

Three phase tooth-concentrated multiple-layer fractional windings with low space harmonic content

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Abstract --The possibility of obtaining lower space harmonic content for the fractional-slot, tooth-concentrated windings by multiplying the number of coils, leading to bigger number of layers in the armature slots is presented. By using multiple layer windings it is possible to reduce or even to cancel some space sub-harmonics having as final result lower eddy current losses induced by the armature reaction in the iron structure of the rotor. The general method of doubling (or trebling) the winding and relatively shifting by one (or more) slots is presented in the paper. Two examples of three phase concentrated windings are presented and analyzed as primitive windings, 12 slots/10poles and 9 slots/8 poles. In the first case the only existing space sub-harmonic is reduced firstly from 35.9% (from fundamental wave) to 9.6% and finally it is canceled by using different number of turns per coils. In the second case the two existing sub-harmonics are reduced and balanced by using the developed method.

Index Terms— interspersed windings, magnetomotive force, permanent magnet synchronous machines, space harmonics.

I. INTRODUCTION

Fractional three-phase permanent magnet (PM) synchronous machines are becoming more and more attractive solutions for low speed, high torque applications for domestic appliances, automotive, aerospace or wind power generation. However, it is known that these windings, due to the low number of slots/pole/phase, are characterized by high magnetomotive force (mmf) space harmonic content. The lower order mmf space harmonics of the armature reaction, rotating not synchronous to the rotor, have a negative effect because of the induced eddy currents and correspondingly losses in the surface mounted PMs and iron structure of the rotor.

There have been many papers in the last decade devoted to performance analysis or synthesis of the fractional concentrated windings [1-4]. The best combination of number of stator slots (Z) and total number of poles ($2p$) have been found and used in order to obtain higher value of the fundamental winding factor, lower cogging torque and sinusoidal back emf [4-6]. The number of winding layers was investigated [7, 8] and it was concluded that for lower space harmonic content it is compulsory to avoid single layer windings (“all-teeth wound” instead of single layer).

In the Nakano’s papers [9, 10] the eddy current losses induced in the rotor structure by the armature reaction mmf space harmonics are deeply investigated in time and space. It is shown that the distribution of the rotor eddy-current density is different depending on the armature space harmonics as amplitude and speed of rotation.

However *there have been no papers so far investigating tooth-concentrated windings with more than two layers*, except for the paper of Di Gerlando et al [11] and the recent patents of Kometani et al [12] and Ito et al [13]. The technical solution developed in the Ito’s patent [13] is essentially based on doubling the two-layer winding in the 12 slots/10 poles configuration and shifting the two halves of winding by one slot. In this way the fundamental winding factor is reduced by 3.4% but some space harmonics can be reduced or even canceled.

Two basic types of tooth concentrated windings wound in more than two-layers are investigated in the paper. First, the principle of method is demonstrated for 12 slots/10 poles winding. Starting from single layer configuration, the double layer winding is developed and after that, by doubling again and shifting, the four-layer winding is developed. Finally, by merging together some coils, the three layer winding is obtained having the first (mechanical) space harmonic canceled. The second analyzed winding in the paper is based on 9 slots/8 poles primitive configuration. Again, the four layers winding is developed starting from the double layer configuration and finally the three or four layer winding is

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obtained having the main sub-harmonics balanced and strongly diminished.

II. ARMATURE REACTION MMF ANALYSIS.

The tooth concentrated windings can be analyzed by classical methods (star of the slots, star of the coils) irrespective of the number of layers. The method used in the paper is an analytical one, equivalent to the star of the slot method for any space harmonic order. The method allows for calculation the harmonic winding factors k_{wv} , the amplitude of the space harmonics and the differential leakage coefficient τ_d .

