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Advanced optimization methods for fractional slot concentrated windings

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Abstract
Usage of fractional slot concentrated windings (FSCWs) in electrical machines offers several advantages due to their simplicity and compactness. However, the magnetic field of FSCWs has more space harmonics, including sub-harmonics that lead to undesirable effects. High rotor losses, noise, vibrations and thermal problems are the main drawbacks caused by FSCWs. These disadvantages limit the suitability of this winding type for some applications. In order to improve winding performances, several methods and techniques have recently been developed and analysed. This paper provides an update of latest research activities in terms of optimization of FSCW machines. These include efforts to reduce only sub-harmonics, to simultaneously reduce sub- and high harmonics or to use a higher harmonic for rotor excitation in current-excited synchronous machines. Simplest and most effective methods are considered, and their functionalities are explained briefly. Moreover, the effectiveness of said optimization methods is shown by simulation and experimental results, obtained from various optimized FSCW machines.

Keywords Fractional slot concentrated winding · Losses · Radial force · Noise and vibrations · Efficiency · Optimization · Permanent magnet machines · Asynchronous machines · Current-excited synchronous machines

1 Introduction

In the recent past, electrical machines equipped with fractional slot concentrated windings (FSCWs) have increasingly been used in different applications, such as automotive, aerospace and wind power generation. This is mainly due to significant advantages of concentrated windings over distributed ones, like high power density and efficiency, short end turns, high slot fill factor, high phase inductance (which limits the short-circuit currents), fault tolerance, simple manufacturing, and so on [1–7]. For many years, FSCWs have been most commonly used in permanent magnet (PM) machines. However, possibilities of using these windings for other machine types, such as synchronous reluctance machines (SRMs) [11, 12] and asynchronous machines (ASMs) [13–15], are currently under examination.

Despite their advantages, FSCWs are also characterized by several drawbacks. Concentrated windings produce a non-sinusoidal magnetomotive force (MMF) distribution along the air gap. Hence, the air-gap flux density has many low- and high-order spatial harmonics. In PM machines, these harmonics induce large rotor magnet losses. In asynchronous machines, they induce high rotor bar losses as well as various parasitic torque components that degrade machine's average torque. In synchronous reluctance machines, they lead to high torque ripples. Moreover, spatial harmonics cause local saturation, additional stator and rotor losses, acoustic noise and vibration [16–23].

To overcome problems associated with FSCWs, several novel solutions have been developed and investigated in recent years [25–63]. This article covers the key optimization methods and techniques concerning FSCW machines.

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Depending on applied solution and the operating principle, regarded methods can be classified into three groups:

Modification of the stator core structure by applying

- Magnetic flux barriers in stator yoke
- Magnetic flux barriers in tooth region.

Modification of the winding structure using

- Coils with different turns per coil side
- Multilayer FSCW
- Multiphase FSCW
- Dual multiphase FSCW
- Dual slot layer stator
- Stator shifting concept.

Self-excitation concept

- Rotor excitation using high-order MMF harmonics.

Section 2 gives a short overview of the theory of FSCWs, beginning with winding topologies, continuing with MMF harmonic analysis and winding selection criteria and closing with opportunities and challenges. The first optimization method, which is based on modification of magnetic flux paths in the stator, is presented in Sect. 3. Many articles deal with the flux barriers' effect on power density and efficiency of different PM machines; however, there is another survey that addresses a new cooling concept based on this technology. Further, Sects. 4, 5, 6, 7, 8 and 9 cover a wide range of works concerned with winding structure modification. In order to reduce MMF sub-harmonics, some articles address multilayer windings, while others take a closer look at coils with different turns per coil side. In addition, several papers examine stator shifting, dual multiphase FSCW and dual slot layer stator concepts. Different machine types are considered by these publications: PMSMs, ASMs and SRMs. Finally, Sect. 10 includes main publications on possibilities to excite the rotor field winding of current-excited synchronous machines (CESMs) using high-order MMF harmonics. In contrast to the previously mentioned methods, which aim at mitigating MMF harmonics, the idea behind this concept is to exploit existing spatial MMF harmonics for rotor excitation. Hence, this solution eliminates the brush-type exciter.

For the sake of clarity and for better understanding, Table 1 gives a short overview of optimization methods, their impacts and corresponding references addressed in this paper.

2 FSCW theory

In general, FSCWs can be realized in two different ways. Concentrated coils may be wound either around each stator tooth (double-layer winding, DL) or around every second stator tooth (single-layer winding, SL). These two kinds of concentrated windings offer different features, and hence, they are suitable for different applications. Their main characteristics are well described in [3].

Using the FSCWs in combination with PM machines, there are many possible slot number and pole number combinations. Figure 1 illustrates three different common DL windings for PM machines: 3-teeth/2-poles (3T/2P), 9-teeth/8-poles (9T/8P) and 12-teeth/10-poles (12T/10P) winding. Besides each winding topology, a corresponding MMF distribution and its space harmonics are shown. The following points have to be considered when selecting the most suitable winding topology for a specific application:

Table 1 Quick overview of discussed topics

Principle	Concept	Harmonic cancellation	Effect on the working wave	References
Magnetic circuit modification	Magnetic flux barriers in stator yoke	Low-order harmonics	Increase	[25, 26]
	Magnetic flux barriers in tooth regions	Low-order harmonics	Increase	[26–29]
Winding structure modification	Coils with different turns per coil side	Low-order harmonics	Unaffected	[30, 31]
	Multilayer FSCW	Low-order harmonics	Slight decrease	[32–39]
	Multiphase FSCW	Low-order harmonics	Increase	[40–44]
	Dual FSCW	Low- and high-order harmonics	Slight decrease	[45, 46]
	Dual slot layer stator	Low- and high-order harmonics	Decrease	[47–49]
	Stator shifting	Low- and high-order harmonics	Slight decrease	[50–60]
Self-excitation	Rotor excitation using high-order harmonics	–	–	[61–63]

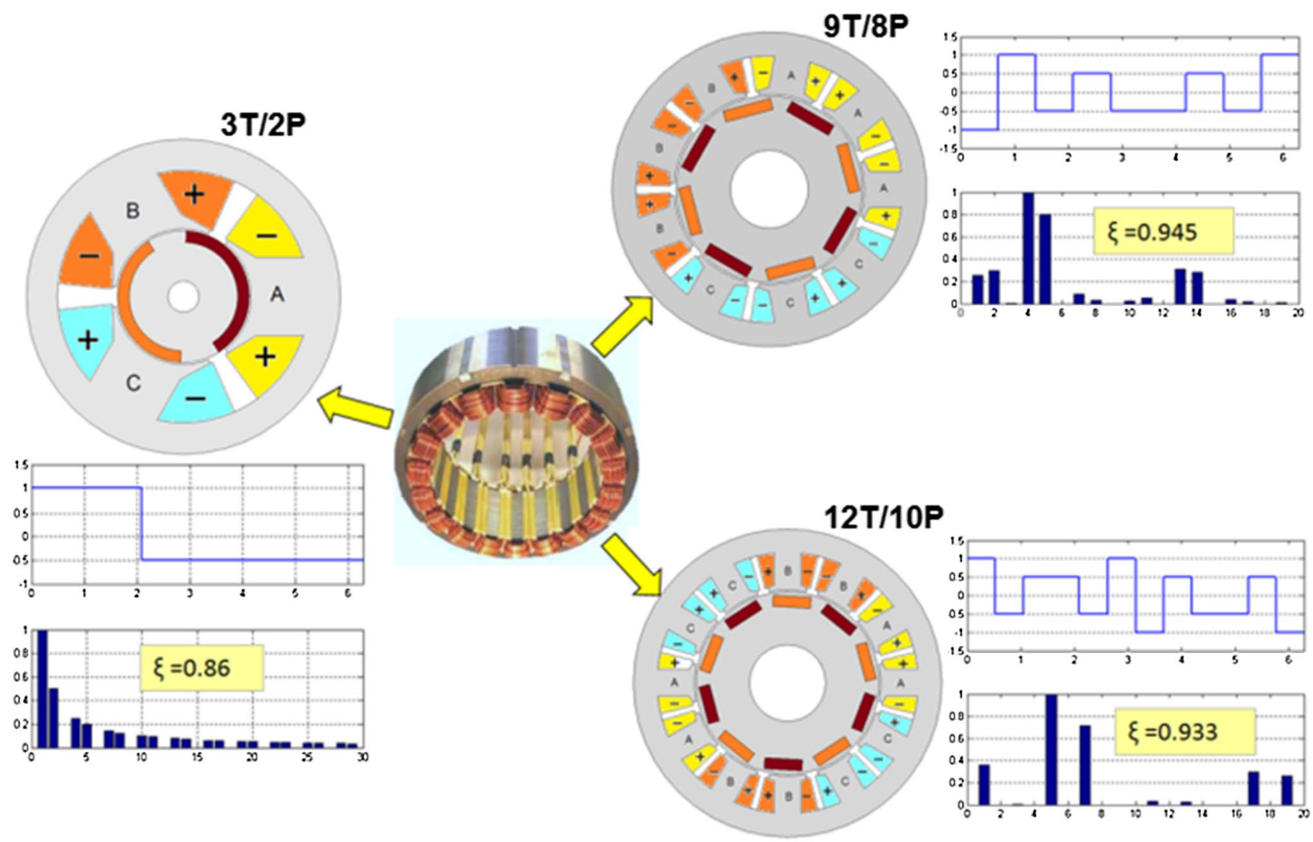


Fig. 1 Commonly used FSCWs for PM machines

1. The winding factor of the main (working) harmonic has to be as high as possible.
2. The harmonic content in the MMF spectrum should be as low as possible.

