Expansion of the Feasible Slot/Pole Combinations in the Fractional Slot PM Machines by Applying Three-Slot Pitch Coils

Pezhman Jalali, Samad Taghipour Boroujeni, and Javad Khoshtarash

***Abstract*—In this paper, existing feasible slot/pole combinations of the fractional slot permanent magnet (FSPM) machines are extended. In comparison with the existing slot/pole combinations, the proposed ones could result in a higher winding factor, lower torque ripple, and lower cogging torque. This diversity in the number of the slot/pole combinations brings the designers more alternative solutions. To reach such slot/pole combinations three-slot pitch coils are applied. The existing slot/pole combinations are limited to the designs with an integer number of slots per phase in one periodicity of the FSPM machine. In the presented work, FSPM machines with fractional numbers of the slots per phase in one periodicity of the machines are introduced. However, the phase back electromotive force signals are balanced. Moreover, to achieve a slot/pole combination with small unbalance magnetic force (UMF) and low THD value of the armature MMF, the multilayer winding technique is applied. In addition, a simple technique is presented to find an arrangement of the multilayer winding with very small UMF. Extensive finite element simulations are used to compare the FSPM machines with the proposed slot/pole combinations with the traditional FSPM machines.**

***Index Terms*—Fractional slot, harmonic content, multi-layer winding, permanent magnet machine, torque ripple, unbalanced magnetic force.**

I. Introduction

INTEREST in applying Fractional Slot Permanent Magnet (FSPM) machines is increasing day by day. They are used in many applications due to their simple winding, high-efficiency and low cogging torque [1]. The main drawback of the FSPM machines is the harmonic content of the armature Magneto-Motive Force (MMF) which results in undesired effects such as the eddy current PM loss and the torque pulsation [2]. In addition, depends on the slot/pole combination of the FSPM machines, Unbalance Magnetic Force (UMF) could result. The produced torque ripple and UMF cause vibration and noise [3]. The torque ripple is due to the machine cogging torque and the interaction of the PMs with harmonic components of the armature reaction field. The influence of the number of the slot/pole on the cogging torque of the PM machine is investigated in [4] by introducing a goodness factor. It is shown that having a low value of least common multiple between the number of poles and slots will result in a very low cogging torque [5]. However, all slot/pole combinations are not recognized as feasible combinations in the FSPM machines. In the feasible slot/pole combinations, there is an integer number of slots per phase in one periodicity of the machine [6]. In the other words, the slot/pole combination of the FSPM machine is selected such that simultaneously having very small torque ripple and providing feasible winding configuration. So the previously presented literature for the FSPM machines mainly focused on the machines with specific slot/pole combinations and try to reduce the torque ripple component due to the harmonic content of the armature reaction field [7]–[13]. In these papers, variant techniques are proposed to reduce the harmonic content of the armature MMF in the FSPM machines. Applying Magnetic Flux Barrier (MFB) in the stator yoke [7], and using ingenious schemes for the armature winding are the main solutions for reducing the harmonic content of armature MMF in FSPM machines. Applying MFB in the stator is not a straightforward solution. On the other hand, applying a proper winding scheme is an appropriate and low-cost solution to improve the performance of the FSPM machines. Multilayer windings [8], [9], two-set of armature windings [10], [11], and winding with different turn number per coil [12] are well-known examples of the ingenious winding schemes in the FSPM machines.

The slot/pole combination of the FSPM is extended by introducing two-slot pitch windings [2]–[13]. In this method, the number of the poles is kept constant while the number of the slots is doubled for the FSPM machines with Ns $= 2p \pm 1$ [2] and Ns $= 2p \pm 2$ [13], where N_s and p are the number of slots and pole pairs, respectively. However, the proposed slot/pole combinations in [13] are used only for reducing the harmonic content of the armature reaction field and the machine UMF. Studying the impact of the slot/pole combination on the machine cogging torque and the torque ripple is not considered in [2], [7]– [13].

The previously proposed winding topologies are limited to the machines with an integral number of slots per phase in one periodicity of the machine. In the other words, to have a balanced condition the assigned slots to different phases in

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one periodicity of the machine must be equal together. Therefore, some slot/pole combinations are not accepted as feasible configurations in FSPM machines, e.g., there are no machines with 33/12 or 39/12 slot/pole combination. The feasibly recognized slot/pole combinations for 12-pole machine, i.e., 9/12 and 18/12 slot/pole combinations, result in a low winding factor ($k_w = 0.866$) [13].

In this paper, feasible slot/pole combinations are extended to include the schemes with fractional slots per phase in one periodicity of the machine. The approach is applied to the 12-pole FSPM machine as a case study. It is shown that one of the proposed slot/pole combinations result in a lower cogging torque, lower torque ripple and better THD of the armature MMF. However, the proposed slot/pole combination causes very small UMF. Therefore, the winding layout is optimized to reach the minimum possible value of the UMF. For this purpose, the multilayer winding solution is applied and a simple technique is used to find an arrangement of the multi-layer winding with the minimum possible value of UMF without carrying out FEA. In addition, adopting multilayer windings, the sub-harmonics of the armature MMF is decreased and its THD is improved more. Extensive finite element simulations are used to compare the FSPM machines with the proposed slot/pole combinations with the traditional FSPM machines.