If the geometrical space angle of the slot “k” is θ_k and it contains N_{ck} conductors of phase A, w is the total number of turns per phase, c is the number of parallel path, k_{wv} the v-order phase winding factor and φ_{vA} the space angle of the v-order space harmonic, the general equations of the winding distribution are:

$$2cwk_{wvA} = \sqrt{\left(\sum_{k \in \{K_A\}} N_{ck} \cos v\theta_k \right)^2 + \left(\sum_{k \in \{K_A\}} N_{ck} \sin v\theta_k \right)^2}; \quad (1)$$

$$\varphi_{vA} = \frac{1}{v} \operatorname{arctg} \frac{\sum_{k \in \{K_A\}} N_{ck} \sin v\theta_k}{\sum_{k \in \{K_A\}} N_{ck} \cos v\theta_k}$$

The set of the armature’s slots containing conductors of phase A was noted by K_A . The number of conductors N_{ck} is including the sign (\pm) depending on the current sense in the respective slot. Taking into account that generally the currents of the three phase machines are time delayed by $2\pi/3$ the resulting air gap mmf can be written as:

$$F_{rez}(\theta, t) = \frac{3wI\sqrt{2}}{\pi} \sum_{v=1}^{\infty} \left[\frac{k_{wdv}}{v} \sin(v\theta - \omega t) + \frac{k_{wiv}}{v} \sin(v\theta + \omega t) \right] \quad (2)$$

where the CW, CCW winding factors are:

$$k_{wdv} = \frac{2}{3} \sqrt{C_{1v}^2 + C_{2v}^2}; \quad k_{wiv} = \frac{2}{3} \sqrt{D_{1v}^2 + D_{2v}^2}$$

$$C_{1v} = \frac{1}{2} [k_{wAv} \cos \varphi_{vA} + k_{wBv} \cos(\varphi_{vB} + \frac{2\pi}{3}) + k_{wCv} \cos(\varphi_{vC} - \frac{2\pi}{3})]; \quad (3)$$

$$C_{2v} = -\frac{1}{2} [k_{wAv} \sin \varphi_{vA} + k_{wBv} \sin(\varphi_{vB} + \frac{2\pi}{3}) + k_{wCv} \sin(\varphi_{vC} - \frac{2\pi}{3})]$$

$$D_{1v} = \frac{1}{2} [k_{wAv} \cos \varphi_{vA} + k_{wBv} \cos(\varphi_{vB} - \frac{2\pi}{3}) + k_{wCv} \cos(\varphi_{vC} + \frac{2\pi}{3})];$$

$$D_{2v} = -\frac{1}{2} [k_{wAv} \sin \varphi_{vA} + k_{wBv} \sin(\varphi_{vB} - \frac{2\pi}{3}) + k_{wCv} \sin(\varphi_{vC} + \frac{2\pi}{3})]$$

The amplitudes of the magnetic waves calculated by (2) and (3) are calibrated by the factors 2/3 in order to be comparable by the phase mmf winding factors. The essential assumption for the previous equation is that the system of the phase currents keeps on being symmetric despite the spatially unbalanced distribution of the phase conductors, if any.

A remarkable property of the three phase windings is the differential reactance coefficient (τ_d). It synthetically characterizes the space harmonic content of the air gap mmf.

A general method of calculation the τ_d for pure waves is given by Heller and Hamata [16] starting from the magnetic energy stored in the air gap. In the most general case some space harmonics could be un-pure waves, it means the CW and the CCW component could coexist. In the paper this coefficient is defined as having two components, the first is time-constant (τ_{dC}) and can be calculated exactly as in the literature, the second is time-dependent (τ_{dV}) and its magnitude can characterize the degree of spatial unbalance of the winding:

$$\tau_d = \left(\frac{P}{k_{wp}} \right)^2 \sum_{v \neq p} \left[\left(\frac{k_{wdv}}{v} \right)^2 + \left(\frac{k_{wiv}}{v} \right)^2 + 2 \frac{k_{wdv} k_{wiv}}{v^2} \cos 2\omega t \right] = \quad (4)$$

$$= \tau_{dC} + \tau_{dV} \cos 2\omega t$$

In the paper, as the studied windings are balanced, the coefficient τ_{dC} is used as an important criteria of the design.

III. EXAMPLES OF APPLICATION

A. Primitive winding with $Z=12$ slots, $2p=10$ poles.

The main (fundamental) space harmonic has the order $v=5$ and, due to the uniform slotting, there will always exist the $Z \neq p$ order space harmonics having the same winding factors, it means that it is impossible to cancel the space harmonics of order $v=7$ and $v=17$. These mmfs harmonics will have the amplitude always diminished in the ratio 5/7 (CCW) and 5/17 (CW), respectively. However, even if all the even-order space harmonics are zero, usually there will be the odd space harmonics of orders $v=1$ (sub-harmonic), $v=11$ and $v=13$, having, due to the known periodicity, the same winding factor. The most annoying is the first space harmonic because of its higher relative speed in respect to the rotor. The frequencies of the eddy currents induced in the rotor are 60 Hz and 120 Hz for the $v=1$ and $v=7$ space harmonics, respectively, supposing that the stator base frequency is 50 Hz [6].

