Dr. Norbert Cheung's Series in Electrical Engineering

Level 5 Topic no: 31

Stator PM EV motors

Contents

Reference:

KT Chau, "Electric Vehicles – Machines and Drives" John Wiley and Sons, 2015.

Email: norbert.cheung@polyu.edu.hk **Web Site:** www.ncheung.com

1. Introduction

Differing from traditional permanent magnet (PM) brushless motor drives, stator-PM motor drives takes the definite advantages that all PM materials are located in the stator while the rotor is simply iron core with salient poles, leading to offer higher robustness for high-speed operation and better thermal stability for PM materials. These two features are highly desirable for electric vehicle (EV) motor drives that need to operate at harsh working environment. Currently, there is a wide variety of stator-PM machines, and some of them are considered viable for EV propulsion.

In this chapter, various stator-PM motor drives, including the doubly-salient permanent magnet (DSPM), flux-reversal permanent magnet (FRPM), flux-switching permanent magnet (FSPM), hybrid-excited permanent magnet (HEPM), and flux-mnemonic permanent magnet (FMPM) topologies,

PM: permanent Magnet
DS: Doubly Salient
HE: Hybrid Excited
FS: Flux Switching
FM: Flux Mnemonic
FR: Flux Reversal

Flux controllable and flux non-controllable motor drives:

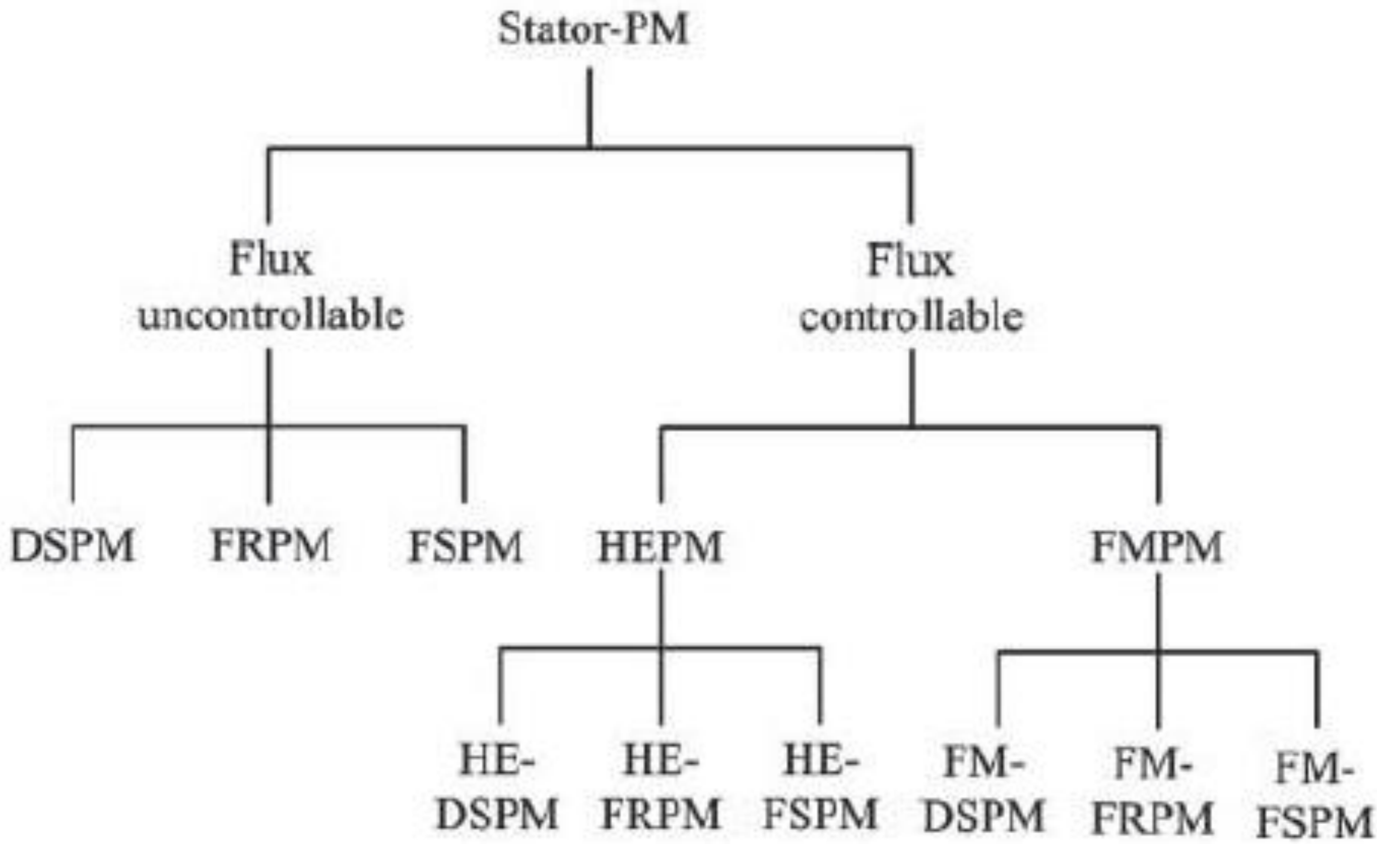

Figure 6.1 Viable members of stator-PM machines

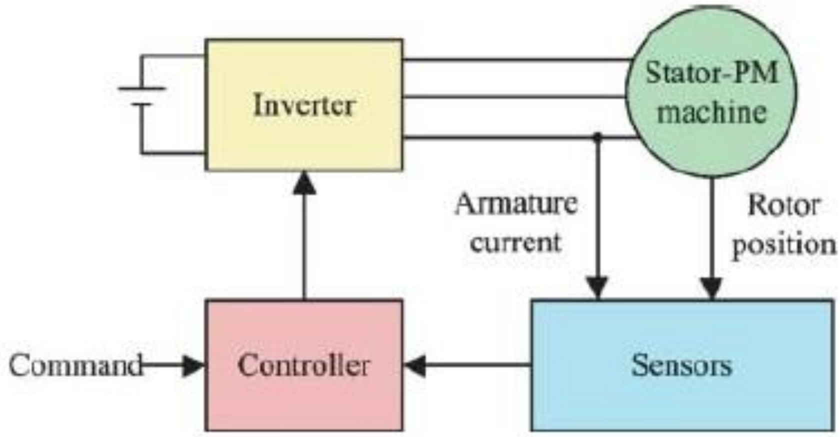

Figure 6.2 Configuration of singly-fed stator-PM motor drives

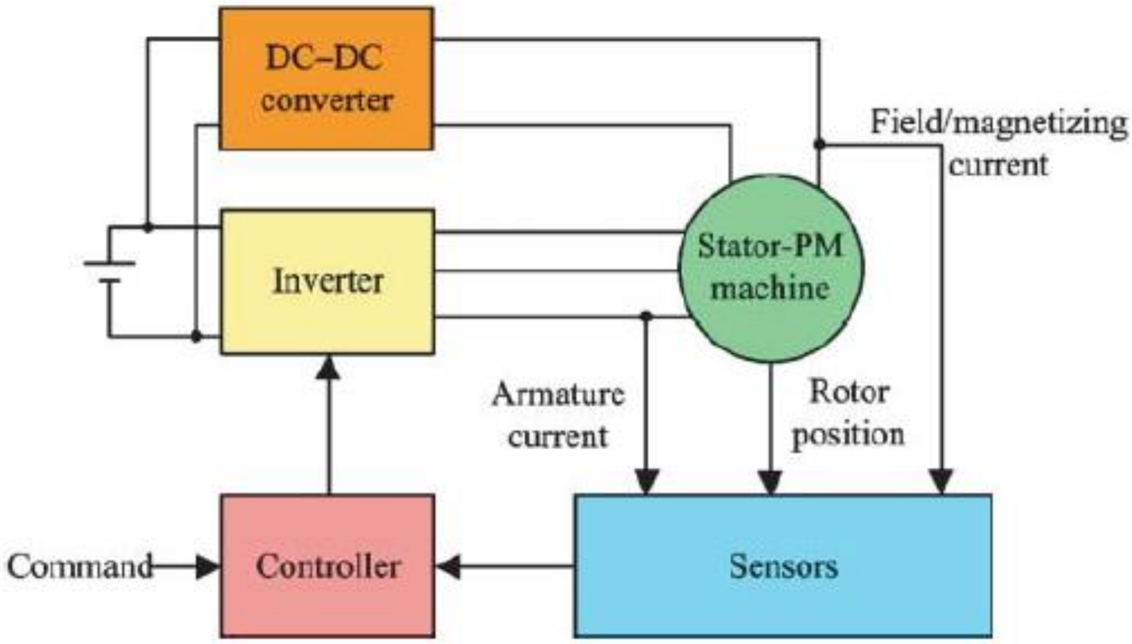

Figure 6.3 Configuration of doubly-fed stator-PM motor drives

It should be noted that the DC–DC converter for the doubly-fed stator-PM motor drives should allow for bidirectional current flow. That is, for flux strengthening, the field or magnetizing current should be positive, whereas for flux weakening, the field or magnetizing current should be negative. Between the two doubly-fed families, the HEPM machines desire continual DC field current for field excitation whereas the FMPM machines need only temporary current pulses for PM magnetization or demagnetization. Thus, their DC–DC converter designs and ratings are different.

2. Doubly Salient PM Motor Drives

It is the most mature. And it can be viewed as a combination or SR motor and BLDC motor.

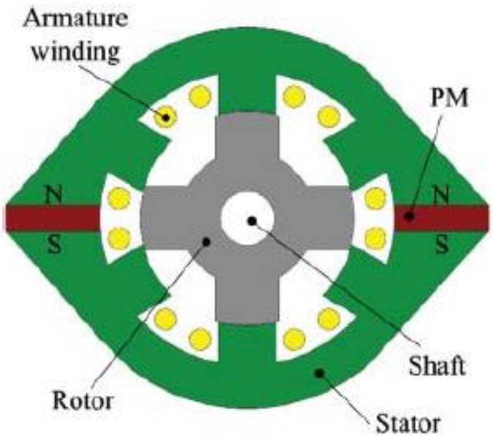

Figure 6.4 Structure of DSPM machine

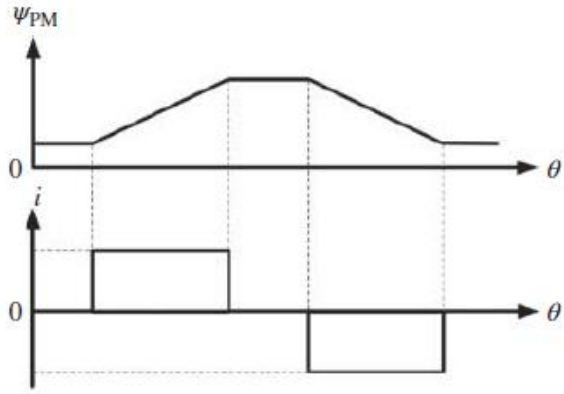

Figure 6.5 Brushless DC operation of DSPM machine

By properly designing the stator and rotor pole arcs, the air-gap reluctance seen by the PMs are invariant. Consequently, the PM flux linkage, ψ_{PM} varies linearly with the rotor position as shown in Figure 6.5. As the PM flux linkage and hence the back EMF waveforms are trapezoidal, the DSPM machine generally operates at the BLDC mode in which a positive armature current i is applied during the PM flux linkage increasing zone while a negative armature current is applied during the PM flux linkage decreasing zone. Notice that the zero-current interval between the positive and negative currents is purposely provided to ensure successful current reversal.

