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Review Article

Performance Enhancement of Flux Switching Motor for Electric Vehicle Applications: An Overview

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As the reduction of greenhouse gas emissions becomes crucial, electric vehicles (EVs) are expected to enter the market extensively in the coming years. The efficiency of the electrical motor used in EVs plays a significant role in their overall performance. This paper explores the flux switching motor (FSM) and its applications in EVs. The FSM is compared to other electrical motors, highlighting its potential as a suitable choice for EV traction. Various configurations and techniques are reviewed to enhance the performance of FSMs, including magnetic materials, torque ripple alleviation, and magnetic flux weakening. The advantages and disadvantages of these methods are discussed, providing valuable insights for designing FSMs for EVs. Generally, EV traction requires high torque density and high power density electrical motor. To achieve these goals, high electric and magnetic loading must be considered in design stage of the motor. Application of the FSM may be one of the appropriate option. For many reasons, three-phase FSM is preferred. Considering the base speed of machine in the EV and high electric loading, the FSM with 12 stator teeth and 10 rotor teeth may be the most appropriate choice in which the stator core is oriented and rotor core is nonoriented iron. To enhance the torque density and applied flux weakening method, combination of Nd and Al–Ni–Co magnets is preferred.

1. Introduction

Nowadays, global warming and reduction of fossil fuel reserves are the most important concerns of the world. Reduction of greenhouse gas emissions, caused by vehicles as the largest consumer of the fossil fuels, is important aspect. Therefore, electric vehicles (EVs) will widely enter to the market in the coming years. Electrical motor is the most important part of the EV and its efficiency has direct impact upon wheel to wheel of the EV. High efficiency, high torque density, and range of constant speed–power are the most important requirements of electrical motor for this application. Comparison of different electrical motors indicates that flux switching motor (FSM) can be one of the appropriate choice for EV traction.

The FSM has high torque density and with robust rotor. However, the large cogging torque of the motor leads to unsmooth operation and mechanical stress [1].

In this paper, the FSM is reviewed and various available configurations for enhancement of its performance in EV are compared. First, the FSM and its applications are introduced. Then, principles of operation of the motor and impacts of different parameters upon its performance are given. Magnetic materials used in the FSM, torque ripple alleviation techniques, and magnetic flux weakening methods in the motor are presented.

At the end of each section, advantages and disadvantages of the suggested methods and overall verdict for choosing parameter fit with EV are given. This review can be a solid foundation for FSM design used in the EV.

2. Introduction to Flux Switching Motor

The FSM was first introduced in 1943, designed as a single-phase external rotor motor. Fundamental of its design as a high-speed generator was proposed in 1955 [2]. Figure 1 shows initial samples of FSM [3]. Continued development of FSMs, substituting permanent magnet (PM) with direct current (dc) excited winding was investigated. Of course, this substitution led to reduction of torque density and efficiency

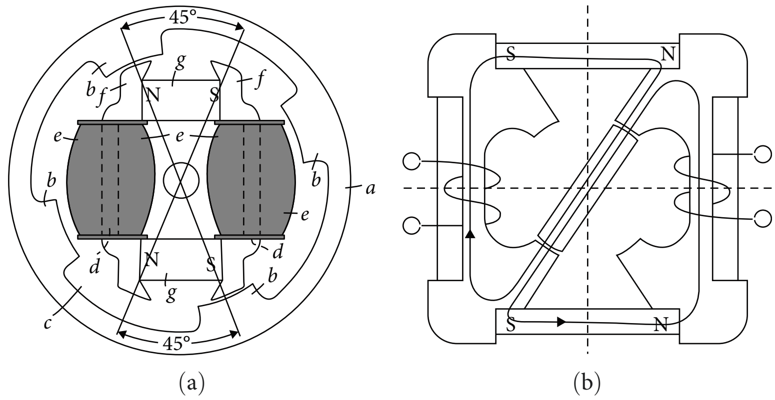


FIGURE 1: Initial samples of FSM: (a) external rotor and (b) internal rotor [3].

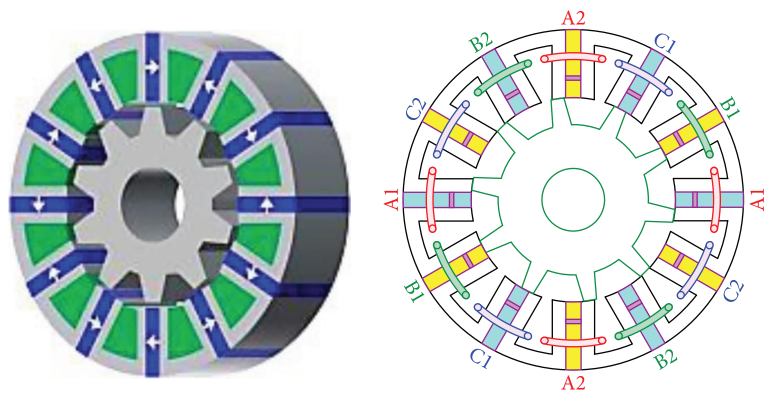


FIGURE 2: Structure of three-phase FSM [6].

of the machine [4]. A more complete structure of three-phase version of the motor was introduced in [5]. This structure has enough room for three-phase windings and PMs have been radially located between the windings. Figure 2 presents the structure of this motor in which concentrated windings are wound around PMs. The PMs or dc excited windings generate the main flux.

2.1. Attributes of FSM. Torque density of FSM is comparable with other PM motors [7]. The PM located on the stator leads to easier cooling. The rotor is similar to the rotor of switched reluctance motor (SRM) and is one piece with no PM and winding and it is mechanically and electrically robust. Only an half of the surface under each winding sees the maximum magnetic flux. The reason is that one of two teeth surrounded by the winding passes the concentrate flux in positive half-cycle. In the negative cycle, the other tooth plays similar rule. Nevertheless, this motor develops higher torque per PM compared with the conventional PM motors. Overload capability of this motor is lower than that of the surface PM synchronous motor because the teeth of the motor are designed for high magnetic flux density [8]. Normally, the overload of the motor leads to the saturation of teeth. The peak air gap flux density is about 1.8 T. This large flux density can generate a high radial force leading to the generation of vibration and noise. If the number of rotor teeth is even, the mutual forces in two sides of stator neutralize each other leading to better operating conditions.

Using ferrite PM in the place of Nd-type PM increases the risk of PM demagnetization in high currents [9]. Of course, the cost of Nd PM is many times of the ferrite PM. The L_d and L_q inductances of the FSM are almost equal. Besides, these inductances are larger than that of the surface PM and inner-PM motors and this widens the range of constant power speed of the FSM. On the other side, high inductance leads to a lower power factor compared to the conventional PM motors. In generator mode, this machine needs a higher voltage regulation. It seems that external rotor FSM reduces the losses in FSM; however, this claim has not been experimentally validated [10].

Compared to other stator-PM machines, FSM has a higher torque density, efficiency, less PM used, and flux weakening capability [7]. Briefly, the most important advantages of the FSM include [11]:

(i) Capability of generating rather high torque density: On contrary to doubly salient machine, the flux under stator teeth of the FSM is bidirectional. Therefore, the torque density of this motor is higher than that of the doubly salient-pole motor and it can develop a torque close to SPM motor. Although the FSM does not develop reluctance torque, the torque of the motor is lower than the interior PM (IPM) motor.

(ii) Fixing excitation on the stator of machine: Excitation winding on the rotor of PM motor complicates the control of PM temperature and using hybrid excitation. However, PM of the FSM is placed on the stator, which makes it possible to employ the hybrid excitation.

(iii) Simplicity and robustness of rotor: Similar to the SRM, rotor of this motor is made of iron, and there are no copper and PM on the rotor, this causes simplicity and robustness of the rotor.

(iv) A better flux weakening: There are diverse methods for flux control of FSM, which use the advantage of placing PM on the stator. Therefore, most mechanical flux control methods and flux control by memory magnet methods have no possibility to use in surface PM motor.

(v) Simplicity of cooling: In the FSM, most losses heat are generated in the stator. On the other hand, rotor with no winding and PM makes possible of higher temperature tolerance. Therefore, taking out the heat caused by the losses is easier than the motors with considerably higher losses in the rotor [12].

In return, some disadvantages of the FSM are as follows:

(1) It develops very small reluctance torque.
(2) PM torque ratio is larger than that of IPM machine.
(3) It has a lower overload capability compared to the IPM machine.
(4) Fewer works for FSMs are available compared to the IPM machine.

2.2. Applications of Flux Switching Machine. Considering the characteristics of the FSM and its different structures, this motor can be designed for powers of several watts to several megawatts, as well as designed for low speeds to high speeds. Hence, FSM can be suggested for a wide variety of applications. Since it is appropriate for high torque applications, 1 MW power superconducting FSM has been chosen for aircraft [13]. On the other hand, its high performance and robustness make it suitable for low-power axial fan motor [14]. Moreover, FSM has been suggested for several specific applications from aircraft oil breather [15] to generators in small-scale wind turbines and hydroelectric power plants [16, 17]. Besides, linear FSM (LFSM) has some advantages which make it appropriate for different applications. An LFSM is suggested for dry gravity energy storage, taking into account its high power factor and efficiency [18]. The LFSM has been proposed for self-bearing linear motion platform [19]. Many other applications have been so far introduced for this motor [20, 21]. The most important applications of FSM are as follows:

(1) In electric transportation systems: The most important requirement of electric motor design in EV is its appropriate torque density and efficiency. Since this motor is compatible with the existing motors, it has been designed as such that its long rotor is built from iron and short stator has PM. Therefore, advantages of PM application and cheap rotor are simultaneously achieved [22]. Robustness of its rotor is also considerable and this makes it appropriate for transportation application [23]. Outer rotor in-wheel FSM is proposed in Ahmad et al.'s [24] study. Many have confirmed the effectiveness of using FSM for EVs and hybrid EVs [25–28].

(2) In renewable energy systems: Using axial flux FSM has been suggested for wind energy conversion [29]. In this case, the generator has smaller dimensions compared with other generators and develops more torque. Cost-effective and fault-tolerant wound-field FSMs (WF-FSM) have been studied experimentally in Udosen et al.'s [30] study. In addition, linear FS generator has been suggested for converting wave energy to electrical energy [31].

(3) In industry: Multiphase FSM has good reliability and is suitable for special applications. In high powers, the number of power electronics components decreases. On the other hand, higher number of phases is considered an important advantage in application of vector control method. Since multiphase machine can be designed as such that electric and magnetic circuits of each phase are independent from other phases, this type of machine has high fault tolerance capability and is suitable for special applications in industry [20].

3. Principles of Operation of FSM

Principles of operation of FSM are based on switched flux passing through its windings. By changing the rotor angle, the PM is conducted to a path that the flux surrounding the winding changes its direction. Figure 3 shows a single-phase FS generator. Figure 3(a) presents how the PMs flux passes through winding. Figure 3(b) shows by changing the rotor angle the magnetic flux path varies and consequently the passing flux through the winding inverses.

