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Harmonic Analysis of the Magnetomotive Force in Combined Windings of Induction Motors

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ABSTRACT- This study examines the variation of magnetomotive force (MMF) distribution and its harmonic spectrum during the transition from a conventional winding configuration to a combined winding. The MMF waveform is constructed according to the instantaneous current directions in the winding conductors, resulting in a stepped integral MMF waveform. Slot width and slot skew are neglected, and the current in each slot is assumed to be concentrated at a single point. The resulting MMF distribution is symmetrical about the horizontal axis, ensuring equal positive and negative areas. Harmonic analysis of the MMF waveform is performed for both winding configurations. Harmonic amplitudes are determined from the discrete MMF values using an analytical Fourier-based DFT approach, and selected harmonic components are reconstructed as sinusoidal spatial MMF components to evaluate their individual contributions to the overall MMF waveform. The results show that the combined winding reduces several higher-order harmonic components while providing a higher fundamental winding factor. This reduction improves the spectral quality of the MMF distribution, reduces harmonic distortion, and results in a more sinusoidal MMF waveform for the combined winding.

Keywords: Standard Winding, Combined Winding, MMF Curve, Higher Harmonic Content, Harmonic Distortion.

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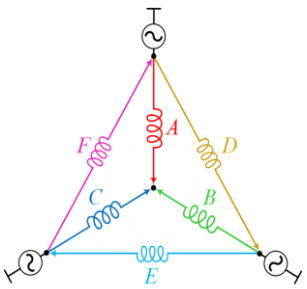
1. INTRODUCTION

The magnetomotive force (MMF) integral curve enables the determination of MMF values at any angular position in the air gap, as well as the identification of its maximum value, and allows the decomposition of the MMF waveform into a harmonic series using established graphical and analytical methods for evaluating harmonic amplitudes [1–3]. Harmonic analysis of MMF distribution is widely used to improve winding design and optimize parameters such as winding pitch, while combined winding structures have recently gained attention due to their influence on MMF harmonic content. In this context, the MMF of each phase is represented as a step function and expanded into a Fourier series to describe its spatial and temporal harmonic components [4,5]. For an integer number of slots per pole per phase (q), the MMF waveform is periodic, and it is sufficient to analyze it over one pole pitch (2τ), since the pattern repeats identically in subsequent intervals, which simplifies harmonic evaluation and supports comparison between conventional and combined winding configurations.

Previous studies have investigated combined star-delta windings and their effects on higher spatial harmonics. However, a direct quantitative comparison of the MMF harmonic spectra of conventional and combined windings, including harmonic winding factors and individual harmonic amplitudes, has not been sufficiently addressed. Therefore, the main contribution of this study is a quantitative, slot-by-slot comparison of the MMF harmonic spectra of conventional and combined windings, incorporating harmonic winding factors and an overall THD-based assessment. This approach enables a quantitative assessment of the harmonic redistribution in the combined winding and its improvement in harmonic content compared with the conventional winding.

2. METHODS AND RESEARCH

Two basic circuit configurations of this type of winding are possible: parallel and series, as shown in *fig. 1(a)* and *fig. 1(b)*, respectively. In this study, the parallel configuration is considered.



(a)

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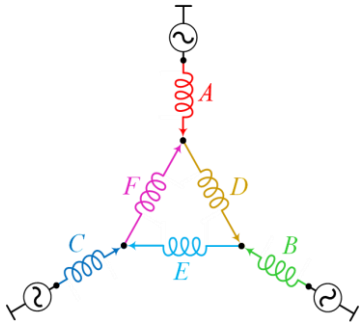

(b)

Figure 1. Basic circuit scheme of the combined winding: (a) parallel; (b) series

The MMF waveform of each phase is represented by a symmetrical stepped function, in which the positive half-wave is symmetrical to the negative half-wave with respect to the horizontal axis. Assuming a sinusoidal voltage in the winding [2], the MMF can be represented by a fourier series consisting of its fundamental and higher-order spatial harmonics. The ν-th harmonic component of the MMF is expressed as follows:

$$F_{fv} = F_{fmv} \cdot \cos(\omega \cdot t + \xi_f) \cdot \cos(v \cdot (\varphi' + \varphi_f)) \quad (1)$$

here f - index that determines the winding phase; F_{fmv} - amplitude of the v- harmonic of the MMF; ξ_f - initial phase of the current, rad; φ' - angular coordinate, rad; φ_f - angular coordinate of the magnetic axis of the winding phases, rad.

