Chapter 2
Electromagnetic Parameters of Sinusoidal Three-Phase Windings

The determination of electromagnetic parameters for three-phase windings analyzed in this work is based on the harmonic analysis of instantaneous periodic functions of rotating magnetomotive force generated by these windings. The instantaneous spatial graphical images of such magnetomotive force are created using winding electrical diagram layouts, real relative values of coil turn numbers in coil groups, and phasor diagram of phase currents formed at a respective point of time. The relative values of instantaneous magnitudes of winding currents and their flow directions are identified from this diagram.

Since the rotating magnetomotive forces of the fundamental and higher-order space harmonics generated by three-phase windings do not change their amplitude values over time, it is sufficient to determine instantaneous currents as well as plot the space distribution of magnetomotive force at a single designated time point, for example $t = 0$.

It is assumed that the relative values of current amplitudes in phase windings are $I^*_{m\mathrm{U}} = I^*_{m\mathrm{V}} = I^*_{m\mathrm{W}} = 1$. Then the relative values of instantaneous electric current magnitudes in phase windings at time $t = 0$ are as follows:

$$\begin{cases} i^*_{\mathrm{U}} = \sin\omega t = \sin 0^\circ = 0; \\ i^*_{\mathrm{V}} = \sin\left(\omega t - 120^\circ\right) = \sin\left(-120^\circ\right) = -0.866; \\ i^*_{\mathrm{W}} = \sin\left(\omega t - 240^\circ\right) = \sin\left(-240^\circ\right) = 0.866. \end{cases} \tag{2.1}$$

Based on the determined real relative values of coil turn numbers in coil groups N^*_i (Tables 1.2–1.21) and instantaneous magnitudes of currents in phase windings i^* (2.1), the conditional values of magnetomotive force changes ΔF_n are determined at time $t = 0$ in the slots of magnetic circuit:

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$$\Delta F_n = \Delta F_n^{'} \pm \Delta F_n^{''}; \tag{2.2}$$

where $\Delta F_n^{'}$ is the change of magnetic potential difference generated by the side of the coil located in the top layer of n-th slot; $\Delta F_n^{''}$ is the change of magnetic potential difference generated by the side of the coil located in the bottom layer of the same slot.

The space distribution of rotating magnetomotive force at time $t=0$ is created by calculating changes of magnetic potential difference in the slots of magnetic circuit for the corresponding winding. In this way a non-sinusoidal (stair-shaped) periodic space function is obtained.

In general case, a symmetric three-phase current system in the distributed symmetric three-phase winding creates curves of magnetomotive force which move in space and periodically change over time, as well as have a characteristic stair-shaped form (consisting of several rectangular magnetomotive forces of different height and width) (Fig. 2.1).

The conditional magnitudes of ν-th harmonic amplitudes of rotating magnetomotive forces of the analyzed simple and sinusoidal three-phase windings are calculated analytically according to this expression:

$$F_{m\nu} = \frac{4}{\pi \ \nu} \sum_{j=1}^{k} F_{jr} \sin\left(\nu \frac{\alpha_j}{2}\right); \tag{2.3}$$

where: k is the number of rectangles forming the half-periods of the stair-shaped magnetomotive force; ν is the number of odd space harmonic; F_{jr} is the conditional height of the j-th rectangle of the stair-shaped magnetomotive force half-period; α_j

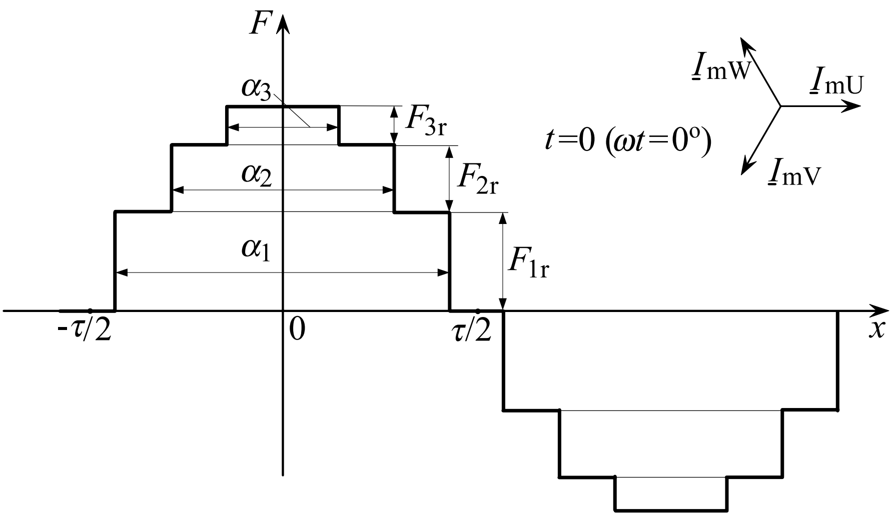

Fig. 2.1 Instantaneous graphical image of the stair-shaped rotating magnetomotive force generated by three-phase windings and symmetric in respect of the coordinate axes

is the width of the j-th rectangle of the stair-shaped magnetomotive force curve, expressed in electrical degrees of the fundamental harmonic.

Since the magnetomotive forces of the higher-order space harmonics negatively impact the operation of the alternating current electrical machines, for this reason the absolute relative values of the amplitudes of these harmonics are considered as negative. All these negative relative magnitudes are combined into a single equivalent magnitude which is equal to the square root of the sum of squares of the relative amplitude values of higher-order magnetomotive force harmonics. Based on such reasoning, three-phase windings of any type can be evaluated from electromagnetic point of view using the electromagnetic efficiency factor, which is expressed as:

$$k_{\mathrm{ef}} = 1 - \sqrt{\sum_{\nu=1}^{\infty} f_\nu^2 - 1}; \tag{2.4}$$

where f_ν is the absolute relative amplitude value of the ν-th harmonic of rotating magnetomotive force:

$$f_\nu = \frac{F_{m\nu}}{F_{m1}}; \tag{2.5}$$

where F_{m1} is the conditional amplitude value of the first (fundamental) harmonic of rotating magnetomotive force; $F_{m\nu}$ is the conditional amplitude value of the ν-th harmonic of rotating magnetomotive force.

