The main principles of the approach to the construction of combined windings with one set of terminations

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Abstract. The principle of the construction of an AC combined winding with one set of terminations with $p_1$ and $p_2$ polarities of the MMF is proposed. Equations of the MMF and the turn phase of the combined winding, which create accordant and counter-rotating harmonics of the MMF polarity $p_1$ and $p_2$, are obtained. The cases of construction of CO with accordant- and counter-rotating harmonics of MMF of different polarity are considered in detail. The main relation for the distribution of conductors in the slots is presented. The spatial pattern of accordant and counter-rotating harmonics of the MMF polarity $p_1=5$ and $p_2=3$ with equal angular frequencies are shown.

1. The approaches in the construction of combined windings.

The idea of combining electrical machines implementing the principles of a magnetic combination of systems in a broad magnetic core and an electrical combination of windings has been known for a long time [1]. Today it has allowed creating a number of combined machines with high technical and economic performances [2, 3, 4]. There are a single-armature converter and a cross-field control amplifier, a synchro motor and motors amplifiers, a single-machine frequency converter and cascaded electrical machines.

There are two approaches in the construction of combined windings.

The half-bridge and the bridge combined windings have two groups of terminations as well as the pole-switchable windings [2]. The construction principles of these combined windings types are based on the theory of the pole-amplitude modulation [4]. The method consists in the amplitude modulation of the main harmonic by a spatial wave, called the modulation wave. A single-amplitude modulation wave has $p_m$ periods. The result of the modulation can be described using the following equation [4]:

$$I_{1\text{mod.}} = I_1 \cdot \sin(p_m \cdot \alpha) = I_{1m} \cdot \sin(p_n \cdot \alpha - \omega t) \cdot \sin(p_m \cdot \alpha) = 0.5 \cdot I_{1m} \{\cos[(p_n - p_m) \cdot \alpha - \omega t] - \cos[(p_n + p_m) \cdot \alpha - \omega t]\} \tag{1}$$

Since a magnetomotive force (MMF) wave is integral towards current distribution wave, the winding forms two rotating waves of MMF with $(p_n - p_m)$ and $(p_n + p_m)$ pole pairs. One of them can be used as the second working field provided that the other one is fully or partly neutralized. Practically, the pole-amplitude modulation is not a sinusoidal, but a square wave. That provides reversing half of the winding coil groups coinciding in space with one of the half-periods of the modulating wave. In
order to do that, two sources are connected to the winding so that the currents in half of the coil groups flow in the same direction, and on the other one in the opposite direction.

The second approach in creating of combined windings is to use the fact that m-phase 2p-pole winding with a fractional number of slots per pole and phase creates rotating harmonics of a magnetic field, when current flows through it. The harmonics order is [3]:

\[ \nu = \frac{2m}{d} \cdot k \pm 1 \]  

(2)

where \( k \) is a positive integer (including 0) at which \( \nu > 0 \), the “+” sign refers to the forward harmonics, and “-” sign refers to the backward harmonic. In equation \( 2 \) \( \nu \) can be as integer, as fractional [3, 5].

The fractional-order harmonics have small winding coefficients in the conventional windings with fractional \( q \). So application of these windings as combined is not effective enough. However, winding coefficient for one of the fractional order harmonics can be increased, as a result of changing the connection diagram of winding coils with fractional \( q \). It allows applying such winding as combined with the effective use of both main and fractional harmonics. The circuits of three- and two-phase windings, which have quite high winding coefficients, are presented in [3]. For example, the winding that creates counter-rotating harmonics with MMF polarity of \( p_1 = 4 \) and \( p_2 = 2 \) has \( K_{a1} = 0.73 \) and \( K_{a2} = 0.48 \). Also the winding that creates counter-rotating harmonics with a MMF polarity of \( p_1 = 5 \) and \( p_2 = 7 \) has higher winding coefficients [6].

A great number of patents issued for the invention of such windings in the full absence of recommendations for drawing circuits. It indicates a great interest in the issue under consideration and a certain heuristics of the design process [7, 8].

It is necessary to determine the distribution law of conductors along the machine bore to formalize the analysis of the principles of combined winding construction. This is possible if all turns are connected in series having a general equation of MMF of winding.

The function of the combined winding with one set of terminations is to provide two working harmonics of MMF with equal or almost equal amplitudes and the number of periods \( p_1 \):

\[ F_1 = F_{1m} \cdot \cos(\omega t - p_1 \alpha) \]  

(3)

and the number of periods \( p_2 \):

\[ F_1 = F_{2m} \cdot \cos(\omega t - p_2 \alpha) \]  

(4)

when the m-phase system of the sinusoidal current flows in it.