II. Slot/Pole Combinations of FSPM Machines

A. A Brief Review of the Existing Slot/Pole Combinations

Feasible slot/pole combinations are reported in [6]–[13]. A feasible winding is such a winding that provides a balanced 3-phase back-emf. Proposed slot/pole combinations for the FSPM machines include $q = 0.25$, $q = 0.5$, $N_s = 2p \pm 1$ and $N_s = 2p \pm 2$, where, q is the number of slots per pole per phase. In addition, adopting two-slot pitch coils, combinations of $N_s = 2(2p \pm 1)$ and $N_s = 2(2p \pm 2)$ are introduced as possible designs [13].

It is known that in the FSPM machines with the periodicity greater than 1, the cogging torque is high. Although in the machines with one periodicity, the cogging torque is very small, but there is a significant UMF. Although the FSPM machines with q = 0.5 have no UMF, their winding factor is low and the cogging torque is high. The machines with $N_s = 2(2p \pm 1)$ have a great winding factor. Since the periodicity of these machines is 1, the cogging torque is small but the machine UMF is not zero. In the machines with $N_s = 2(2p \pm 2)$, the machine periodicity is greater than 1 and consequently the machine UMF is zero. However, the machines cogging torque is small in these machines. All previously presented FSPM machines have an integral number of slots per phase in one periodicity of the machine.

B. The Proposed Slot/Pole Combinations

The machine periodicity is defined as the Greatest Common Divisor of the slot number and the pole pairs, i.e., $t = \mathrm{GCD}(N_s, p)$ [14]. In the proposed slot/pole combinations, it is not necessary

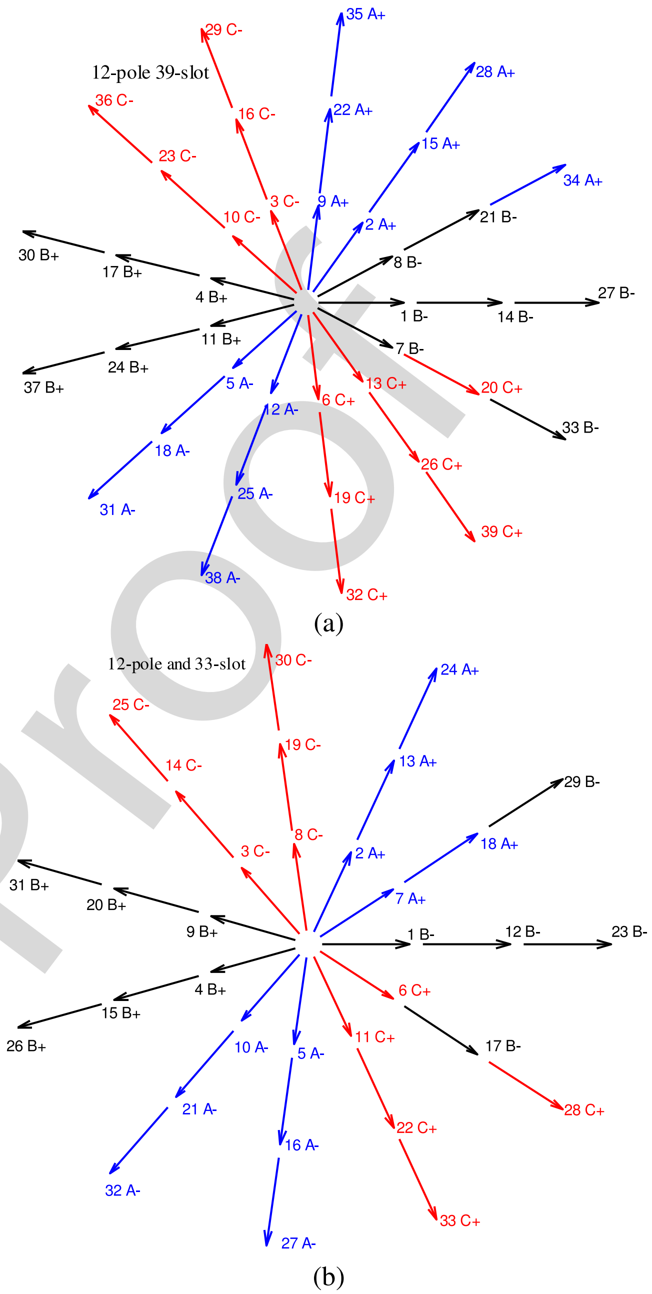
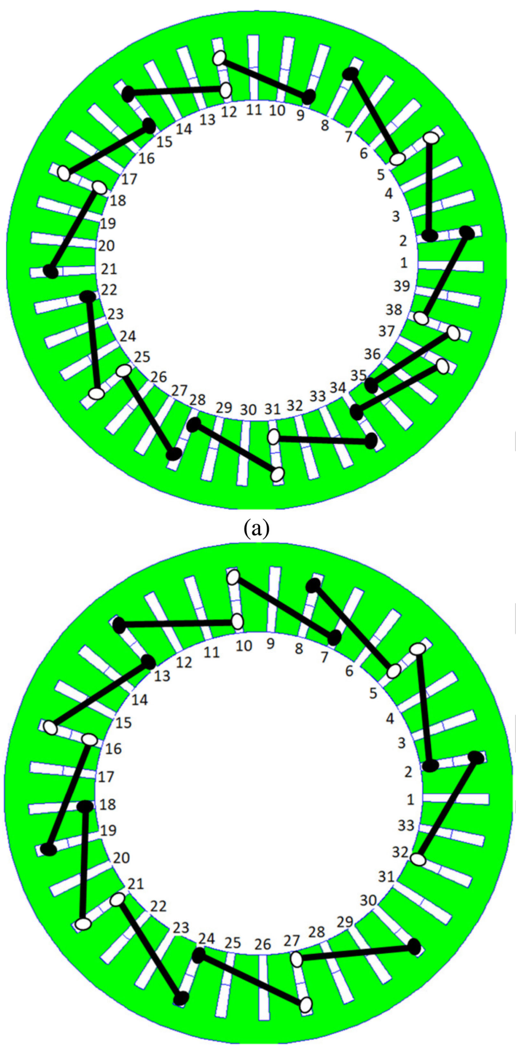