By proper design of dimensions and parameters of the FSM, it is possible that the flux surrounding the winding of the machine varies sinusoidally with the rotor position. Figure 4 presents the linear FSM for simpler description. When rotor tooth aligns with the stator teeth, total flux of PMs exits from the rotor through the machine winding and as a result, maximum positive flux passes the winding. In part B, by 90° rotation of rotor to the right direction, the magnetic path varies as such that the exiting flux from stator under winding is equal to the entering flux to it. Therefore, the observed flux from winding is zero. In part C, when the rotor tooth is in the front of the stator tooth, total flux of PM enters stator through winding. As a result, maximum negative flux passes the winding. In part D, again magnetic path is

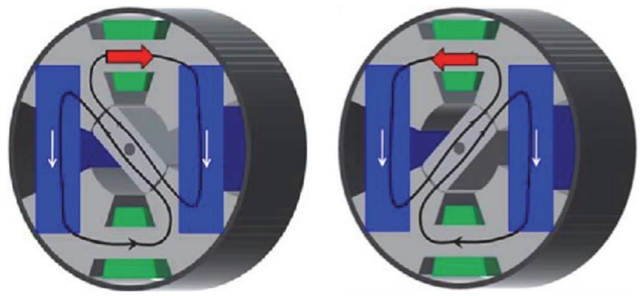


FIGURE 3: (a, b) Changing winding flux direction in a single-phase FSM [32].

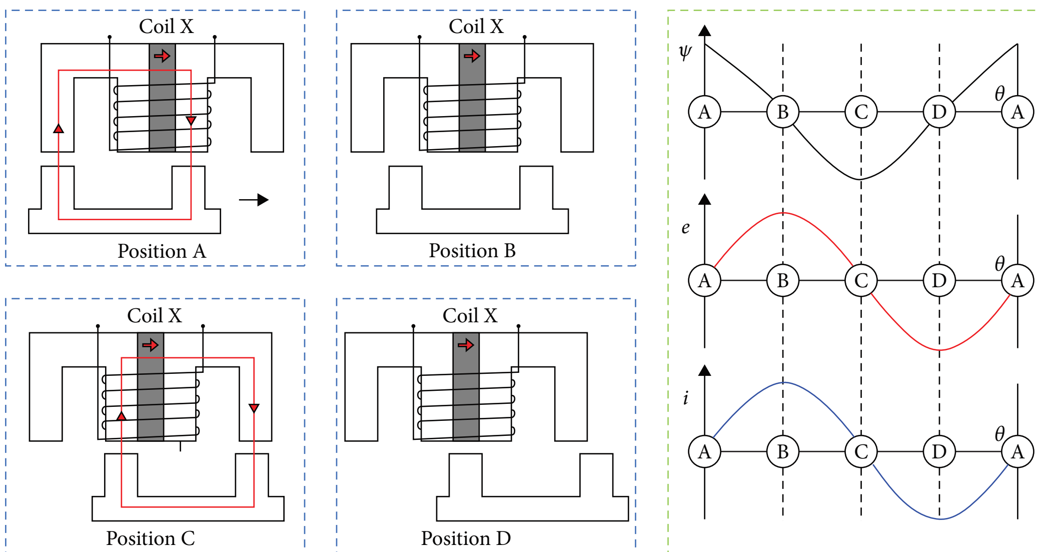


FIGURE 4: Flux surrounding winding of LFSM [3].

as such that the total exiting flux from the stator under windings is equal to the flux entering to it, so, the observed flux from winding is equal to zero.

Sinusoidal flux and consequently the sinusoidal induced voltage make it possible to control it as an AC machine (BLAC). Taking into account the above conditions, injecting current to the winding of the machine develops torque. Therefore, the machine can operate in generator and motor modes.

The FSM develops very low reluctance torque [33]. This machine has good flux weakening capability because the generated flux due to armature reaction does not pass through the PM. Thus, there is no the risk of losing the PM magnetization intensity by the armature reaction. On the other hand, cheap PMs such as ferrite can be used [10].

4. Single-, Three-, and Multi-Phase FSM

The designed prototype single-phase FSM has been reported in Sulaiman et al.'s [34] study, and later the three-phase version was preferred [2], which has advantages of high power density and low torque ripple. The FSM with higher number of phases, particularly five-phase one, has been mainly received attention as fault tolerant machine [32]. Besides, increasing the number of phases can lead to the reduction of torque ripple and the required phase current [35]. The five-phase FSM having 10 stator teeth and 19 rotor teeth has been designed for critical applications [36]. The machine with 19 rotor teeth has a better sinusoidal induced voltage compared with 18 teeth machine. However, odd number of rotor teeth causes some problems.

The five-phase FSM with 20 stator teeth and 18 rotor teeth has been designed for EV. Its base speed is 1,500 rpm and its base frequency is 225 Hz. In addition, nine-phase FSM with 24 teeth has been designed for sensitive applications; and it is a fault-tolerance machine [35].

Three-phase machine is still the most common type of FSM because higher number of phases requires more power electronics switches and more complicated control system. Back electromotive force (EMF) vectors of windings in FSM are described in Zhu and Chen's [11] and Chen and Zhu's [37] studies. Back EMF of two adjacent windings has the following α degree difference:

$$\alpha = \frac{2\pi \cdot N_r}{N_s}, \tag{1}$$

where N_s is the number of the stator slots and N_r is the number of rotor teeth. For a 12/10 FSM α is equal to $5\pi/3$. Then, the minimum order of the working flux harmonics P_w is defined as follows:

$$P_w = N_r - P_{PM}, \tag{2}$$

where P_{PM} is the PM pole-pair number. The machine periodicity τ defined as follows:

$$\tau = \text{GCD}\left(N_s \frac{k_l}{2}, P_w\right), \tag{3}$$

where GCD is the greatest common divisor, k_l is 1 or 2 for single-layer or double-layer winding machine. The spokes-per-phase in FSPM machines, q_{ph}, is defined as follows:

$$q_{ph} = \frac{N_s \cdot k_1}{2\tau \cdot m}. \tag{4}$$

The FSM develops torque only when there is an effective interaction between the main harmonic of the air gap flux and the magnet flux [38]. This happens only when the following relation is satisfied:

$$n\frac{N_s}{m} = \pm N_r \mp \frac{N_s}{2}. \tag{5}$$

The number of phases can be normally increased by higher number of stator teeth accommodating with more rotor teeth. Considering a given speed for application of the FSM, increase of the number of rotor teeth leads to the increase of the base frequency of the motor which imposes particular limits on the design.

5. Number of Stator and Rotor Poles of FSM

Number of poles of electrical machines depends on the poles per phase and must be even [39]. For a two-pole per phase machine, the flux observed from the winding is nonsinusoidal leading to nonsinusoidal induced voltage. In Figure 5, the flux seen by a winding has been compared with the first harmonic. If other winding with 90° mechanical phase difference from the first winding is considered, the flux waveform seen from it will be as shown in Figure 6. The main harmonic of these two windings are in phase, but their even harmonics have phase difference of 18°.

To eliminate the even harmonics of the induced voltage in every phase winding, the number of poles per phase of the machine can be taken to be four, and two-pole pair with 180° (electrical) phase difference are connected in series. Figure 7 shows the sum of flux-linkage seen by two series winding with 90° displacement [40]. Therefore, for a three-phase machine, the number of stator poles is 12. Generally, in machines with phase number higher than 3, the number of stator teeth is higher. For instance, the stator of the machine of five-phase of the previous section has 20 teeth. The number of rotor teeth of the FSM plays a major role. By increasing the number of rotor teeth, the base speed of the machine reduces. On the other side, the optimum torque in the machine is developed when the number of rotor teeth is close to the number of stator poles [32]. For example, for a 20 poles at its base speed, according to the following equation:

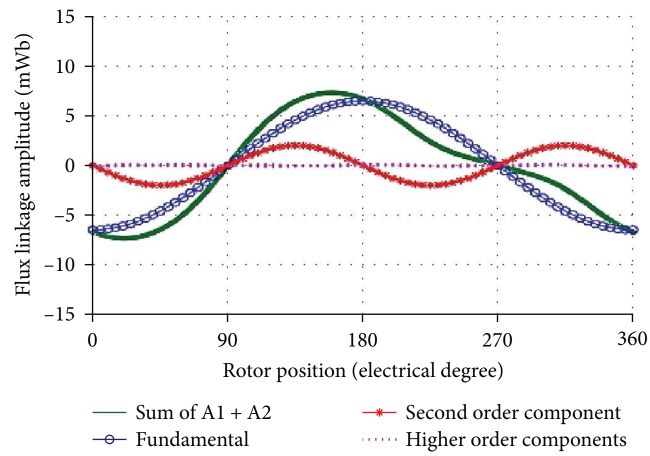


FIGURE 5: Waveform of flux linkage seen from winding [40].

$$\omega_e = N_r.\omega_m, \tag{6}$$

for a machine with 20 stator poles, rotor can have 21, 19, 18, or 22 teeth and a machine with 12 stator poles, rotor may have 10, 13, 11, or 14 teeth. Figure 8 shows the impact of the number of rotor teeth on the developed torque of the FSM with 12 stator teeth. The optimum torque for a typical machine with 12 stator poles is developed when the rotor has 12 teeth. However, choice of rotor with odd number of teeth generates other problems, and from stator point of view, the rotor has no mechanical symmetry. As a result, the force exerted on the rotor from two directions is not equal.

Figure 9 presents the lateral exerted force to the rotor for a machine with odd number of teeth. For the rotors with 11 and 13 teeth, the force is produced in different directions at different times. In addition to mechanical stress on the rotor, these forces cause vibration on the machine. This is the reason that in high-power machine, particularly for EV, the odd number of rotor teeth must be chosen. Therefore, even number of rotor teeth must be considered for high-power machine. On the other side, higher number of rotor teeth reduces the base speed of the machine at a specific frequency. Thus, generally number of rotor teeth is chosen two teeth less than that of the stator. For five-phase FSM with 20 stator teeth, the number of rotor teeth is generally chosen 18. In a three-phase FSM, 12 stator teeth and 10 rotor teeth offer a good performance and this version is widely used.