This factor indicates what relative part of rotating magnetomotive force of the fundamental harmonic remains after the negative impact of its higher-order harmonics-induced magnetomotive force is compensated.

From electromagnetic standpoint, the three-phase winding would be optimal if the factor k_{ef} was equal to one. This means that the closer is the value of this indicator to one for a real three-phase winding, the higher is the electromagnetic quality of this winding.

The expression required to calculate the winding factor of the first harmonic for sinusoidal three-phase windings was created based on related literature [12]:

$$k_{w1} = \sum_{i=1}^{q} 2N_i^* \sin\left(\frac{\pi\ y_i}{2\tau}\right). \tag{2.6}$$

Similarly, the expression of the winding factor of the ν-th harmonic is:

$$k_{w\nu} = \sum_{i=1}^{q} 2N_i^* \sin\left(\nu\frac{\pi\ y_i}{2\tau}\right). \tag{2.7}$$

Winding factors indicate only the relative values of respective harmonic amplitudes of rotating magnetomotive force in regard of the corresponding harmonic amplitudes of concentrated full-pitched three-phase winding, but do not represent similar reciprocal relative values of harmonics of rotating magnetomotive force for the analyzed three-phase winding. Furthermore, because winding factors form a multi-value system, it is difficult to use these factors to compare three-phase windings of different parameters or windings which belong to several different electromagnetic types.

2.1 Electromagnetic Parameters of Simple and Sinusoidal Three-Phase Windings with $q=2$

To calculate the conditional magnitudes ΔF_n related to the changes of magnetic potential difference in the slots of magnetic circuit in simple and sinusoidal three-phase windings with $q=2$, the electrical diagram layouts of these windings presented in Figs. 1.4 and 1.5, earlier-acquired results related to the relative values of coil turn numbers listed in Tables 1.2, 1.7, 1.12, 1.17, as well as the relative values of electric current magnitudes of phase windings determined at time $t=0$ using equation system (2.1) were used. Values of ΔF_n are calculated using formula (2.2). Calculation results for the discussed windings are listed in Table 2.1.

Symbols from the second row of the table above have the following designations: $\mathbf{O_{12}}$—maximum average pitch concentric (simple) three-phase winding; $\mathbf{P_{12}}$—maximum average pitch STW with the optimized pulsating magnetomotive force; $\mathbf{R_{12}}$—maximum average pitch STW with the optimized rotating magnetomotive force; $\mathbf{O_{22}}$—short average pitch concentric (simple) three-phase winding; $\mathbf{P_{22}}$—short average pitch STW with the optimized pulsating magnetomotive force; $\mathbf{R_{22}}$—sort average pitch STW with the optimized rotating magnetomotive force.

According to the results presented in Table 2.1, the space distributions of magnetomotive force were created for simple and sinusoidal three-phase windings at the selected point in time (Figs. 2.2b and 2.3b).

Table 2.1 Conditional magnitudes related to the changes of magnetic potential difference in the slots of magnetic circuit (ΔF_n) in simple and STW with $q=2$ at time $t=0$

Slot no.	Winding type					
	$\mathbf{O_{12}}$	$\mathbf{P_{12}}$	$\mathbf{R_{12}}$	$\mathbf{O_{22}}$	$\mathbf{P_{22}}$	$\mathbf{R_{22}}$
1	0	0	0	–0.2165	–0.204	–0.1160
2	–0.2165	–0.201	–0.232	–0.2165	–0.229	–0.317
3	–0.433	–0.464	–0.402	–0.433	–0.433	–0.433
4	–0.433	–0.402	–0.464	–0.433	–0.433	–0.433
5	–0.433	–0.464	–0.402	–0.2165	–0.229	–0.317
6	–0.2165	–0.201	–0.232	–0.2165	–0.204	–0.1160
7	0	0	0	0.2165	0.204	0.1160
8	0.2165	0.201	0.232	0.2165	0.229	0.317
9	0.433	0.464	0.402	0.433	0.433	0.433
10	0.433	0.402	0.464	0.433	0.433	0.433
11	0.433	0.464	0.402	0.2165	0.229	0.317
12	0.2165	0.201	0.232	0.2165	0.204	0.1160

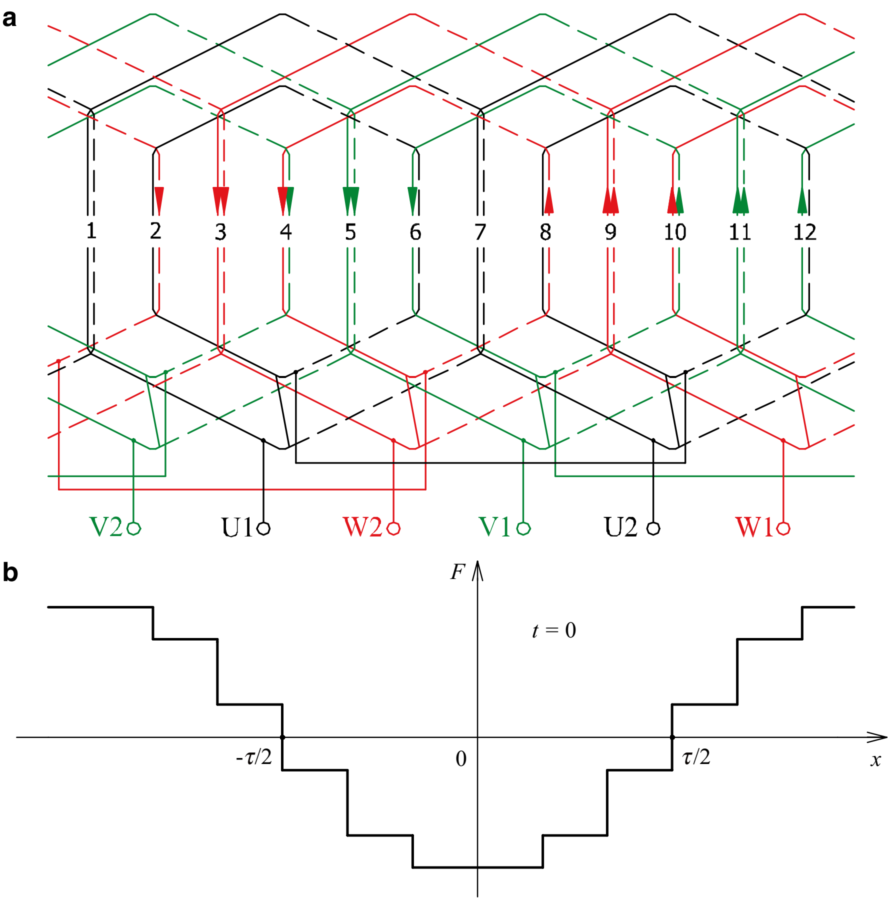

Fig. 2.2 Electrical diagram layout of the maximum average pitch concentric three-phase winding ($\mathbf{O}_{12}$) with $q = 2$ (**a**) and the distribution of its rotating magnetomotive force at $t = 0$ (**b**)