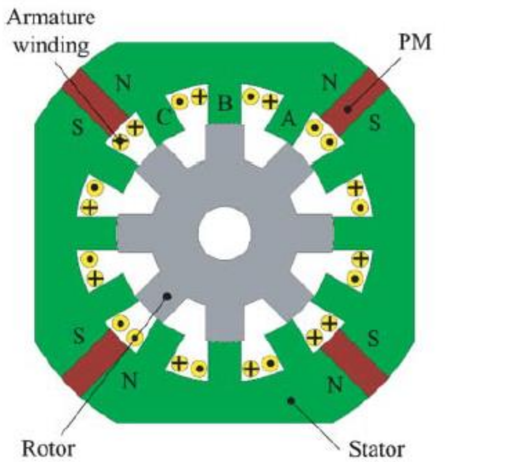

Figure 6.6 Structure of three-phase 12/8-pole DSPM machine

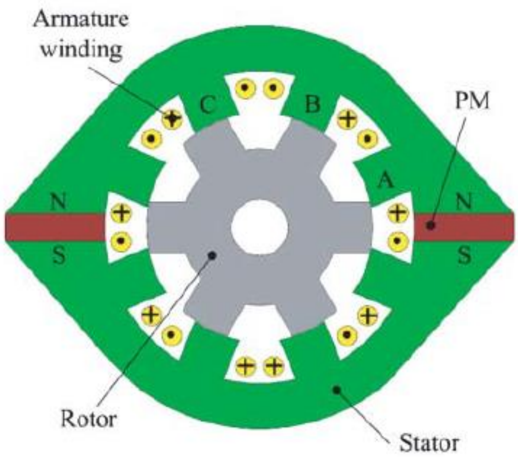

Figure 6.7 Structure of four-phase 8/6-pole DSPM machine

When the rotor is purposely skewed to minimize the cogging torque, the characteristic of PM flux linkage and hence the back EMF are more sinusoidal. Typically, the skewing angle δ is selected to be about one-half the stator pole pitch. In order to take into account the effect of rotor skewing, a skewing

Consequently, the DSPM machine can operate at the brushless AC (BLAC) mode as shown in Figure 6.8, where the phase current is fed at 90° phase shift with the PM flux linkage or actually in phase with the back EMF.

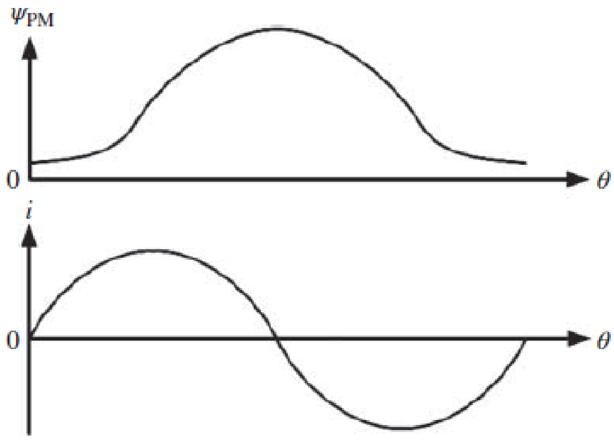

Figure 6.8 Brushless AC operation of DSPM machine

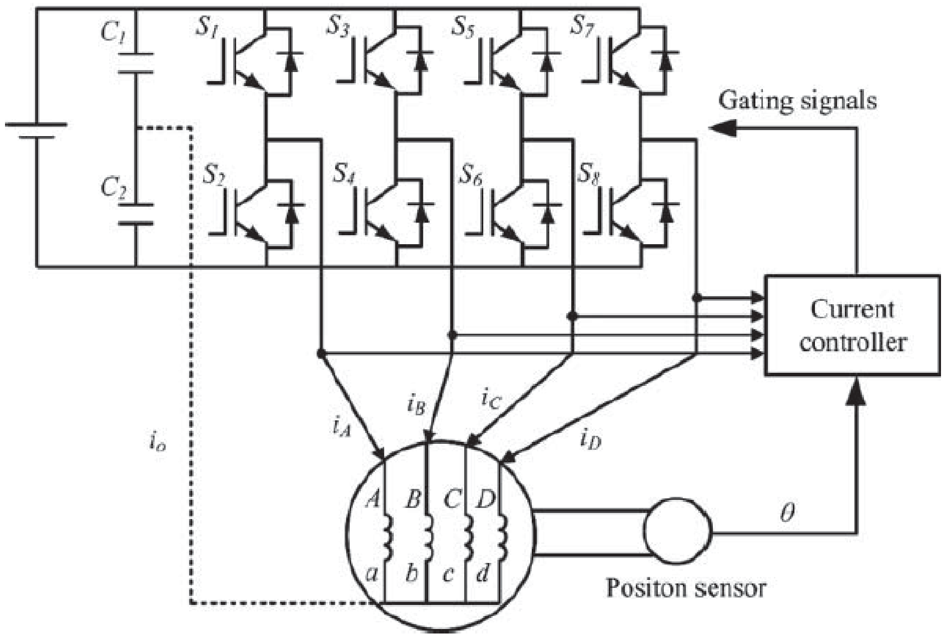

Figure 6.9 Half-bridge inverter with split capacitors for DSPM motor drive

To supply the DSPM motor drive, a bipolar converter is preferred so as to bring the merit of the DSPM machine into full play. To control the phase currents individually for bidirectional operation of the DSPM machine, there are two possible inverter topologies: the full-bridge inverter and the half-bridge inverter with split capacitors. The latter topology is usually selected for the DSPM motor drive because it minimizes the number of power devices. Figure 6.9 shows a four-phase 8/6-pole DSPM motor drive in which the connection between the central point of the split capacitors and the neutral of machine windings is indicated by a dashed line. This connection is mainly used to accommodate the unbalanced current during the commutation period.

In accordance with the operation principle of the DSPM machine, the phase winding should be turned on or off at specific rotor positions. Hence, the rotor position information is indispensable for proper operation of the DSPM machine. Such positions can readily be measured by a simple position sensor as shown in Figure 6.10. It consists of a slotted disc connected to the rotor shaft and two optocouplers

mounted onto the stator housing. The two optocouplers are nominally located 45° apart from each other along the circumference of the disc. The output waveforms of the sensor are shown in Figure 6.11. The sensor generates a signal edge for every 15° of mechanical rotation. The transitions of these outputs determine the specific angles. According to the relationship between the position signals and PM flux linkages, the control logic of the four-phase 8/6-pole DSPM motor drive can be obtained as given in Table 6.1.