6. Different Types of Windings in FSM

Generally concentrated and distributed windings are used in electrical machines. In many machines, such as induction machine, the distributed winding is employed to decrease

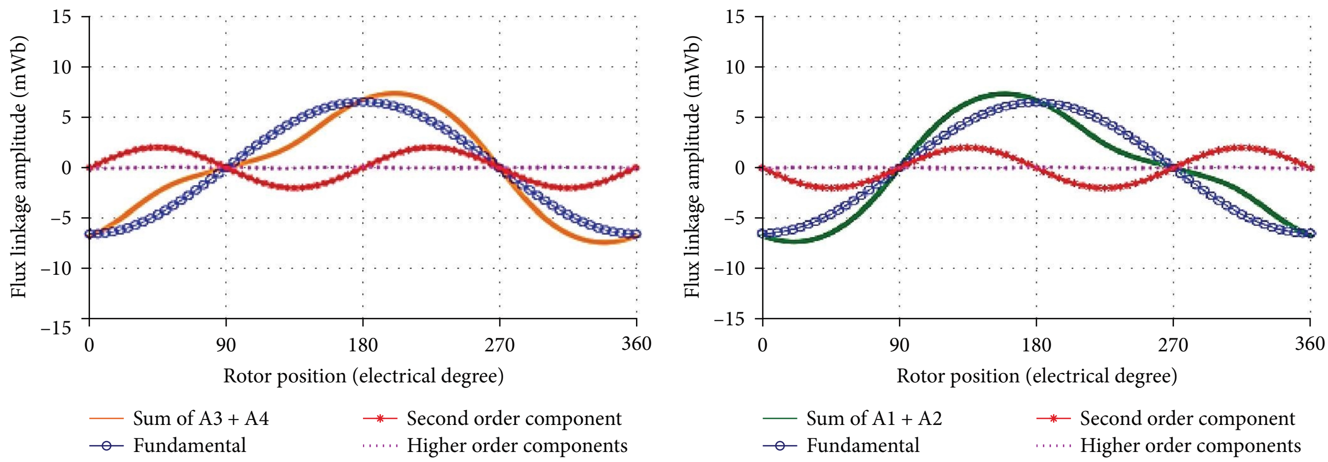


Figure 6: Comparison of flux linkage of two windings with 90° mechanical angle [40].

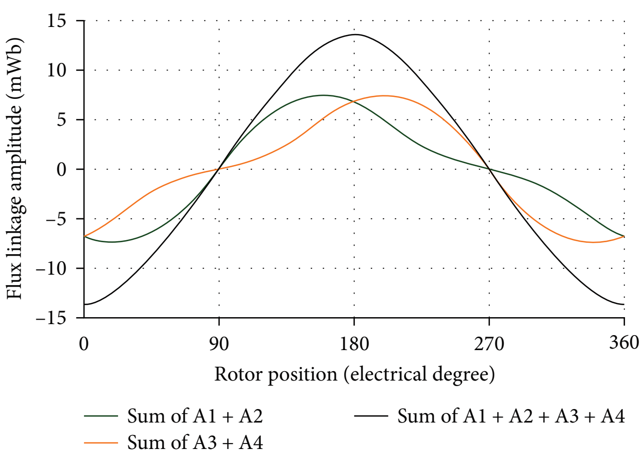


Figure 7: Sum of flux linkage seen by two series winding with 90° [40].

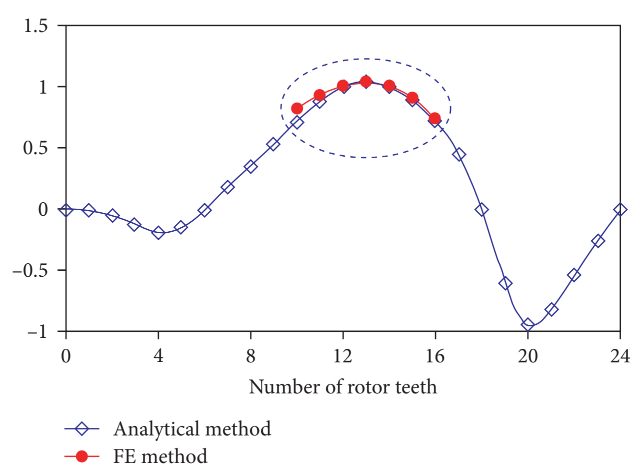


Figure 8: Impact of number of rotor teeth on developed torque of FSM with 12 stator teeth [32].

the magnetic flux and voltage harmonics. However, in some machines, such as low-power machines and FSMs, concentrated winding is preferred due to specific conditions of the machine. Concentrated winding machines have higher efficiency and torque density because their end-winding is shorter [41].

Generally, number of wound coils in the FSM is equal to the number of stator teeth. In some circumstances, the number of coils of the machine can be halved but at the same time the number of phases winding turns are kept constant. This type of winding is called active pole winding. Figure 10 shows the active pole winding of a 10/12 FSM. If the number of rotor teeth is odd, higher voltage is induced in the active pole winding and voltage waveform is symmetrical, but in the case of even number, the waveform is asymmetrical [39]. The active poles winding have higher inductance and by increasing the current, the core of the machine saturate. This is the reason that such winding is not suitable for high electric loading [41].

In FSM with even number of rotor teeth, all stator teeth are wound. If number of coils in a phase is higher than two, it is possible to have series coils in the machine in two different forms. For example, there arefour coils for each phase in a three-phase FSM with 12 stator teeth, and two forms of coils connections are possible. In the first group, the coils are in series, and in the second group, the coils have 30 mechanical degrees difference from the first group. This connection for FSM is appropriate when the number of rotor teeth is odd. For instance, Figure 11 shows this connection in the 12/13 machine.

In this case, the coils of every phase are placed beside each other. Figure 12(a) shows this type of winding and angle of voltages of coils. For phase A, coils 1 and 8 are connected in series, inverse of coils 2 and 7. Figure 12(b) shows the voltages of the coils. Although separate voltage of every coil containing harmonics and not fully sinusoidal, summation of the voltages of four coils has nearly sinusoidal waveform. In the second case, two groups of coils are in series, where the second group has 180 electrical degrees phase difference from the first group. In this case, the phase coils have been distributed on four sides of the machine. This connection is suitable for even number of rotor teeth. For example, Figure 13 shows this connection for the 12/14 FSM.

The coils 1, 4, 7, and 10 of Phase A are connected in series.

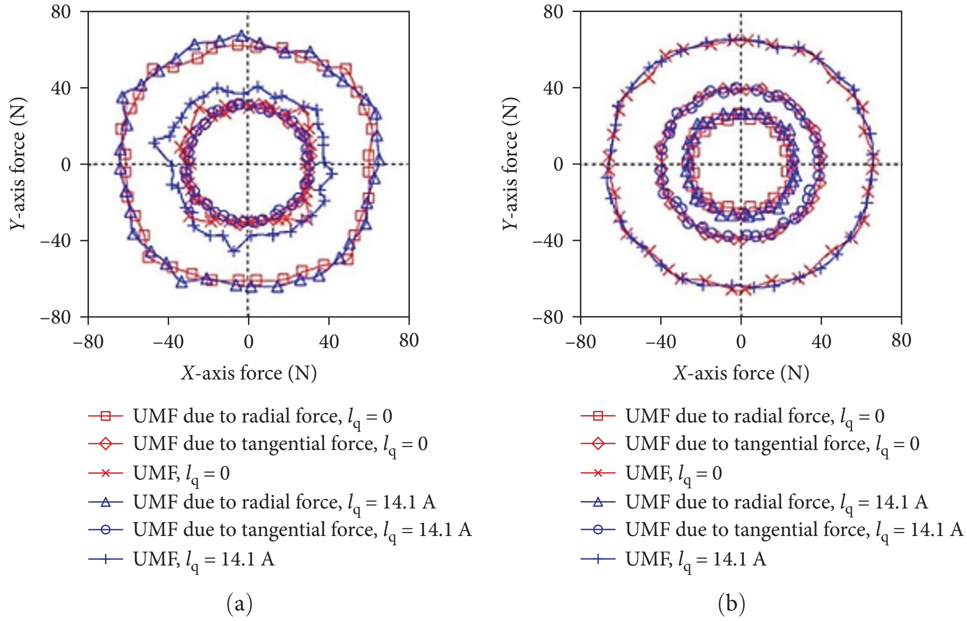


Figure 9: Lateral forces applied to rotor for (a) 11 (b) 13 rotor teeth [39].

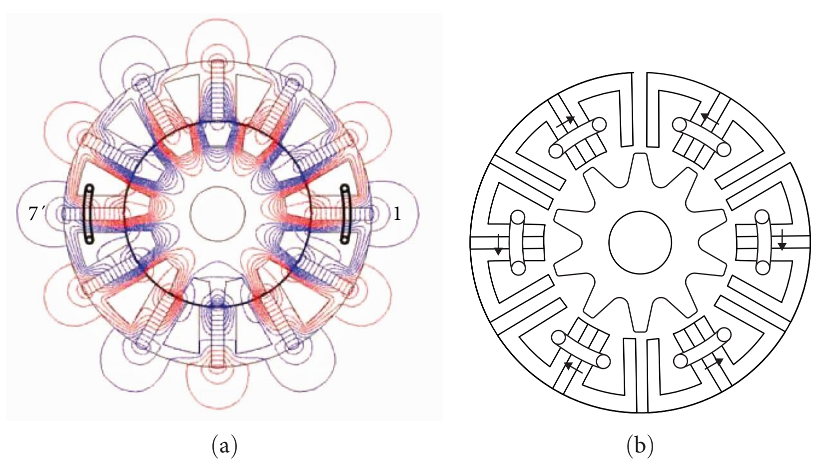


Figure 10: (a) Phase A coils in active poles winding of a FSM and (b) total coils in active poles winding of a FSM [41].

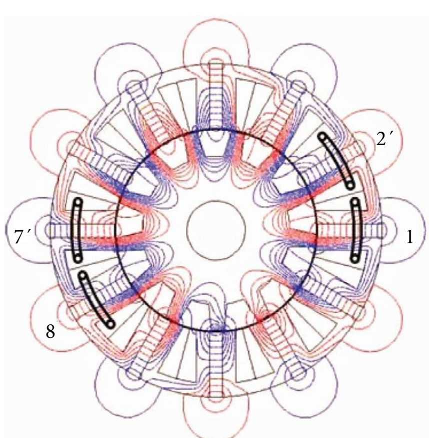


Figure 11: Coils of phase in FSM with 13 rotor teeth [36].

Figure 14(a) presents these coils in which their first harmonics are in phase. Although voltage of each coil is not connection is suitable for even number of rotor teeth. For example, Figure 13 shows this connection for 12/14 FSM.

The coils 1, 4, 7, and 10 of phase A are connected in series.

Although voltage of each coil is not fully sinusoidal, the summation of voltage of four coils has nearly sinusoidal waveform, as shown in Figure 14(b).

The active poles winding is not appropriate choice for preventing the magnetization saturation in the machine. On the other side, for the machine with even number of rotor teeth the winding must be as such that the coils of each phase have 90 mechanical degrees displacement. Therefore, the second case winding is more appropriate to use in EVs.