The magnetomotive force space distributions for the other maximum and short average pitch three-phase windings ($\mathbf{P}_{12}$, $\mathbf{R}_{12}$, $\mathbf{O}_{22}$, $\mathbf{P}_{22}$) are similar to those presented above. These distributions differ only in the conditional heights of the magnetomotive force rectangles F_{jr}.

Based on the results from Table 2.1 and figures presented above, the parameters of the negative half-period of rotating magnetomotive forces, which are listed in Table 2.2, were determined.

According to the results calculated using expression (2.3) and presented in Table 2.2, the harmonic analysis of the discussed windings was performed. The results of this analysis are shown in Table 2.3.

Based on the results presented in Table 2.3, the absolute relative values of ν-th harmonic amplitudes of rotating magnetomotive forces f_ν were calculated for the analyzed windings using expression (2.5) (Table 2.4).

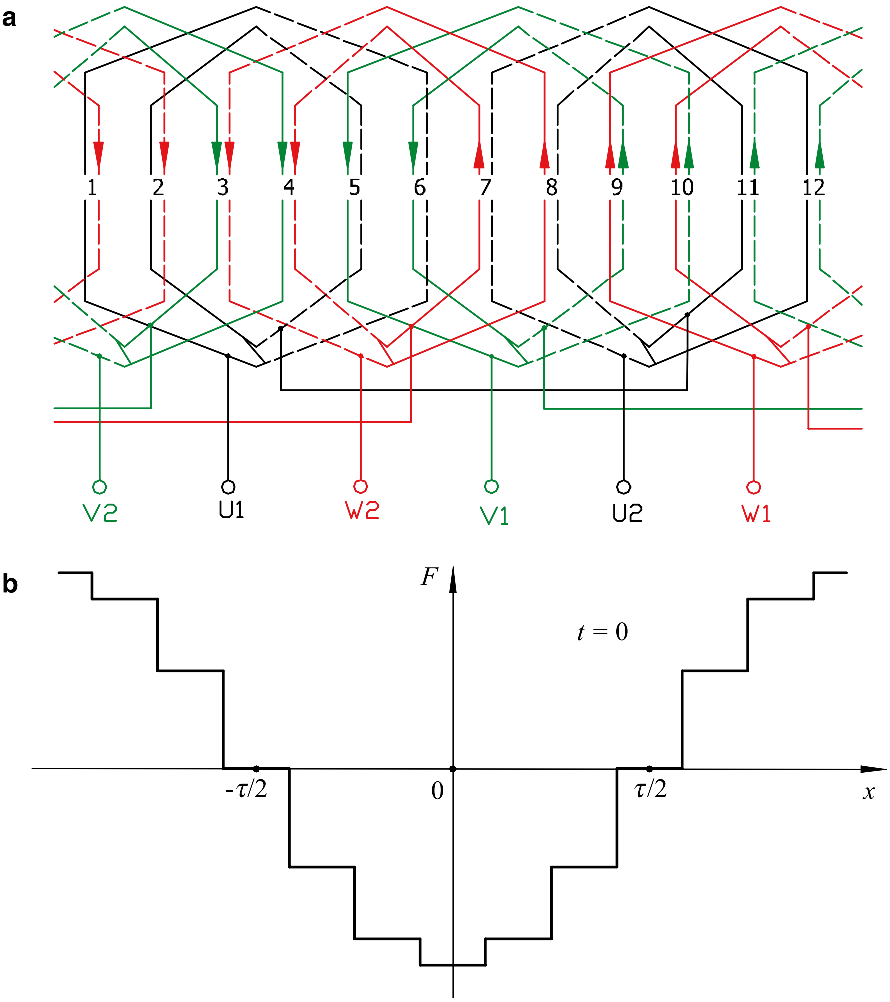

Fig. 2.3 Electrical diagram layout of the short average pitch sinusoidal three-phase winding ($\mathbf{R}_{22}$) with $q = 2$ (**a**) and the distribution of its rotating magnetomotive force at $t = 0$ (**b**)

The electromagnetic efficiency factors k_{ef} of the discussed windings (Table 2.5) were calculated on the basis of results presented in Table 2.4, using expression (2.4). These factors were determined for each winding using the relative amplitude values of rotating magnetomotive forces up to 97-th space harmonic.

Using parameters of the analyzed windings, the winding factors of the first and higher harmonics were calculated for these windings according to formulas (2.6) and (2.7) (Table 2.6).