A high fundamental winding factor is desired in order to maximize torque generation or torque density, while low harmonic content is required to reduce losses and noise problems.

2.1 MMF winding function analysis

Once the pole/slot combination has been fixed, it is possible to follow different methods to obtain the MMF winding function and to determine the winding factors. The MMF wave for a m-phase winding supplied with sinusoidal currents can be expressed as:

$$\Theta(\theta_s, t) = \sum_{\nu} \frac{m}{2} \cdot \frac{2 \cdot N_w \cdot {}^{\nu}\xi_w}{\pi \nu} \cdot \hat{i} \cdot \cos\left(\omega t - \nu\theta_s + \delta\right), \quad (1)$$

where ${}^{\nu}\xi_w$ is the winding factor of the νth MMF space harmonic, $\hat{i}$ is the phase current amplitude, δ is the current load angle, ω is the angular frequency and N_w is the number of serial turns per phase.

Calculation of winding factors can be performed according to the electromotive force (EMF) method. In the literature, this method is also called "voltage vector graph" or "star of slots" method. As shown in [8–10], the winding factor for each harmonic order can be computed graphically from EMF phasor as the ratio between the geometrical and the arithmetical sum of phasors of the same phase

$$\xi_w = \frac{\left| \sum_{i=1}^{n_l \cdot Q_S/3} \vec{E}_i \right|}{n_l \cdot Q_S/3}, \quad (2)$$

wherein the winding element i has the EMF phasor:

$$\vec{E}_i = e^{j(\gamma_i)}. \quad (3)$$

The angle between the phasors of two adjacent slots is:

$$\gamma_i = \frac{2\pi\nu}{Q_S} \cdot i, \quad (4)$$

where Q_S is the number of stator slots.

2.2 FSCW selection criteria

Analysis of the MMF distribution and its harmonics is of main interest when selecting a proper slot/pole combination. In order to achieve a high torque density, preferably a high winding factor of the working harmonic is desired. It can be deduced from [8, 9] that a high winding factor can be achieved when the relation "$2p = Q_S \pm 1$" or "$2p = Q_S \pm 2$" is fulfilled. For concentrated windings considered in Fig. 1, winding factors of the main harmonic are 86.6%, 93.3% and 94.5% for the 3T/2P, 12T/10P and 9T/8P winding, respectively. Thus, at first glance the 12T/10P or the 9T/8P winding seems to be a good choice for a high power density machine. However, for high efficiency and to avoid noise problems low- and high-order harmonics have to be considered very carefully.

Concerning the operating wave, both the 9T/8P and the 12T/10P windings operate with one of the higher space harmonics, the 4th and 5th, whereas the 3T/2P winding operates with the first harmonic. Nevertheless, the conventional 3T/2P winding can be used for high-poled machines as illustrated in Fig. 2, where the basic 3T/2P winding is repeated five times to design a 10-pole machine. Compared to MMF characteristics of the 2-pole design, the space harmonics are shifted accordingly. Thus, the operating harmonic is the 5th, and the first undesired harmonic is the 10th. When applied to high-poled machine, the main advantage of the 3T/2P winding topology is the absence of sub-harmonics.

Figure 3a compares three common winding types for the 8- or 10-pole machine application. As it can be seen, the 9T/8P and the 12T/10P windings, despite their high winding factors of the operating waves, contain a lot of sub- and high

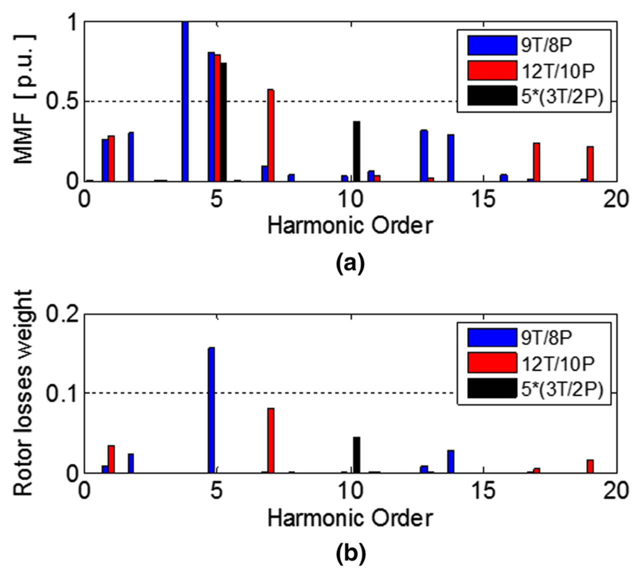
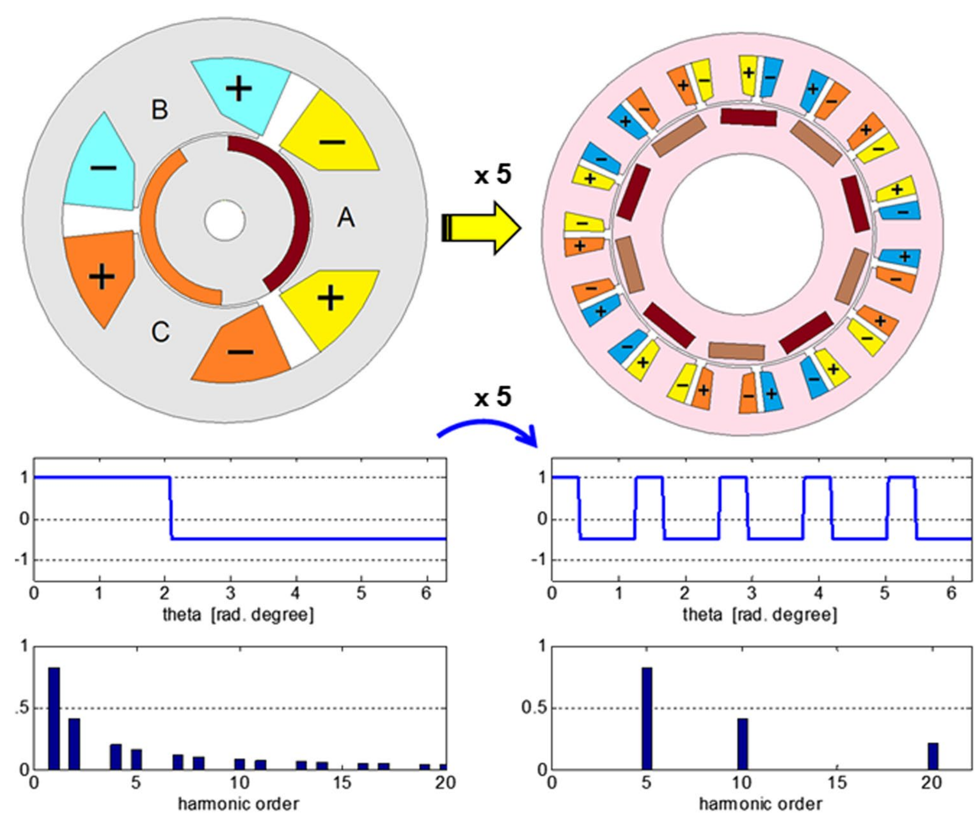


Fig. 3 Comparison of three winding types: **a** MMF space harmonics and **b** rotor loss index

Fig. 2 Application of the basic 3T/2P winding to high-pole machines



harmonics in the MMF spectrum. Moreover, some of these harmonics are located next to the operating wave, resulting in disadvantages concerning losses and vibration. On the other hand, the conventional 3T/2P winding shows a low harmonic content for high-pole machine applications and has no sub-harmonics. Concerning the main drawbacks resulting from concentrated windings, such as losses, rotor heating, noise and vibration, the 3T/2P winding overcomes the other FSCWs. Therefore, this winding topology can be found in several industry applications although its winding factor is comparatively low.

2.3 FSCW challenges

The main challenges of FSCWs are significant rotor losses (iron core and magnet region) [16–18], noise and vibration problems [19–23]. We must also bear in mind that rotor heating and thermal problems are caused by high rotor losses.

Reference [18] proposed a general method for a rapid estimation of rotor losses produced by MMF space harmonics in FSCW PM machines. A rotor loss factor that includes the main winding specifics, such as winding arrangement, winding factors, frequency of various harmonics with respect to the rotor frequency and specific wavelength for each harmonic, is defined as:

$$I_{rl} = \frac{\varepsilon^4}{\sqrt[4]{\left(\varepsilon^4 + \pi^4\right)^3}} \left(\frac{{}^{\nu}\xi_w}{{}^{p}\xi_w}\right)^2 \frac{\nu}{p} k_{\text{gap}}. \quad (5)$$

Using relation (5), the impact of harmonics on the rotor loss index for the three exemplary FSCWs is presented in Fig. 3b. As observed here, for a 8- or 10-pole FSCW PM machine, lowest rotor losses can be achieved using conventional 3T/2P winding topology.

On the other hand, due to the presence of a large number of low- and high-order space harmonics, it is more likely that low modes of vibration will be excited in FSCW PM machines. The magnetic forces causing vibration in electrical machines result from the magnetic flux density in the air gap and can be evaluated analytically by Maxwell's stress method as follows:

$$f_{\text{rad}}\left(\theta_s, t\right) = \frac{1}{2\mu_0} B^2\left(\theta_s, t\right) = \sum_{m=0}^{\infty} {}^{m}\hat{F}_{\text{rad}} \cdot \cos\left(m \cdot \theta_s - \omega_m t - \varphi_m\right), \quad (6)$$

where m is the force mode that is given by the sum and difference of flux density harmonics:

$m = \nu \pm \nu'$.