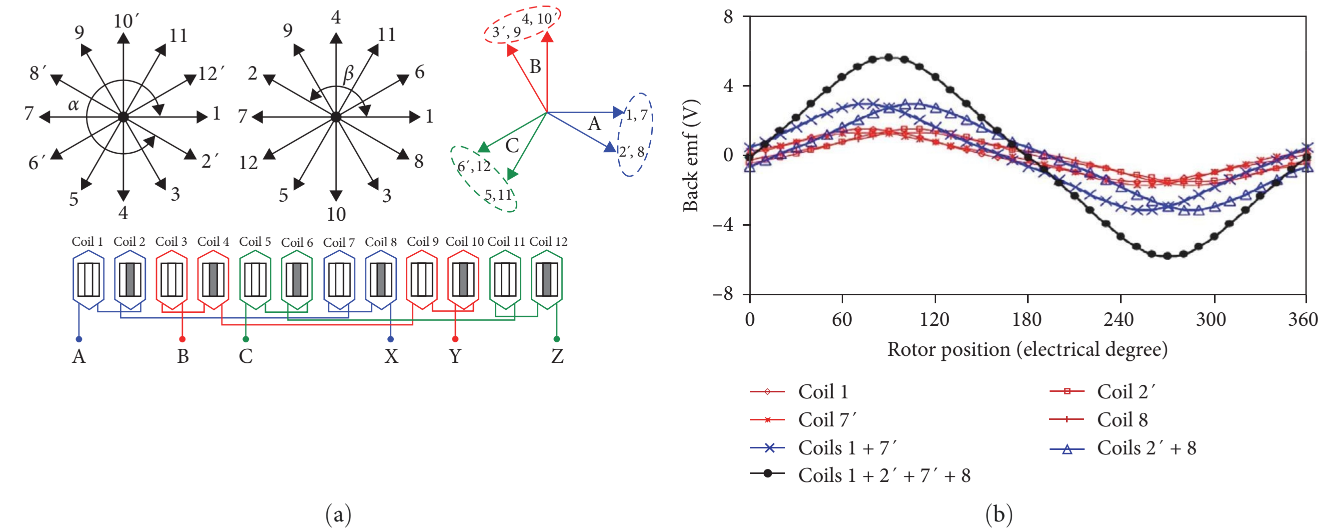


Figure 12: (a) Winding of FSM with odd number of rotor teeth and (b) comparison of winding induced voltage in every coil and summation of coils voltage [3].

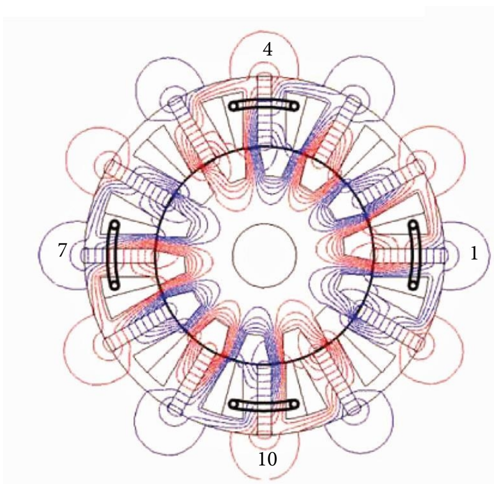


Figure 13: Coils of phase A in FSM with 14 rotor teeth [37].

7. Different Kinds of Stator Cores of FSM

Different types of the FSM structures have been so far introduced. Although new structures have some advantages compared with the previous structures, still in some cases, the first introduced core for the FSM is the best choice. After introducing the FSM with U-shape core, known as conventional type shown in Figure 2, other new cores have been also offered with different windings. Since the main flux path for each phase can pass the center of a winding, it is possible to use more concentrated winding and only an half of the tooth is wound. Figure 10 shows the active poles winding in which the PM between two coils can be removed, without disturbing the performance of the machine. By removing the PM of the inactive poles, an E-core FSM is obtained. Figure 15 shows a E-core FSM which requires less PM compared with the conventional FSM and in some cases distort the developed torque. Therefore, a newer C-core type of the FSM was introduced as shown in Figure 16 [32].

Figure 17 compares the developed torques in three types of core. If electric loading of the FSM is rather low, the C-core develops the maximum torque density. However, by increasing the electric loading of C-core and E-core, they tend to saturation and develop lower torque compared with the conventional U-core [11].

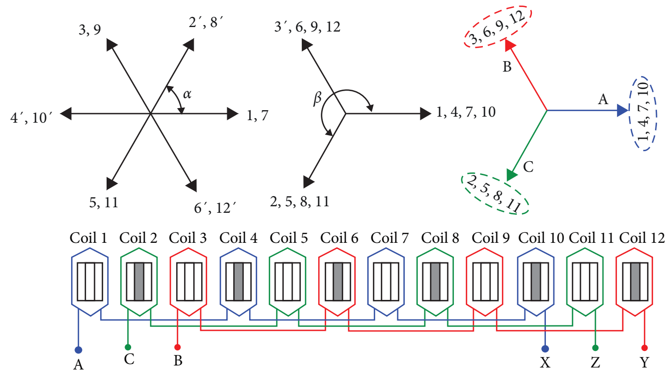
Depending on the application, the choice of C-core or E-core FSM may be chosen. The C-core is recommended if the power density of the machine is less important than the used PM in the machine. However, the torque density and power density are very important in EV. In this machine, generally, the large electric loading is chosen. As a result, the U-core FSM is a better choice for application in EV. It also develops higher torque [43]. By extension of this idea, the magnetic flux path of the machine is determined in another way. By removing the middle tooth in E-core, the magnetic flux of the machine is guided to the adjacent phases and it does not disturb developed torque by the machine. Therefore, a newer type of FSM with C-core is introduced.

8. Other Structures

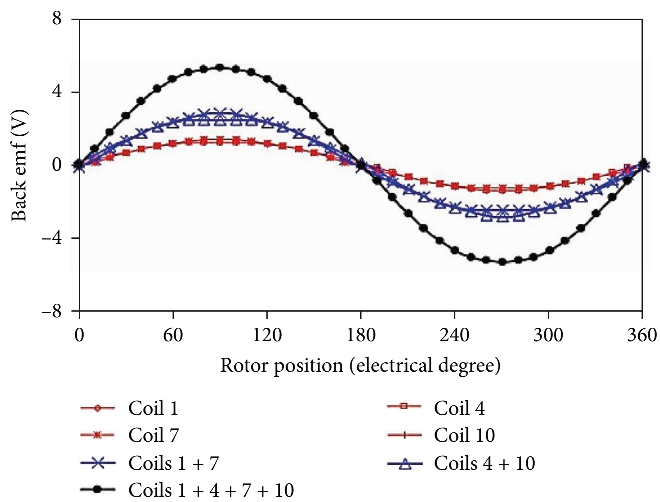
Recently, alternative structures have been suggested for the FSM. A number of most important of them are pointed out in the following subsections and their advantages and disadvantages are briefly given.

8.1. Double-Stator FSM. Two double-stator and single-rotor FSM have been compared in Idoko et al.'s [7] study. Double-stator increases the torque capability of machine. Figure 18(a) presents the cross-section of the machine. The torque density of the double-stator doubly salient rotor FSM is higher.

A double-stator and single-rotor hybrid excited FSM has been suggested in Hua and Zhu's [44] study. Availability of two air gaps in the motor makes it possible to increase the electric loading. This machine has a higher efficiency than the conventional FSM. The reason for its higher torque density compared with the previous machines is the separated excitation stator



(a)



(b)

Figure 14: (a) Winding of FSM with even number of rotor teeth and (b) comparison of winding induced voltage in every coil and summation of coils voltage [3].

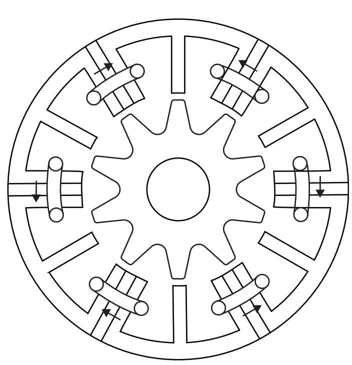


Figure 15: E-core FSM [42].

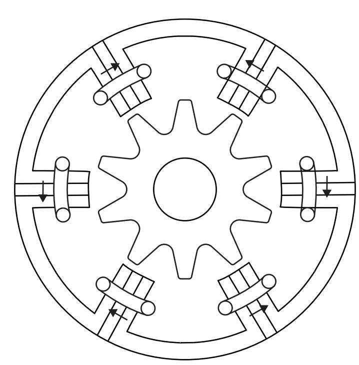


Figure 16: C-core FSM [32].

Table 1: Comparison of C-core, E-core, and conventional FSM [38].

Quantity	C-core	E-core	Conventional
Power density	High	High	Maximum
PM value	Low	Low	High
Overload capability	Lower	Low	Higher
Efficiency	High	High	Maximum
Cogging torque	Maximum	High	Low

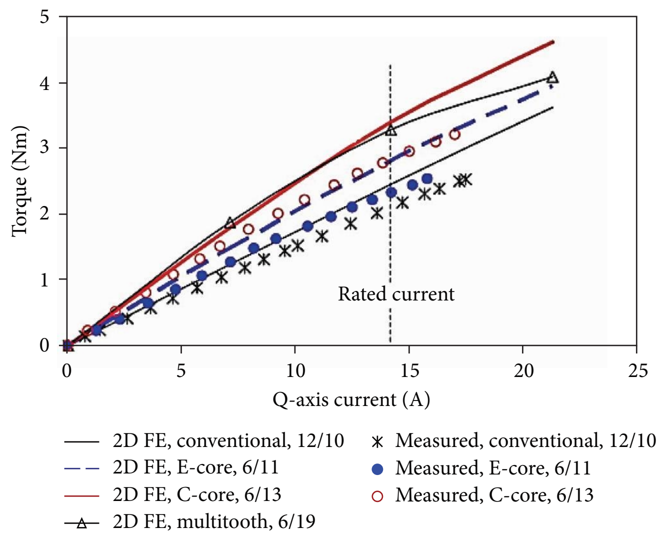


Figure 17: Comparison of developed torque in FSM with different cores [11].

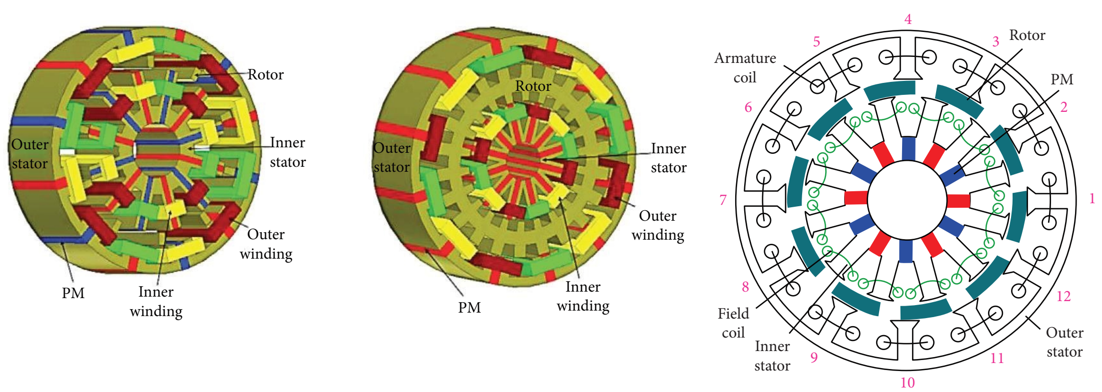


Figure 18: (a, b) Double-stator and single-rotor FSM [7] and (c) cross-section of the hybrid excitation DSFSM [44].

from stator armature winding, leading to a higher electric loading of the machine. On contrary, the rotor of this machine has lower robustness and its reliability decreases in high speeds. This is in conflict with requirements of EV.