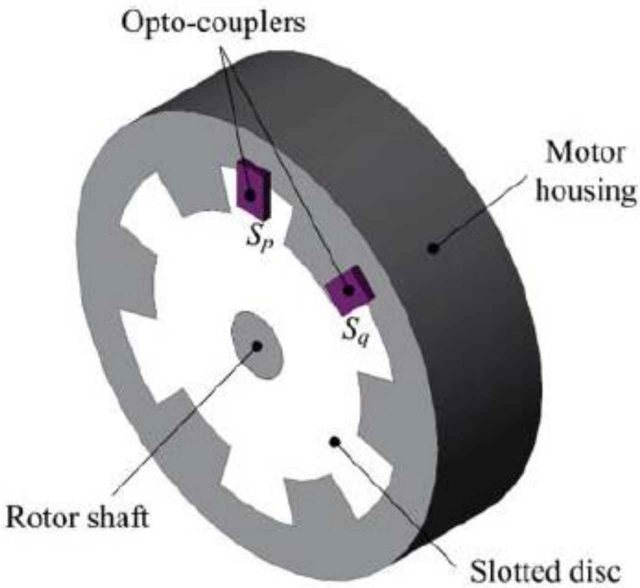

Figure 6.10 Position sensor for DSPM motor drive

Table 6.1 Control logic of 8/6-pole DSPM motor drive

S_qS_p		01	11	10	00
Phase A	S_1	1	1	0	0
	S_2	0	0	1	1
Phase B	S_3	0	1	1	0
	S_4	1	0	0	1
Phase C	S_5	0	0	1	1
	S_6	1	1	0	0
Phase D	S_7	1	0	0	1
	S_8	0	1	1	0

The speed control of the DSPM motor drive can readily be implemented by a closed-loop digital proportional-integral (PI) controller, whose output is the torque reference T^* (Cheng *et al.*, 2003).

