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From transverse flux machine to fractional slot concentrated winding permanent magnet synchronous machine

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Abstract: The article presents the results of research on transverse flux machine (TFM) modifications that led to the development of the cogging machine (PMCM) concept and its further evolutions. The transformation process of the cogging machine from a multi-segment to a single-segment modular design has resulted in a structure identical to the known and commonly used fractional slot concentrated winding permanent magnet synchronous machine (FSCW-PMSM). The paper describes the features gained and lost by the modified machine in various transformation stages. An original method for selecting the number of winding modules is also proposed, depending on the number of coils in a module and the pitch of the pole using a separating tooth between the modules.

Key words: fractional slot concentrated winding permanent pagnet synchronous machine, modular winding, transverse flux machine

1. Introduction

The use of rare earth magnets in the old invention of a transverse field generator [1] has led to the development of a high torque-to-inertia ratio motor [2,3]. The concept presented in [4] was also important for the advancement of this design. As a result of further intensive research, numerous variations of transverse field machines (TFMs) were created, compiled, and described, for example, in [5–7]. In summarising their review, it can be stated that the fundamental characteristic enabling the generation of a greater torque than in other machines of similar dimensions is the dimensional independence of the electrical and magnetic circuits in TFMs, whereas in machines with a radial field, increasing the winding cross-section occurs at the expense of the magnetic circuit's surface area, and vice versa [8]. The absence of end connections in the TFM windings significantly reduces the axial dimension of the machine.

Due to the technologically cumbersome design of the TFM magnetic circuit, it has not yet found broader practical application. Therefore, in [9] and [10], the placement of the TFM winding loop in the traditional slotted core was proposed. The field participating in energy conversion is no longer "transverse", but the operating principle of the machine with such a field is preserved. The power factor is also improved. The resulting modified sinusoidal winding, which generates axial flux, was subsequently replaced by a lap winding, where individual coils surround single teeth of the core. The new design derived from transverse-field machines is called a cogging machine (PMCM). The name originates from the equal pole pitch and tooth pitch covered by the winding coils in the PMCM, which increases the cogging torque. A drawback of such a three-phase construction, similar to the TFM, is its segmented nature, which is necessary to ensure self-starting properties.

Attempts to overcome the multi-segment nature of the TFM were proposed in [11]: three sets of phase windings, appropriately shifted, were placed on the circumference of a shared core. The same approach can be applied to a wave or lap winding PMCM by allocating 1/3 of the slotted core circumference to each phase. This results in a design that shares many characteristics with the commonly used fractional slot concentrated winding permanent magnet synchronous machine (FSCW-PMSM). The main features shared by the PMCM and FSCW-PMSM include:

– excitation of the magnetic field by permanent magnets located on a common cylindrical core,
– The armature consists of a toothed core with winding or windings composed of coils encompassing individual teeth (the coil pitch is equal to the pitch of the armature slots), the windings "do not overlap",
– The number of magnet pairs and the number of teeth (with coils) are closely related.

In the FSCW-PMSM, the phase shift between the individual phase electromotive forces (EMFs) is achieved by an appropriate difference in the number of pairs of permanent magnet poles and the number of teeth on the armature, as well as the proper connection of toothed coils located on a common core. In the PMCM, the method of generating the phase shift of the EMFs depends on the chosen design variant. In the case of the primary three-segment construction of the actuator, the windings of each phase are located on separate segments that are circumferentially shifted by 1/3 of the pole pitch with respect to each other. When the actuator core is common for all windings, the coil groups for each phase are shifted by a corresponding angle around the core circumference relative to the other groups. This requires the existence of small slotless areas between the groups of coils for each phase.

This article presents the results of comparative studies on various versions of TFM machines described in the literature as well as those developed by the author, and FSCW-PMSM machines. The research was conducted with a focus on the average electromagnetic torque and the content of variable torque components in all designs. The article also proposes an algorithm to determine the relationship between the number of poles and the number of coil module units in the phase windings and coils within a module. The work aims to draw attention to the features of intermediate stage designs that may prove useful in various applications of permanent magnet excited motors and generators.