In fig.1-a the winding diagram for single layer configuration is presented. Only one phase (A-X) is shown, the other phases are correspondingly space shifted by 8 slots. In fig. 1-b the double layer winding is presented as it is much known from the literature [2, 3, 6]. It is to be observed that the double layer winding can be obtained from the single layer diagram by doubling the first with half number of turns per coil and shifting by 5 geometrical slots (one electrical slot). Symbolically, if WDG_{σ} is the winding diagram for σ number of layers, the following equation is valid:

$$WDG_2 = WDG_1(0) + WDG_1(+5) \quad (5)$$

The final step in order to make improvements is to double again the double-layer winding and to shift with another 5 geometrical slots, as it can be observed in fig. 1-c. The new winding is a pure 4-layers one. Symbolically the following equation is valid:

$$WDG_4 = WDG_2(0) + WDG_2(+5) \quad (6)$$

As the two coils from the central part of the group, wound for example around the teeth T1 and T7 (fig. 1-c) have the same number of turns, they can be considered as a single coil, so if the coils wound around the teeth T12, T2, T6 and T8 have w turns, the “central coil” wound around the tooth T1 and T7 will have $W=2w$ turns.

In table I the winding factors, calculated using the analytical method from section 2, are presented. It is clear that the single layer winding will never be used in practical machines because of its very high first-order space harmonic. In fact, the winding in fig. 1-a, is mainly a two-pole winding with much shortened pitch and only subsequently a ten-pole, very dirty winding. However, it was introduced in the paper only for explaining the steps to obtain the higher performance, multiple layer windings. One can see that in the four layer winding (fig. 1-c with $W=2w$) the first space harmonic becomes smaller (9.6% from fundamental instead of 35.9% in case of double layer winding). The price to be paid is a little bit lower fundamental factor (0.9012 instead of 0.933).

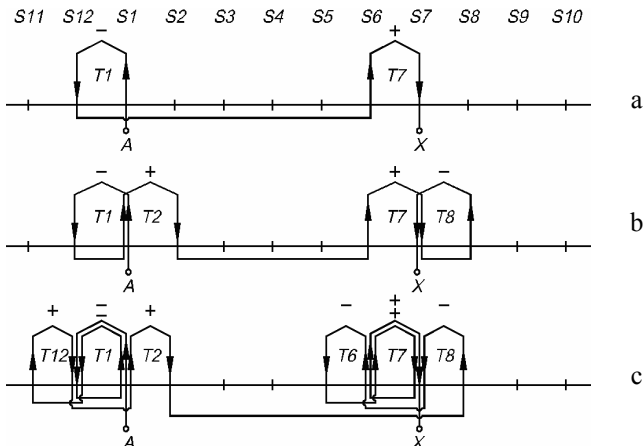


Fig. 1. Winding diagrams for 12 slots/10 poles (only one phase is represented). Single layer (a), double layer (b), four-layer winding (c).

Another improvement can be obtained if the “central coil”, wound around teeth T1 (T7) has the number of turns, only $W=w\sqrt{3}$ instead of $W=2w$. In the last column of table I one can see that in this case all the space harmonics are canceled except for those having the space order $Z \neq p$ (5, 7, 17, ...). The explanation of the special ratio between the number of turns of “central” coil and “marginal” coils results from fig. 2 where the star of the coils is presented for the main space harmonic $v=5$ (left) and main sub-harmonic $v=1$ (right). The electric angles between the two adjacent teeth are 150° in the first case and 30° in the second case. As it can be observed from the fig. 2 the winding factors k_{wv} can be expressed depending on pitch factors k_{y_v} and distribution factors k_{q_v} as:

$$k_{w5} = k_{y5} \times k_{q5} = \sin 75^\circ \times \frac{W + 2w \cos 30^\circ}{W + 2w} \quad (7)$$

$$k_{w1} = k_{y1} \times k_{q1} = \sin 15^\circ \times \frac{W - 2w \cos 30^\circ}{W + 2w}$$

From the second eq. (7) it results the necessary relation between the number of turns W and w ($W=w\sqrt{3}$) for canceling the first order space harmonic. For this ratio, from the first eq. (7) the main space harmonic will become 0.8966 as it was calculated in table I, last column.