Fig. 1. The star-of-slot for the proposed machines with slot/pole combinations 39/12 (a) and 33/12 (b).

to have an integer number of slots per phase in one periodicity of the FSPM machine. However, the machine periodicity must be a multiplier of the number of the phases and the windings with the pitch coil equal or more than two slots must be adopted. The slot/pole combinations such as 21/6, 21/12, 33/12, 39/12, 33/18, 39/18, are examples which are not recognized as the possible combinations in the previous literature. Hereafter, the machines with 33/12 and 39/12 slot/pole combinations are investigated. The periodicity of these machines is 3 and their slot/phase/periodicity are respectively 13/3 and 11/3. The start-of-slot diagrams of these machines are shown in Fig. 1(a)

TABLE I
THE COILS CONNECTION IN THE PROPOSED MACHINES WITH SLOT/POLE COMBINATIONS 39/12 AND 33/12

39-slot/12-pole			
	Coils with positive connection	Coils with negative connection	Back-emf (pu)
Phase A	2,9,15,22,28,34,35	5,12,18,25,31,38	1<240.6^{0}
Phase B	4,11,17,24,30, 37	1, 7,8, 14,21,27,33	0.9972<0^{o}
Phase C	6,13,19,20,26,32,39	3,10,16,23,29,36	1<120.3^{o}
33-slot/12-pole			
Phase A	2,7,13,18,24	5,10,16,21,27,32	1<239.54^{o}
Phase B	4,9,15,20,26,31	1,12,17,23,29	0.9947<0^{o}
Phase C	6,11,22,28,33	3,8,14,19,25,30	1<119.1^{o}



(a)

(b)

Fig. 2. The star-of-slot for the proposed machines with slot/pole combinations 39/12 (a) and 33/12 (b).

and (b). All coils of one phase have to be connected in series. The coils' connection layouts are obtained by using the slot-of-slot theory and given in Table I. The winding connection of phase A in the considered machines is shown in Fig. 2. It should be noted that these winding layouts include three-slot pitch coils. Since $t = 3$ in the considered machines, there are three layers of phasors in the star-of-slot diagrams. For example in the 39-slot and 12-pole machine, the first periodicity includes the coils 1–13, the second periodicity contains the coils 14–26 and the last one comprises the coils 27–33. As seen in Fig. 1(a) in each periodicity there is an unbalanced condition among the phases. However, this unbalance condition is transposed among the phases in all machine periodicities. Since the coils of one phase are connected in series, a balance condition yields in the proposed of machines. A complete description of using the star-of-slot and the coil assigning is given in the Appendix.

TABLE II
THE 12-POLE FSPM MACHINES PARAMETERS AND DATA

Slot	9	18	27	33	39
Stator external radius (mm)	240	240	240	240	240
Stator bore (mm)	77.3	77.3	77.3	77.3	77.3
Rotor outer radius (mm)	76.5	76.5	76.5	76.5	76.5
PM thickness (mm)	9	9	9	9	9
PM remanence (T)	1.07	1.07	1.07	1.07	1.07
PM arc to the pole arc ratio	0.76	0.76	0.76	0.76	0.76
Air gap length (mm)	0.8	0.8	0.8	0.8	0.8
Stack length (mm)	50	50	50	50	50
Slot opening (mm)	3.8	3.8	3.8	3.8	3.8
Tern number per phase	54	54	54	55	52
Nominal MMF (Amper.Turn)	500	500	500	500	500

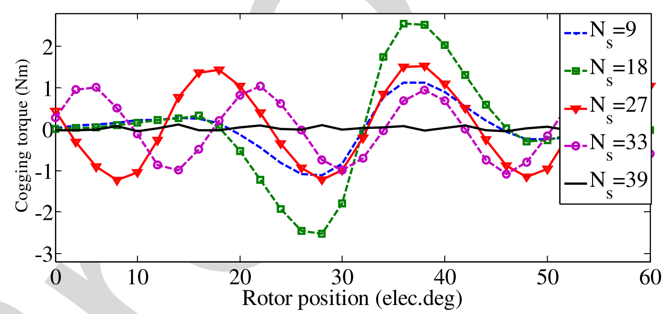


Fig. 3. Cogging torque of the considered 12-pole FSPM machine.