The values of ξ_f and φ_f for the combined winding phases are given in *table 1*.

Table 1. Phase shifts of the MMFs of the winding phases

Winding phases	Initial phase of the current - ξ_f	Angular coordinate of the magnetic axis of the winding phases - φ_f	Projection (MMF step amplitude - F_k)
a «star»	0	0	+1 p.u
b «star»	2π/3	2π/3	-0.5 p.u
c «star»	4π/3	4π/3	-0.5 p.u
d «delta»	π/6	π/6	+0.866 p.u
e «delta»	5π/6	5π/6	-0.866 p.u
f «delta»	3π/2	3π/2	0 p.u
-a «star»	π	π	-1 p.u
-b «star»	5π/3	5π/3	+0.5 p.u
-c «star»	π/3	π/3	+0.5 p.u
-d «delta»	7π/6	7π/6	-0.866 p.u
-e «delta»	11π/6	11π/6	+0.866 p.u
-f «delta»	π/2	π/2	0 p.u

As the reference winding, a three-phase stator winding with Z=36 stator slots, p=2 pole pairs, and q=3 slots per pole and phase is considered, with the winding connected in a star configuration. To obtain the combined winding, the winding sections corresponding to every third slot are transferred to the delta connection in the required proportion. As a result, the combined winding consists of a star-connected section with q = 2 and a delta-connected section with q =1. To maintain approximately equal fundamental MMF in the star- and delta-connected sections, their numbers of turns and currents are selected according to the star-delta circuit transformation. When a symmetrical three-phase voltage is applied to the terminals ($U_{ph\,\Delta} = \sqrt{3} \cdot U_{ph\,Y}$) of the considered winding configuration (*Fig. 1(a)*, Z=36, p=2, q=3), the number of turns per phase in the delta-connected section is taken as $\sqrt{3}$ times that of the star-connected section, with the number of turns per phase w_{ph} adjusted accordingly to achieve a balanced MMF distribution:

$$w_{ph\,\Delta} = \sqrt{3} \cdot w_{ph\,Y} \quad (2)$$

For the selected turns ratio, the phase-current relationship is chosen to preserve equal fundamental ampere-turns in the two sub-windings. Since the delta section has a higher number of turns per phase ($w_{ph\,\Delta}$), its internal phase current ($I_{ph\,\Delta}$) is correspondingly reduced by a factor of $\sqrt{3}$ compared with the phase current of the star-connected section ($I_{ph\,Y}$):

$$I_{ph\,Y} = \sqrt{3} \cdot I_{ph\,\Delta} \quad (3)$$

Therefore, the fundamental ampere-turns of the Y- and Δ-connected sections are equal:

$$w_{ph\,Y} \cdot I_{ph\,Y} = w_{ph\,\Delta} \cdot I_{ph\,\Delta} \quad (4)$$

Thus, the fundamental MMF contributions of the two sections are equal under the adopted turns and current relationships, while the differences in the harmonic spectrum are mainly determined by their spatial distribution and phase displacement of the two sub-windings. For construction of the stepped MMF waveform, each current-carrying slot is assigned a normalized ampere-turn contribution of $w_Y \cdot I_Y = w_\Delta \cdot I_\Delta$=1 p.u. according to its current direction. Both winding configurations have the same Z=36, p=2, and coil pitch y=9, and the slot-by-slot winding arrangement for the standard and combined windings is presented in *tables 2 and 3*, respectively. Because the winding has two pole pairs, only slots 1-18 are explicitly listed in *tables 2* and *3*. The phase-zone sequence and current directions of slots 19-36 repeat the same pattern as those of slots 1-18. Therefore, the 18-slot representation is sufficient to describe the complete winding arrangement used in the analysis. For the single-layer winding with a coil pitch of y=9, the two coil sides are separated by nine slots and carry currents in opposite directions. In *table 3*, *a, b, c* denotes the star-connected (Y) phase groups, while *d*, *e*, *f* denotes the delta-connected (Δ) phase groups, the negative signs indicate the opposite current direction.