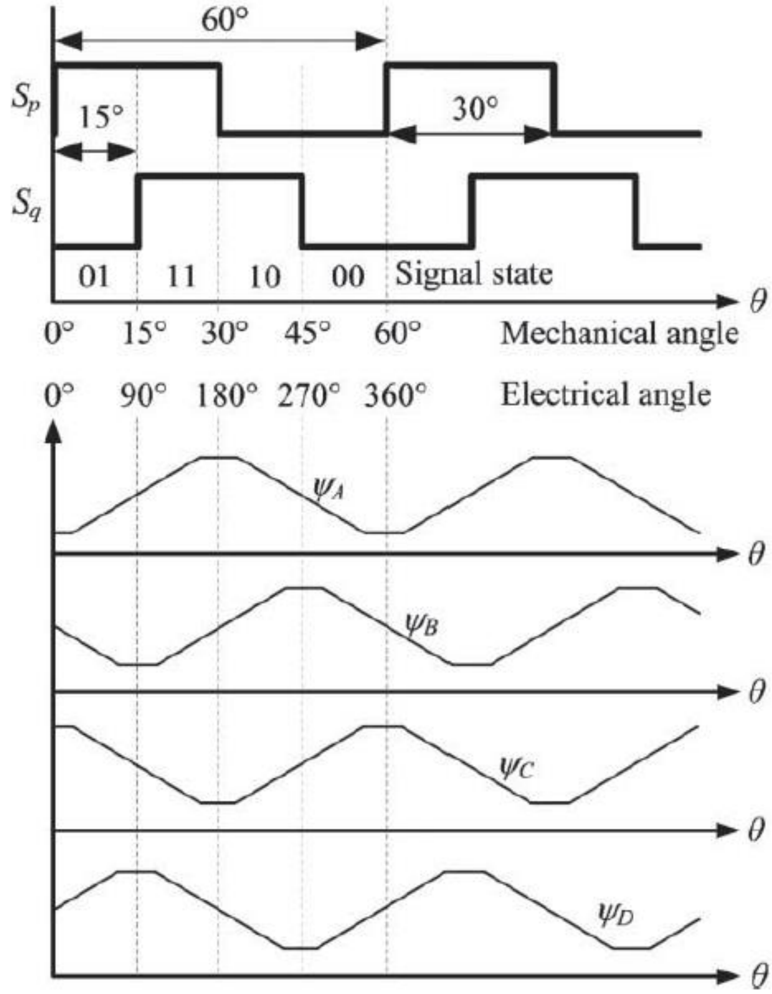

Figure 6.11 Position signals and PM flux linkages of DSPM motor drive

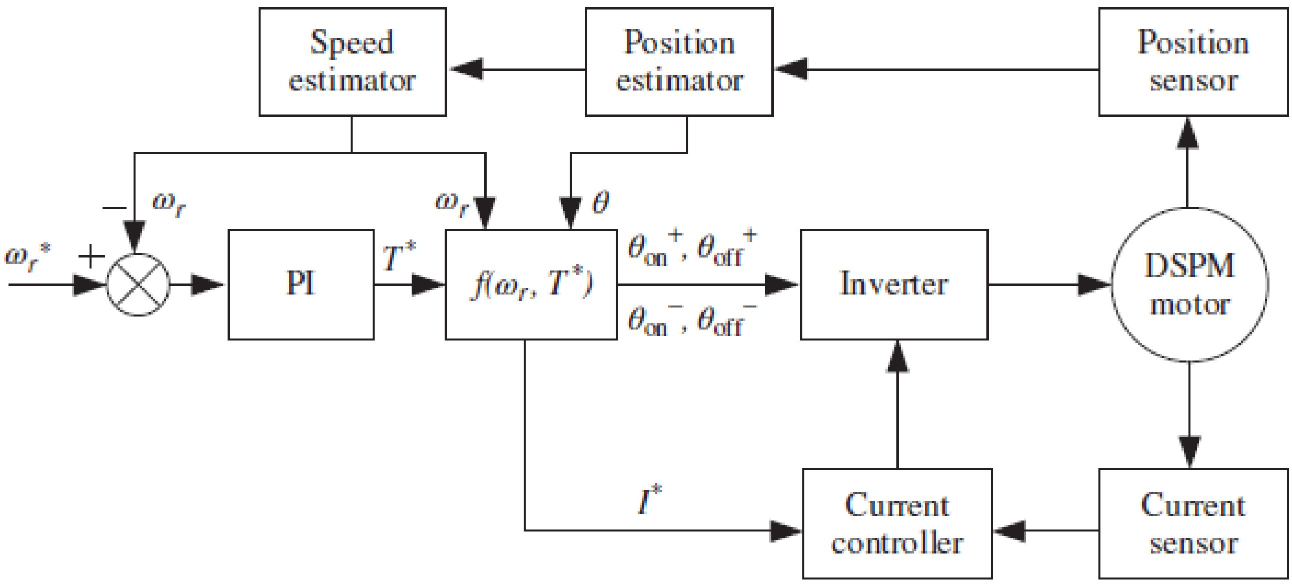

Figure 6.12 Speed control block diagram of DSPM motor drive

3. Flux Reversal PM Motor Drives

The FRPM machine is a kind of stator-PM machine in which the PMs with different polarities are located on the surface of each stator pole, the armature winding generally adopts the concentrated winding

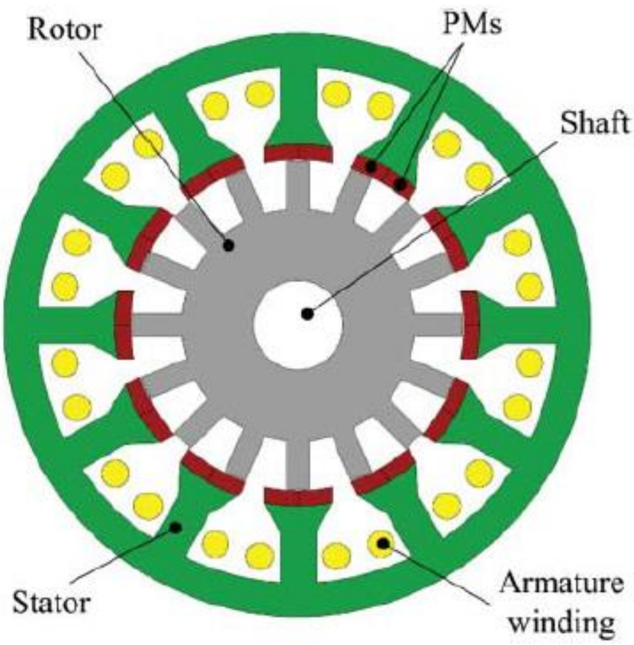

Figure 6.13 Structure of FRPM machine

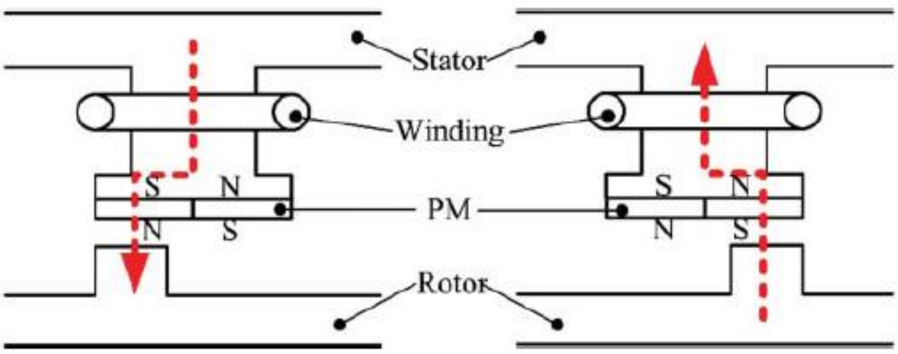

Figure 6.14 PM and winding arrangements of FRPM machine

arrangement, and the rotor is simply iron core with salient poles (Deodhar *et al.*, 1997). Figure 6.13 shows the structure of a three-phase 12/16-pole FRPM machine in which there are 16 stator poles, 12 rotor poles, and 2 PM poles per stator pole. Differing from the DSPM machine, the FRPM machine exhibits bipolar PM flux linkage because the flux linkage with each armature coil reverses polarity as the rotor rotates as depicted in Figure 6.14. Since the bipolar flux linkage variation can have better utilization of iron core than the unipolar counterpart, the FRPM machine inherently offers higher power density than the DSPM machine. Similar to the SR machine, the rotor skewing can also be used to make the air-gap waveform be more sinusoidal, and to reduce the cogging torque.