The per-unit back-emf and winding factor of the studied machines are computed by (1) and (2), respectively, and given in Table I.

$$e = \frac{v_c}{V_{base}} \sum_{i=1}^{N} e^{j\alpha_i p} \tag{1}$$

$$k_w = \frac{1}{2N} \left| \sum_{i=1}^{N} \left(e^{jp(\alpha_i - \frac{\gamma_{ci}}{2})} - e^{jp(\alpha_i + \frac{\gamma_{ci}}{2})} \right) \right| \tag{2}$$

where, N is the number of the coils per phase, α_i and γ_{ci} are the angle of the magnetic axis and the pitch angle of the i^{th} coil of phase *x*, respectively, v_c is the back-emf of the first coil of phase *x*, and V_{base} is the base voltage. Since the distribution of the coils in the phases is not completely symmetrical as exists in the integral-slot and traditional fractional slot machine, there is a negligible imbalance condition in the machine back-emf in Table I.

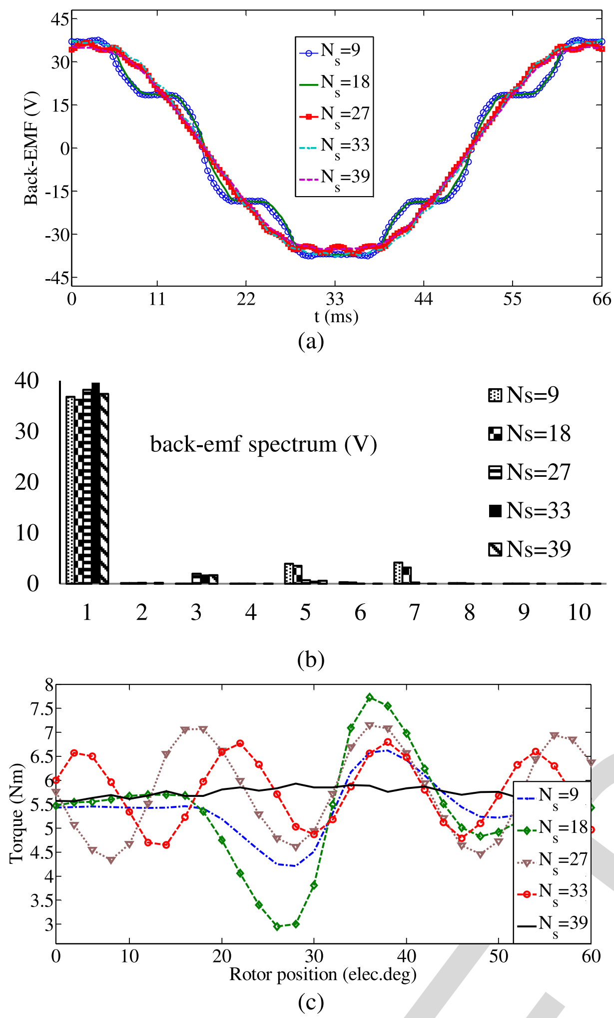


Fig. 4. The machines back-emf waveform (a) and spectrum (b) and the synchronized electromagnetic torque for the 12-pole FSPM machines with nominal electrical loading, at the rotor speed of 900 rpm.

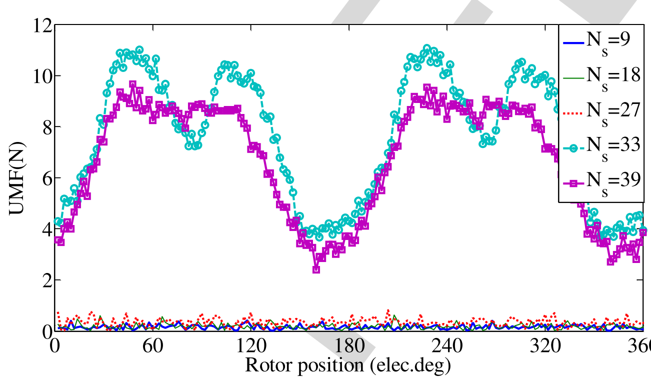


Fig. 5. The produced UMF of the 12-pole FSPM machines for the reported electrical loading with synchronous currents.