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Table 2. Current phasors according to their slot (standard, e.g., q=3)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
a	a	a	-c	-c	-c	b	b	b	-a	-a	-a	c	c	c	-b	-b	-b
0°	0°	0°	60°	60°	60°	120°	120°	120°	180°	180°	180°	240°	240°	240°	300°	300°	300°
Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

Table 3. Current phasors according to their slot (combined, e.g., q_Y=2, q_Δ=1)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
a	a	d	-c	-c	-f	b	b	e	-a	-a	-d	c	c	f	-b	-b	-e
0°	0°	30°	60°	60°	90°	120°	120°	150°	180°	180°	210°	240°	240°	270°	300°	300°	330°
Y	Y	Δ	Y	Y	Δ	Y	Y	Δ	Y	Y	Δ	Y	Y	Δ	Y	Y	Δ

To simplify the analysis, a commonly used methodology is employed [6], which includes the distribution factor $\xi_{d,v}$ and the pitch factor $\xi_{p,v}$ for determining the MMF amplitude:

$$F_{fmv} = \xi_{d,v} \cdot \xi_{p,v} \cdot \frac{2\sqrt{2}\cdot w\cdot I}{\pi\cdot v\cdot p} = \frac{\sin(\frac{q\cdot v\cdot \pi\cdot p}{Z})}{q\cdot\sin(\frac{v\cdot\pi\cdot p}{Z})} \cdot \sin\left(\frac{v\cdot y\cdot\pi}{2\cdot\tau}\right) \cdot \frac{2\sqrt{2}\cdot w\cdot I}{\pi\cdot v\cdot p} \quad (5)$$

where w - is the number of windings turns of the considered winding section; I - is the RMS value of the corresponding phase current, A; p - is the number of pole pairs; q - is the number of slots per pole and per phase; Z - is the number of slots; y - is the coil pitch; τ - is the pole pitch.

For the standard winding, the harmonic MMF amplitude can be determined directly from the distribution and pitch factors given in *eq. (5)*. For the combined winding, the resultant MMF is obtained by superposition of the MMF contributions of the star- and delta-connected sections. For each winding section, the harmonic MMF amplitude is determined from its corresponding number of turns, current, and harmonic winding factor. Thus, the ν- harmonic component is expressed as:

$$F_{v_comb} = F_{v_Y} + F_{v_\Delta} \quad (6)$$

where F_{v_Y} and F_{v_Δ} denote the ν- harmonic MMF components produced by the star- and delta-connected sections, respectively. This formulation accounts for the different slot distributions and winding factors of the two sections. In addition to the winding-factor approach, the harmonic amplitudes of the stepped MMF waveform can be determined analytically using its Fourier-series representation:

$$F_v = \frac{2}{\pi\cdot v}\Sigma_{k=1}^{N} F_k \cdot sin \cdot \left(\Theta_k \cdot \frac{v\cdot\pi}{180}\right) \quad (7)$$

where F_k is the MMF step amplitude corresponding to the k-slot interval, Θ_k is the angular position of the corresponding interval, and N is the number of intervals considered.

The required MMF step amplitudes and angular positions can be obtained from the data given in *table 1*. For the combined winding, the harmonic amplitudes of the star- and delta-connected sections are calculated similarly and combined according to *eq. (6)*. The MMF curves of the various winding phases can be summed based on the superposition principle (*fig. 2*), taking into account their spatial and temporal shifts [7,8].

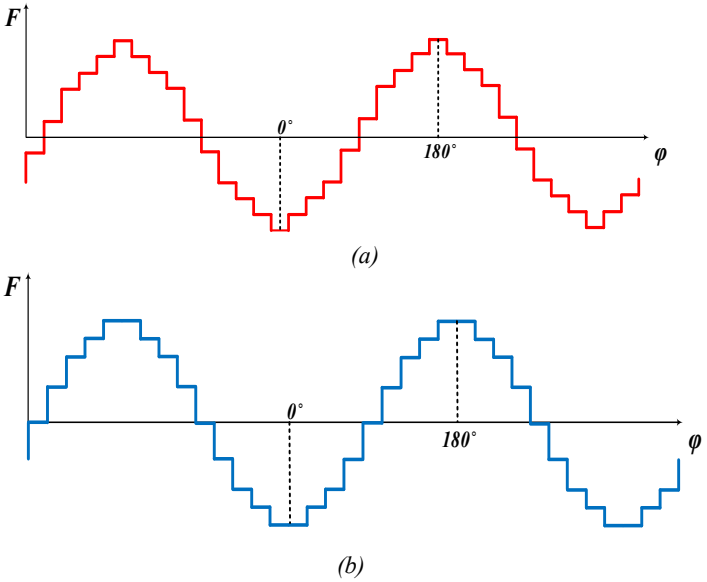

Figure 2. MMF distribution curve for a single-layer winding with *Z=36, p=2, y=9:* (a) standard winding; (b) combined winding