Table 2.2 Parameters of the negative half-period of rotating magnetomotive forces for simple and STW with $q = 2$

Parameter	Winding type					
	O_{12}	**P_{12}**	**R_{12}**	**O_{22}**	**P_{22}**	**R_{22}**
k	3	3	3	3	3	3
F_{1r}	–0.2165	–0.201	–0.232	–0.433	–0.433	–0.433
F_{2r}	–0.433	–0.464	–0.402	–0.2165	–0.229	–0.317
F_{3r}	–0.2165	–0.201	–0.232	–0.2165	–0.204	–0.1160
α_1	180°	180°	180°	150°	150°	150°
α_2	120°	120°	120°	90°	90°	90°
α_3	60°	60°	60°	30°	30°	30°

Table 2.3 Harmonic analysis results of rotating magnetomotive forces of simple and STW with $q = 2$

ν—Harmonic sequence number	Winding type					
	O_{12}	**P_{12}**	**R_{12}**	**O_{22}**	**P_{22}**	**R_{22}**
1	–0.891	–0.896	–0.886	–0.799	–0.806	–0.856
5	0.013	0.026	0	–0.043	–0.037	0
7	–0.009	–0.018	0	–0.031	–0.027	0
11	0.081	0.081	0.081	–0.073	–0.073	–0.078
13	–0.069	–0.069	–0.068	0.061	0.062	0.066
17	0.004	0.008	0	0.013	0.011	0
19	–0.003	–0.007	0	0.011	0.010	0
23	0.039	0.039	0.039	0.035	0.035	0.037
25	–0.036	–0.036	–0.035	–0.032	–0.032	–0.034
29	0.002	0.004	0	–0.007	–0.006	0
31	–0.002	–0.004	0	–0.007	–0.006	0

Table 2.4 Absolute relative values of ν-th harmonic amplitudes of rotating magnetomotive forces (f_ν) for simple and STW with $q = 2$

ν—Harmonic sequence number	Winding type					
	O_{12}	**P_{12}**	**R_{12}**	**O_{22}**	**P_{22}**	**R_{22}**
1	1	1	1	1	1	1
5	0.015	0.029	0	0.054	0.046	0
7	0.010	0.020	0	0.039	0.033	0
11	0.091	0.090	0.091	0.091	0.091	0.091
13	0.077	0.077	0.077	0.076	0.077	0.077
17	0.004	0.009	0	0.016	0.014	0
19	0.003	0.008	0	0.014	0.012	0
23	0.044	0.044	0.044	0.044	0.043	0.043
25	0.040	0.040	0.040	0.040	0.040	0.040
29	0.002	0.004	0	0.009	0.007	0
31	0.002	0.004	0	0.009	0.007	0

Table 2.5 Electromagnetic efficiency factors k_{ef} of simple and STW with $q=2$

Winding type					
$\mathbf{O_{12}}$	$\mathbf{P_{12}}$	$\mathbf{R_{12}}$	$\mathbf{O_{22}}$	$\mathbf{P_{22}}$	$\mathbf{R_{22}}$
0.8517	0.8485	0.8531	0.8364	0.8412	0.8534

Table 2.6 Winding factors of the first and higher harmonics ($k_{w\,\nu}$) of simple and STW with $q=2$

ν—Harmonic sequence number	Winding type					
	$\mathbf{O_{12}}$	$\mathbf{P_{12}}$	$\mathbf{R_{12}}$	$\mathbf{O_{22}}$	$\mathbf{P_{22}}$	$\mathbf{R_{22}}$
1	0.933	0.938	0.928	0.8365	0.844	0.897
5	0.0670	0.1342	0	–0.224	–0.1971	0
7	–0.0670	–0.1342	0	–0.224	–0.1971	0
11	–0.933	–0.938	–0.928	0.8365	0.844	0.897
13	0.933	0.938	0.928	–0.8365	–0.844	–0.897
17	0.0670	0.1342	0	0.224	0.1971	0
19	–0.0670	–0.1342	0	0.224	0.1971	0

2.2 Electromagnetic Parameters of Simple and Sinusoidal Three-Phase Windings with $q=3$

To calculate the conditional magnitudes ΔF_n related to the changes of magnetic potential difference in the slots of magnetic circuit in simple and sinusoidal three-phase windings with $q=3$, the electrical diagram layouts of these windings presented in Figs. 1.9 and 1.21, earlier-acquired results related to the relative values of coil turn numbers listed in Tables 1.3, 1.8, 1.13, 1.18, as well as the relative values of electric current magnitudes of phase windings determined at time $t=0$ using equation system (2.1) were used. Values of ΔF_n are calculated using formula (2.2). Calculation results for the discussed windings are listed in Table 2.7.

According to the results presented in Table 2.7, the space distributions of magnetomotive force were created for simple and sinusoidal three-phase windings at the selected point in time (Figs. 2.4b and 2.5b).

The magnetomotive force space distributions for the other maximum and short average pitch three-phase windings ($\mathbf{P_{13}}$, $\mathbf{R_{13}}$, $\mathbf{O_{23}}$ $\mathbf{P_{23}}$) are similar to those presented above. These distributions differ only in the conditional heights of the magnetomotive force rectangles F_{jr}.

Based on the results from Table 2.7 and figures presented above, the parameters of the negative half-period of rotating magnetomotive forces, which are listed in Table 2.8, were determined.

Table 2.7 Conditional magnitudes related to the changes of magnetic potential difference in the slots of magnetic circuit (ΔF_n) in simple and STW with $q=3$ at time $t=0$

	Winding type					
Slot no.	$\mathbf{O_{13}}$	$\mathbf{P_{13}}$	$\mathbf{R_{13}}$	$\mathbf{O_{23}}$	$\mathbf{P_{23}}$	$\mathbf{R_{23}}$
1	0	0	0	–0.1444	–0.1116	–0.0522
2	–0.1444	–0.1226	–0.1044	–0.1444	–0.1503	–0.1504
3	–0.1444	–0.1503	–0.1963	–0.1444	–0.1710	–0.230
4	–0.289	–0.320	–0.264	–0.289	–0.283	–0.282
5	–0.289	–0.273	–0.301	–0.289	–0.301	–0.301
6	–0.289	–0.273	–0.301	–0.289	–0.283	–0.282
7	–0.289	–0.320	–0.264	–0.1444	–0.1710	–0.230
8	–0.1444	–0.1503	–0.1963	–0.1444	–0.1503	–0.1504
9	–0.1444	–0.1226	–0.1044	–0.1444	–0.1116	–0.0522
10	0	0	0	0.1444	0.1116	0.0522
11	0.1444	0.1226	0.1044	0.1444	0.1503	0.1504
12	0.1444	0.1503	0.1963	0.1444	0.1710	0.230
13	0.289	0.320	0.264	0.289	0.283	0.282
14	0.289	0.273	0.301	0.289	0.301	0.301
15	0.289	0.273	0.301	0.289	0.283	0.282
16	0.289	0.320	0.264	0.1444	0.1710	0.230
17	0.1444	0.1503	0.1963	0.1444	0.1503	0.1504
18	0.1444	0.1226	0.1044	0.1444	0.1116	0.0522

According to the results calculated using expression (2.3) and presented in Table 2.8, the harmonic analysis of the discussed windings was performed. The results of this analysis are shown in Table 2.9.