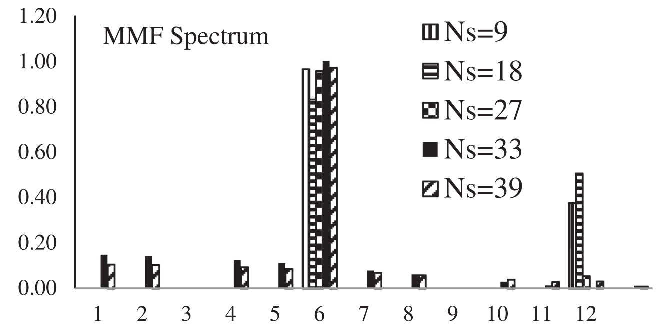


Fig. 6. Harmonic spectrum of the normalized magnetomotive force in the considered 12-pole FSPM machines.

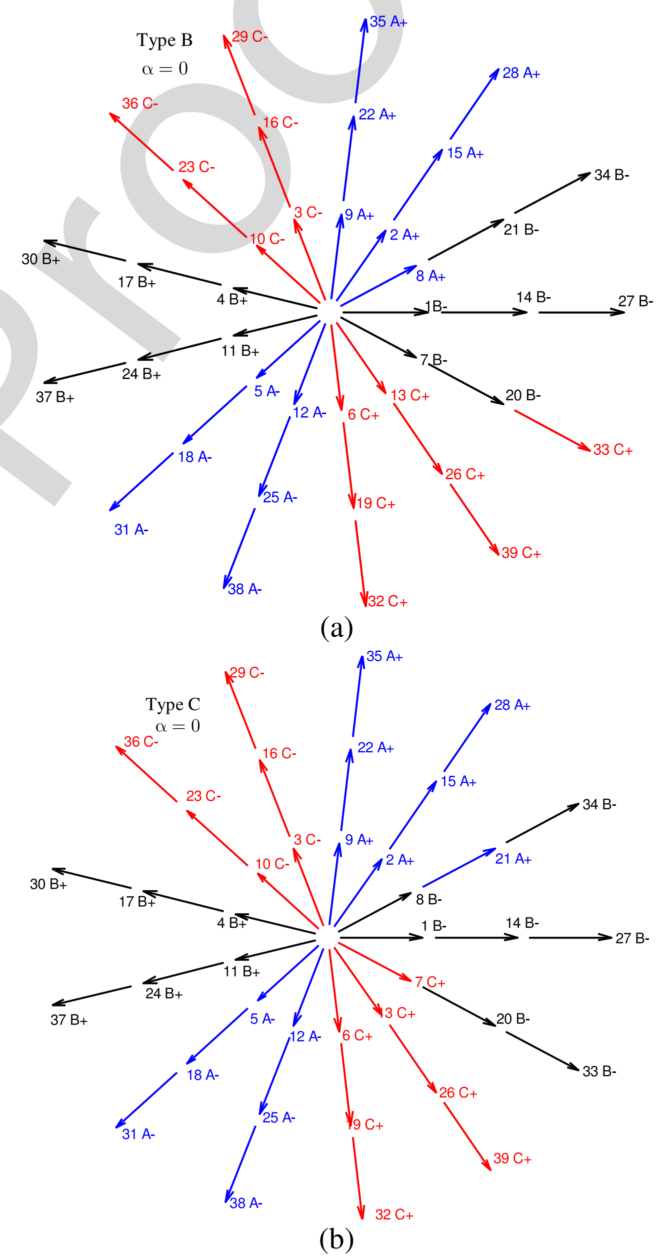


Fig. 7. The star-of-slot for second set of three-phase winding in the 4-layer FSPM machine with slot/pole combinations 39/12 (a) and 33/12 (b).

III. Performance of the Proposed Machines

In this section, the performance of the proposed 12-pole FSPM machines is compared with the existing FSPM machines with a similar number of poles. The winding schemes with one-, two- and three-slot pitch coils are considered. FSPM machines