To determine the harmonic content of the proposed spatial MMF waveforms, discrete Fourier Transform (DFT) analysis based on the winding configuration was conducted. The angular sampling step of $\Delta\Theta = 20°$ corresponds directly to the slot pitch in electrical degrees, defined as α_{el} = 360°·p/Z. Within the analysis window bounded by the MMF extrema (indicated by the vertical black lines in *fig. 2*), the sampling grid captures exactly 9 discrete points for the standard winding and 8 discrete points for the combined winding, with both configurations evaluated at the respective MMF step vertices. Based on these waveforms, the spatial harmonic spectrum and amplitude values for the characteristic winding orders (ν = 5, 7, 11, 13, 17, 19, 23, and 25) were explicitly evaluated using customized analytical DFT approach in Excel, which implements the mathematical model expressed in *eq. (7)*. Subsequently, within the specified interval of -π to +π, each individual harmonic amplitude was generated into a discrete spatial signal waveform to construct the overall spatial distribution plot (*fig. 3*).

Table 4. Calculated parameters of the considered windings

Winding parameters	standard	combined	
		«star»	«delta»
q	3	2	1
y	9	9	9

As shown in *fig. 3*, at the time moment t=0, when the current in phase A reaches its amplitude value, the fundamental (v=1) and higher harmonic content (v=*5, 7, 11, 13, 17, 19, 23, 25*) of the MMF are compared for the standard and combined winding.

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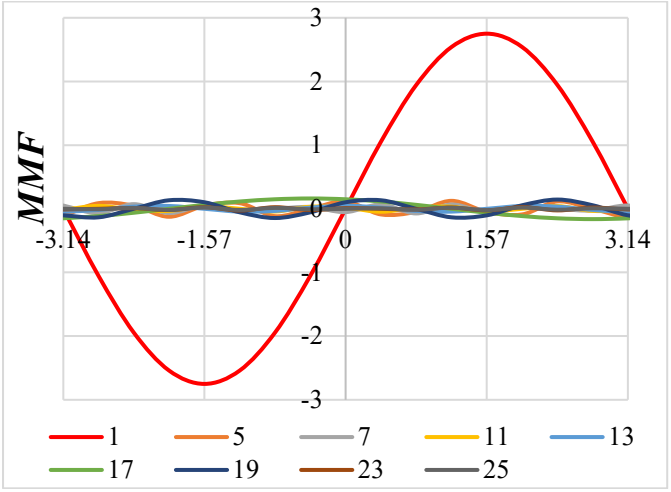

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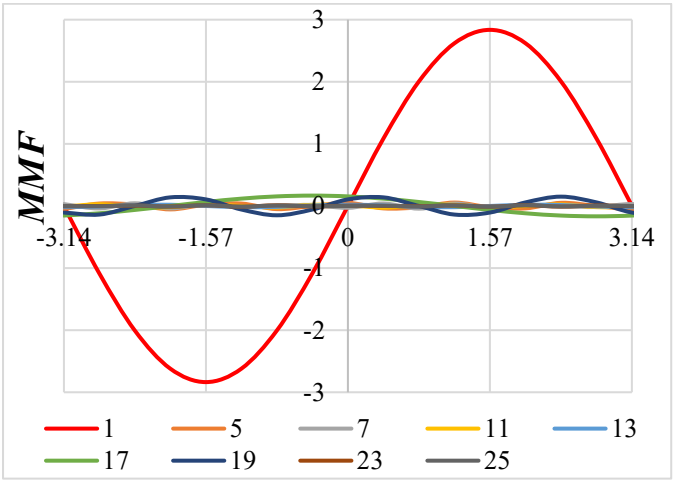

(b)

Figure 3. Spatial MMF harmonic spectrum obtained by DFT analysis: (a) standard; (b) combined

The calculated MMF samples were used as the input data, and the amplitude of each harmonic component was obtained through this analytical decomposition. To facilitate comparison between the standard and combined windings, the amplitude of each harmonic was normalized with respect to the fundamental component. The relative amplitude of the v – harmonic, expressed in percentage, was calculated as presented *table 5* using *eq. (8):*

$$F_{mv\%} = \frac{F_{mv}}{F_{m1}} \cdot 100\% \tag{8}$$

where F_{mv} is the amplitude of the ν-th harmonic and F_{m1} is the amplitude of the fundamental harmonic (determined by *eq. (7)*).