2. Comparison of the PM-TFM machine with the PMCM machine

The starting point and, simultaneously, the reference object is the PM-TFM construction presented in the publication [12]. The declared rated torque of this machine is $T_N = 400 = 3\times133.3$ Nm, with a phase rms current of 157 A. The amplitude of the variable torque component under rated load conditions is approximately 4 Nm. The current density calculated based on the dimensions provided in the article is $j = 7.8$ A/mm^2. The external dimensions of the entire structure are as follows: diameter 250 mm, axial dimension 196 mm. The relationship between torque and current obtained from the graphs and data in [12] is shown in Fig. 3 in red.

The principle of torque generation used in the TFM will be preserved if the winding loops of individual segments are "interwoven" into the slots of three-toothed cores, packaged in a traditional manner with laminated sheets [10]. The number of teeth on each of the cores should be equal to the number of poles (magnets). The resulting wave winding can be replaced with a lap winding, composed of coils encircling individual teeth, connected in series alternately. The cores placed on a common shaft should be circumferentially offset by 120° electrical degrees, similar to the arrangement in the TFM. Due to the fact that the number of armature teeth is equal to the number of pairs of magnets, the design has been given the working name "cogging machine". (PMCM). In Fig. 1, a general view of one segment of the PMCM is presented from the ANSYS Maxwell 3D simulation layout. Figure 2 presents the field distribution in the segment of the PMCM machine.

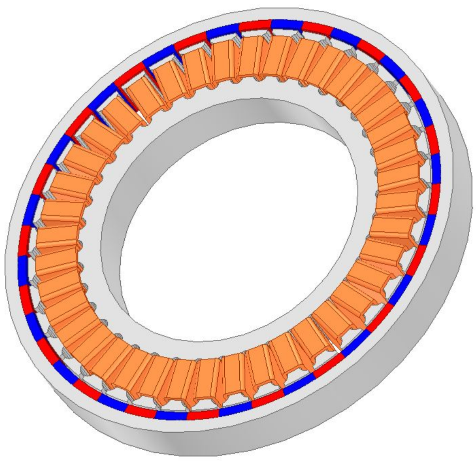

Fig. 1. General view of the PMCM segment

Model parameters:

- the number of pairs of magnets *pp* – 20,
- outer diameter – 0.25 m,
- radial dimension of the gap – 0.001 m,
- axial dimension of the end winding – 0.009 m,
- total axial dimension of the 3 segments – 0.196 m.

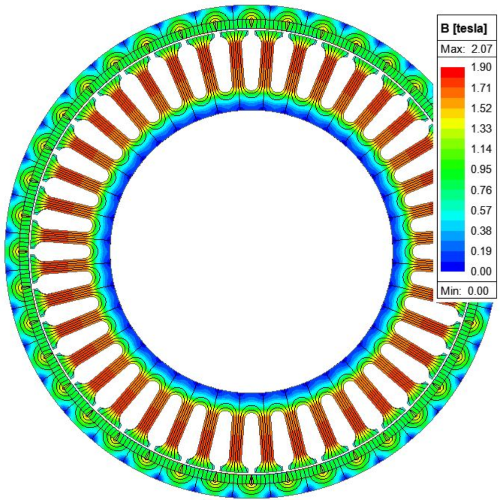

Fig. 2. Field distribution in the segment of the PMCM machine

The number of magnets has been selected in a way that, maintaining the outer dimensions, the cross-sectional area of the slots is similar to the cross-sectional area of the winding groove in the TFM segment. Of course, the fill factors for rectangular copper filling open the TFM groove, and a semi-closed PMCM slot must differ significantly. The nominal ampere-turns adopted for the PMCM slot are 495 A_{rms} compared to 1570 A_{rms} in the TFM. With the assumed copper slot fill factor of 0.4 and a slot cross-sectional area of 219 mm^2, this corresponds to the current density:

$$j = \frac{495}{219 \cdot 0.4} = 5.65\ \text{A/mm}^2. \tag{1}$$

Figure 3 presents the dependencies of the average torque for a three-segment system (3-phase machines) on the slot current densities of the TFM segment of [12] and the PMCM of Fig. 2, resulting from FEM simulations. The calculations assumed a sinusoidal current waveform in the winding, with the current being a function of the rotor position and remaining in phase with the back electromotive force (back-EMF) originating from the permanent magnets (control id = 0).

