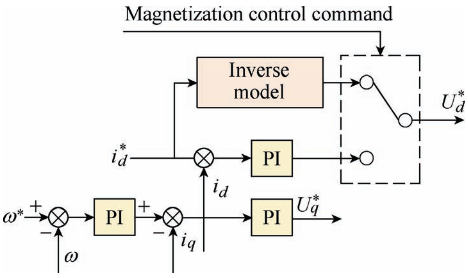


Fig.35 Magnetization control strategy for TOSHIBA IPMM[70]

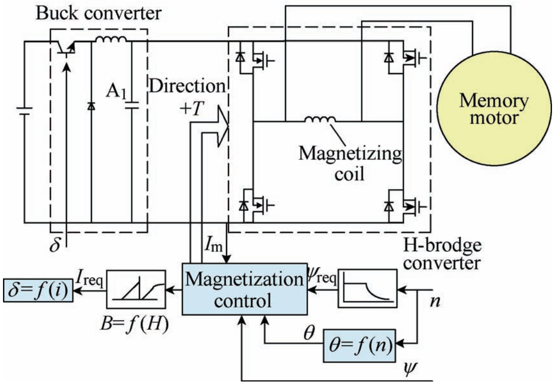


Fig.36 Block diagram of flux control of DSMM[71]

FW $d$-axis current, a new control strategy with stepwise magnetization manipulation is presented and implemented with the overall control strategy illustrated in Fig.37. It can be found that the high-speed FW region can be further subdivided into two regions, in which the transition speed can be numerically identified by using FE method. For FW region I, the negative $I_d$ and demagnetization controls should be combined to extend the speed range, while the demagnetization control becomes useless during the deep FW region II.

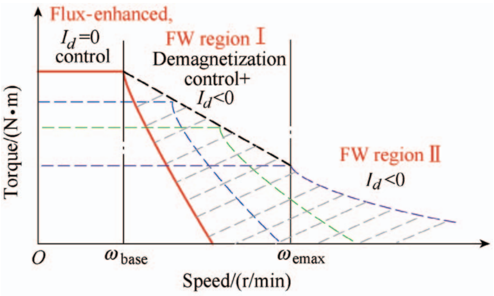


Fig.37 Illustration of global FW control and $d$-axis current flux weakening control for SFMM[93]

## 7 Conclusions

In this paper, the principles and classifications of FAPMMs have been reviewed with particular emphasis on their topologies, operating principles and characteristics. Their corresponding opportunities and challenges are summarized as follows.

For HEM:

1) Due to the incorporation of controllable field excitation, the advanced topologies can be further exploited by simplifying the coupling between electrical excitation and armature fields to improve operating efficiency and dynamic performance.

2) Novel theories and techniques should be developed to guide the design, modeling and control of HEMs, since their operational principles and characteristics are significantly different from conventional PMMs.

3) Systematic integration and optimization of drive and control techniques of HEMs should be studied in-depth to minimize total losses, improve reliability and dynamical response.

For mechanically-adjusted FAPMMs, the proposals, which are able to simplify both the machine structure and the mechanical devices, are greatly preferable for those applications with low cost requirements. Approaches which purposely and accurately regulating the air-gap flux assisted by mechanical devices will be of growing interests in the future as well.

For MMs:

1) Further investigation on the magnetism of AlNiCo, such as hysteresis modeling, physics of online flux regulation, hybridization by AlNiCo and NdFeB, will provide comprehensive support to the design, control and analysis of MMs.

2) Novel topologies can be explored for both AC-magnetized and DC-magnetized MMs. It is possible to convert various conventional IPMMs into AC-magnetized MMs while the exploitation of DC-magnetized MMs remains at an early stage. SFMM will be of great feasibility for industrial applications because of high torque density, easy thermal management and structural robustness.

3) How to balance the armature and magnetizing currents and choose the coercivity of the remanence-changeable PMs are two major design challenges.

4) In order to reduce the system cost, integrated dual-control systems will be a hot research topic in the future. The iron loss, in particularly the hysteresis loss due to the online magnetization of PMs, should be evaluated comprehensively. However, it is naturally complicated due to the minor hysteresis loops. How to alleviate the transient torque ripple and electromagnetic shock during PM magnetization is another key topic for MMs.

For FAPMM control strategies:

1) Current component optimization for maximum efficiency under all the operation conditions considering the whole driving cycle is desired for all FAPMMs. The influence of iron loss should be considered as well.

2) Decoupling control and integrated power converter and magnetization/demagnetization control are two other topics to be investigated.

3) Implementation of stepped flux regulation instead of continuous regulation may significantly simplify the machine structure and control strategies.

However, due to the merits of excellent flux-adjustable capability and high operating efficiency, FAPPMs are promising candidate machines for applications including ISG, wide speed-range servo drive and aircraft generators. Novel FAPMM topologies and techniques will continue to emerge. Therefore, various opportunities and challenges exist and further investigation needs to be carried out.

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