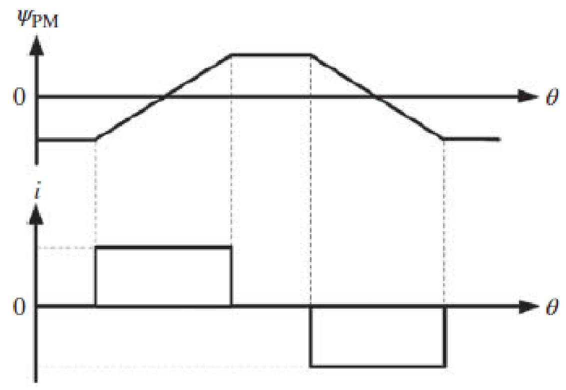

Figure 6.15 Brushless DC operation of FRPM machine

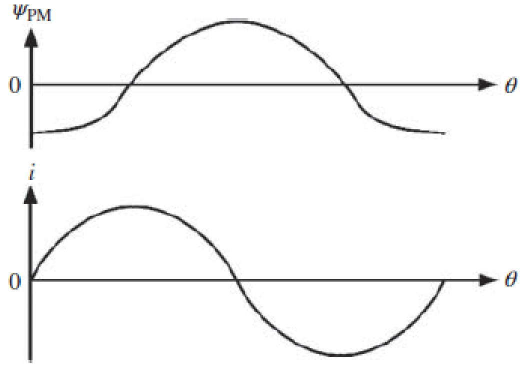

Figure 6.16 Brushless AC operation of FRPM machine

4. Flux Switching PM Motor Drives

The FSPM machine has attracted wide attention in recent years. Among the three major stator-PM machines, the DSPM, FRPM, and FSPM, the stator configuration of the FSPM machine is relatively complex as shown in Figure 6.17. In this topology, each stator pole consists of two adjacent laminated segments and a PM, and each of these segments is sandwiched by two circumferentially magnetized PMs which enables flux focusing (Zhu *et al.*, 2005). In general, the concentrated winding arrangement is adopted, and each coil is wound around the adjacent stator poles. Hence, the polarity of the PM flux linkage in the coil reverses when the rotor pole aligns the successive stator tooth that belongs to the same phase, the so-called flux-switching action, as illustrated in Figure 6.18.