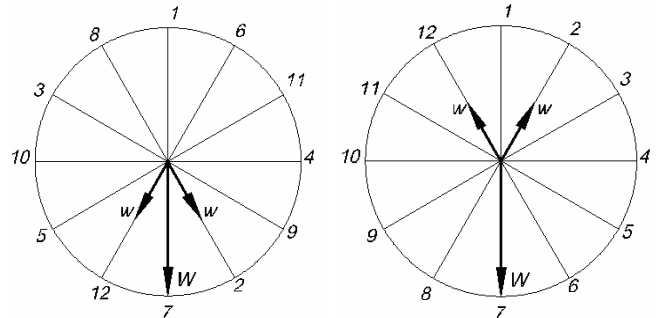


Fig. 2. Star of the coils for $v=5$ (fundamental, left) and $v=1$ (sub-harmonic, right) for winding in fig. 1-c.

In fig. 3 the 12 slots arrangement is presented with the first layer of “central coils” with $W=2w$ (or $W=w\sqrt{3}$) turns wound around the odd order teeth (T1, T3, T5, T7, T9 and T11), the coil sides being placed in the bottom part of the slots. The remaining “marginal coils”, having w number of turns, are wound in the other two layers around the even order teeth. The connection between the coils is shown only for the phase A-X according to the drawing in fig. 1-c. After merging the coils, the resulting winding in fig. 3 has three layers in each slot, sharing the slot area horizontally.

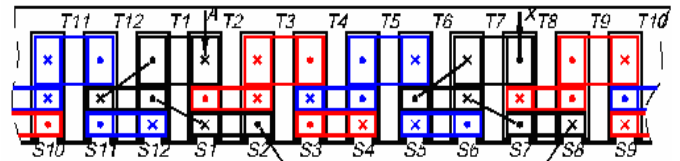


Fig. 3. Three layer winding arrangement with merged coils for 12 slots/10 poles winding according to fig. 1-c

TABLE I.
WINDING FACTORS AND RELATIVE AMPLITUDE OF MMF SPACE HARMONICS FOR 12 SLOTS/10 POLES CONFIGURATION

v	Single layer (fig. 1-a)			Double layer (fig. 1-b)			Four layers (fig. 1-c, $W=2w$)			Special three layers (fig. 1-c, $W=w\sqrt{3}$)		
	CW	CCW	%	CW	CCW	%	CW	CCW	%	CW	CCW	%
1	0	0.2588	134	0	0.067	35.9	0	0.0173	9.6	0	0	0
5	0.9659	0	100	0.933	0	100	0.9012	0	100	0.8966	0	100
7	0	0.9659	71.4	0	0.933	71.4	0	0.9012	71.4	0	0.8966	71.4
11	0.2588	0	12.2	0.067	0	3.26	0.0173	0	0.87	0	0	0
13	0	0.2588	10.3	0	0.067	2.76	0	0.0173	0.74	0	0	0
17	0.9659	0	29.4	0.933	0	29.4	0.9012	0	29.4	0.8966	0	29.4
τ_{dc}	2.6685			0.9641			0.8418			0.8323		

In fig. 4 the air gap mmfs for the four windings from table I are presented as fundamental 5-th harmonic (green), first (geometrical) space harmonic (red) and the resultant mmf (blue) for the same moment of time. It is to be observed the first space harmonic which is smaller and smaller as the winding is more and more complicated.