Table 5. Shares of harmonic amplitudes relative to the fundamental harmonic, F_v/F_1 in %

v	standard	combined
1	100	100
5	4.545454	1.939351
7	2.654545	1.516220
11	1.672727	0.952045
13	1.745454	0.740479
17	5.890909	5.888575
19	5.272727	5.253878
23	0.981818	0.423131
25	0.727272	0.423131

The harmonic winding factors were also calculated for the fundamental and higher-order harmonics considered in this study. The winding factor for the ν- harmonic is determined as $\xi_\upsilon = \xi_{d\upsilon} \cdot \xi_{p\upsilon}$, where $\xi_{d\upsilon}$ and $\xi_{p\upsilon}$ are the distribution and pitch factors, respectively. When q_{stan} is odd, the widths of the star and delta subzones differ by one slot. Consequently, the fundamental winding factor is determined by the combined contributions of the two sub-windings. Since the total phasors of the fundamental MMF of the star- and delta-connected sub-windings are oriented in the same direction, their contributions can be added arithmetically [9]:

$$\xi_{1,Y\Delta} = \frac{\sin\left(\frac{\pi\cdot(q_{stan}+1)}{4\cdot m_{stan}\cdot q_{stan}}\right)+\sin\left(\frac{\pi\cdot(q_{stan}-1)}{4\cdot m_{stan}\cdot q_{stan}}\right)}{q_{stan}\cdot\sin\left(\frac{\pi}{2\cdot m_{stan}\cdot q_{stan}}\right)} \tag{9}$$

The fundamental winding factor was calculated as 0.9598 for the standard winding (using ξ_{dv} and ξ_{pv}), while *eq. (9)* gives a value of 0.9899 for the combined winding. Furthermore, based on *eq. (10)*, the winding factors corresponding to each harmonic order can be determined relatively easily using the ratio of the MMF harmonic amplitudes:

$$\xi_v = v \cdot \xi_1 \cdot \frac{F_v}{F_1} \tag{10}$$

Eq. (10) can be derived directly from *eq. (5)* or *eq. (7)* by substituting the corresponding harmonic winding factor and MMF amplitude expressions. The corresponding F_v/F_1 values are provided in *table 5*.

Table 6. Harmonic winding factors of the standard and combined windings

v	ξ_υ (standard)	ξ_υ (combined)
1	0.959	0.989
5	0.218	0.095
7	0.177	0.105
11	0.177	0.105
13	0.218	0.095
17	0.959	0.989
19	0.959	0.989
23	0.218	0.095
25	0.177	0.105

For the considered winding, the winding factors of the fundamental and the higher-order harmonics present in the MMF waveform were calculated, and the obtained results are presented in *table 6*. The results obtained in this part are analyzed in the following section. To provide an overall quantitative comparison of the harmonic content, the THD calculated from the considered higher-order harmonic components was used:

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$$THD = \frac{\sqrt{\Sigma_{v \in n} F_{mv}^2}}{F_{m1}} \cdot 100\% \quad (11)$$

where F_{m1} is the fundamental MMF amplitude, F_{mv} is the amplitude of the ν-harmonic, and n={5,7,11,13,17,19,23,25} is the set of harmonic orders included in the THD calculation.

3. RESULTS AND DISCUSSION

For the investigated standard winding with a coil pitch of y=9, the calculated MMF spectrum contains, in addition to the fundamental harmonic, the *5th, 7th, 11th, 13th, 17th, 19th, 23rd* and *25th* spatial harmonics within the considered harmonic range. Their amplitudes relative to the fundamental harmonic are 4.545%, 2.654%, 1.672%, 1.745%, 5.890%, 5.272%, 0.981%, and 0.727%, respectively.