Comparison of the plots reveals that the PMCM exhibits significantly superior torque-producing capacity at the given current densities. It should be noted here that the TFM, as presented in [12], has a higher rated current with the same dimensions, so its torque-producing ability at rated current will be greater. However, the relationship depicted in Fig. 3 better facilitates the comparison of the properties of both designs as energy converters.

Reducing the number of magnets and teeth to 38 while maintaining the other dimensions of the PMCM affects the torque to a lesser extent than being linearly dependent on the number of magnets. In this case, it amounts to 230.3 Nm, whereas with 40 magnets, it is 235.85 Nm. This is due to the reduced saturation and elongation of the front connections when the number of teeth decreases. Figure 4 illustrates the torque waveforms generated by individual segments of the PMCM with 40 and 38 magnets, as well as the resultant torque waveforms.

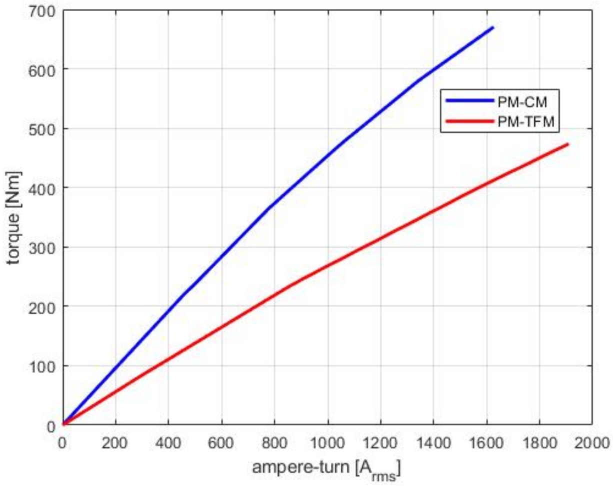

Fig. 3. Comparison of the torque generated by PMCM and TFM as a function of ampere-turns

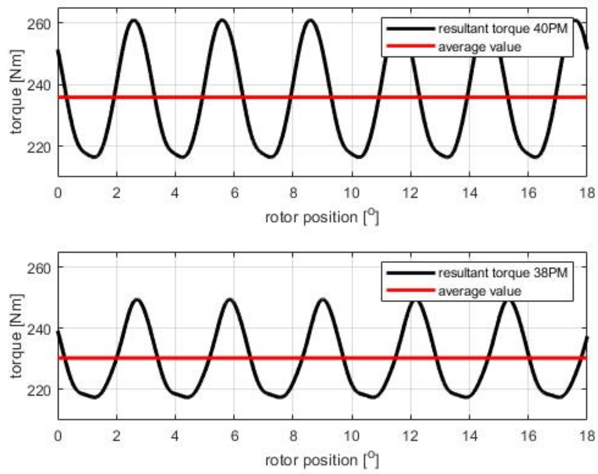

Fig. 4. Torque waveforms for 40 and 38 magnet PMCM

3. Common core PMCM

The PMCM is a radial field machine, where the axial dimension of the end connections significantly impacts the dimensions, even in the case of concentrated windings with coils encompassing individual teeth. This dimension is technologically conditioned. For windings produced in such a way that the sides of the coils placed in the same slot occupy parts of the slot on both sides of the cross-sectional axis of this slot, the end connection dimension would be the smallest, and such winding configuration was adopted in the simulations of the machine from