Magnetic radial force characteristics of three different traction PM machines with 230 mm outer diameter and 150 mm active length are compared in Fig. 4. With the exception of mode-0, both the 9T/8P and the 12T/10P

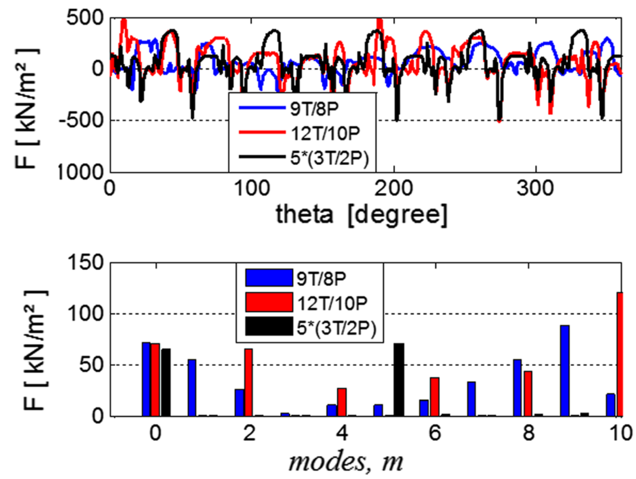


Fig. 4 Magnetic radial forces of three different traction machines under the same load condition

machine designs are characterized by low radial force modes, e.g. mode-1 and mode-2, while the lowest mode of the 5 * (3T/2P) design is mode-5. Considering that the natural frequencies of stator structures for low-order shapes are usually located at the low-frequency range, one can deduce that the acoustic behaviour of the 9T/8P and the 12T/10P machine could be critical. Of course, an analysis presented in [24] shows that the 3T/2P machine topology can also be noisy, but in this case time harmonics of mode-0 are the main reason for this behaviour.

To overcome the problems related to FSCW PM machines, which result mainly from winding sub- and high harmonics, several methods have been developed in the recent past. The following chapters cover the main publications on different optimization approaches.

3 Flux-barrier PM machines

Considering the field solution of the 12-teeth SL FSCW under one-phase excitation (e.g. phase A), it seems to be a two-pole machine (Fig. 5), even though this winding type usually uses the 5th or the 7th harmonic as the operating wave. The first component of the flux density has relatively high amplitude and rotates with asynchronous speed referred to the synchronous wave. Due to the large wavelength, it deeply penetrates the rotor region and induces large rotor losses in the iron core and the magnets. Moreover, it induces additional iron losses in the stator core region and causes torque ripples.

To reduce the effects of sub-harmonics in PM machines with FSCWs, references [25, 26] present two new stator structures with magnetic flux barriers (FBs) in specific stator core areas, as illustrated in Fig. 6a, b. It is found that

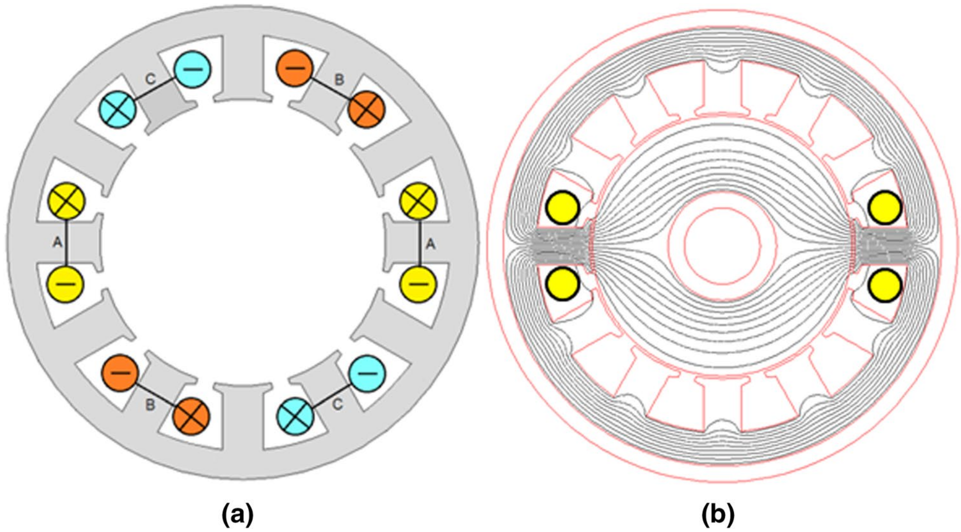


Fig. 5 **a** Winding layout for the 12-tooth SL FSCW and **b** flux lines distribution under one-phase excitation

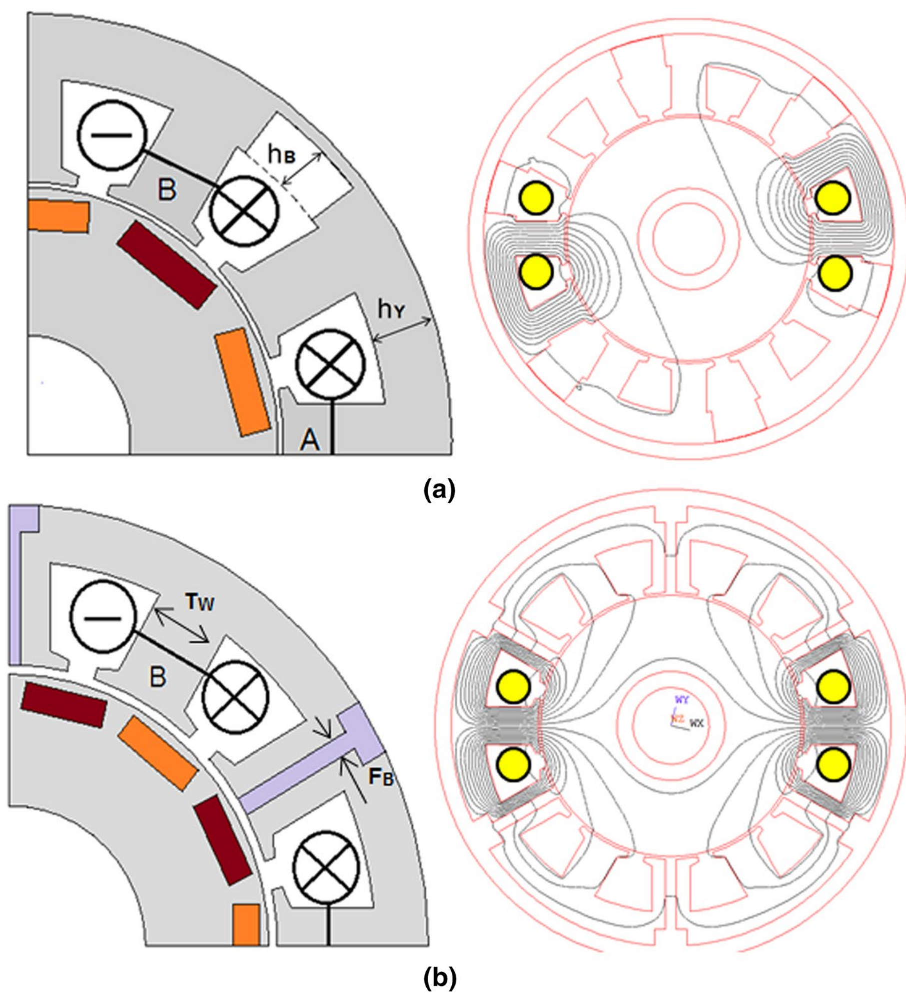


Fig. 6 **a** Stator structure with FBs in yoke region (beside alternate slots), **b** stator structure with FBs in tooth region

with FB in the stator yoke beside alternate slots the sub-harmonics can be cancelled for the DL winding, while for the SL winding they can be decreased by more than 60%. On the other hand, the second method with FBs at alternate teeth yields further advantages. In addition to sub-harmonic reduction, FBs increase the torque density of the 12T/14P machine up to 20%.

Figure 7 shows different prototypes of PM machines designed according to the FB method. In [25], a 12T/10P PM machine with DL winding and FBs in the yoke region is designed. Additionally, Ref. [28] validates the functionality of the FBs technique applied to the tooth region and shows the high torque density provided by the 12T/14P FB machine. Furthermore, as investigated in [29], the flux gaps can be used as water ducts to significantly improve cooling efficiency.