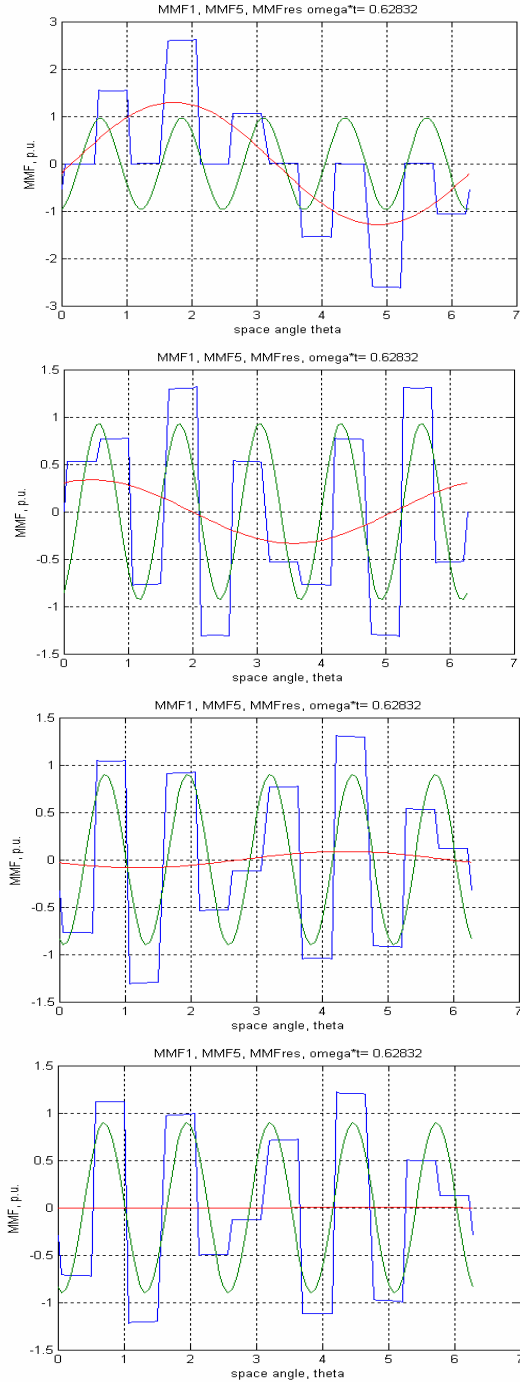


Fig. 4. Armature reaction mmf for 12 slots/10 poles of the windings defined in table I. (red-first space harmonic, green-fundamental, blue-resultant)

B. Primitive winding with $Z=9$ slots, $2p=8$ poles.

Due to the possible radial forces and vibration [14] this winding is usually used only multiplied (example 18 slots/16 poles, 27 slots/24 poles, etc.). However the possibility to reduce the space harmonic content can be studied on the primitive winding. As it is known from the literature [2, 3, 14], each phase contains three alternating adjacent coils, it means that the periphery of the armature is divided in three equal zones where the three phases have coils. A coil wound around a given tooth is contained in one and only one phase. Starting from the known double layer winding represented for only one phase (fig. 5-a), three improved four layer windings are derived using the same procedure as in the section A. In fig. 5-b each coil of the initial winding is divided in two sub-coils with half number of turns. The two sub-windings are shifted each other by one slot and after that they are again series connected. In fig. 5-c the same procedure is applied but the two sub-windings are shifted by two slots. In fig. 5-d each coil of the initial winding is divided into three sub-coils having one third number of turns. The two of the three sub-windings are shifted by one slot, first to the left and the second to the right face to the third one on the periphery of the armature.

As one can see from fig. 5 b-d, the phase zones are no more separated but they are interspersed. There are sub-coils wound around the same tooth but belonging to different phases.

To be more specific, in the case represented in fig. 5-d, the initial winding has three full coils noted $(-9, +1, -2)$. The winding in fig. 5-d has three series of three sub-coils, it means $(8, -9, +1)$, $(-9, +1, -2)$ and $(+1, -2, +3)$. In fig. 6 the star of the coils (more exactly the star of the teeth) is represented for the main space harmonic ($v = 4$) of the winding in fig. 5-d.

If k_{w4-a} is the fundamental space harmonic for the winding in fig. 5-a and k_{w4-b} , k_{w4-c} , k_{w4-d} the same for the windings in fig. 5 b-d, it is obvious that the following relations are valid:

$$\begin{aligned} k_{w4-b} &= k_{w4-a} \times \cos 10^\circ; \\ k_{w4-c} &= k_{w4-a} \times \cos 20^\circ; \\ k_{w4-d} &= k_{w4-a} \times \frac{1}{3} (1 + 2 \cos 20^\circ) \end{aligned} \quad (8)$$

The distribution of the phase conductors is extended from 4 slots in the initial case, to 5 and 6 slots respectively, leading to lower space harmonic content. The layout of the winding represented only for one phase in fig. 5-d is represented in fig. 7 for all the three phases. Each phase has a full coil around one tooth, two coils wound on 2/3 of the tooth height and another two coils wound only on 1/3 of the tooth height. Strictly speaking and counting the layers, it is clear that there are 6 slots containing 3 layers and 3 slots

containing 4 layers. The sharing of the slot area by the winding layers is a “vertical” one.