Fig. 2. However, such winding configuration may prove troublesome in industrial implementation. The most probable approach would involve placing the sides of each coil in different layers: one side in the upper layer and the other in the lower layer of adjacent slots. In this situation, the axial dimension of a single end connection can be defined as half the length of the largest segment that can be inscribed between the sides of adjacent slots. For the diameter of the armature of 220 mm and 40 slots, the axial dimension of the end connection, as defined, will be 17 mm instead of 8.5 mm. To maintain the same dimensions, this will necessitate a reduction in the axial dimension of the core and will consequently decrease the average torque. A more favourable approach could involve placing all three windings on a single core, allocating 1/3 of the armature circumference for each winding. Such a solution has also been proposed for the TFM [11]. The modules of windings for individual phases must be circumferentially shifted by an angle that ensures the appropriate phase displacement of the back electromotive forces (EMF) generated by the permanent magnets, the quantity of which determines the tooth pitch. These interdependencies can be expressed by the following equation:

$$M\tau n_c + M\frac{2}{3}\tau = 2pp\tau \rightarrow 2pp = M\left(n_c + \frac{2}{3}\right), \tag{2}$$

where: M is the number of phase winding coil modules, n_c is the number of coils in the module, τ is the pole/tooth pitch.

Since M, nc, and pp must be integers, the chosen number of modules corresponds to only certain pairs of magnet poles. For three-phase windings, the lowest number of modules is 3, which requires a value of nc that ensures an integer and an even value of the sum $(3n_c + 2)$. For example: for $nc = 1, 2, 3, \ldots, (3nc + 2) = 5, 8, 11, \ldots, 35, 38, 41, \ldots$. For the selected $pp = 19$, the winding of each phase consists of $n_c = 12$ coils covering single armature teeth – Fig. 5. Within each module, the tooth pitch is equal to the pole pitch. To allow the axial dimension of the wound core to not exceed 0.196 m, the packet can only be $(0.196 - 0.018) = 0.178$ m. As shown in

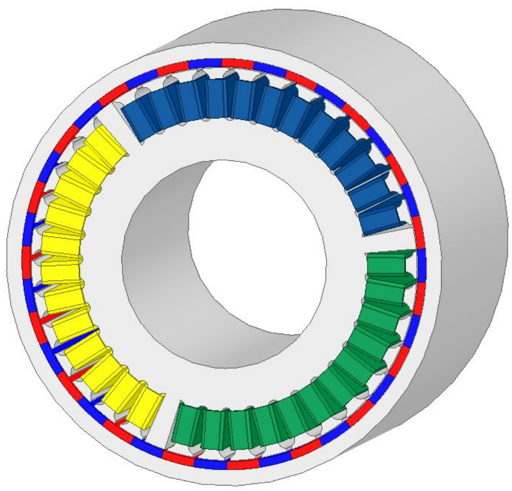

Fig. 5. General view of the common core PMCM

Fig. 5, one of the three teeth without a coil, separating the modules of phase windings, has a span: $\frac{1}{3}360\left(1-3\cdot 12\cdot\frac{1}{38}\right)\approx 6.3°$. Other dimensions were left unchanged. Figure 6 presents the field distribution in common core PMCM.

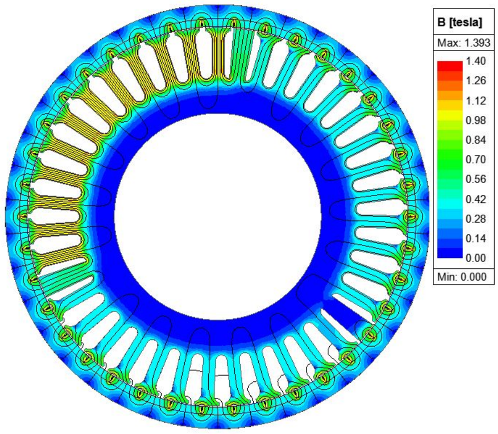

Fig. 6. Field distribution in common core PMCM

In Fig. 7, the torque waveforms of the machine from Fig. 5 are presented. The average torque, T_{av}, is 273 Nm, and the amplitude of the 6-th harmonic component is 7.8% T_{av}. An attempt to slightly increase the slot pitch from 360/389.47° to 9.75° (i.e., by 5.7° el.) at the expense