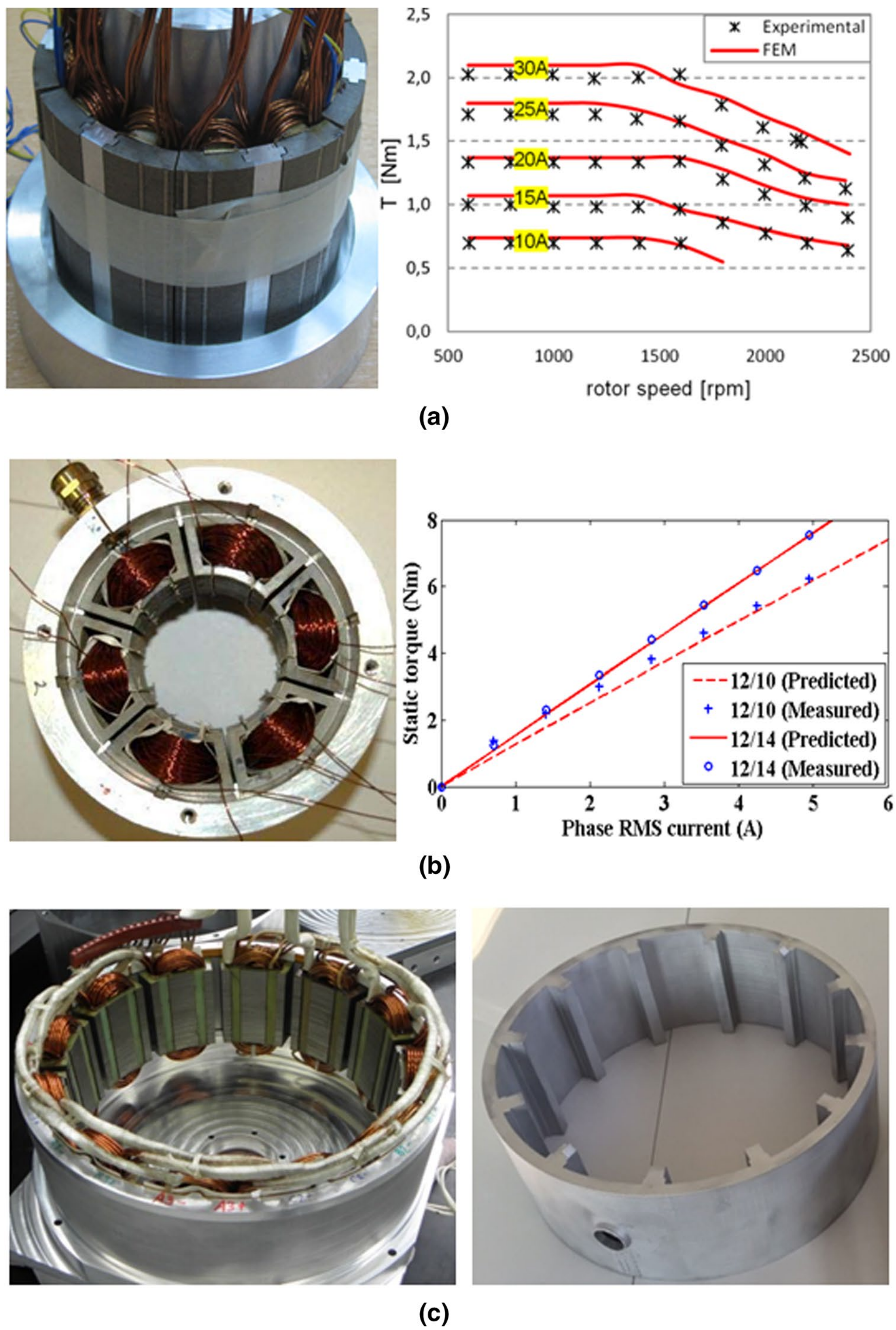


Fig. 7 Different prototype concepts: **a** 12T/10P PM machine with FBs in stator yoke and DL winding [25], **b** 12T/14P PM machine with FBs in stator teeth and SL winding [27, 28], **c** new cooling concept for a 24T/28P traction PM machine with FBs in stator teeth and SL winding [29]

4 Coils with different turns per coil side

A simple method to reduce sub-harmonics of DL tooth-concentrated windings would be using coils with different turns per coil side, as presented in [30]. Considering the 12T/10P winding type, Fig. 8a shows the corresponding winding layout using the proposed solution. Figure 8b illustrates its MMF distribution. For the sake of simplicity, only coils of phase A are presented in the sketch; n_1 and n_2 are numbers of turns per coil side and the relation between n_1 and n_2 is:

$n_1 = n_2 - 1, \quad \text{and} \quad 50\% \leq n_1/n_2 < 100\%.$

The winding factor for the 12T/10P unequal-turn winding topology can be determined as:

$$ {}^{\nu}\xi_{w,new} = \frac{2n_1}{n_2 + n_1} \cos\left(\nu \frac{5}{12}\pi\right) \cdot \sin\left(\nu \frac{\pi}{12}\right) + \frac{n_1 - n_2}{n_2 + n_1} \sin\left(\nu \frac{\pi}{3}\right) \tag{7} $$

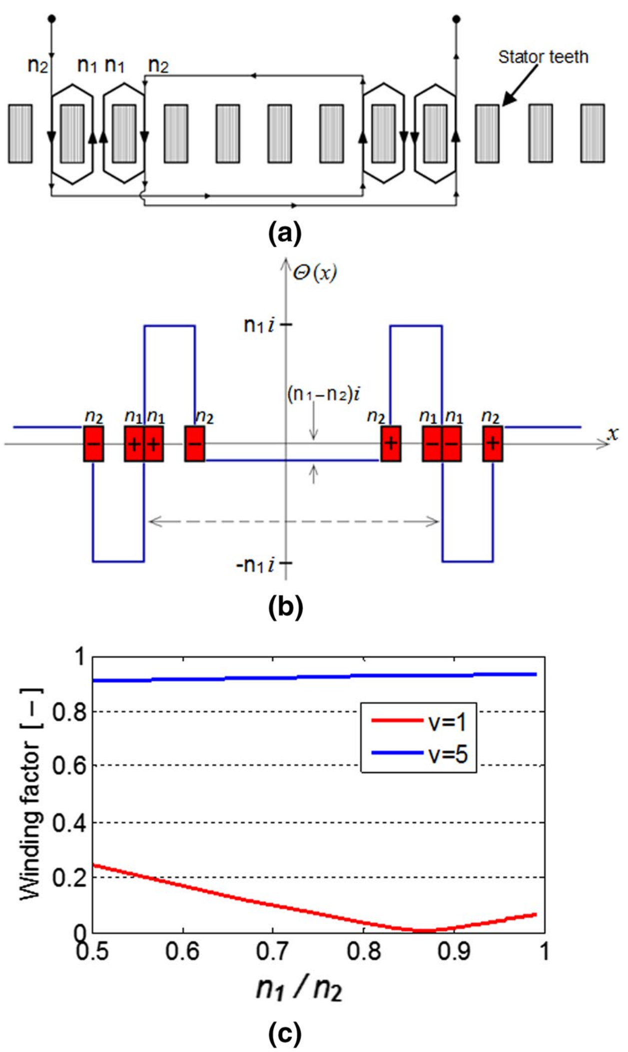


Fig. 8 **a** Winding layout of phase A, **b** MMF distribution of one phase (e.g. phase A), **c** winding factors versus n_1/n_2

It can be seen from Eq. (7) that the winding factors for the proposed winding vary with the ratio between turns of different coil sides. Simulation results show that if n_1/n_2 is between 80 and 90%, e.g. $n_1/n_2 = 6/7, = 7/8, = 8/9$ and so on, the 1st sub-harmonic of the considered winding type can be reduced by more than 90% while leaving the working (5th) harmonic unaffected (less than 0.45%). This is illustrated in Fig. 8c).

In [31], the unequal-turn winding configuration is applied to a five-phase 20-tooth/22-pole (20T/22P) PMSM to cancel the low-order harmonics. The presented analysis shows that for an optimal point with $n_1/n_2 = 0.95$ the MMF sub-harmonic is reduced to zero, while the fundamental harmonic is reduced only by 0.06%. Moreover, in comparison with conventional 20T/22P winding torque ripples as well as machine losses are reduced.

5 Multilayer FSCW

In order to reduce the amplitude of low-order MMF harmonics, different configurations of multilayer windings have been proposed in the literature [32–39]. For example, in [32, 33] the classical 12T/10P DL winding combination is considered where a four-layer winding is obtained by doubling the conventional DL layout. Thereby halved number of turns per coil is used and the second winding system is shifted by a specific number of slots. The MMF function of the resulting four-layer winding is given by:

$$ \Theta(\theta_s, t) = \sum_{\nu} \frac{m}{2} \cdot \frac{2 \cdot N_w \cdot {}^{\nu}\xi_w \cdot {}^{\nu}\xi_Z}{\pi \nu} \cdot \hat{i} \cdot \cos\left(\omega t - \nu\left(\theta_s - \frac{\alpha_w}{2}\right) + \delta\right) \tag{8} $$

where α_w is a shifting angle between winding sets and ${}^{\nu}\xi_Z$ represents the distribution factor

$$ {}^{\nu}\xi_Z = \cos\left(\nu \cdot \pi \frac{n_{Qs}}{Q_S}\right). \tag{9} $$

Shifting the second winding system by a certain number of slots reduces low-order harmonics significantly but affects the working harmonic as well, as illustrated in Fig. 9a. It becomes obvious that an effective reduction (approx. 75%) of the first sub-harmonic is achieved using a 5-slot or 7-slot shift, whereas the 5th (working harmonic) and the 7th harmonic are only slightly decreased by approximately 5%. For further reduction in MMF sub-harmonics alternative three-layer FSCW solutions using coils with different numbers of turns are presented in [33]. Selection of a proper number of turns per coil side leads to a complete cancellation of the 1st sub-harmonic.