8.2. The FSM with PM on Rotor. An alternative FSM for application in EV has been introduced in Su et al.'s [45] study. However, its required PM is fixed on the rotor. This machine produces a power density close to the conventional FSM and its efficiency is higher. Figure 19 shows the structure of the machine. This structure provides the possibility of higher electric loading and winding room compared with the conventional FSM. However, it has some drawbacks which prevent competition of this structure with conventional machines. Inserting the PM on the rotor eliminates one of the important advantages of the FSM. The rotor of this machine has lower robustness and heat can be hardly transferred from PM. On the other side, the power factor of this machine is lower than that of the FSM.

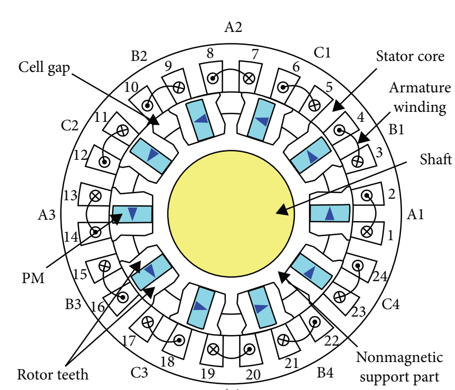
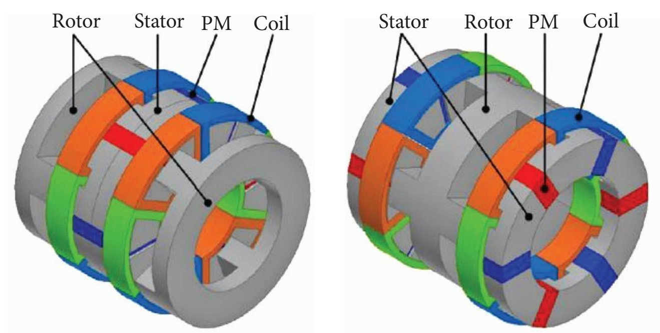


Figure 19: Structure of FSM with PM on rotor [45].

8.3. Axial Flux FSM. The axial flux FSM may generate higher torque density compared to the radial flux FSM. However, efficiency of the radial flux FSM is generally lower than that of the axial flux machine. A typical axial flux FSM for home appliances

Figure 20: A single-rotor and single-stator axial flux FSM [46].



(a) (b)

Figure 21: Axial-flux FSM with: (a) single stator and double rotor and (b) single rotor and double stator [47].

has been introduced in Liu et al.'s [46] study, aiming to reduce its cost. In this machine, a ferrite PM has been used to reduce the cost of the machine. Figure 20 shows a single-rotor and single-stator axial flux FSM. This configuration generates asymmetrical force on the rotor. In a single-stator and double-rotor design, the mechanical force exerted on the rotor can be eliminated [11]. Figure 21 presents an axial-flux FSM with different number of rotor and stator. The high-power machine has some mechanical problems. Efficiency and torque density of the axial-flux FSM with single-stator and double-rotor is higher than that of the single-rotor and double-stator machine. However, its efficiency is still lower than the radial FSM [3]. On the other hand, design of high power axial-flux machine for EV has some mechanical problems because of centrifugal force, it is not possible to enlarge the rotor diameter over high speeds.

8.4. Multiple-Tooth Stator FSM. For more optimal use of PM and increase of the PM weight per developed torque in the FSM, the stator can be designed as multitooth version. By increasing the number of stator teeth, the base speed of the machine and its torque density increase [48]. Figure 22 shows a multitooth stator FSM. If electric loading of the machine is rather low, the developed torque of the multitooth stator FSM is higher than that of the conventional FSM. However, if electric loading of the machine is increased or machine is overloaded, the torque density of the machine drops due to the stator core saturation [11]. This machine is suitable to use in the wheel of EV with low speed and high torque. However, in the EV, the speed of electric machine is high and the multitooth stator FSM is not recommended.

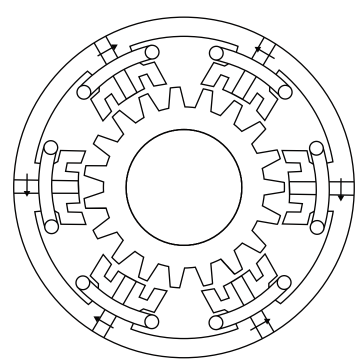


Figure 22: A multitooth stator FSM [20].

8.5. Modular Rotor FSM. An alternative type of a modular rotor FSM has been introduced in Ali et al.'s [42] study. This machine has short end-winding and on contrary to the conventional FSM, the stator tooth flux flows in two directions. Figure 23 presents a PM-less modular rotor FSM.

This configuration develops low torque ripple and cogging torque. The copper losses have been reduced due to shorter end winding. Besides, the machine flux weakening is easily done due to flux generation by dc winding. On contrary, efficiency of the machine is lower and its rotor has lower robustness than the conventional FSM. Therefore, this configuration cannot compete with the conventional FSM.

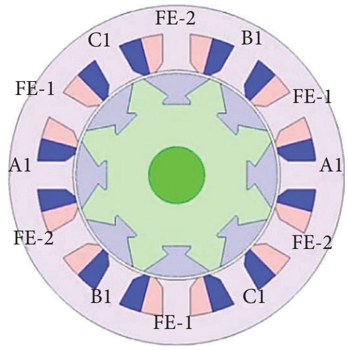


FIGURE 23: A modular rotor PM-less FSM [42].

Another less important structure of FSM has been introduced in Shen and Fei's [49] study. In spite of introducing various structures for the FSM, still development of the conventional FSM is emphasized, particularly in applications with rather high electric loading and final speed of the machine, the conventional FSM is an appropriate choice.

9. Magnetic Materials in FSM

Choosing magnetic materials for stator, rotor, and PM is an important part of the electrical machine design process. Choosing an appropriate core has a considerable impact of the losses of the machine; since the stator tooth magnetic flux density in a FSM is taken to around 1.8 T [3], a better core considerably improves the efficiency of the machine.

9.1. Core Type Selection. Magnetic flux in different parts of stator and rotor of the FSM has a particular direction. As an example, flux direction in each stator tooth is always unidirectional. Figure 24 shows the flux direction in different parts of the stator and rotor of the FSM [45].

Unidirectional flux of the stator tooth causes core losses reduction in this part of the machine. In addition, the stator of the conventional machine has been made from U-shape pieces. On contrary to conventional machines, in which whole stator has a circular shape, a smaller U shape can be used here. In conventional machines such as induction machine and PM synchronous machine, the stator core must be certainly nonoriented electrical steel because flux in different parts differs. However, in the FSM, the stator has a few pieces and mold shape and grain oriented electrical steel can be used in the stator core [50]. Magnetic saturation in the grain-oriented electrical steel occurs at higher magnetic flux density. Figure 25 shows the magnetic flux and permeability against flux intensity in different sheets. The core losses in the grain-oriented electrical steel are lower than that of the nonoriented electrical steel. It has been shown in Kim et al.'s [47] study that using the grain-oriented electrical steel in the stator and the nonoriented electrical steel in the rotor of the FSM leads to the reduction of the core losses of the machine. Figure 26 presents the core losses in different sheets at frequency 50 Hz and its impact on the losses of the FSM.

9.2. Selecting PM. Three types of PM are most used magnets in electrical machines. Ferrite PM is used in electrical machines due to its lower cost. The energy density of the

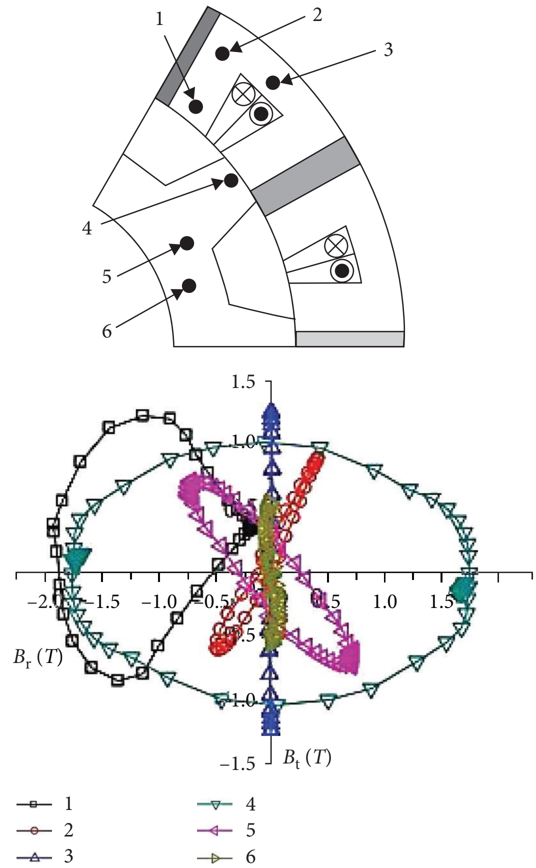


FIGURE 24: Flux direction in different parts of the stator and rotor of the FSM [24].

ferrite PM is rather low; therefore, it is often used in high power density machines. Neodymium magnets are generally used in high power density electrical machines and this leads to high cost machines. However, in this case, the volume and weight of machines reduce and it is still the best choice in some applications. Figure 27 shows the stored energy in the ferrite PM and samarium cobalt magnet [51]. It is noted that the high cost samarium cobalt magnet has low efficiency and rarely used in electrical machines.

In recent years, a new type of PM called low coercive force, similar to Al–Ni–Co, has been paid more attention. This PM stores the PM passing flux to some extent. By applying a current pulse to the excitation winding, the PM magnetic flux can be reduced and even reversed. A new type of PM machines has been designed in which this new type of PM has been fixed on its rotor; this machine is called memory machine. In this machine, the PM flux is controlled in a proper time by applying a current pulse to the stator winding. Estimation of an appropriate time for applying the pulse is one of the challenges in these machines, while using this PM in the machine with PM on the stator does not need the time estimation and control of the flux of the machine is very simpler.