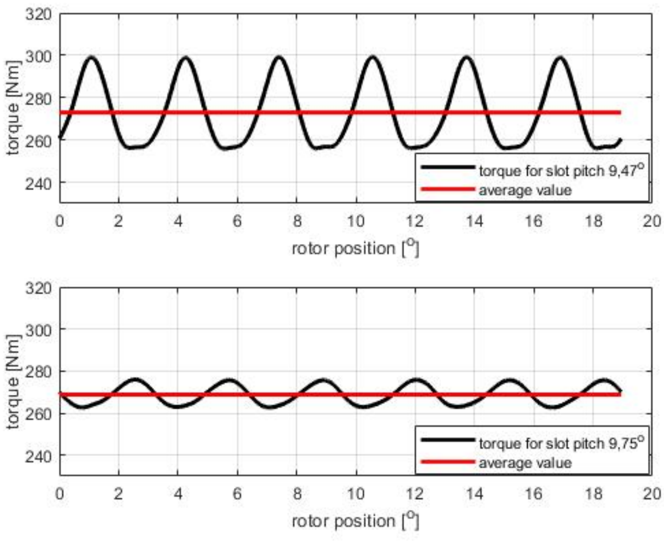

Fig. 7. Torque waveforms for the common core PMCM – slot pitch 9.47° and 9.75°

of the phase separation tooth significantly affects the variable torque component, causing the amplitude of the sixth harmonic component of the variable to decrease to 2.4% of T_{av}. However, the average torque also decreases to 268.8 Nm. This is due to the increase in the dimension of the end connections to 2×17 mm, which shortens the core from 178 mm to 162 mm and reduces the torque in both cases by 9%.

A slight change in the slot pitch also causes relatively significant changes in the derivatives of the unitary phase flux and cogging torque. Figures 8 and 9 present the results of the comparison of harmonic amplitudes and the derivative waveform of the unitary associated flux.

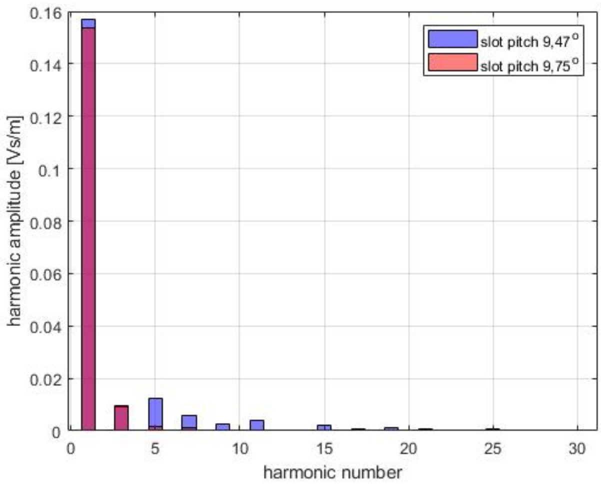

Fig. 8. Amplitudes of the harmonic derivatives of the unitary flux

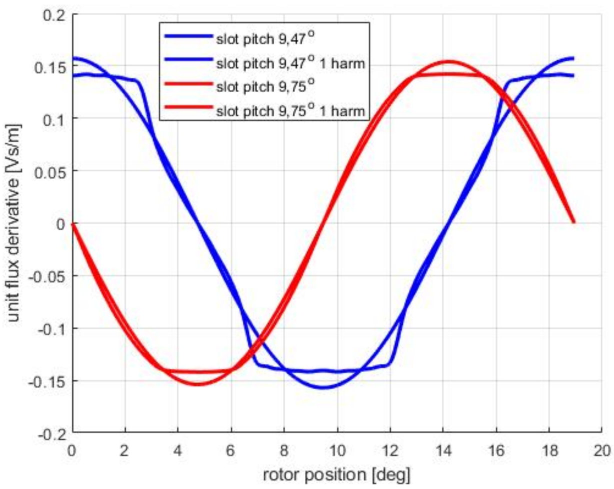

Fig. 9. Phase unit flux derivative and first harmonic

The cogging torque presented in Fig. 10 is also radically reduced.