Based on the results presented in Table 2.9, the absolute relative values of ν-th harmonic amplitudes of rotating magnetomotive forces f_ν were calculated for the analyzed windings using expression (2.5) (Table 2.10).

The electromagnetic efficiency factors k_{ef} of the discussed windings (Table 2.11) were calculated on the basis of results presented in Table 2.10, using expression (2.4). These factors were determined for each winding using the relative amplitude values of rotating magnetomotive forces up to 97-th space harmonic.

Using parameters of the analyzed windings, the winding factors of the first and higher harmonics were calculated for these windings according to formulas (2.6) and (2.7) (Table 2.12).

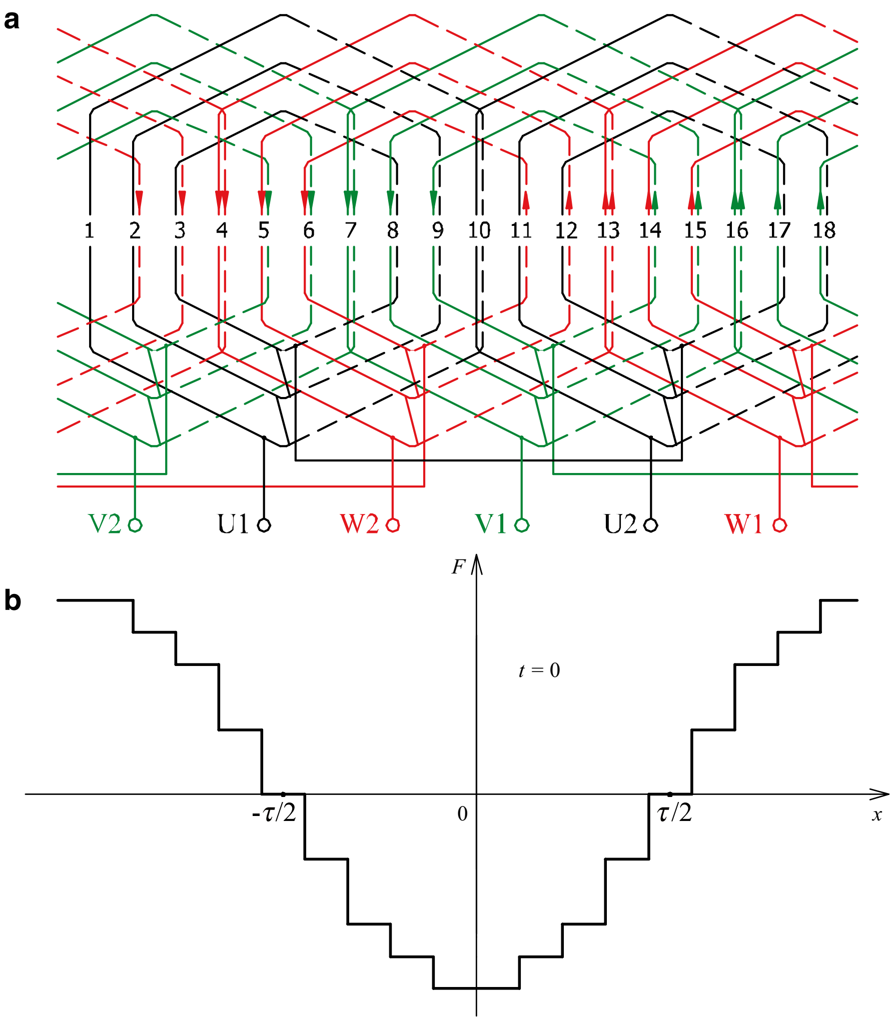

Fig. 2.4 Electrical diagram layout of the maximum average pitch concentric three-phase winding (**O**$_{13}$) with $q = 3$ (**a**) and the distribution of its rotating magnetomotive force at $t = 0$ (**b**)