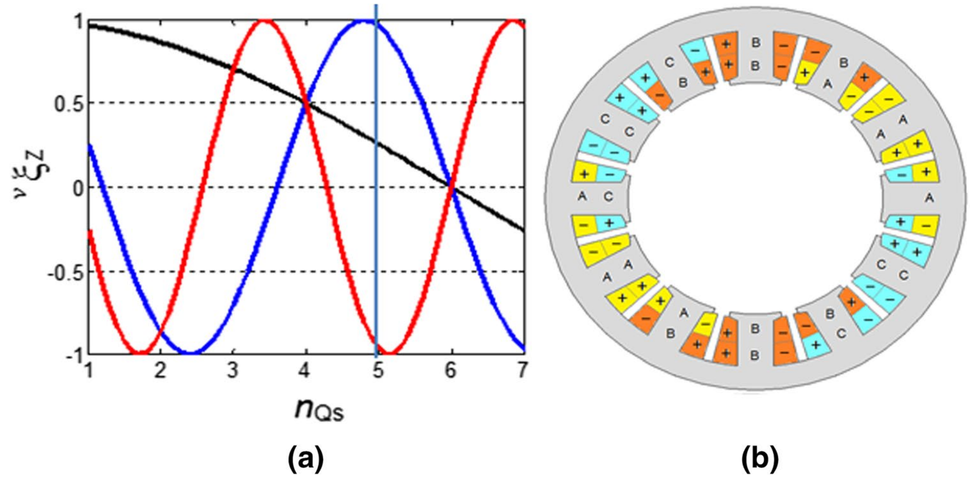


Fig. 9 **a** Distribution factors versus number of stator slots, **b** optimized four-layer 12T/10P winding

Figure 9b shows the winding layout for an optimized four-layer 12T/10P winding. In the presented exemplary winding, the second winding system is shifted by 5 slots (counterclockwise).

Moreover, Fig. 10 presents different prototypes realized using multilayer FSCWs [33, 36, 38], wherein experimental results show improved torque ripple and rotor loss characteristics, compared to the conventional DL windings.

6 Multiphase FSCW

To improve fault tolerance capability, redundancy and integration of power electronics, several multiphase FSCW machine concepts are proposed and considered in [40–44]. Usually multi-3-phase winding sets (such as 2×3-phase or 3×3-phase) are applied to different 6- and 9-phase machines. An $n \times 3$–phase motor has n identical winding sets each supplied by a separate inverter. Figure 11a illustrates a 12-tooth winding topology realized as a 6-phase machine fed by two separate 3-phase inverters [40]. Another multiphase 12-tooth winding construction is presented in Fig. 11b, where phase coils that belong to one winding system are located oppositely [41].

In addition to the advantages mentioned before, the multiphase FSCW configuration also offers improvements in terms of MMF characteristics. Figure 11c compares normalized MMF spectra of the three-phase and the dual three-phase 12-tooth FSCWs. Obviously, in the dual three-phase configuration the winding sub-harmonic is completely cancelled, while the fundamental harmonic is increased by a few percents. Improvement of the fundamental winding factor results in a higher torque per ampere ratio, which in turn increases the power density of the machine. Moreover, reduction in winding sub-harmonics reduces local saturation in the stator yoke as well as rotor losses.

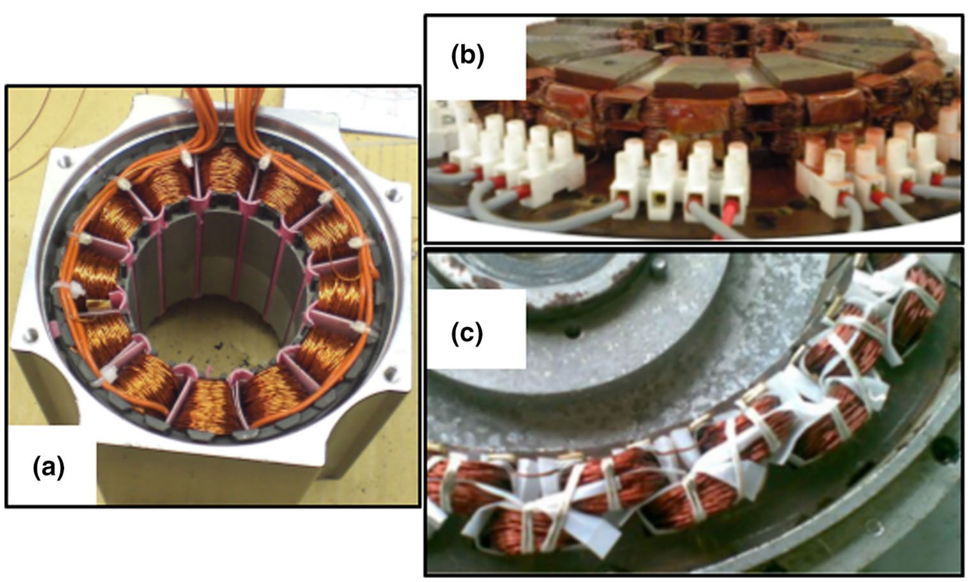


Fig. 10 **a** Four-layer 12T/10P PM machine [36], **b** four-layer 12T/10P axial flux SPM machine [38], **c** 36T/30P three-layer PM machine [33]

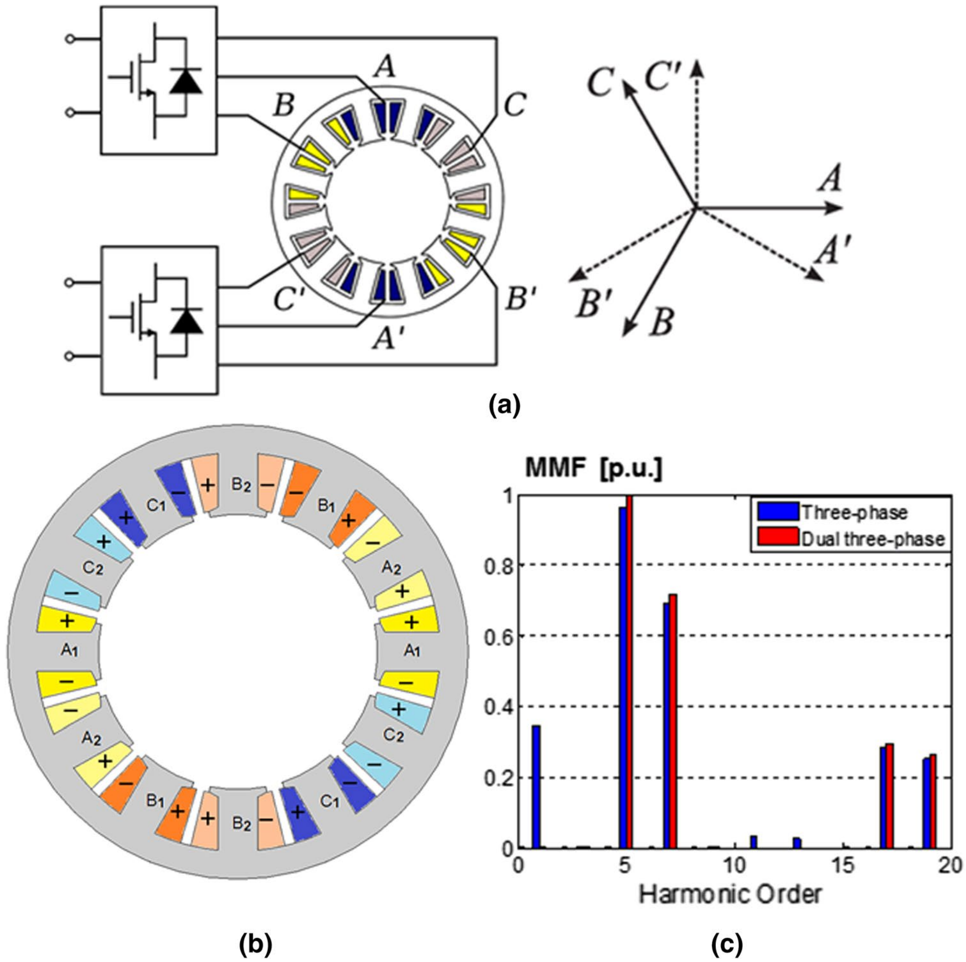


Fig. 11 **a** Schematic of the dual three-phase motor drive [40], **b** dual three-phase 12-tooth/10-pole winding [41], **c** comparison of MMF winding harmonics

In [40], the well-known 12T/10P PM motor equipped with a dual three-phase winding, supplied by separate inverters, shows improved performance in terms of torque ripples and efficiency. An alternative solution is presented in [41] where the dual three-phase winding system is obtained using combined star-delta series connection. In this case, the star-connected winding system is connected between the supply and the inner delta-connected winding system (Fig. 12).

To increase system power density, a highly integrated drivetrain based on the multiphase concept is presented in [44]. The 9-phase drive solution consists of nine smaller inverter modules which are incorporated directly in the motor housing. Component integration into a common housing including gearing mechanism and liquid cooling minimizes size and maximizes system power density.

In addition, there are numerous applications of multiphase techniques for fractional slot two-tooth windings that are considered below in Sect. 9. Combination of the multiphase supply and these winding types significantly improves the quality of their MMF distributions [55–57].

7 Dual FSCW

In a dual FSCW configuration, there are two different concentrated winding topologies that are combined in the same stator core, where each of them is supplied by a separate three-phase current system. Applying this method, Ref. [45] presents a new 18T/10P FSCW design with improved MMF winding characteristics, see Fig. 13. Considering the conventional 12T/10P reference winding and taking the dual FSCW concept into account, the new winding topology is obtained by increasing the number of stator slots from 12 to 18 and combining two different winding systems which are shifted in space and time. The first winding system is similar to the 12T/10P single-layer winding (yellow winding); the second winding system is similar to the 12T/10P double-layer winding (blue winding).