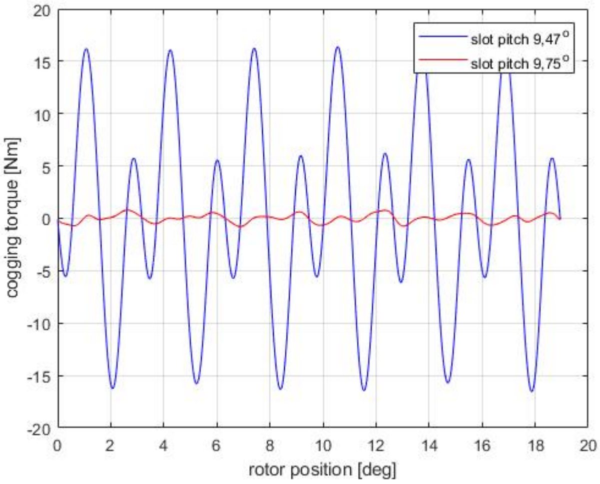

Fig. 10. Cogging torque of the common core PMCM

The process of replacing diametrical coils with coils that have a different pole pitch can be continued until the phase splitting tooth. This will result in a system of 19 pairs of magnets and 36 teeth with three modules of circumferential coils evenly distributed around the circumference. Consequently, this leads to further reduction of higher harmonics of the derivative of the combined unit flux and a significant decrease in the first harmonic. In Fig. 11, the harmonic amplitudes of the derivative of the combined unit flux are presented along with the waveform of the derivative of the unit flux of the phase. As can be observed, it is practically sinusoidal.

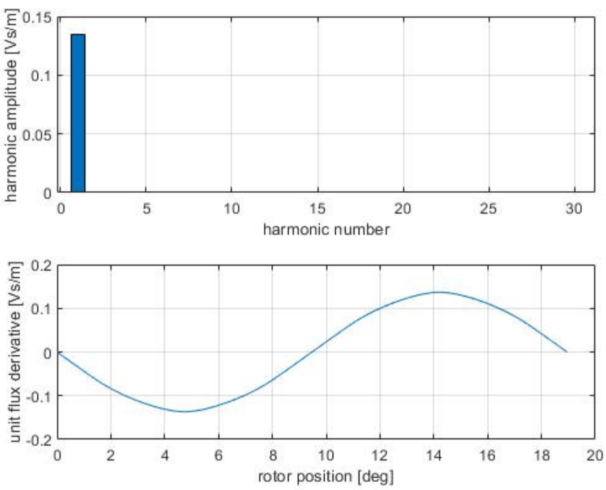

Fig. 11. Harmonics of the unit flux derivative and its waveforms in a system without a phase-separating tooth

The amplitude of the sixth harmonic of the variable component of the torque decreases to 1% of T_{av}, however, T_{av} = 234.9 Nm, which means it decreases to 86% of the value achieved with diametrical coils. The width of the separating tooth allows you to select the most advantageous tooth pitch from the range of (360/38) to 10°. It is also possible to reduce the number of coils in one module, thus increasing the number of modules with teeth separating phases or without them, which generally depends on the chosen number of pairs of magnet poles. In the case considered of pp = 19, the aforementioned core with evenly distributed 36 slots along the circumference and coils wound around the teeth can be used for this purpose, with only the method of connection modified. The arrangement of the windings and the field distribution are shown in Figs. 12 and 13, respectively. An odd number of pole pairs, pb, necessitates a change in the polarity of coils separated by 180 degrees. The average torque, T_{av}, developed by the motor in Fig. 12, is 270.6 Nm, with an amplitude of the sixth harmonic component of 1.9% T_{av}.