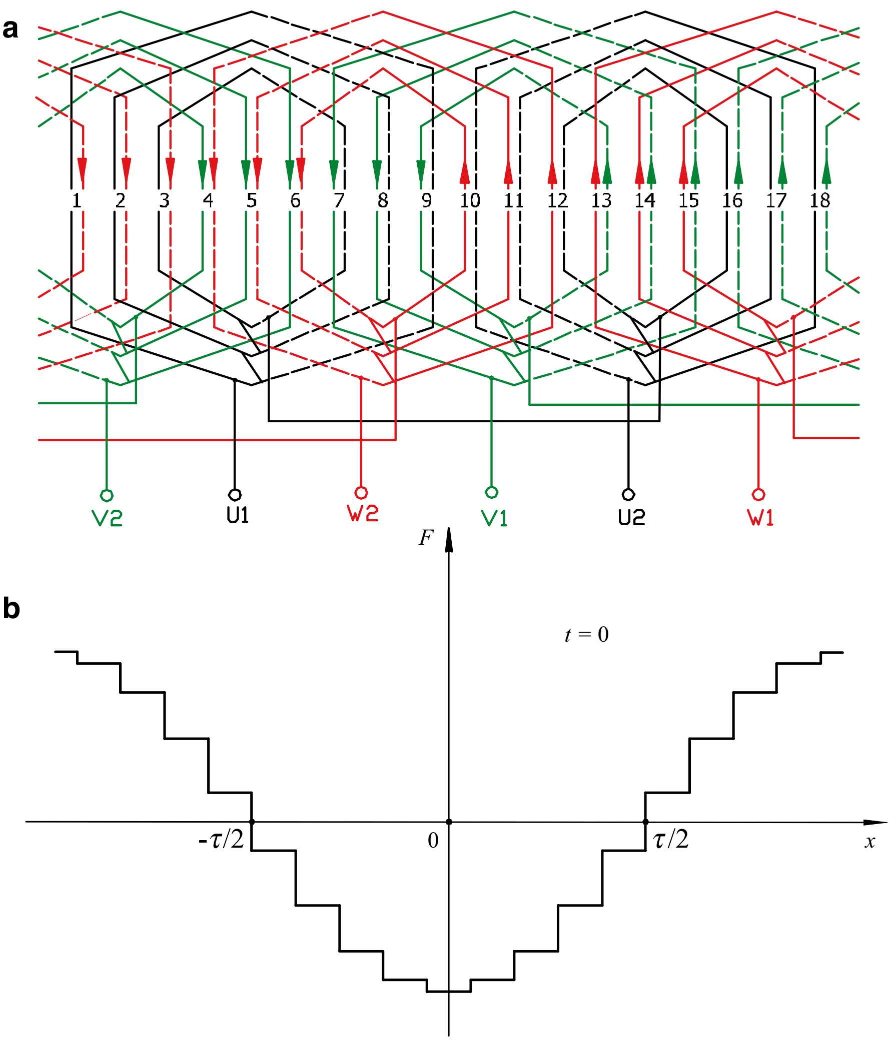

Fig. 2.5 Electrical diagram layout of the short average pitch sinusoidal three-phase winding ($\mathbf{R}_{23}$) with $q = 3$ (**a**) and the distribution of its rotating magnetomotive force at $t = 0$ (**b**)

Table 2.8 Parameters of the negative half-period of rotating magnetomotive forces for simple and STW with $q=3$

Parameter	Winding type					
	O$_{13}$	**P**$_{13}$	**R**$_{13}$	**O**$_{23}$	**P**$_{23}$	**R**$_{23}$
k	4	4	4	5	5	5
F_{1r}	–0.289	–0.273	–0.301	–0.1445	–0.1505	–0.1505
F_{2r}	–0.289	–0.320	–0.264	–0.289	–0.283	–0.282
F_{3r}	–0.1444	–0.1503	–0.1963	–0.1444	–0.1710	–0.230
F_{4r}	–0.1444	–0.1226	–0.1044	–0.1444	–0.1503	–0.1504
F_{5r}	0	0	0	–0.1444	–0.1116	–0.0522
α_1	160°	160°	160°	180°	180°	180°
α_2	120°	120°	120°	140°	140°	140°
α_3	80°	80°	80°	100°	100°	100°
α_4	40°	40°	40°	60°	60°	60°
α_5	0	0	0	20°	20°	20°

Table 2.9 Harmonic analysis results of rotating magnetomotive forces of simple and STW with $q=3$

ν–Harmonic sequence number	Winding type					
	O$_{13}$	**P**$_{13}$	**R**$_{13}$	**O**$_{23}$	**P**$_{23}$	**R**$_{23}$
1	–0.862	–0.872	–0.875	–0.794	–0.817	–0.861
5	–0.007	0.008	0	–0.036	–0.026	0
7	–0.019	–0.021	0	–0.021	–0.012	0
11	0.012	0.013	0	–0.013	–0.008	0
13	0.003	–0.003	0	–0.014	–0.010	0
17	0.051	0.051	0.051	–0.047	–0.048	–0.051
19	–0.045	–0.046	–0.046	0.042	0.043	0.045
23	–0.002	0.002	0	0.008	0.006	0
25	–0.005	–0.006	0	0.006	0.003	0
29	0.004	0.005	0	0.005	0.003	0
31	0.001	–0.001	0	0.006	0.004	0

Table 2.10 Absolute relative values of ν-th harmonic amplitudes of rotating magnetomotive forces (f_ν) for simple and STW with $q=3$

ν–Harmonic sequence number	Winding type					
	O$_{13}$	**P**$_{13}$	**R**$_{13}$	**O**$_{23}$	**P**$_{23}$	**R**$_{23}$
1	1	1	1	1	1	1
5	0.008	0.009	0	0.045	0.032	0
7	0.022	0.024	0	0.026	0.015	0
11	0.014	0.015	0	0.016	0.010	0
13	0.003	0.003	0	0.018	0.012	0
17	0.059	0.058	0.058	0.059	0.059	0.059
19	0.052	0.053	0.053	0.053	0.053	0.052
23	0.002	0.002	0	0.010	0.007	0
25	0.006	0.007	0	0.008	0.004	0
29	0.005	0.006	0	0.006	0.004	0
31	0.001	0.001	0	0.008	0.005	0

Table 2.11 Electromagnetic efficiency factors k_{ef} of simple and STW with $q=3$

Winding type					
$\mathbf{O_{13}}$	$\mathbf{P_{13}}$	$\mathbf{R_{13}}$	$\mathbf{O_{23}}$	$\mathbf{P_{23}}$	$\mathbf{R_{23}}$
0.9001	0.8993	0.9047	0.8864	0.8965	0.9045

Table 2.12 Winding factors of the first and higher harmonics ($k_{w\,\nu}$) of simple and STW with $q=3$

ν—Harmonic sequence number	Winding type					
	$\mathbf{O_{13}}$	$\mathbf{P_{13}}$	$\mathbf{R_{13}}$	$\mathbf{O_{23}}$	$\mathbf{P_{23}}$	$\mathbf{R_{23}}$
1	0.902	0.913	0.916	0.831	0.855	0.902
5	–0.0378	0.0432	0	–0.1884	–0.1350	0
7	–0.1359	–0.1528	0	–0.1536	–0.0883	0
11	–0.1359	–0.1528	0	0.1536	0.0883	0
13	–0.0378	0.0432	0	0.1884	0.1350	0
17	0.902	0.913	0.916	–0.831	–0.855	–0.902
19	–0.902	–0.913	–0.916	0.831	0.855	0.902

2.3 Electromagnetic Parameters of Simple and Sinusoidal Three-Phase Windings with $q=4$

To calculate the conditional magnitudes ΔF_n related to the changes of magnetic potential difference in the slots of magnetic circuit in simple and sinusoidal three-phase windings with $q=4$, the electrical diagram layouts of these windings presented in Figs. 1.11 and 1.23, earlier-acquired results related to the relative values of coil turn numbers listed in Tables 1.4, 1.9, 1.14, 1.19, as well as the relative values of electric current magnitudes of phase windings determined at time $t=0$ using equation system (2.1) were used. Values of ΔF_n are calculated using formula (2.2). Calculation results for the discussed windings are listed in Table 2.13.