The price of Al–Ni–Co PMs is almost quarter of the Nd PM. Of course, this PM has lower energy density and flux

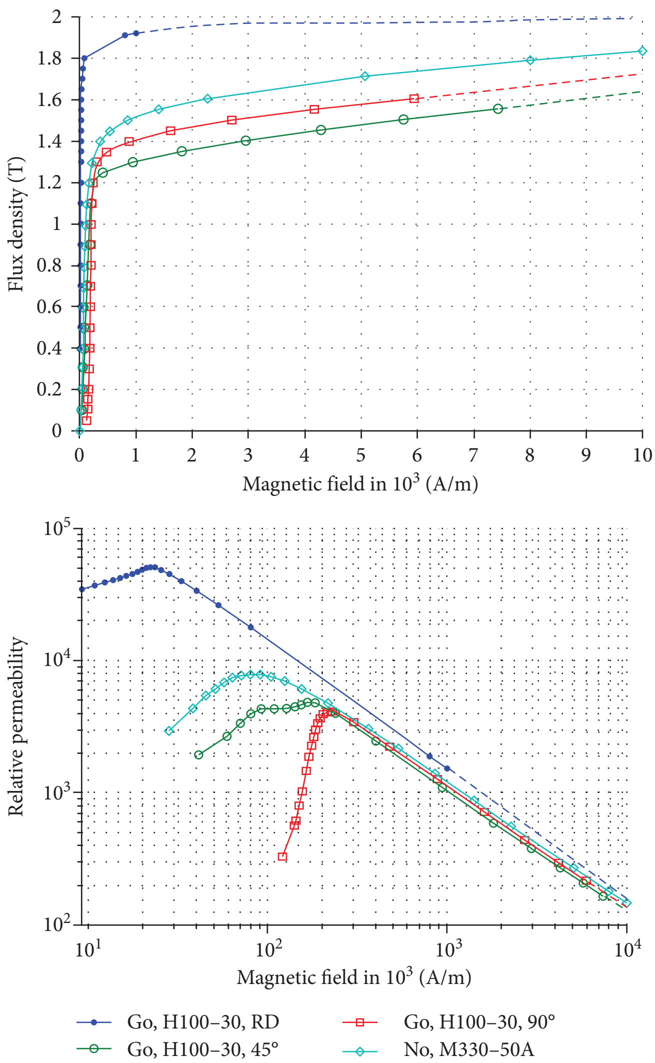


Figure 25: Magnetic flux and permeability against flux intensity in different sheets [19].

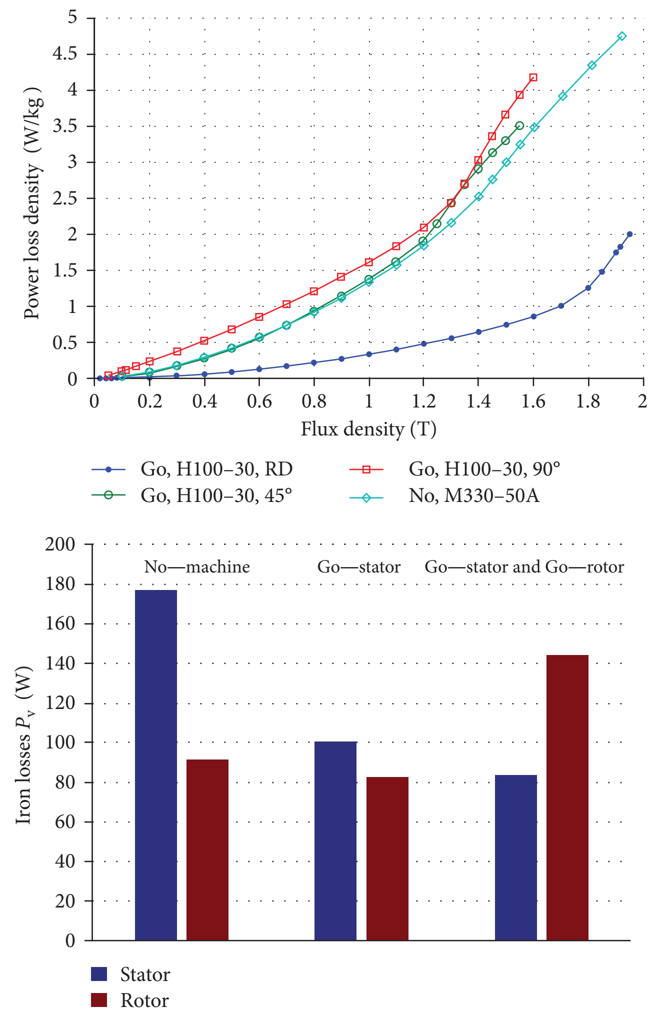


Figure 26: Core losses in different sheets at frequency 50 Hz and its impact on the losses of the FSM [51].

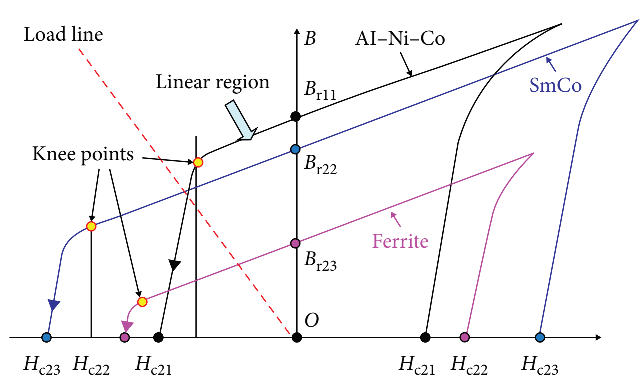


Figure 27: Stored energy in different magnets [20].

density compared to the Nd PM. Figure 28 shows the flux and MMF of the aluminum nickel cobalt PMs.

The flux of Al–Ni–Co PMs is adjusted by excitation current pulse. For example, in Figure 28, the operating point of PM is P_1, by applying negative pulse, the operating point of PM is transferred to point F and then point G. By switch-off of the current, the operating point is located in point P_2 and the produced flux is reduced by the PM. If amplitude of the pulse is large enough, the PM is excited inversely and it provides a suitable condition for flux weakening of the machine. On contrary, by applying a positive current pulse to the excitation winding the PM flux increases [51].

The grain-oriented sheet in the stator and nonoriented sheet in the rotor are the best choice for the FSM core. The choice of PM type depends on the operating conditions of the machine, but as a whole, the Nd PM is suggested for increasing the torque density, and Al–Ni–Co PMs is recommended for increasing the flux weakening capability of the machine.

10. Torque Ripple Reduction Techniques

Torque ripple in electrical machine is one of the negative parameters particularly when it is used in the EV. The FSM has rather high torque due to doubly salient structure and high air gap flux density [21]. Cogging torque, induced

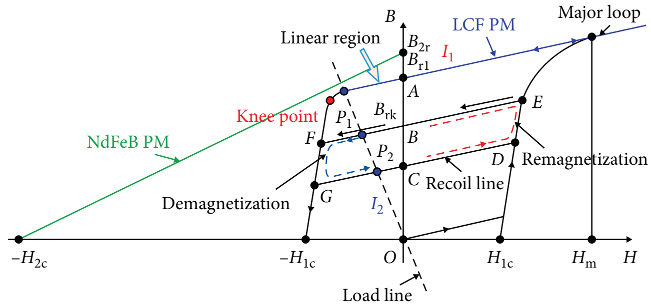


Figure 28: Flux and MMF of aluminum nickel cobalt magnets [51].

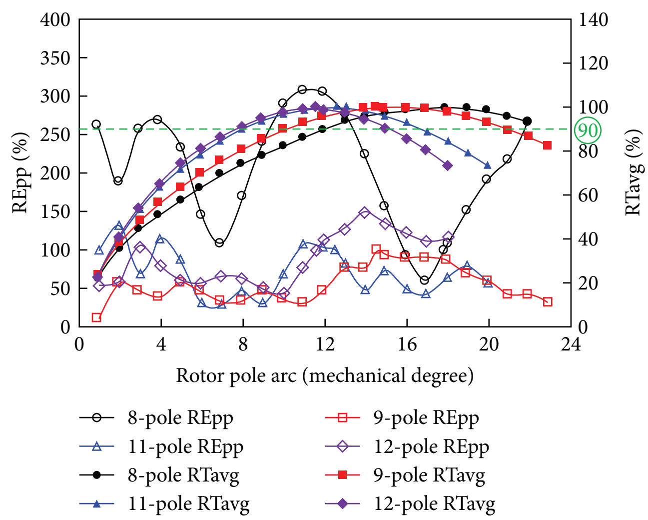


Figure 29: Impact of rotor tooth width in FSM with different number of poles [33].

voltage harmonics, and reluctance torque are three factors of generating the torque ripple [49].

Various methods have been so far suggested to reduce the torque ripple in the FSM. Generally, torque ripple reduction comes at the cost of reducing efficiency and the developed torque of the machine. The machine is designed optimally as such that it develops the minimum torque ripple and maximum mean torque [52]. The most important recommended methods for torque ripple reduction of the FSM are described in the next section.

10.1. Changing Rotor Tooth Width. This is one of the most important parameters for optimum design of the FSM. Changing the rotor tooth width causes the mean torque variation and torque ripple. Optimum choice of the rotor tooth width causes the induced voltage harmonics reduction [53]. Figure 29 shows the impact of the rotor tooth width in the FSM with different number of poles upon the torque ripple.

Increasing the rotor tooth width up to a specific point leads to increasing the developed torque. Beyond this point, increasing the rotor tooth width reduces the mean torque of the motor. However, effect of this width on the torque ripple is not easily predictable. This is the reason that in the design stages, the rotor tooth width must be determined around the maximum torque point using optimization algorithm.

10.2. Chamfering Rotor Tooth Surface. Variation of the rotor tooth surface causes the magnetic reluctance change and consequently magnetic flux waveform variation under rotor tooth [53]. The torque ripple can be reduced by chamfering rotor tooth surface. Figure 30 shows the chamfering of the rotor tooth surface and its effect on the developed torque of the machine.

For rotor tooth chamfering, the considered center of the circle for rotor surface moves. Increasing the rotor surface causes the torque ripple and also developed mean torque.

Therefore, this surface must be increased to obtain a suitable balance between the torque ripple and mean torque of the machine.

10.3. Variation of Width of Half of Rotor Tooth. Increasing the rotor tooth width changes the value and angle of the torque ripple. If the configuration of machine is as such that by changing the rotor tooth, the torque ripple is produced with angle close to 180°, appropriate conditions is provided using this method [54]. Figure 31 presents the rotor with different tooth width. In this method, an half of the rotor teeth have larger width. Therefore, wider teeth eliminate a part of the developed torque ripple. Of course, by doing this, the developed torque of the machine drops.

An alternative method for rotor tooth variation has been suggested in Okada et al.'s [27] study. In this method, there is

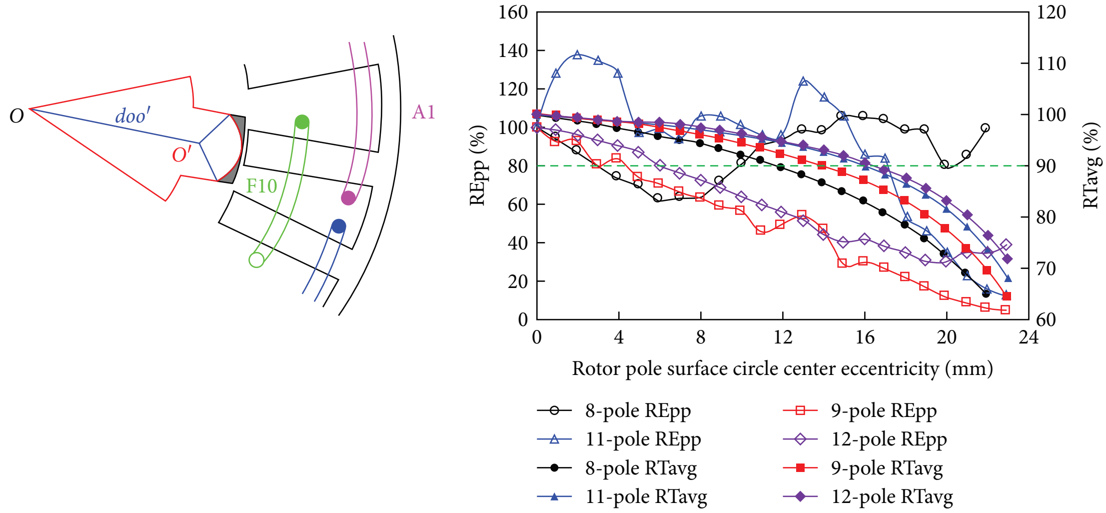


FIGURE 30: Chamfering of rotor tooth surface and its effect on the developed torque of machine [53].