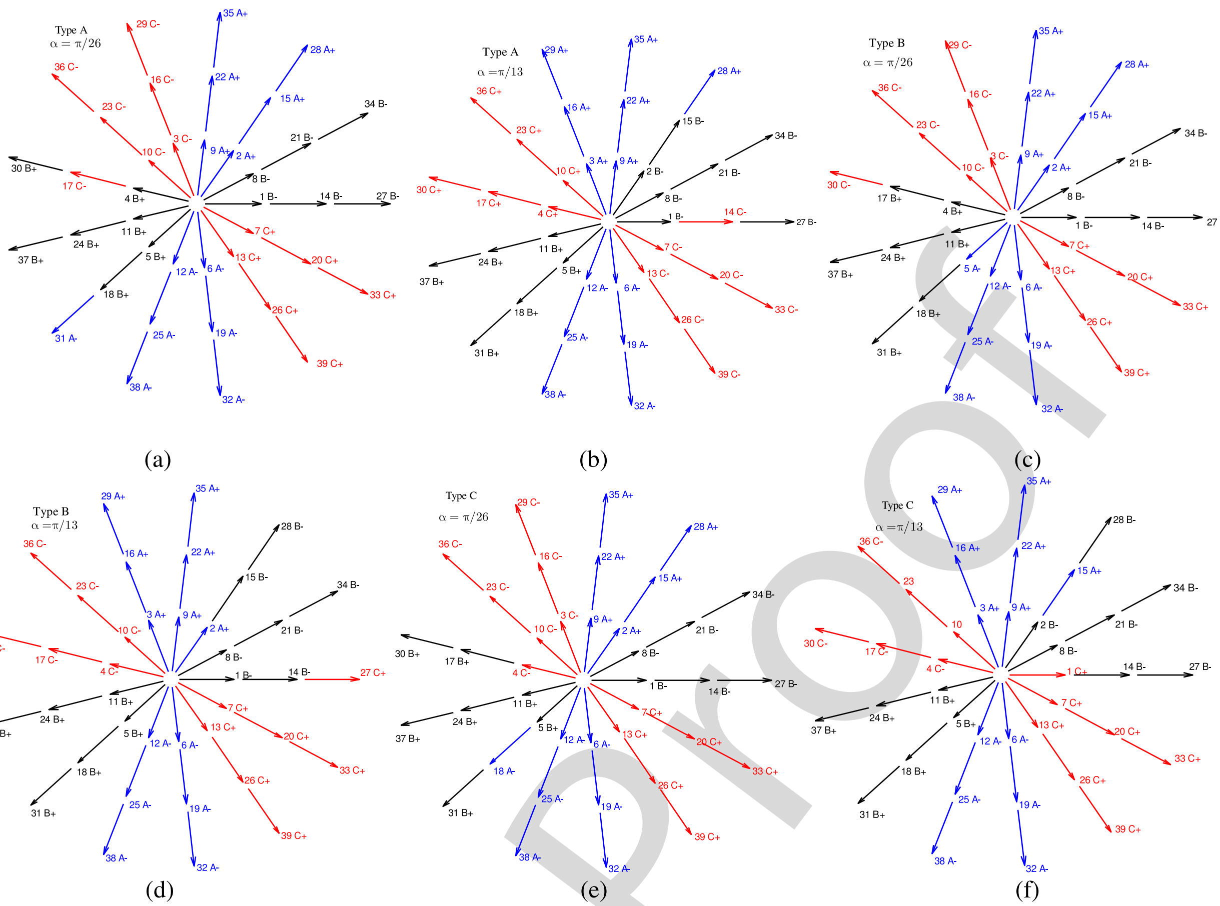


Fig. 8. The 4-laye candidate winding schemes for 12-pole 39-slot FSPM machine.

with 33- and 39-slots and 12-pole are the proposed three-slot pitch coils which are not recognized as the feasible winding schemes. They are compared with the existing 12-pole FSPM machines; i.e., machines with 9, 18 and 27 numbers of slots. The coil pitch of these machines is one-, two- and three-slot, respectively. In this study, some variables such as the harmonic content of the machine back-emf, electromagnetic torque, cogging torque and the machine UMF are investigated. These variables are obtained using extensive FEA. To have a correct comparison the main design parameters of the considered machines such as the stack length, the stator bore, the air gap length, the rotor geometry, the slot opening, type of the PMs and the electrical loading of the machines are considered same as together. The machine parameters and specifications are reported in Table II. Definitely the rotor structure affects the performance of the machines. However the topic of this study is the influence of the stator winding and the slots, so the rotor structures in all machines are same.

Cogging torque of the considered machines is illustrated in Fig. 3. Although all of the considered FSPM machines have the same periodicity, GCD$(N_s, p) = 3$, the cogging torque of the FSPM machine with 39 slots is considerably lower than the other machines.

The waveform and spectrum of the machines back-emf at the rotor speed of 900 rpm are given in Fig. 4(a) and (b), respectively. In the other test, the machines are excited with the synchronized nominal electrical loading (see Table II) and the electromagnetic torque is computed by FEA and shown in Fig. 4(c). Very low torque ripple and good average torque in the 39-slot FSPM machine is observable.

The resultant UMF of the 12-pole FSPM machines at 900 rpm rotor speed for the reported electrical loading in Table II with AC synchronous currents is shown in Fig. 5. Although the GCD of the machines with 39 and 33 slots is greater than one, against the existing machines there is non-zero UMF. However, the UMF value is very low. The normalized MMF spectrum of the considered 12-pole machines is shown in Fig. 6. As seen in Fig. 5 the MMF of the proposed machines ($N_s = 33$ and 39) includes some content of sub-harmonics. To minimize the UMF of the FSPM machine with 39-number of slots, 4-layer winding is adopted. Applying a 4-layer winding scheme is discussed hereafter.