According to the results presented in Table 2.13, the space distributions of magnetomotive force were created for simple and sinusoidal three-phase windings at the selected point in time (Figs. 2.6b and 2.7b).

The magnetomotive force space distributions for the other maximum and short average pitch three-phase windings ($\mathbf{P_{14}}$, $\mathbf{R_{14}}$, $\mathbf{O_{24}}$, $\mathbf{P_{24}}$) are similar to those presented above. These distributions differ only in the conditional heights of the magnetomotive force rectangles F_{jr}.

Based on the results from Table 2.13 and figures presented above, the parameters of the negative half-period of rotating magnetomotive forces, which are listed in Table 2.14, were determined.

According to the results calculated using expression (2.3) and presented in Table 2.14, the harmonic analysis of the discussed windings was performed. The results of this analysis are shown in Table 2.15.

Based on the results presented in Table 2.15, the absolute relative values of ν-th harmonic amplitudes of rotating magnetomotive forces f_ν were calculated for the analyzed windings using expression (2.5) (Table 2.16).

The electromagnetic efficiency factors k_{ef} of the discussed windings (Table 2.17) were calculated on the basis of results presented in Table 2.16, using expression (2.4). These factors were determined for each winding using the relative amplitude values of rotating magnetomotive forces up to 97-th space harmonic.

Using parameters of the analyzed windings, the winding factors of the first and higher harmonics were calculated for these windings according to formulas (2.6) and (2.7) (Table 2.18).

Table 2.13 Conditional magnitudes related to the changes of magnetic potential difference in the slots of magnetic circuit (ΔF_n) in simple and STW with $q=4$ at time $t=0$

	Winding type					
Slot no.	**O_{14}**	**P_{14}**	**R_{14}**	**O_{24}**	**P_{24}**	**R_{24}**
1	0	0	0	–0.10825	–0.0795	–0.0295
2	–0.10825	–0.0865	–0.0590	–0.10825	–0.1036	–0.0865
3	–0.10825	–0.1059	–0.1141	–0.10825	–0.1205	–0.1376
4	–0.10825	–0.1182	–0.1612	–0.10825	–0.1294	–0.1793
5	–0.2165	–0.245	–0.1974	–0.2165	–0.209	–0.209
6	–0.2165	–0.205	–0.220	–0.2165	–0.224	–0.224
7	–0.2165	–0.212	–0.228	–0.2165	–0.224	–0.224
8	–0.2165	–0.205	–0.220	–0.2165	–0.209	–0.209
9	–0.2165	–0.245	–0.1974	–0.10825	–0.1294	–0.1793
10	–0.10825	–0.1182	–0.1612	–0.10825	–0.1205	–0.1376
11	–0.10825	–0.1059	–0.1141	–0.10825	–0.1036	–0.0865
12	–0.10825	–0.0865	–0.0590	–0.10825	–0.0795	–0.0295
13	0	0	0	0.10825	0.0795	0.0295
14	0.10825	0.0865	0.0590	0.10825	0.1036	0.0865
15	0.10825	0.1059	0.1141	0.10825	0.1205	0.1376
16	0.10825	0.1182	0.1612	0.10825	0.1294	0.1793
17	0.2165	0.245	0.1974	0.2165	0.209	0.209
18	0.2165	0.205	0.220	0.2165	0.224	0.224
19	0.2165	0.212	0.228	0.2165	0.224	0.224
20	0.2165	0.205	0.220	0.2165	0.209	0.209
21	0.2165	0.245	0.1974	0.10825	0.1294	0.1793
22	0.10825	0.1182	0.1612	0.10825	0.1205	0.1376
23	0.10825	0.1059	0.1141	0.10825	0.1036	0.0865
24	0.10825	0.0865	0.0590	0.10825	0.0795	0.0295

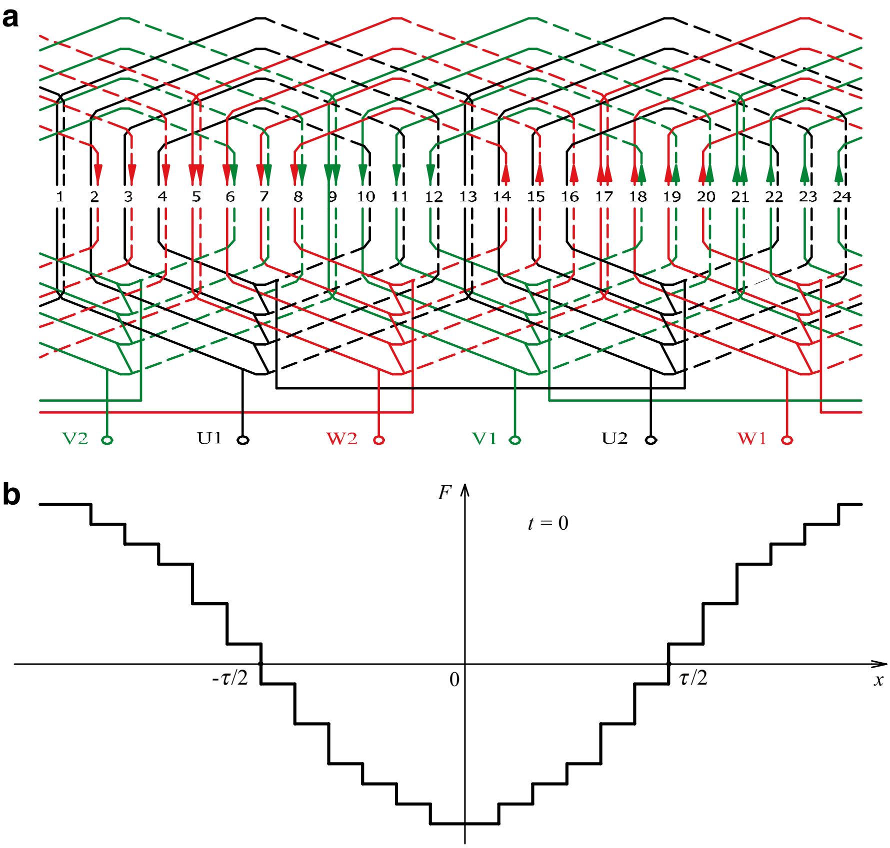

Fig. 2.6 Electrical diagram layout of the maximum average pitch concentric three-phase winding (**O**$_{14}$) with $q = 4$ (**a**) and the distribution of its rotating magnetomotive force at $t = 0$ (**b**)