Figure 13b compares the MMF space harmonics for the new and the reference winding. As it can be seen here, the critical space harmonics, such as the 1st and the 7th, which

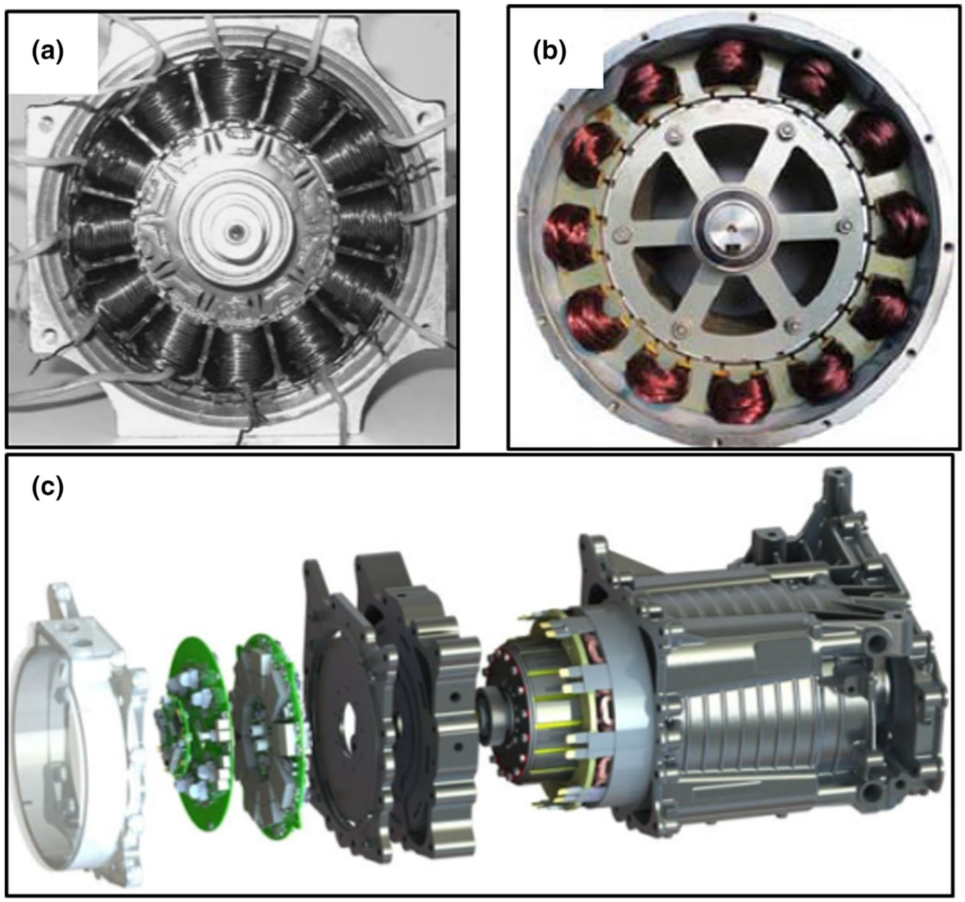


Fig. 12 **a** Six-phase 12T/10P FSCW PM machine [40], **b** six-phase 24T/22P SPM machine [43], **c** highly integrated 9-phase drivetrain [44]

are mostly responsible for rotor losses and noise problems, are completely cancelled. It should be noted that the main drawback of this configuration is the low winding factor for the fundamental wave (about 76%). However, analysis of different PM traction machines, as performed in [24, 46], shows that in spite of the lower winding factor this winding type overcomes the commonly used FSCWs and represents an alternative solution for existing problems of present PM traction machines. The efficiency obtained using this winding type confirms the applicability and operation of the new approach, see Fig. 13c.

8 Dual slot layer stator

In [47], a dual slot layer stator construction combined with a multilayer winding is presented to minimize space harmonics in the air gap MMF, compare Fig. 14a. The proposed design is applied to reduce the sub- and the high harmonics of the 12T/10P FSCW where only slot harmonics, such as 19th, 29th, 43th, and so on, are present in the air gap.

Another FSCW topology for low-poled machines based on the dual slot layer stator construction is presented in [49]. Different from [47], the new winding configuration consists of two different FSCW sets and all coils are wound around each single stator tooth (Fig. 15a). The MMF winding distribution obtained with this winding type is analogous to that of conventional distributed windings with $q=2$ (q is the number of slots per pole per phase) as shown in Fig. 15b, while the winding factor of the fundamental wave is lower (~37%). However, investigations performed for high-voltage machine applications show that, as a result of the short end windings, this winding type could replace commonly used distributed windings in some specific applications. Figure 15c, d presents the geometry with field solutions as well as torque response for a 720-kW, 6-kV asynchronous machine which has been designed using the proposed dual 6T&12T/2P winding topology. In this particular case, a high efficiency of 96.3% at nominal speed has been reached. Thus, compared to existing ASMs with distributed windings, the proposed machine design shows better performance in terms of power density, efficiency and manufacture.

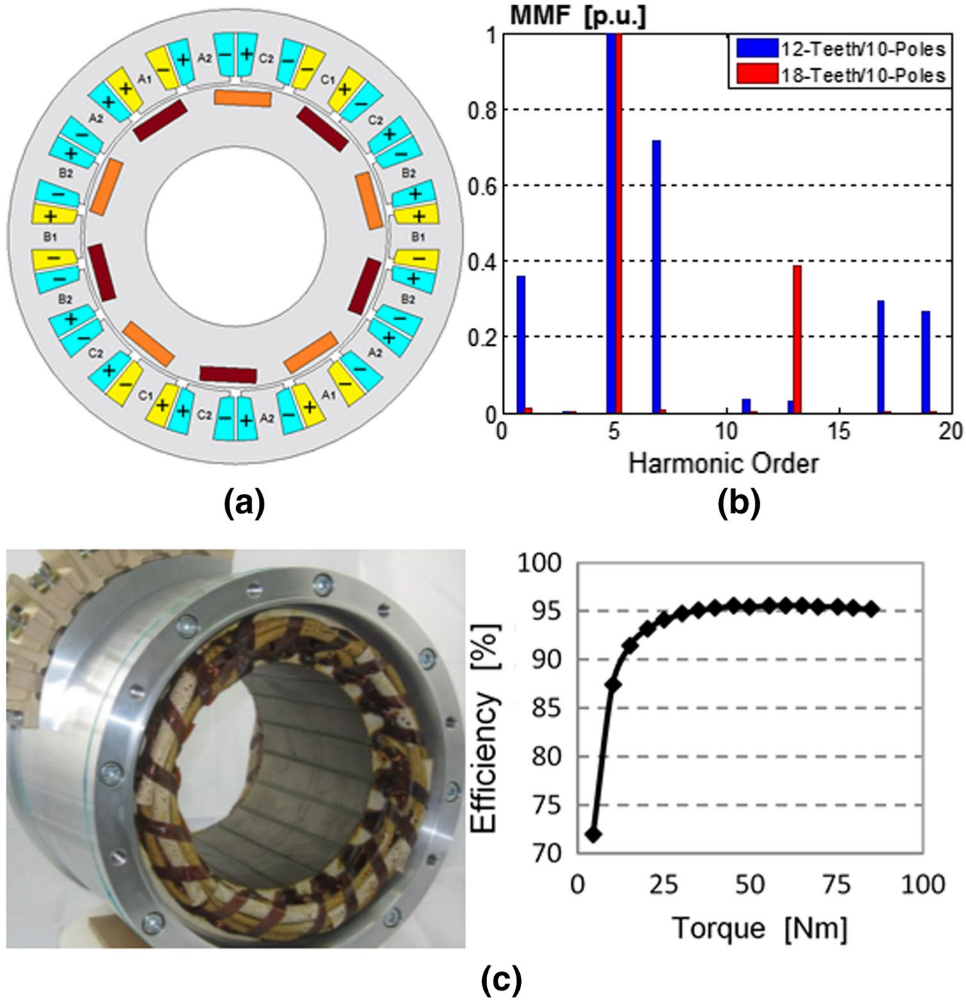


Fig. 13 **a** Dual 18-tooth/10-pole FSCW, **b** comparison of MMF winding harmonics with the reference 12-tooth winding, **c** the 18T/10P prototype traction PM machine and first efficiency measurements [46]

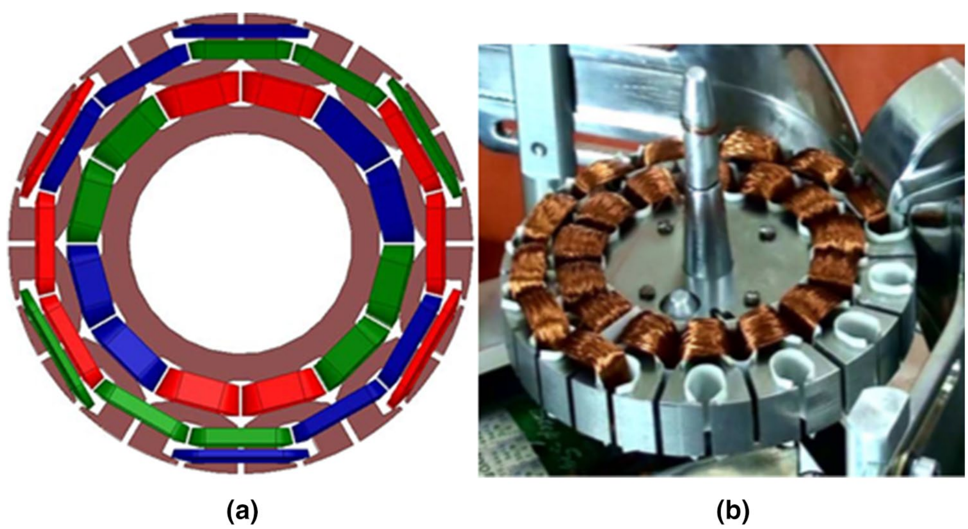


Fig. 14 **a** Dual slot layer 24-slot/10-pole stator [47], **b** in-slot winding machine used to create the stator winding [48]