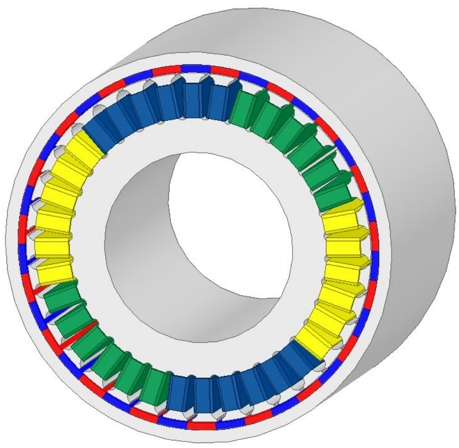

Fig. 12. General view of the common core PMCM without the module separating the tooth

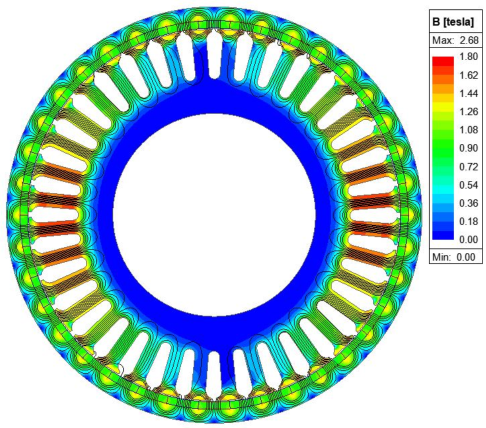

Fig. 13. Field distribution in common core PMCM without module separating tooth

A core with teeth that separate the modules can also be used to obtain a 6×6 coil arrangement. For $M = 6$, the number of coils n_c must provide an integer and an even value of the product $2(3n_c + 2)$.

For $nc = 1, 2, 3, \ldots$ expression $2(3n_c + 2) = 10, 16, 22, \ldots, 34, 40, 46, \ldots$.

For the selected $pp = 20$, the winding of each phase will be composed of two modules containing $n_c = 6$ coils covering single armature teeth – Fig. 14. Two of the six teeth without coils visible in Fig. 14, separating the phase winding modules, have a width of $\frac{1}{6}360(1 - 6 \cdot 6 \cdot \frac{1}{40}) = 6°$. Other dimensions were left unchanged. The average torque T_{av} is 266.5 Nm, and the amplitude of the 6-th harmonic variable component is 10% T_{av}. As before, increasing the pitch of the slot from $360/40 = 9°$ to 9.47° (i.e. by 9.4° el.) at the expense of the phase separation tooth significantly affects the variable torque component, which decreases to approx. 1%. Fig. 15 presents the field distribution in a common core PMCM in the layout 40PM 6×6Za.