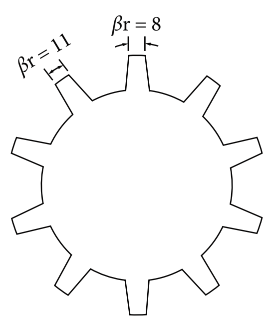


FIGURE 31: Rotor with different tooth width [52].

FIGURE 32: Two-piece rotor with different width [54].

no need to make asymmetrical rotor teeth [53], but the rotor can be divided into two pieces along axial direction and the teeth width differs in two pieces. Figure 32 presents two-piece rotor with different width.

10.4. Multistepped Rotor and Rotor Angular Variation. A torque ripple and cogging torque reduction have been recommended in Mendonça et al.'s [21] study. In this method, rotor of the machine is divided into two or more parts and initial angle of each part varies up to a particular value. Figure 33 shows a multistepped rotor by variation of the rotor angle.

The rotor angle steps variation can well influence the torque ripple reduction. However, increasing this angle causes the developed torque reduction. Two latter methods have been compared in Fei et al.'s [52] study. The rotor angle steps variation causes torque ripple reduction over all operating

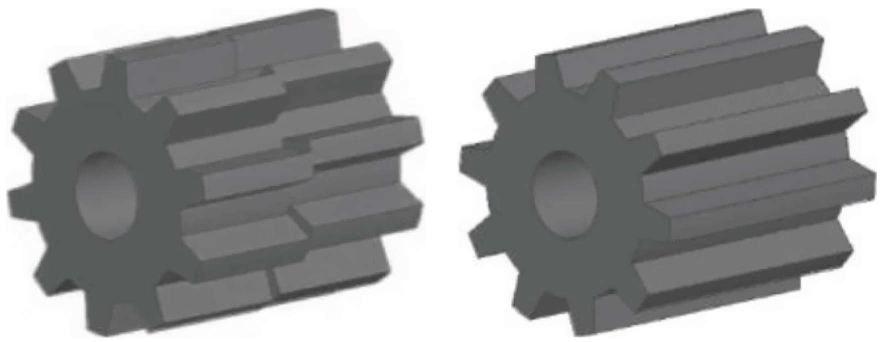


Figure 33: Multistepped rotor by variation of the rotor angle [49].

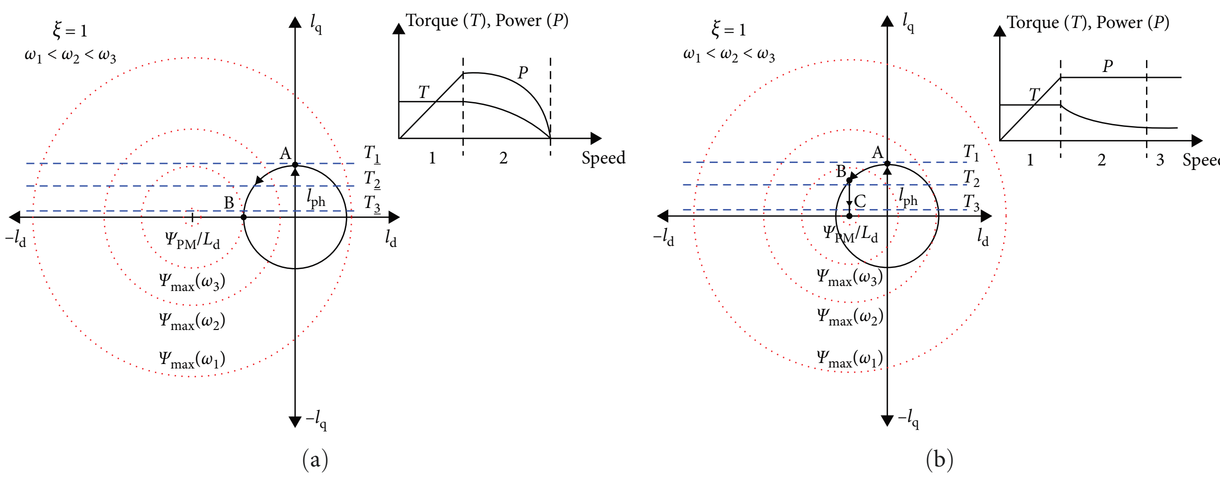


Figure 34: (a, b) Impact of magnetic field intensity on the speed–power curve of PM machine [56].

conditions of the machine. However, variation of the rotor teeth width is only useful under light load, and by increasing the load, its positive impact upon the torque ripple decreases. It seems that by combination of two or more method, the torque ripple can be reduced and prevent serious reduction of the mean torque of the machine.

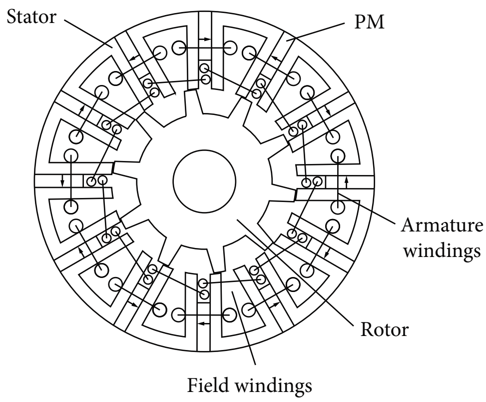
11. Flux Weakening Techniques in FSM

Flux weakening capability is one of the design requirements for the electrical machines used in EV. In the EV and some other cases, the speed of electrical machines increases up to several times of the base speed. At this end, it is necessary to reduce the surrounding flux of the machine winding. The flux weakening range differs in different machines. A number of methods have been suggested for flux weakening in the FSM, which enable to diminish the flux. The next section describes the most important flux weakening methods in the FSM.

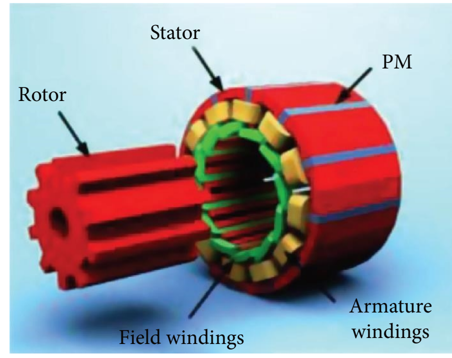
11.1. Flux Weakening by i_d Current Injection. The most popular method for flux weakening PM is i_d current injection. In this method, the control circuit obtains the rotor position of the machine and as the flux of the machine decreases, the current of the machine is injected. Comparison of different structures of FSM in Lee et al.'s [55] study shows that the performances of C-core and E-core machines are better than that of the multitooth machine and conventional FSM machines. Figure 34 shows the impact of the magnetic field intensity on the speed–power curve of the PM machine.

If the magnetic field of PM (Ψ_{PM}) in a PM machine is higher than the product of L_d and peak current of the machine ($L_d I_{max}$) (Figure 34(a)), the flux weakening capability will be limited. If the magnetic field of PM is lower than $L_d I_{max}$, (Figure 34(b)), the machine has unlimited flux weakening capability over very high speeds [56]. In the first case, the flux weakening of the machine is low, and the range of speed–power of the machine is not wide and the torque in higher speeds decreases seriously compared to the rated speed. However, in the second case, the flux weakening capability is suitable and the range of speed–power of the machine is very wide.

11.2. Flux Control by Hybrid Excitation. PM of electrical current can produce magnetic flux. If both winding and PM are used, the machine operates as hybrid excitation [57]. The dc winding can be employed for boosting the PM flux. In the PM machines with PMs fixed on the rotor, using hybrid excitation is difficult while for PM machines with the PMs fixed on the stator such excitation is rather



(a)



(b)

Figure 35: (a, b) A FSM with hybrid excitation [57].

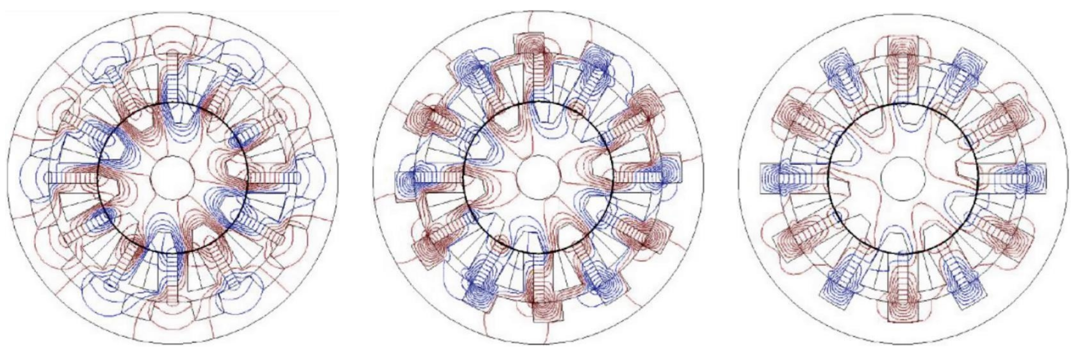


Figure 36: Mechanical method of flux weakening [59].

simple and economical. Figure 35 presents an FSM with hybrid excitation.

In the hybrid excitation, the i_d current of the machine is near zero over a wide range. Efficiency of the hybrid excitation machine in some speeds is better than the common methods. On the other hand, the required PM in this case is less than the PM machine. The hybrid excitation FSM has rather high torque density, a wide speed–power range and an appropriate speed increase capability [58]. In spite of all advantages of the hybrid excitation, for flux boosting and weakening, a dc current must be applied to the excitation winding. This causes losses and efficiency reduction [34].

11.3. Mechanical Method of Flux Weakening. To weaken the flux of PM machine, it is enough to create a flux path as such that the flux does not pass through the active winding. A mechanical method for flux weakening of the FSM has been given in Zhu et al.'s [59] study. In this method, the iron pieces are fixed on the moving outer surface of the stator. However, rotation of these pieces and passing the PMs, the path of a part of the PM flux is closed through these pieces. Figure 36 presents the mechanical method of flux weakening. In this method, it is necessary that the rotation rate of the iron pieces is precisely estimated. The reason is that near the PM edge of the machine largely depends on the iron pieces angle. On the other hand, mechanical rotation of the iron pieces on the stator surface is not easy and needs a specific design. To solve these problems, a method has been suggested in Liu et al.'s [60] study, in which the iron pieces are getting close to the stator surface vertically, as shown in Figure 37.