The mmf Fourier analysis leads to the results presented in table II. One can see that all the space harmonics are diminished compared to the initial winding. In fig. 8 the calculated armature reaction mmfs are presented for the four windings defined in fig. 5. It is to be mentioned that the winding diagram according to fig. 5-b is the same as that in the second embodiment of Kometani’s patent [12] and the values of the space sub-harmonics winding factors ($v=1, v=2$) calculated in table II are exactly the same as those in the cited patent. The windings diagram in the fig. 5-c and -d are much more improved from the space harmonic content point of view. The last has all of the space harmonics (except those of order $Z\pm p$) less than half of those of Kometani [12].

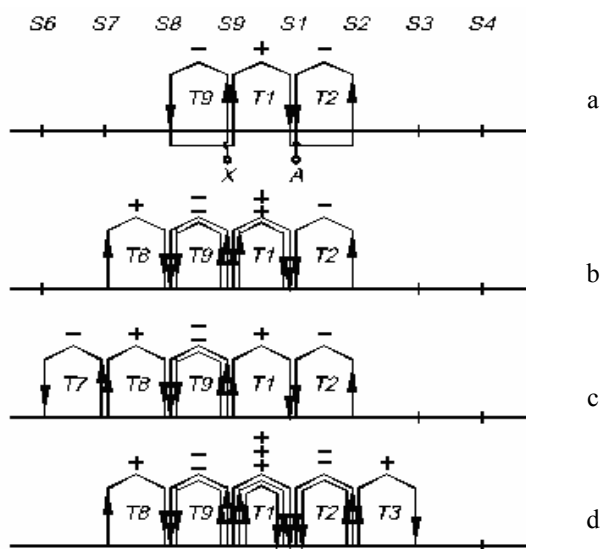


Fig. 5. Winding diagrams for 9 slots/8 poles (only one phase is represented). Normal double layer (a), four layer one slot shifted (b), four-layer two slots shifted (c), four layer one slot double shifted left and right.

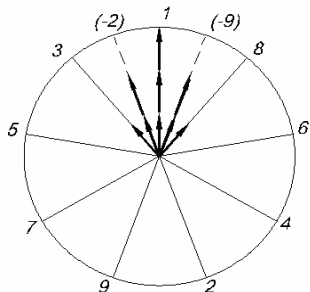


Fig. 6. Star of the coils (one phase) for the winding in fig. 5-d

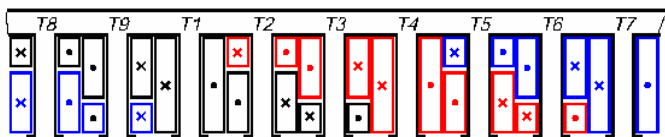


Fig. 7. Three/four layers winding arrangement with merged coils for 9 slots/8 poles three phase winding according to fig. 5-d

TABLE II
WINDING FACTORS AND DIFFERENTIAL COEFFICIENT FOR 9 SLOTS/8 POLES CONFIGURATION. THE CW WAVES ARE NOTED BY (+), THE CCW WAVES ARE NOTED BY (-).

v	k=1 (9 slots, 8 poles)			
	Fig. 5-a	Fig. 5-b	Fig. 5-c	Fig. 5-d
1	+0,0607	+0,0207	+0,0465	+0,0108
2	-0,1398	-0,0899	-0,0243	-0,0304
4	+0,9452	+0,9309	+0,8882	+0,9072
5	-0,9452	-0,9309	-0,8882	-0,9072
7	+0,1398	+0,0899	+0,0243	+0,0304
8	-0,0607	-0,0207	-0,0465	-0,0108
τ_{dc}	1.1784	1.0589	1.0557	1.0143