IV. Winding Optimization

From Figs. 3–6, it is obvious that the proposed two-layer 39-slot FSPM machine with three-slot pitch coils is the best 12-pole machine. The small amount of UMF in the 39-slot/12-pole machine is the result of having diametrical asymmetry in the distribution of the phases' coils. To reduce the produced

TABLE III
SYMMETRY INDEX AND WINDING FACTOR OF DIFFERENT 4-LAYER WINDINGS FOR FSPM MACHINE 39 SLOTS AND 12 POLES

Number of the spoke shifts	sequence of the phases' Coil					
	Fig.1 (a)(Type A)		Fig.6 (a)(Type B)		Fig.6 (b)(Type C)	
1 (α=0)	S	5.7147	S	2.8573	S	2.8573
	k_w	0.9462	k_w	0.9462	k_w	0.9462
2 (α=2π/26)	S	5.5487	S	3.9587	S	1.5899
	k_w	0.9462	k_w	0.9462	k_w	0.9462
3 (α=2π/13)	S	5.0601	S	4.8300	S	0.2301
	k_w	0.9187	k_w	0.9187	k_w	0.9187

UMF in the 39-slot/12-pole machine, 4-layer winding scheme (two sets of two-layer three-phase windings) is applied. However, different 4-layer winding schemes are possible to apply. In these schemes, up to two-spoke shifts ($\alpha = 2\pi/13$ and $\alpha = 2\pi/26$ mech. deg) are considered between the first and second sets three-phase windings. More shift angles are not considered because the winding factor decreases very much. In addition, there are three possible sequences for the phases' coils in three periodicities of the machine as shown in Fig. 1(a) and Fig. 7(a) and (b). Therefore, there are nine different 4-layer winding candidates as shown in Fig. 1(a), Fig. 7 and Fig. 8. To provide a winding scheme with the lowest UMF a mechanical symmetry index is defined as (3). In fact, the symmetry index shows the symmetry in the mechanical distribution of one phase coils. The computed symmetry indexes for these nine 4-layer possible windings as well as their winding factors are reported in Table III.

$$S = \left| \sum_{i=1}^{N} e^{j\alpha_i} \right| \tag{3}$$

From the reported results in Table III, it is expected that applying the winding with three-slot shift ($\alpha = 2\pi/12$) and start-of-spoke of Fig. 7(b) (Type C) as the second set of three-phase winding is the best scheme and will result in the lowest UMF. The machine back-emf waveform and its spectrum, and the synchronized electromagnetic torque of this four-layer winding machine with 39 slots at the rotor speed of 900 rpm are illustrated in Fig. 9(a)–(c), respectively.

The UMF of the 4- and 2- layer winding machines at 900 rpm rotor speed for the reported electrical loading in Table II with AC synchronous currents is shown in Fig. 10. The normalized MMF spectrum of 4- and 2- layer winding machines with 12 poles and 39 slots are shown and compared together in Fig. 11.

Although there is a negligible reduction in the back-emf and electromagnetic torque of the 4-layer winding machine (Fig. 9(b) and (c)), the machine UMF and MMF sub-harmonics of the 4-layer winding machine are also decreased.

Finally, the THD of the stator MMF, winding factor, average torque and the torque ripple of the existing and the proposed 12-pole FSPM machines are computed by FEA and reported in Table IV. It is obvious that there is a significant improvement in the winding factor, THD and the torque ripple of the 12-pole FSPM machine by using the proposed winding scheme, i.e., applying 39 slots with three-slot pitch coils.

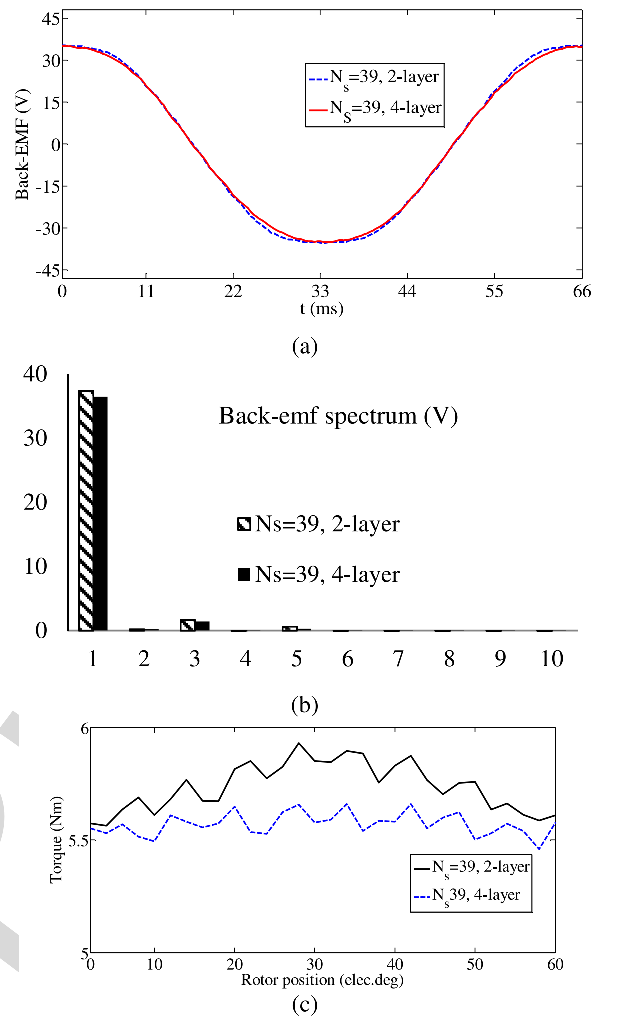


Fig. 9. The back-emf waveform (a), spectrum (b), and synchronized electromagnetic torque (c) for the 2- and 4-layer winding FSPM machines with 39-slot/12-pole machine at 900 rpm.