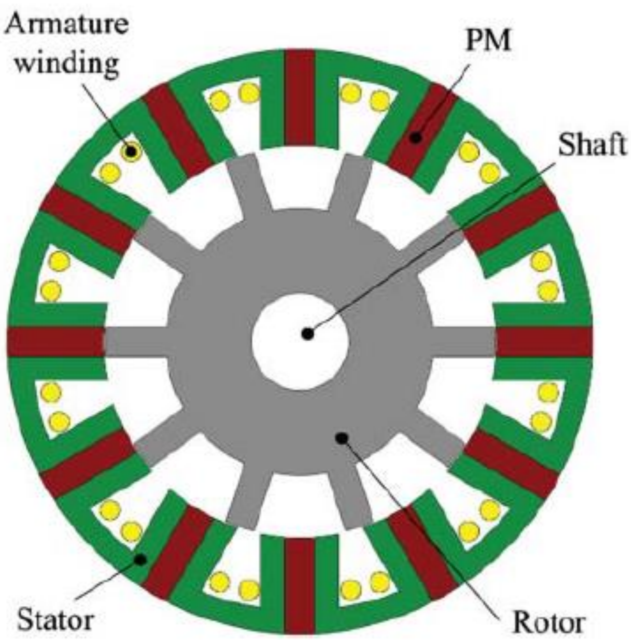

Figure 6.17 Structure of FSPM machine

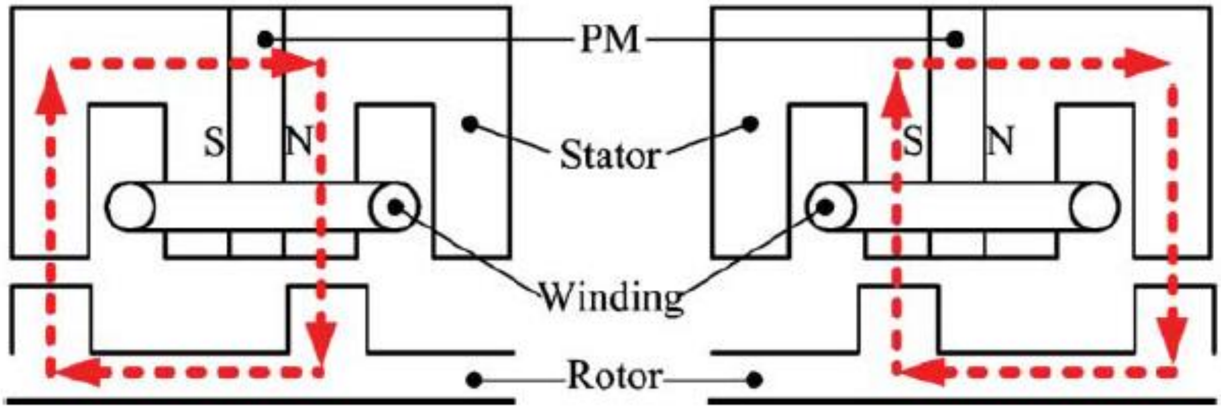

Figure 6.18 PM and winding arrangements of FSPM machine

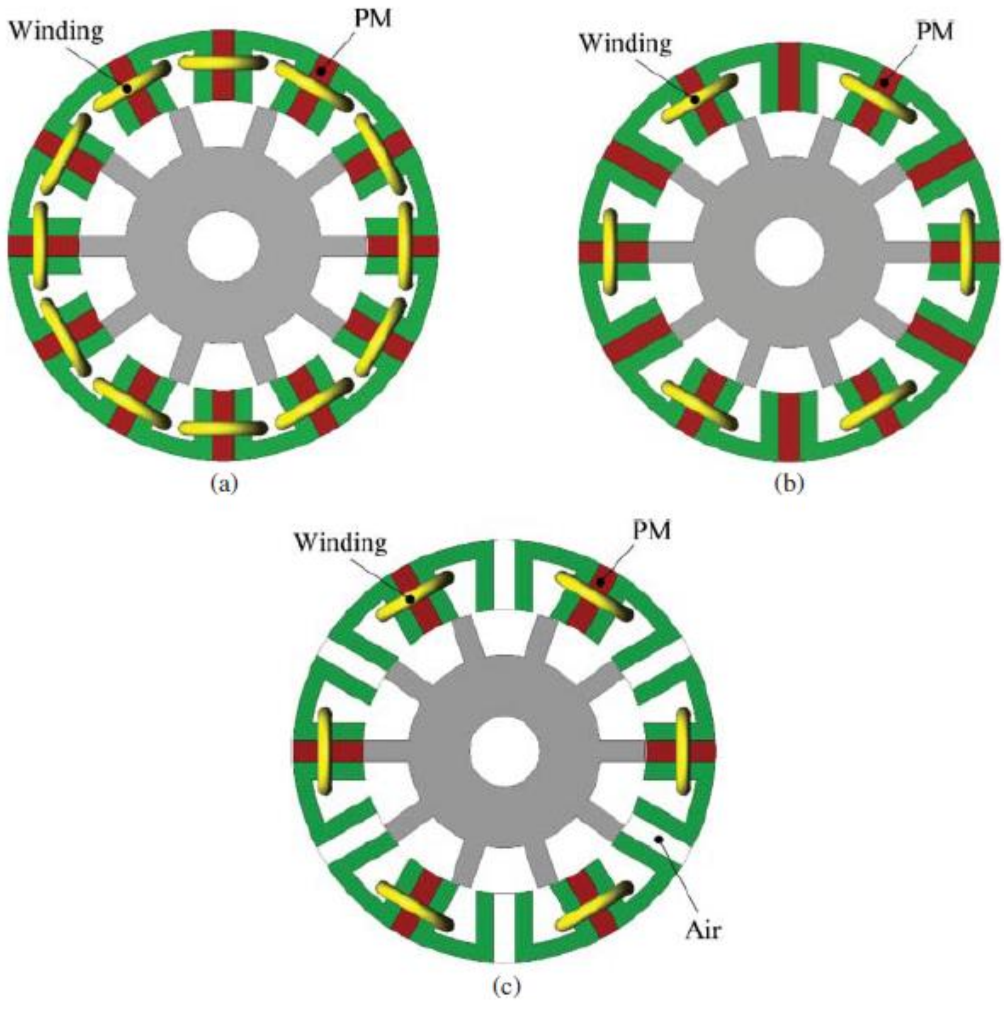

Figure 6.19 Variation of FSPM machine topologies: (a) original, (b) alternate poles wound, and (c) alternate poles wound with reduced magnets

5. Hybrid Excited PM Motor Drives

Similar to the conventional rotor-PM machines such as the PM synchronous machine and PM BLDC machine, the stator-PM machines have difficulty in air-gap flux control because of an uncontrollable PM

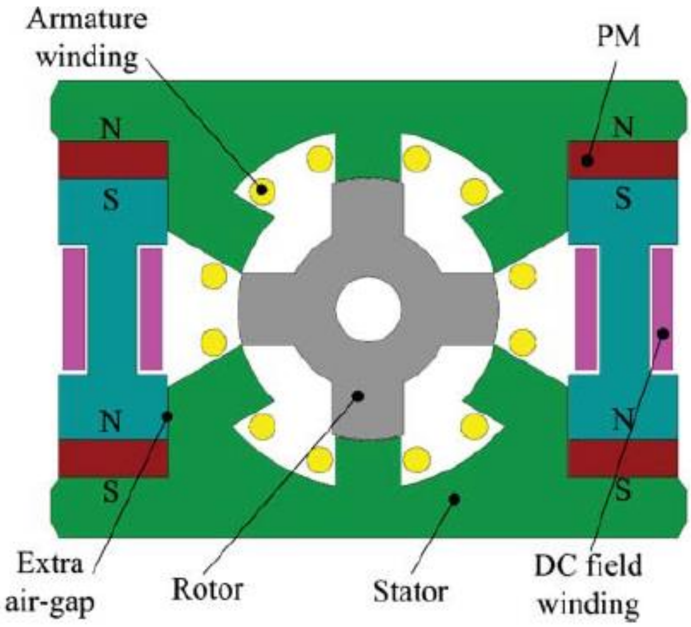

Figure 6.20 Structure of HE-DSPM machine

flux. Although the corresponding air-gap flux control can be provided by using sophisticated vector control or advanced conduction angle control, it involves complicated control algorithms and costly control hardware. The concept of hybrid excitation, including both the PM and field winding excitation, can enable the air-gap flux of the stator-PM machines directly controllable. Theoretically, the aforementioned three main types of stator-PM machines, the DSPM, FRPM, and FSPM, can incorporate the concept of hybrid excitation.

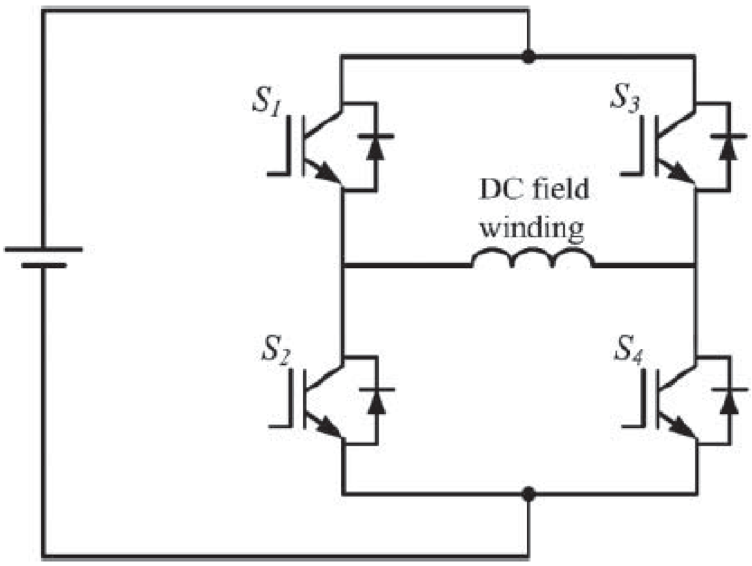

Figure 6.21 Power circuit for DC field winding in HE-DSPM machine

The operation principle of this HE-FSPM machine is similar to that of the original FSPM machine except that it can offer the feature of direct air-gap flux control. As depicted in Figure 6.23, by controlling the polarity and value of the DC field current, the air-gap flux density can be easily strengthened or weakened. Meanwhile, this arrangement of hybrid excitation does not need to increase the overall machine size.