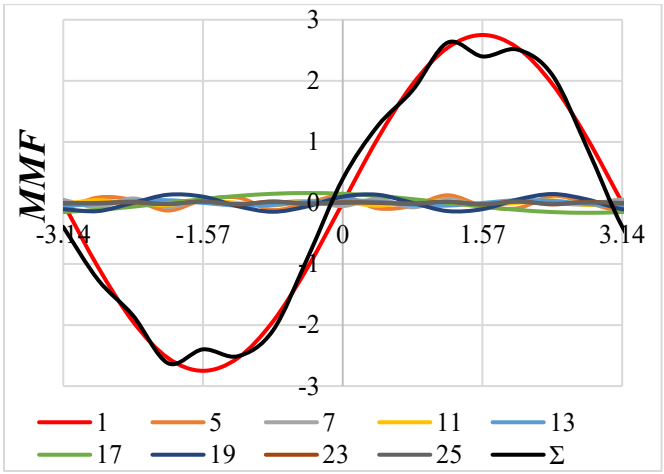
In the same manner, for the combined winding with the same pitch y = 9, the MMF waveform also contains, in addition to the fundamental harmonic, the *5th, 7th, 11th, 13th, 17th, 19th, 23rd* and *25th* harmonics, whose amplitudes relative to the fundamental harmonic are respectively 1.939%, 1.516%, 0.952%, 0.740%, 5.888%, 5.253%, 0.423%, and 0.423%.

By comparing these values, it can be observed that for the combined winding, the amplitudes of several higher harmonics are reduced compared with the standard winding: by 57.37% for the 5th harmonic, 42.88% for the 7th harmonic, 43.09% for the 11th harmonic, 57.56% for the 13th harmonic, 0.04% for the 17th harmonic, 0.36% for the 19th harmonic, 56.9% for the 23rd harmonic, and 41.81% for the 25th harmonic.

The obtained THD values are 9.88% for the standard winding and 8.38% for the combined winding. Thus, the combined winding demonstrates an approximately 15.2% reduction in the overall MMF harmonic distortion compared with the standard winding, confirming the improved harmonic quality of the combined winding. In addition, the winding factor increased by 3.13% for the fundamental, 17th, and 19th harmonics, while for the remaining harmonics, it decreased by 56.42% for the 5th, 13th, and 23rd harmonics and by 40.68% for the 7th, 11th, and 25th harmonics compared with the standard winding.

The obtained results show that the MMF of the combined winding exhibits lower amplitudes of the considered higher-order harmonics compared with the MMF of the standard winding. In addition, the most significant higher harmonics in the MMF of the combined winding are the 11th,13th,17th,19th and others harmonics, whereas in the standard winding the most significant ones are the 5th and 7th harmonics. Taking this into account, a shortened coil pitch with a pitch ratio of y/τ=5/6, which is commonly employed to improve the harmonic content of conventional windings, is not necessary in the present case. In the considered combined winding, the reduction of the 5th and 7th harmonics is achieved without shortening the coil pitch. In such winding variants, due to the uneven distribution of phase zones, a question may arise as to which of the two parts should be connected in "delta" and which in "star". In principle, arranging the winding parts in "star/delta" or "delta/star" configuration does not change the winding factor or the harmonic content, so the choice can be made based on technological considerations. However, if triple harmonics are present in the air gap and the standard winding circuit is connected according to a certain scheme, then the larger portion of the slots per pole and phase {q} should also correspond to that part of the combined winding. This can be justified as follows.

For example, if the standard winding is connected in "delta" and during the transition to the combined winding {q} is larger in the "delta" part, then the number of turns and resistance will be higher [9]. The circuit current in the "delta" part affects the compensation of harmonics in the air gap field that can be divided by three. At the same time, the current in the circuit decreases as the number of turns increases. Since the winding losses are quadratically dependent on the current and linearly dependent on the winding resistance, a larger value of {q} for the "delta" circuit relatively reduces the additional losses. This method allows the construction of a MMF curve that is even closer to a sinusoidal shape compared to standard three-phase windings. This difference can be clearly seen when the higher harmonic content in the MMF is expanded into a Fourier series (FFT) (*Fig.4.*).