In other words, the resulting MMF of the combined winding should be described by the following equation [9, 10]:

\[ F_1 + F_2 = F_{m} \cdot \cos(\omega t - \frac{P_1 \pm P_2}{2} \cdot \alpha) \cos\left(\frac{P_1 \pm P_2}{2} \cdot \alpha \right). \]  

(5)

The above equation provides for both accordant- and counter-rotating of harmonics of MMF. Using the terminology of amplitude-pole modulation theory and introducing appropriate designations, the equation of an accordant-rotating harmonics of MMF is:

\[ F_1 = F_{m} \cdot \cos(\omega t - p_n \cdot \alpha) \cos(p_n \cdot \alpha) \]  

(6)

and a counter-rotating harmonics of MMF:

\[ F_1 = F_{m} \cdot \cos(\omega t - p_n \cdot \alpha) \cos(p_n \cdot \alpha) \]  

(7)

where \( p_n = 0.5(p_1 + p_2) \) - the number of periods of the harmonic carrier modulated MMF,

\( p_n = 0.5(p_1 - p_2) \) - the number of periods of modulating harmonics of MMF.

Considering obtained equations, it can be noted that due to accordant rotating of the working harmonics of MMF with equal amplitudes of polarity \( p_1 \) and \( p_2 \), the rotating carrier harmonic of MMF
with the number of periods \( p_n \) that are modulated by the fixed in space harmonic with the number of periods \( p_m \) is formed. The carrier harmonic becomes fixed in space, and the modulating harmonic moves with the angular rate \( \omega \) due to counter rotating of the working harmonics with \( p_1 \) and \( p_2 \).

The equations (6) and (7) in phase coordinates accordingly are:

\[
F_\phi = F_{m}\cdot \cos(\omega t - \Phi) \cdot \cos(p_n - \phi) \cdot \cos(p_m \cdot \alpha)
\]

(8)

for an accordant-rotating of harmonics,

\[
F_\phi = F_{m}\cdot \cos(\omega t - \Phi) \cdot \cos(p_m \cdot \alpha - \phi) \cdot \cos(p_n \cdot \alpha)
\]

(9)

for a counter-rotating of harmonics \( p_1 \) and \( p_2 \).

Since the MMF wave is integral towards current distribution wave, the possibility of the winding implementation is determined by the possibility of distribution its conductors along the machine bore according to the following law:

\[
W_f(\alpha) = W_{mf} \cdot \sin(p_n \cdot \alpha - \Phi) \cdot \sin(p_m \cdot \alpha)
\]

(10)

for an accordant-rotating of working harmonics,

\[
W_f(\alpha) = W_{mf} \cdot \sin(p_m \cdot \alpha - \Phi) \cdot \sin(p_n \cdot \alpha)
\]

(11)

for a counter-rotating of working harmonics.

In these equations:
- \( \Phi_i \) – the phase angle corresponding to the \( i \) phase in the \( m \)-phase system.
- \( W_{mf} \) – the maximum number of phase turns per machine circumference unit.

The equations (10), (11) describing the distribution law of the turn’s numbers of each phase for the combined winding determine the algorithm for their construction.

2. Combined windings creating counter-rotating harmonics of MMF

Consider the case of the counter-rotating working harmonics of MMF, when the phase turns distribution of the combined winding is determined by the equation (11). In this case, the spatial pattern of the current distribution should have a form of a standing wave with the number of periods \( p_n \), modulated by a running wave with the number of periods \( p_m \) (7) (Figure 1).

![Figure 1. The spatial pattern of counter-rotating harmonics of MMF polarity \( p_1=5 \) and \( p_2=3 \) with the equal angular frequencies.](image)

The MMF of the combined winding phases should have a pulsating wave form with the number of periods \( p_n \) modulated by a pulsating wave with the number of periods \( p_m \). The MMF of the phases differs from one another by the shift of the modulating harmonic by the corresponding phase angle \( \Phi_i \).
(9). Thus, the phases must be shifted in space by the angle $\Phi_i$ in degrees of the modulating harmonic and must not be shifted along the carrier harmonic.

From here the satisfiability condition of combing winding in the form of identical phases shifted by the corresponding phase angles can be obtained:

$$\psi_i \cdot \frac{p_m}{p_n} = 2 \cdot k \cdot \pi \quad \text{and} \quad \frac{p_1 + p_2}{p_1 - p_2} = k \cdot m$$

where $k = 1, 2, 3, \ldots$ - integer.