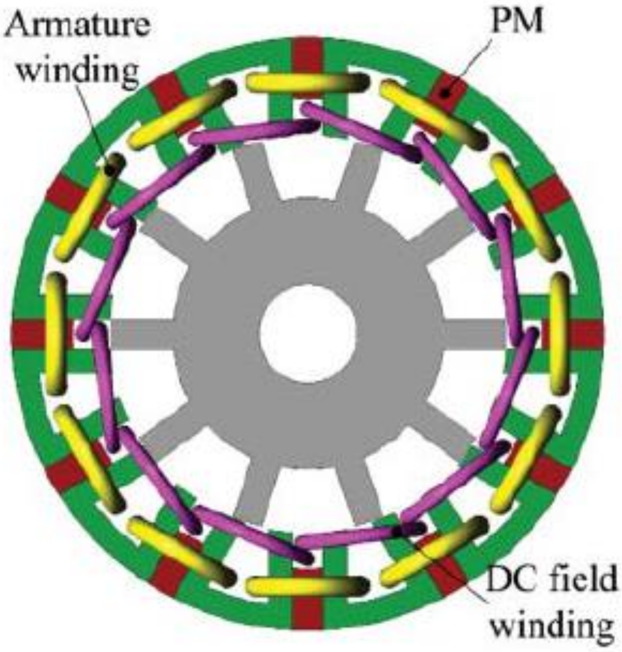

Figure 6.22 Structure of HE-FSPM machine

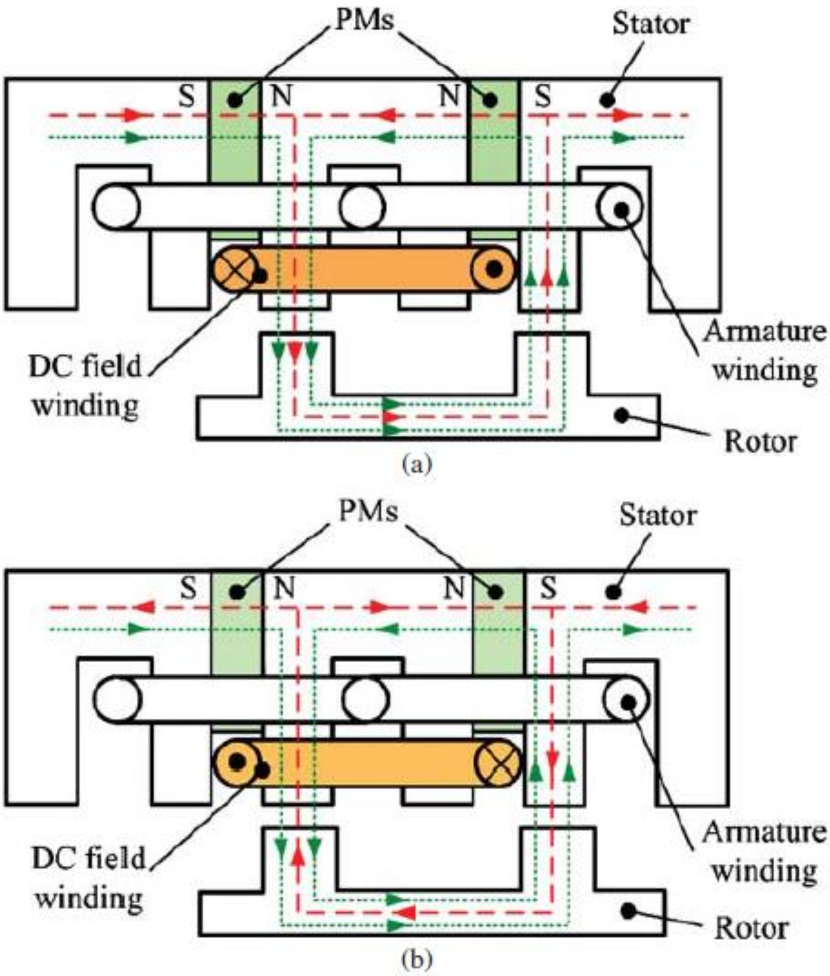

Figure 6.23 Flux control of HE-FSPM machine: (a) flux strengthening and (b) flux weakening

6. Conclusion

Table 6.4 Evaluation of stator-PM motor drives for EVs

	DSPM	FRPM	FSPM	HEPM
Power density	Medium	Good	High	Medium
Torque density	Medium	Good	High	High
Efficiency	Good	Good	Good	High
Controllability	Medium	Medium	Medium	Superb
PM immunity	Medium	Weak	Good	Good
Robustness	Strong	Medium	Medium	Medium
Manufacture	Easy	Medium	Medium	Hard
Maturity	High	Medium	Medium	Low

In terms of power density and torque density, the FSPM motor drive is the best because it employs the flux-focusing arrangement. Meanwhile, the power density of the doubly-fed HEPM and FMPM is degraded because of the use of additional field or magnetizing winding. Nevertheless, the corresponding torque, especially during starting, can be temporarily boosted up by instantaneous flux strengthening. Those doubly-fed HEPM and FMPM motor drives possess the capability of air-gap flux control, which can achieve higher efficiency than those with singly-fed DSPM, FRPM, and FSPM motor drives. Concerning controllability, those doubly-fed HEPM and FMPM motor drives are much better than the singly-fed motor drives.

As the PM material is relatively delicate, their immunity to accidental demagnetization and mechanical abuse are of concern. The PM immunity of the FRPM motor drive is relatively weak because the corresponding PMs are mounted on the surfaces of stator poles that are prone to be partially demagnetized under high armature field or high temperature operation and are vulnerable to physical damage under severe vibration.

In terms of robustness and manufacturability, the DSPM motor drive is the best because it offers the highest simplicity in both the stator and rotor, leading to very robust nature and easy manufacturing. On the contrary, the doubly-fed HEPM and FMPM motor drives need to install two sets of windings in the stator, which degrades their manufacturability.

Concerning maturity, the DSPM motor drive is the most mature one because it has been developed for over two decades. Next, the FSPM and FRPM motor drives are quite mature, which have been developed for over a decade. As the HEPM and FMPM motor drives are recently derived from the singly-fed stator-PM motor drives, they are immature.

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