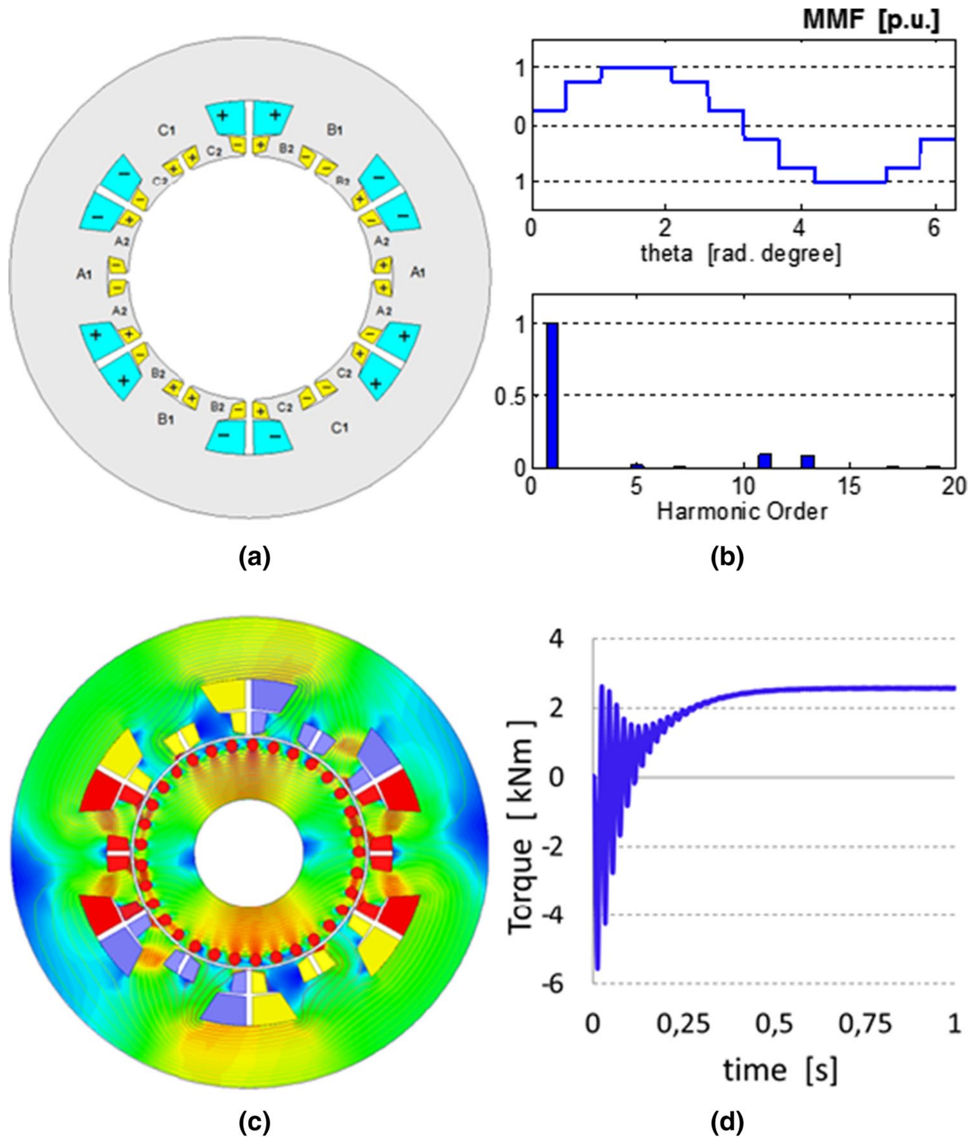


Fig. 15 **a** Dual 6T&12T/2P FSCW [49], **b** corresponding MMF characteristics, **c** high-voltage (6 kV) ASM equipped with new winding, **d** torque response at nominal speed

9 Stator shifting concept

For simultaneous reduction in sub- and high harmonics of FSCWs, the first stator shifting concept has been proposed in [50]. This method is based on doubling the number of stator slots using two identical winding systems connected in series and shifting one against the other for a specific angle, using stator core with different tooth width and/or using different turns per coil for the neighbouring phase coils. Depending on the shift angle and turn relation, the 5th or the 7th as well as the 1st MMF harmonic can be completely cancelled. Figure 16a presents the winding layout (winding coils of phase A are highlighted) for the 24T/10P winding in case the winding arrangement is selected to cancel the 7th and the 1st harmonics, whereas the 17th is reduced by about 50%, see Fig. 16b. It is important to point out that by doubling the number of stator slots each coil is wound around two adjacent stator teeth instead of one single tooth.

The concept of harmonic cancellation in FSCW based on the stator shifting method has been followed and further analysed in several papers which optimize different winding topologies and machine types in accordance with this approach [51–60]. References [51, 52] analyse stator shifting effect on harmonic components of the stator MMF, on winding factors, power density, efficiency, as well as on torque ripples for various slot/pole combinations of fractional slot PM machines. Further, in [53, 54] the 9-tooth FSCW is optimized whereby the 18-tooth fractional slot winding is obtained, see Fig. 16c, d. In order to improve safety and availability in traction applications, this winding configuration is realized as a six-phase machine fed by two independently controlled three-phase systems [55, 56] as shown in Fig. 17b. An analogous multiphase solution is also

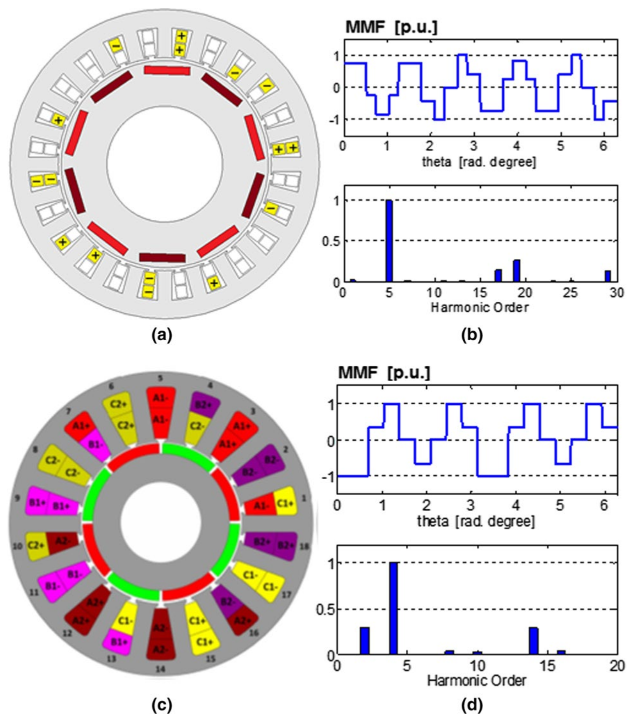


Fig. 16 **a** 24-tooth/10-pole winding, **b** MMF winding characteristic [50], **c** 18-tooth/8-pole winding, **d** MMF winding characteristic [53]

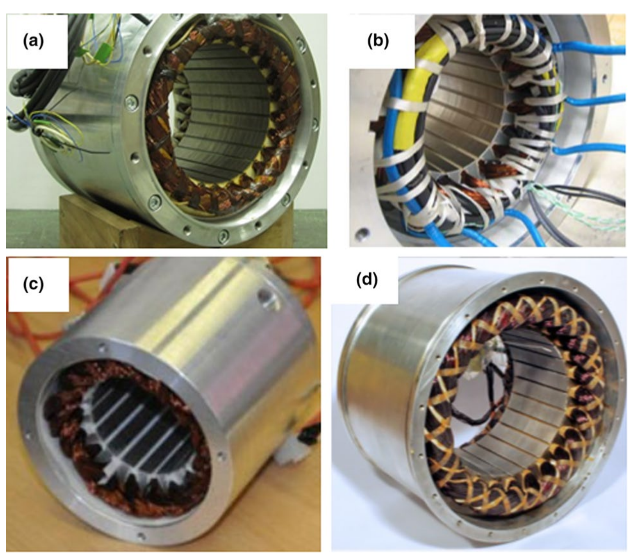


Fig. 17 **a** 36-tooth/10-pole winding, **b** MMF winding characteristic [58], **c** 6-tooth/2-pole winding, **d** MMF winding characteristic [59]

used in [57], where it is applied for design and analysis of a 24T/10P six-phase fractional slot PM traction machine, as shown in Fig. 17d.