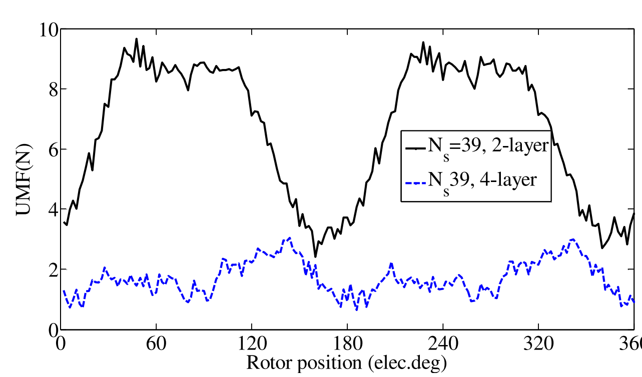


Fig. 10. UMF of the 2- and 4-layer winding FSPM machines with for the reported electrical loading with synchronous currents.

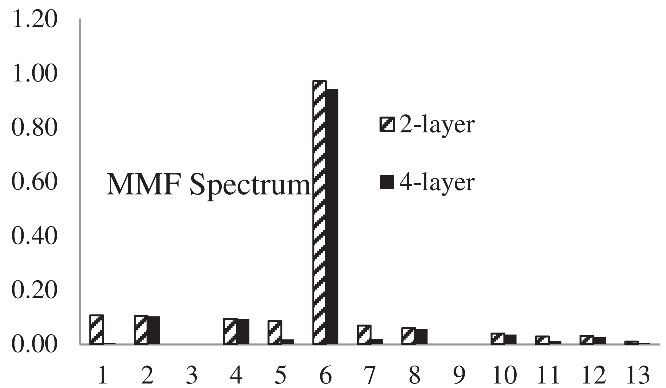


Fig. 11. Harmonic spectrum of the magnetomotive force in the 12-pole 39-slot FSPM machines.

TABLE IV
PERFORMANCE OF THE 12-POLE FSPM MACHINES WITH EXISTING AND PROPOSED SLOT/POLE COMBINATIONS

N_s	Coil pitch	No. of layers	k_w	Torque Average (N.m)	Torque Ripple (N.m)	THD of back-emf (%)	THD of MMF (%)
9	1-slot	2	0.866	5.40	0.50	15.8	16.9
18	2-slot	2	0.866	5.33	0.90	13.4	23
27	3-slot	2	0.945	5.76	0.49	6	28.5
33	3-slot	2	0.942	5.71	0.40	5	57
39	3-slot	2	0.946	5.73	0.07	4.9	60.9
39	3-slot	4	0.918	5.56	0.048	3.9	39

V. CONCLUSION

In this paper, the existing slot/pole combinations for FSPM machines are extended. The only requirement of the new proposed slot/pole combinations is that the machine periodicity is as a multiplier of the machine phases. In these slot/pole combinations, there is a fractional number of slots per phase in one periodicity of the machine. Two FSPM machines with 33/12 and 39/12 slot/pole combinations with three-slot pitch coils are studied as examples. They are compared with the existing one-, two and three-slot pitch windings. In addition, to reduce the MMF sub-harmonics and the machine UMF 4-layer windings are applied. To find the best 4-layer winding scheme without carrying out FEA, a symmetry index is defined and used to find the winding scheme with minimum UMF. Applying FEA, it is shown that the proposed winding scheme results in a higher winding factor, lower THD in the stator MMF and back-emf, and lower cogging torque and torque ripple.

APPENDIX

To assign the stator coils to the phases and find the right connection for the coils the machine star-of-slot is used. Hereafter, the used approach is described for the 33-slot 12-pole machine. The periodicity of this machine is 3 and there are three layers of the phasors in the star-of-slot diagram in Fig. 1(b). Each periodicity includes 11 coils. The first periodicity includes the coils 1–11, the second periodicity contains the coils 12–22 and the last one comprises the coils 23–33. Therefore, the number of the coils per phase in one periodicity is not an integer number. In other words, in each periodicity, one phase must compromise 3 coils while each of the other phases includes 4 coils ($3 + 4 + 4 = 11$). Applying the well-known two 60-degree Opposite Sectors (60OSs) [14] on the first periodicity of the machine, four coils are assigned to the phases A and C (two coils with positive and two other coil with negative connection), and 3 coils (two coils with positive and one coil with negative connection) are given to the phase B. To provide a balanced condition, in the second periodicity of the machine the 60OSs are shifted such that 3 coils are assigned to another phase (phase C) and the phase A and B include 4 coils. Finally, in the last machine periodicity, again the 60OSs are shifted such that 3 coils are assigned to the remained phase (phase A) and the phase B and C include 4 coils. In other words, the 60OSs are selected in each periodicity such that the unbalanced condition is transposed among the phases in all machine periodicities.

As described in the paper, to provide a balance condition there are some possible shifts for 60OSs. However, the amount of the shifts must be as small as possible to avoid the significant reduction in the machine winding factor.

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