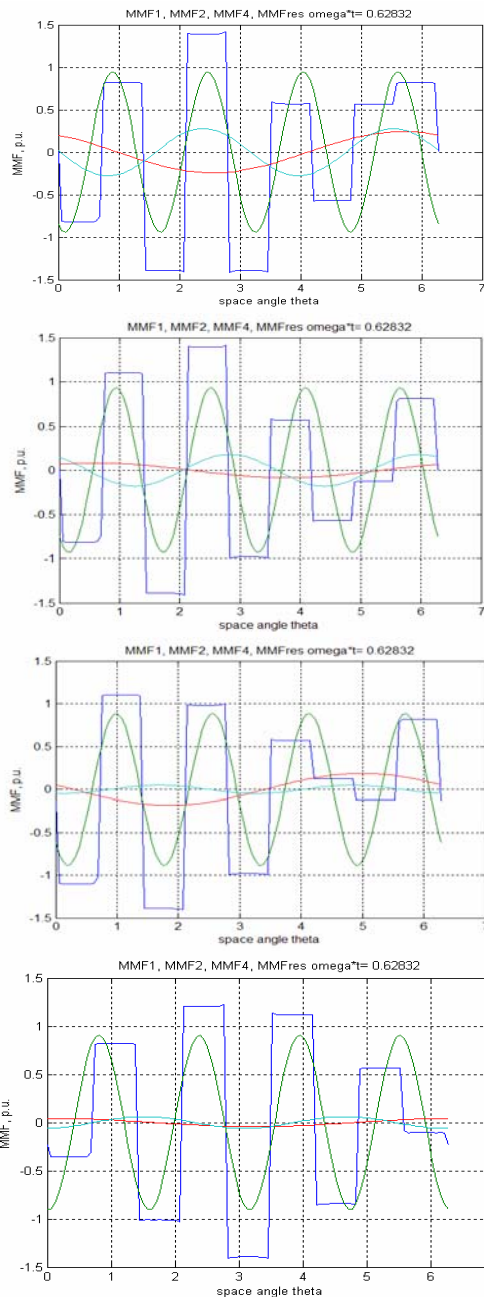


Fig. 8. Armature reaction mmf for 9 slots/8 poles of the windings defined in table II. (red-first space harmonic, magenta-second space harmonic, green-fundamental, blue-resultant)

IV. EXPERIMENTAL RESULTS.

The 12 slots/10 poles winding configuration investigated in the paper (fig. 1-c with $W=w\sqrt{3}$) was experimented in a permanent magnet, low speed synchronous generator with surface mounted magnets for wind energy conversion. The winding configuration in fig. 3 was multiplied by four in the real machine. The main characteristics of the manufactured machine are given below:

- outer diameter of stator	395 mm
- inner diameter of stator	285 mm
- length of the stack	35 mm
- rated length of the air gap	2 mm
- permanent magnets 45SH	35/21/10 mm
- number of stator slots	36
- number of poles	30
- rated power	1.5 kVA
- line to line rated voltage	3x230 V
- rated speed	200 rpm
- rated frequency	50 Hz
- turns per phase	1074
- turns per "central" coils	83
- turns per "marginal" coils	48
- phase resistance @ 20°C	3.97 Ω
- conductor diameter	1 mm

The stator and rotor details are shown in fig. 9. It can be observed the so called "central" coils having 83 turns wound around the odd order teeth, placed bottom of the slots and the pair of "marginal" coils, belonging to different phases, having each 48 turns, wound around the even order teeth and placed in the top of the slots.



Fig. 9. Stator and rotor details of the manufactured prototype

The ratio of number of turns of central coil to marginal coil (83/48) is not exactly $\sqrt{3}$ but very close to it, it means that the actual fundamental winding factor will differ from the theoretical one by less than 0.06%. In order to investigate the air gap magnetic field in the manufactured machine, three additionally test coils have been mounted in the slots besides the main winding, as follows:

- first test coil, U_1U_2 , ten turns around a tooth as in fig. 1-a, tooth T1. The winding factor of this concentrated test coil is reduced to the pitch factor which is $\sin 75^\circ = 0.9659$
- second test coil, V_1V_2 , two coils series connected, wound around two adjacent teeth, 5 turns each, as in fig. 1-b, teeth T1 and T2. The winding factor of this test coil is depending both on the pitch and distribution factor, it means it is $(\sin 75^\circ)^2 = 0.9330$
- third test coil, W_1W_2 , three coils series connected, first with 7 turns wound on a tooth (T1) and another two coils

having 4 turns each, wound on the adjacent teeth (T2, T12) as in fig. 1-c. In this case the ratio between 7 and 4 is much more different by $\sqrt{3}$, however the winding factor of this test coil is close to the phase winding factor:

$$k_{w_w1w2} = \sin 75^\circ \times \frac{7 + 2 \times 4 \times \cos 30^\circ}{15} = 0.8969 \quad (9)$$