According to equation (11), the conductors of the designing combing winding phase should be distributed along the machine bore according to a sinusoidal law with a period $2\pi/p_n$ modulated by a sinusoid with a period $2\pi/p_m$. The degree of approximation of the real distribution of conductors to the required law, as in the "conventional" windings, is determined by the number of slots that filled by the winding, and the number of layers (with the same number of turns in the coils). In a two-layer winding the number of coils equals $Z$. Several poles of the carrier harmonic that fixed in space fit in a half the period of the modulating harmonic. Thus, the winding pitch must be diametrical to this harmonic for creation the carrier harmonic of MMF [10]:

$$y_n = \frac{Z}{p_1 + p_2}.$$  

Figure 2. The spatial pattern according to the rotating harmonics of MMF polarity $p_1=5$ and $p_2=3$ with the equal angular frequencies.

The modulation provides varying of the amplitude of the carrier field along the gap of the machine, which can be achieved by appropriately distributing the number of turns of the winding among the
slots. Also modulation of the carrier field harmonics with the number of periods of \( p_n \) and harmonics with the number of periods of \( p_m \) provides changing the polarity of the carrier harmonics according to the modulating law, which can be ensured either by opposing connection of the coil groups \( 2p_n \) polarity, separated from each other by \( \pi/p_m \) radian, either by making coil groups with \( \pi/p_m \) pitch, connection diagram that corresponds to the polarity of \( 2p_n \). In the above condition \( p_n/p_m \) is even number.

In the case under consideration, the individual phases of the pole-modulated winding should be shifted in space relative to each other by the corresponding phase angles in electrical degrees of the carrier harmonic \((2\pi/mp_n \text{ geometric degrees})\) (8).

Since the MMF wave is integral towards current distribution wave, and the current with the same magnitude and phase flows through all phase conductors, the possibility of constructing the winding, the MMF of the phase is calculated by the equation (8), determined by the possibility of distributing the number of phase conductors over the slots according to the law (10). However, as with designing the convention anchor windings of AC machines, it should be taken into account that the turns of the windings are arranged in the form of the coils that discrete in the slots, but the number of turns in the individual coils are often set equal due to the technological reasons. Therefore, turns number distribution law (as well as the MMF) of the winding is expressible as a stepped curve. Obviously, the number of steps is determined by the number of layers of the winding with the accepted restriction. The conductors distribution law of the pole-modulated winding phase in the slots (10) differs from the dependence for conventional anchor windings only by a multiplier \( \sin(p_m/\alpha) \). This multiplier determines the modulation of conductors’ distribution and accordingly the modulation of the combined winding MMF. Therefore, the implementation of a pole-modulated winding creating accordant rotating working harmonics with the number of poles \( 2p_1 \) and \( 2p_2 \) is possible when the winding is designed as convention m-phase anchor winding with the number of pole pairs \( p_n=0.5(p_1 + p_2) \), changing the number of conductors in the slots along the bore of the machine according to the law \( \sin(p_m/\alpha) \) where \( p_n=0.5(p_1 + p_2) \). The latter assumes an unequal filling of the slots with copper windings and the polarity changing of the turning on the coils \( 2p_n \) pole windings separated from another by \( \pi/p_m \) degrees. The feature of this winding is the impossibility of its formation from the identical phases by simply shifting them relative to each other by the corresponding phase angles along the machine bore. It is possible to choose the number of poles \( 2p_1 \) and \( 2p_2 \) and the corresponding number of winding phases in such a way that \((2\pi/m)-(p_m/p_n)=2\pi k\), where \( k \) is integer, then \((2\pi/m)-(p_m/p_n)=2\pi k\) for a winding creating counter-rotating harmonics, because \( p_m \) is always less than \( p_n \). The latter suggests that the phases of the winding are shifted one relative the other by modulating polarity of \( 2\pi p_n/p_m \) m in electrical degrees of modulating harmonics while designing polar-modulated winding creating accordant rotating harmonics of MMF from the identical phases by their relative spatial shift on phase angles equal to \( 2\pi/p_n \). Also it causes the backward running components of each working harmonics.

4. Results and conclusion
The relations given in this paper were used in the design of the combined windings for series of prototypes of reversed replenishment synchronous motor with electromagnetic reduction of rotation speed used as motorized drums for belt conveyor drives. The tests of the motorized drums in the laboratory and the industrial conditions showed good convergence of calculated and experimental characteristics which indicates the reliability of the obtained results. Therefore it should be noted that it makes possible to use this type of the combined windings in the synchronous motor with an electromagnetic reduction of a rotation speed for the power common industrial electric drives.
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