Moreover, in [58] the stator shifting concept is applied to the 18T/10P FSCW described in Sect. 7 with the derived

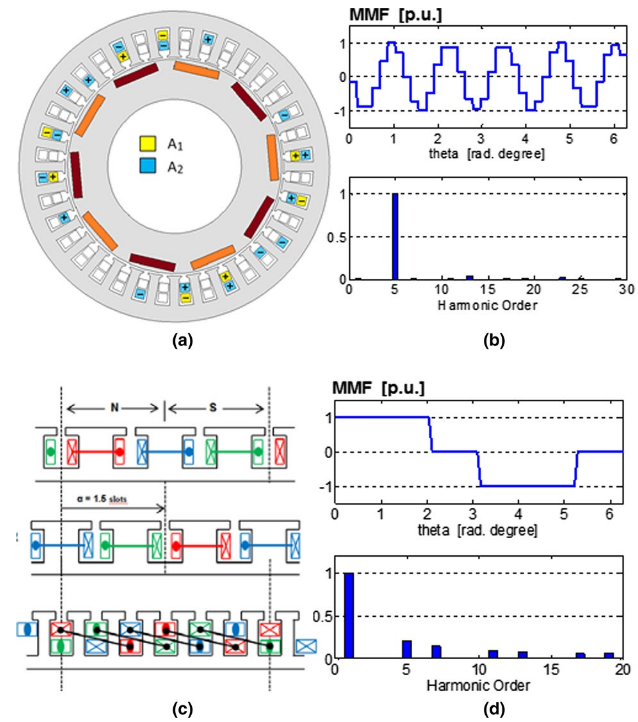


Fig. 18 Different fractional slot winding topologies based on the stator shifting concept: **a** 24T/10P three-phase winding [50], **b** 18T/8P dual three-phase winding [55], **c** 18T/10P three-phase winding [54], **d** 24T/10P six-phase winding [57]

36T/10P winding showing a high-quality MMF distribution, as shown in Fig. 18a, b. Last but not least, in order to minimize the magnet losses resulting from the winding MMF harmonics Ref. [59] analyses the 6T/2P two-tooth winding which is designed by optimization of the conventional 3T/2P FSCW, as shown in Fig. 18c, d.

10 Self-excited synchronous machine

Contrary to the methods mentioned above which eliminate the lower and higher space MMF harmonics, references [61–63] utilize some specific space harmonics to produce the rotor excitation for current-excited synchronous machines (CESMs). This machine concept avoids brushes and slip rings and is called self-excited synchronous machine (SESM).

Figure 19 illustrates the basic block circuit diagram for the self-excited machine concept. The FSCW in the stator simultaneously generates the main working air-gap harmonic, which is responsible for the electromagnetic torque, and a specific high harmonic, which is used to excite the rotor winding. The rotor consists of two winding sets: the excitation winding **E** and the field winding **F**. Both rotor windings are connected via a rotated rectifier. Thus, under

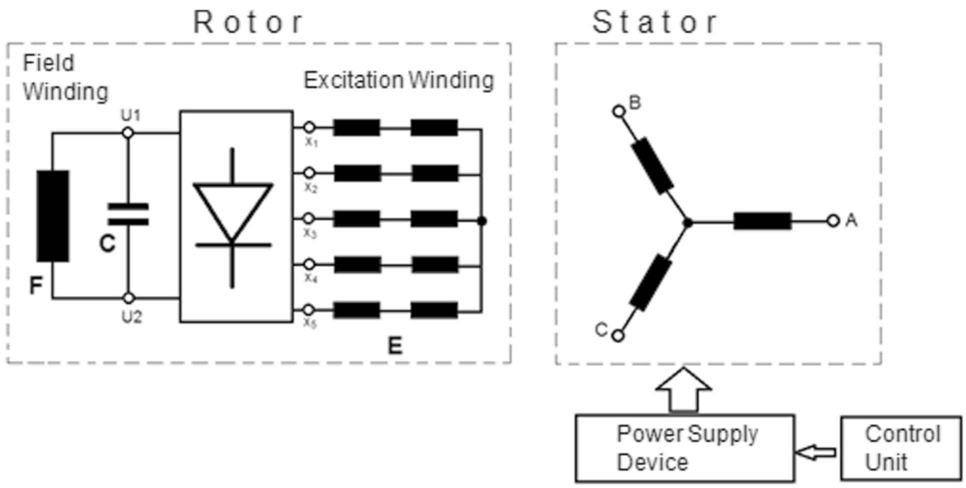


Fig. 19 Block circuit diagram for the new self-excited synchronous machine

load excitation conditions, the high space MMF harmonics induce electromagnetic forces into the rotor excitation winding **E**. These are rectified by the diode bridge circuit and supply the field winding **F** with DC currents.

According to this concept, Ref. [61] presents a SESM designed with the 18T/10P concentrated winding described in Sect. 8. There, the 5th MMF harmonic is used as the working wave, whereas the 13th is used as an excitation wave, as shown in Fig. 20a. In [62], an alternative

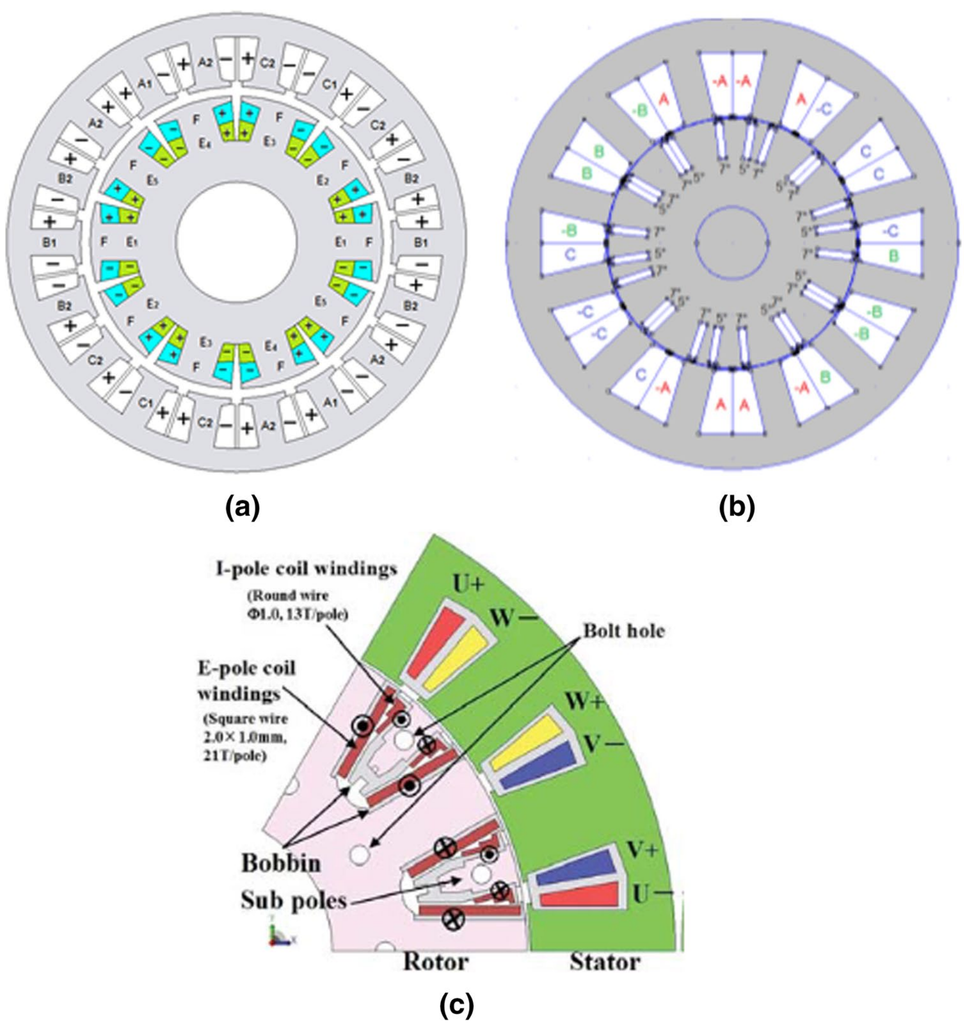


Fig. 20 Different SESM concepts with concentrated winding: **a** 18T/10P SESM [61], **b** 12T/10P SESM [62], **c** 18T/12P SESM [63]

self-excited machine is proposed, which has been designed using conventional 12T/10P FSCW, as shown in Fig. 20b. Furthermore, the same method is also applied in [63] for the 18T/12P SESM, which is based on the conventional 3T/2P FSCW, as shown in Fig. 20c.

11 Conclusion

This paper provides an overview of recent research activities in the area of FSCW machine optimization. To avoid problems resulting from FSCW space harmonics, several novel methods have been developed and investigated in the recent past. There are many works that focus on the elimination of undesirable harmonic components. However, one can find other articles which utilize the winding harmonics for rotor excitation of CESMs.

In general, the methods applied to meet the challenges of FSCWs can be classified into three categories. In the first category, which includes flux-barrier machines, the reduction in MMF sub-harmonics is achieved by magnetic flux barriers which are inserted into specific stator yoke or stator tooth regions. In addition to torque density and efficiency improvements, this approach can also be used for direct cooling of the stator by exploiting the stator flux barriers as cooling ducts.

The second category contains a couple of methods which are based on winding layout and winding supply modification. Three different winding designs are found to reduce the MMF sub-harmonics. The first one uses concentrated coils with different turns per coil side, the second one works with an increased number of layers per slot (three or more layers; multilayer windings) and the last one uses a multiphase supply. Moreover, for the simultaneous reduction in sub- and high MMF harmonics an 18T/10P winding topology with two different FSCWs can be used. Furthermore, a dual slot layer stator equipped with FSCWs or a combined tooth-concentrated and two-tooth winding leads to further improvement of the MMF characteristics. Finally, there are various works about two-tooth windings that are based on the stator shifting concept.

In conclusion, the above-mentioned self-excited synchronous machines (SESMs) can be assigned to the third category. This optimization approach uses specific space harmonics for the rotor field excitation of current-excited synchronous machines.

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