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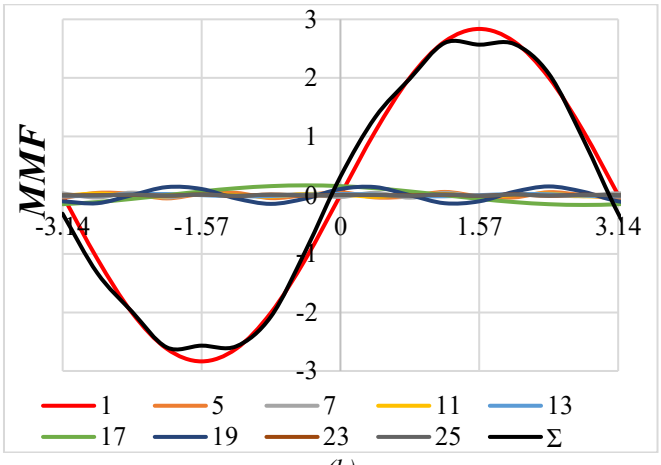

(b)

Figure 4. Spatial MMF harmonic spectrum obtained by DFT analysis: (a) standard; (b) combined

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One of the necessary conditions for this is the generation of nearly identical flux in each slot, which is achieved by increasing the number of winding turns in the "delta" section by a factor of $\sqrt{3}$. Due to the lower current and the limited slot area, a corresponding reduction in the cross-sectional area of the winding conductors is required.

As mentioned above, the electromagnetic characteristics of such three-phase windings are quite close to those of six-phase windings, in particular, the proportion of higher harmonics relative to the fundamental harmonic in the MMF distribution curve is comparatively low.

According to the literature, higher-order spatial harmonics in the air-gap can negatively affect motor operation by contributing to additional electromagnetic losses, torque pulsations, noise, and vibration [8,9]. These additional losses may account for up to 6% of the power consumed by the motor [10]. Therefore, reducing the higher-order MMF harmonic components can contribute to mitigating their associated harmonic effects and may potentially improve the electromagnetic performance of the motor. In the present study, these effects (torque pulsations, noise, and vibration) are not evaluated directly; the proposed winding is analyzed based on the reduction of higher-order MMF harmonic components and the corresponding THD, indicating a more sinusoidal MMF waveform.

4. CONCLUSIONS

The analysis of the MMF harmonic spectrum for the combined winding with a coil pitch of y=9 shows that, in addition to the fundamental component, the 5th, 7th, 11th, 13th, 17th, 19th, 23rd, and 25th harmonics are present, with relative amplitudes of 1.939%, 1.516%, 0.952%, 0.74%, 5.888%, 5.253%, 0.423%, and 0.423%, respectively. Compared with the standard winding, the combined configuration significantly reduces several higher-order harmonic amplitudes, with reductions of 57.37% (5th), 42.88% (7th), 43.09% (11th), 57.56% (13th), 0.04% (17th), 0.36% (19th), 56.9% (23rd), and 41.81% (25th).

The winding factor increased by 3.13% for the fundamental, 17th, and 19th harmonics, while it decreased by 56.42% for the 5th, 13th, and 23rd harmonics and by 40.68% for the 7th, 11th, and 25th harmonics compared with the standard winding.

The results show that the combined winding configuration leads to a significant redistribution of the MMF harmonic spectrum. In the considered combined winding, the 17th and 19th harmonics remain the largest higher components, while the 5th, 7th, 11th, 13th harmonics are significantly reduced compared with those of the standard winding.

Overall, the combined winding provides a more favorable harmonic profile and improved MMF quality. The results further show that the observed reduction of the 5th and 7th harmonics is achieved without shortening the coil pitch. Therefore, in the considered combined winding with y=9, a shortened coil pitch with a pitch ratio of y/τ=5/6 is not necessary to obtain the observed improvement in these harmonic components.

The overall harmonic assessment further confirms the advantage of the combined winding, the THD calculated from the considered higher-order harmonic components decreases from 9.88% to 8.38%, corresponding to an approximately 15.2% reduction in MMF harmonic distortion.

Author Contribution: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization, Nuralibek.Rashidov. and Furkat. Tuychiev.; methodology, Makhsud. Bobojanov.; validation, Makhsud. Bobojanov and Nuralibek.Rashidov.; formal analysis, Furkat. Tuychiev; investigation, Nuralibek.Rashidov.; resources, Nuralibek.Rashidov; data curation, Nuralibek.Rashidov.; writing—original draft preparation, Nuralibek.Rashidov.; writing—review and editing, Makhsud.Bobojanov.; visualization, Nuralibek.Rashidov.; supervision, Makhsud.Bobojanov. All authors have read and agreed to the published version of the manuscript".

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