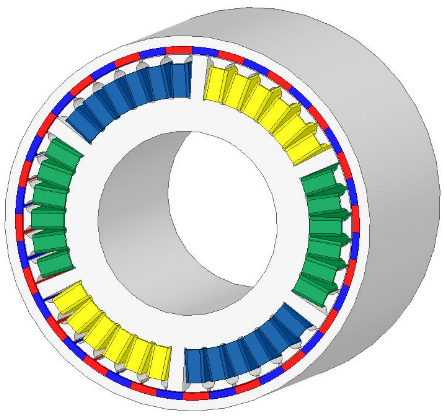

Fig. 14. General view of common core PMCM in 40PM 6×6Za

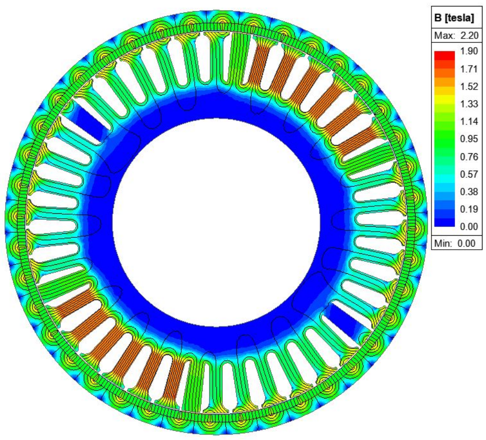

Fig. 15. Field distribution in common core PMCM in layout 40PM 6×6Za

4. From PM TFM to FSCW-PMSM

Increasing the tooth pitch until the elimination of the separating tooth leads to a reduction in variable torque, but also to a significant decrease in average torque (see Table 1). Constructions resulting from the elimination of separating teeth can be classified as widely used and described FSCW-PMSM designs. [13–15] present, for example, the number of slots per pole and phase for a machine 38PM-36Za $q = 36/38/3 = 6/19$. As indicated by the data presented in Table 1, these design variants may not necessarily yield the best results for a given number of magnets and coils, at least in terms of torque. The presence of separating teeth creates the possibility of changing the slot pitch within a small mechanical angle range but a significant electrical one. Among the commonly used combinations of pp/n_c, only some are derived from Eq. (1). For example, the frequently used basic combination in the FSCW-PMSM is 10PM/9Za, which consists of 10 magnets and 3 three-coil modules, replicated 4 times; it provides the average torque and torque harmonic components similar to those achieved in the referenced designs – see Table 1, item 10.

Table 1. Torque for all considered PMCM configurations and FSCW-PMSM with the same dimensions

No	**Configuration**		**T_{av}[Nm] – average value**		**Coging torque [Nm]**				
			1 h	**6 h**	**2 h**	**6 h**	**12 h**	**14 h**	**18 h**
1	PMCM 3-segments	38PM – 38Za	292.1	19.86	–	5.1	9.9	–	–
2		40PM – 40Za	294.8	28.3	–	2.1	9.7	–	–
3	PMCM common-core	38PM – 3 × 12Za with slot pitch 9.47°	276.08	21.53	–	8.38	10.2	–	–
4		38PM – 3 × 12Za with slot pitch 9.75°	271.8	6.52	–	0.36	0.35	–	–
5		38PM – 3 × 12Za without separation tooth	237.5	2.37	–	0.09	0.06	–	–
6		38PM – 6 × 6Za without separation tooth	275.15	5.22	–	0.076	0.062	0.1	–
7		40PM – 6 × 6Za with slot pitch 9.47°	268.0	26.8	–	2.4	9.6	–	–
8		40PM – 6 × 6Za with slot pitch 9.75°	271.14	3.25	–	5.27	0.16	0.08	–

Continued on next page

Table 1 – *Continued from previous page*

No	**Configuration**		**T_{av}[Nm] – average value**		**Coging torque [Nm]**				
			1 h	**6 h**	**2 h**	**6 h**	**12 h**	**14 h**	**18 h**
9		40PM – 6 × 6Za without separation tooth	240.14	1.44	–	0.03	0.06	0.06	1.16
10	FSCW-PMSM	40PM 12 mod. ×3 coils	278.36	3.75	0.5	0.075	0.079	0.01	1.33

Of course, using Eq. (1) is not a prerequisite for achieving successful FSCW-PMSM designs, many of which have been developed based on information found, among others, in [16–19]. However, starting from the structure with separate teeth provides opportunities for a continuous alteration of the pitch of the slot. This is of significant importance, as in the torque generation process of machines with fractional windings, higher harmonics of the excitation field and armature flow are involved to an incomparably greater extent than in traditional electric machine [20, 21].

5. Conclusion

The paper presents the transformation process of a construction known as the TFM into the commonly used FSCW-PMSM. It describes the characteristics that it gained and lost during different stages of transformation.

The arrangement of the TFM winding loops in the slots of a conventional toothed core [9] created the appearance of a new construction that retained the TFM properties while being much simpler to implement. Unfortunately, the high torque density of machines with a transverse field, greater than in most other machines, is primarily due to the independent dimensioning the winding cross section and the absence of end connections. The proposed successive and highly desirable transition from a segmented construction to a common core with winding modules separated by separating teeth results in the entry into the domain occupied by machines with fractional-slot windings that have been in use for over twenty years. The fundamental element of this construction is a pair of differently polarised magnets along with diametrical coils, or coils with a span scarcely different from the pole pitch of the magnets, much like in the proposed designs derived from the TFM. The calculation results demonstrate a relatively minor impact of changing the configuration of these pairs on the generated torque, of course within some logical bounds. So far, these changes have been made "stepwise" guided by information and indications found in the literature. It appears that the presence of teeth separating the modules can, to some extent, "smooth out" these changes in the pursuit of achieving an optimal design.

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