The rms induced voltage at no-load in any test coil, including the full phase winding, is depending on the average air-gap flux given by the permanent magnets Φ as follows:

$$E = \pi\sqrt{2}fwk_w\Phi \quad (10)$$

where f is the frequency and w is the number of turns series connected. In fig. 10 there are presented the registered EMF induced in the three test coils and in table III one can see the main results as rms values of EMF in the test coils. In the last line of table III it is included the full phase voltage as measured value. The registered line-to-line voltage at 200 rpm is presented in fig. 11. As the average flux per pole is constant at no-load, this fact is used in order to validate the calculated winding factors. In the last column of table III it is given the calculated value of the flux per pole as ratio of $E/(\pi\sqrt{2}fwk_w)$. As one can see the values are differing each other by less than 1%. Taking into account the surface of the magnets it results that the average flux density in the air gap is around 0.95 T.

TABLE III
MEASURED NO LOAD EMF INDUCED IN THE TEST COILS

Test coil	Nr. of turns	Calculated winding factor	EMF@ 200 rpm, [Vrms]	Calculated flux per pole [Wb]
U_1U_2	10	0.9659	1.515	$7.061 \cdot 10^{-4}$
V_1V_2	10	0.9330	1.452	$7.006 \cdot 10^{-4}$
W_1W_2	15	0.8969	2.109	$7.057 \cdot 10^{-4}$
Full phase	1074	0.8965	150.9	$7.055 \cdot 10^{-4}$

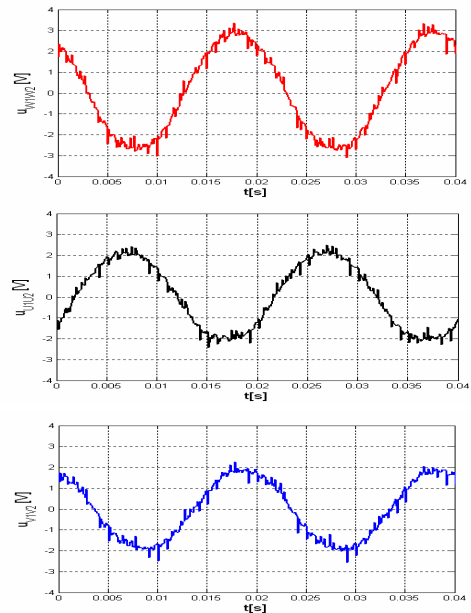


Fig. 10. The induced EMF in the three test coils, U_1U_2 , V_1V_2 , W_1W_2 , according to winding of 12 slots/10 poles configuration in fig. 1 a-c.

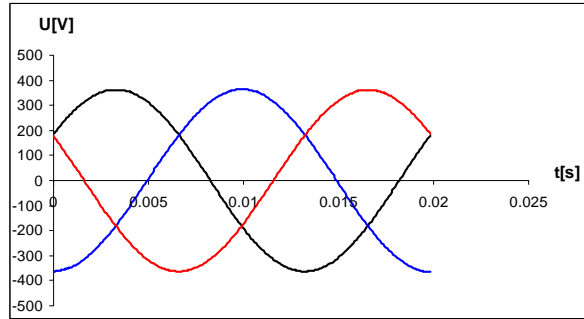


Fig. 11. The line to line no-load EMF at 200 rpm

V. CONCLUSIONS.

The fractional tooth concentrated windings have high space harmonics in the mmf of armature reaction because of very low value of the number of slots/pole/phase. These harmonics lead to additional losses due to the eddy currents induced in the back iron of the rotor. In the paper a new method is presented to reduce or even to cancel some of the space harmonics of the armature reaction based on increasing the number of the winding layers, equivalent to an artificial increase in the number of slots. The method consist in doubling (or trebling) the initial winding and shifting the obtained sub-windings, series connected, by a given number of slots. If in the known tooth-concentrated windings one coil wound around a given tooth is contained in one and only one phase, in the new developed windings there are sub-coils wound around the same tooth but belonging to different phases. The phase windings become more interspersed and the space harmonics are diminished.

Examples are given in the paper for two primitive three phase windings (12 slots/10 poles and 9 slots/8 poles). The four-layer winding layout was developed and the possibility to improve the shape of the armature mmf was demonstrated. The developed method is validated by experimental results obtained on the manufactured and preliminary tested PM synchronous generator having 36 stator slots and 30 poles.

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