The mechanical method of flux weakening does not add new losses to the machine and there is no limitation for flux weakening. This is the reason that efficiency of the machine over high speeds and light load increases. This method has been applied on multitooth, E-core, and C-core SFPMs [59] in which the speed range has been extended without sacrificing the high efficiency. Control of this method is rather simple and does not create any change in the machine winding [60]. Another mechanical flux weakening method has been proposed in Ding et al.'s [61] study, which has 2 degree-of-freedom movement of the rotor. In this approach, axial movement of rotor controls the air gap flux density. Other mechanical flux weakening methods are applicable on double stator FSMs [62]. One of them is proposed in Evans et al.'s [12] and Li et al.'s [63] studies which reduces effective winding flux by controlling the angle of the two stators. The disadvantage of mechanical flux weakening method is that the system needs an external mechanical drive to control the iron pieces. In addition, the response speed of the mechanical system is lower than that of the electrical systems. This method needs a specific mechanical design and complexity of the mechanical system may lead to lower reliability of the machine.

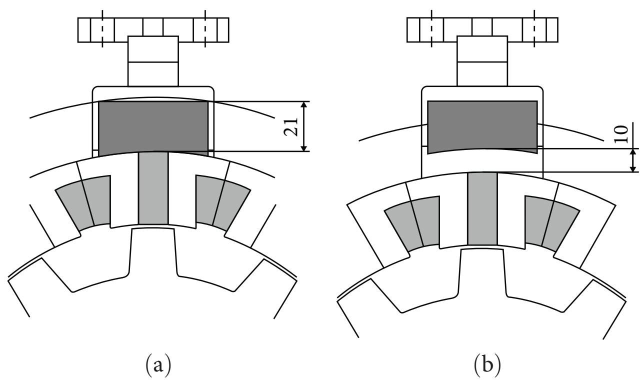


Figure 37: (a, b) Mechanical method of flux weakening [60].

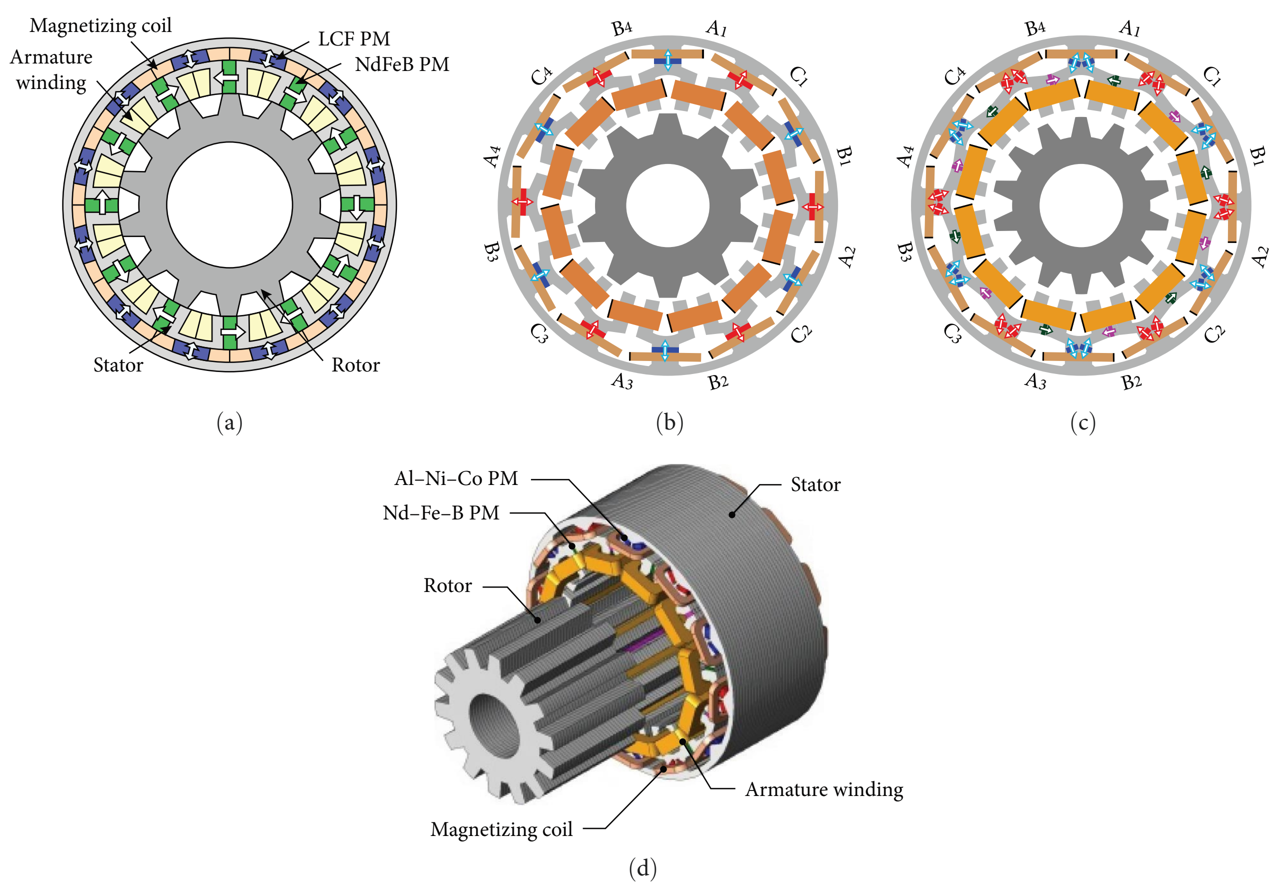


Figure 38: (a–d) A number of FSMs with memory PM [64].

A memory PM is similar to Al–Ni–Co magnet, which is able to store the magnetic flux passing through it. This type of PM is fixed on the rotor and memory machine is built. Fixing this PM on the stator is easier because the excitation winding is on the stator and there is no need to estimate suitable time for applying the pulse current. A novel winding switching concept has been proposed in Yang et al.'s [48] study in which the flux weakening capability has been improved but it suffers from relatively lower air gap flux density. An FSM with combination of Nd and Al–Ni–Co magnets has been suggested in Yang et al.'s [64] study. Figure 38 shows a number of FSMs with memory PM.

11.4. Memory PM Flux Control. Al–Ni–Co magnet is cheaper than Nd magnet. In flux control method by using the memory magnet, the main flux of the machine is generated by the Nd magnet to increase the torque density of the machine. To boost the flux of the machine, the Al–Ni–Co magnet is excited in alignment with the Nd magnet. To weaken the flux of the machine, these two will be in opposite direction.

Using the memory PM in the FSM has many advantages and the most important of these advantages are as follows:

(i) In flux weakening, current i_d is unlimited and the air gap flux can be reduced to an arbitrary level.
(ii) The weight of Nd magnet in the machine reduces.
(iii) Excitation system response speed is suitable.

Flux boosting and weakening do not increase the losses of the system leading to improving the efficiency of the machine in different operating conditions especially in high speeds [64].

(iv) Control system of machine is simpler and a very low i_d current is injected into the machine.

Taking into account the flux weakening advantages using memory PM, this method is the best method for flux weakening of the FSM in the EV.

12. Advancements in FSMs for EV Applications

The selection of an electric motor for EVs involves careful consideration of various parameters. While high-torque density motors like yokeless and segmented armature, IPM, and induction motors have become popular in the transportation industry which have a very high torque density [65–67], ongoing advancements in FSM designs holds the potential for competitive torque density in the future.

In certain EV, torque density may not be the most critical factor in motor selection. However, for specialized applications like the secondary motor-generator used in electronically controlled continuously variable transmission systems of some HVs, the FSM shows promise.

One challenge associated with increasing torque density is raising the torque ripple. This paper suggests several methods for reducing torque ripple, which can enhance the suitability of FSMs for a broader range of applications.

FSMs offer distinct advantages over other motor types. The presence of the PM on the stator allows easier implementation of mechanical methods or memory magnet flux control to widen the constant power speed range, especially when compared to IPM motors. Moreover, these methods improve motor efficiency across a broader range in the efficiency map.

The centralized winding in FSMs enables a higher fill factor, resulting in reduced copper loss and improved control over winding temperature. Additionally, the absence of winding intersection between different phases decreases the likelihood of insulation failure. Also, this winding is simpler and more cost-effective than the extensive winding in the induction machine or IPM.

The choice of iron and PM is crucial for designing electric motors for EVs. Unlike most electric motors, FSMs allow the use of oriented iron in the stator, significantly reducing iron loss. Furthermore, alternative magnets like ferrite magnets can be utilized, trading off some performance for cost reduction.

The reliability of FSMs is a significant advantage that makes them attractive for EVs designs. The separate phases and robust magnetic structure make them relatively fault tolerant [68, 69], while the strong and integrated rotor structure minimizes mechanical challenges at high speeds.

Considering the numerous benefits of FSMs, future research should focus on the following areas for electric motor development for EVs:

(i) Exploring new structures, such as axial flux and outer rotor designs, to further enhance torque density.
(ii) Designing robust motors optimized for high-speed applications.
(iii) Broadening the constant power speed range by considering motor efficiency across all operating regions.
(iv) Incorporating cost-effective production considerations into motor design.
(v) Advancing mechanical flux control methods and simplifying the control system implementation.
(vi) Designing for specialized applications in HVs and electric motorcycles.
(vii) Considering mechanical parameters, including thermal effects, deformation, vibration and noise sources, production tolerances, and mechanical stresses during motor design.

With ongoing advancements and research, FSMs hold great potential as electric motor solutions for EVs. By addressing key challenges and exploring innovative designs, FSMs have the capacity to compete with other high-torque density motors, making them a compelling candidate for the future of EV propulsion.

13. Conclusion

The FSM emerges as a promising option for EV traction due to its high efficiency, torque density, and range of constant speed–power. Application of FSM was described in this paper, which may applicable in EV. The review of different configurations and techniques for enhancing FSM performance has shed light on the advantages and disadvantages of each approach. The capability of FSM for developing high torque density, simplicity and robustness of the rotor, better flux control, and ease of cooling make it a favorable choice for various applications, including EVs, renewable energy systems, and other industrial applications. While the FSM exhibits some limitations such as lower reluctance torque and lower overload capability compared to other motor types, its potential in EVs, and other applications is widely recognized. Considering the dependency of the the stator teeth number in the number of phases, three-phase machine design is preferred. Taking into account the base speed of machine in the EV and high electric loading, the FSM with 12 stator teeth and 10 rotor teeth can be the most appropriate choice for such application. The stator core is made from oriented iron and rotor core from nonoriented iron. To increase the torque density and achieve suitable flux weakening, combination of Nd and Al–Ni–Co magnets are preferred.

Data Availability

No underlying data were collected or produced in this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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