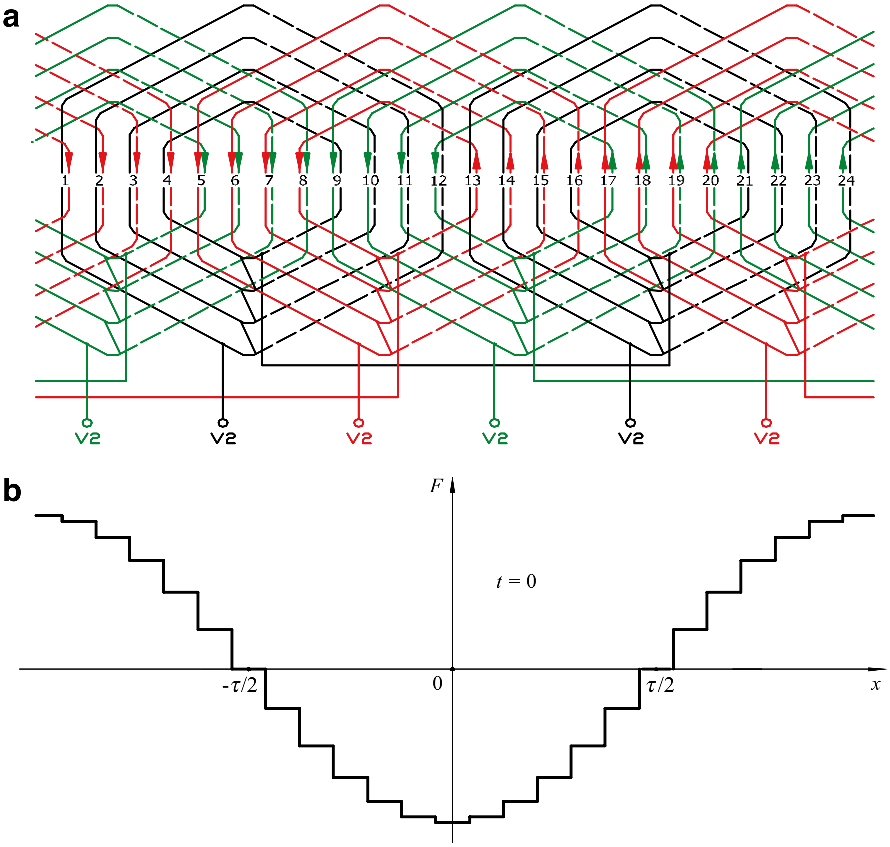

Fig. 2.7 Electrical diagram layout of the short average pitch sinusoidal three-phase winding ($\mathbf{R_{24}}$) with $q = 4$ (**a**) and the distribution of its rotating magnetomotive force at $t = 0$ (**b**)

Table 2.14 Parameters of the negative half-period of rotating magnetomotive forces for simple and STW with $q=4$

Parameter	Winding type					
	O_{14}	**P_{14}**	**R_{14}**	**O_{24}**	**P_{24}**	**R_{24}**
k	6	6	6	6	6	6
F_{1r}	–0.10825	–0.106	–0.1140	–0.2165	–0.224	–0.224
F_{2r}	–0.2165	–0.205	–0.220	–0.2165	–0.209	–0.209
F_{3r}	–0.2165	–0.245	–0.1974	–0.10825	–0.1294	–0.1793
F_{4r}	–0.10825	–0.1182	–0.1612	–0.10825	–0.1205	–0.1376
F_{5r}	–0.10825	–0.1059	–0.1141	–0.10825	–0.1036	–0.0865
F_{6r}	–0.10825	–0.0865	–0.0590	–0.10825	–0.0795	–0.0295
α_1	180°	180°	180°	165°	165°	165°
α_2	150°	150°	150°	135°	135°	135°
α_3	120°	120°	120°	105°	105°	105°
α_4	90°	90°	90°	75°	75°	75°
α_5	60°	60°	60°	45°	45°	45°
α_6	30°	30°	30°	15°	15°	15°

Table 2.15 Harmonic analysis results of rotating magnetomotive forces of simple and STW with $q=4$

ν–Harmonic sequence number	Winding type					
	O_{14}	**P_{14}**	**R_{14}**	**O_{24}**	**P_{24}**	**R_{24}**
1	–0.845	–0.860	–0.871	–0.792	–0.816	–0.863
5	–0.015	0	0	–0.034	–0.025	0
7	–0.020	–0.019	0	–0.019	–0.010	0
11	0.004	0.008	0	–0.009	–0.006	0
13	–0.004	–0.007	0	–0.008	–0.005	0
17	0.008	0.008	0	–0.008	–0.004	0
19	0.004	0	0	–0.009	–0.007	0
23	0.037	0.037	0.038	–0.034	–0.035	–0.038
25	–0.034	–0.034	–0.035	0.032	–0.033	–0.035
29	–0.003	0	0	0.006	–0.004	0
31	–0.004	–0.004	0	0.004	–0.002	0

Table 2.16 Absolute relative values of ν-th harmonic amplitudes of rotating magnetomotive forces (f_ν) for simple and STW with $q=4$

ν–Harmonic sequence number	Winding type					
	O_{14}	**P_{14}**	**R_{14}**	**O_{24}**	**P_{24}**	**R_{24}**
1	1	1	1	1	1	1
5	0.018	0	0	0.043	0.031	0
7	0.024	0.022	0	0.024	0.012	0
11	0.005	0.009	0	0.011	0.007	0
13	0.005	0.008	0	0.010	0.006	0
17	0.009	0.009	0	0.010	0.005	0
19	0.005	0	0	0.011	0.009	0
23	0.044	0.043	0.44	0.043	0.043	0.044
25	0.040	0.040	0.40	0.040	0.040	0.041
29	0.004	0	0	0.008	0.005	0
31	0.005	0.005	0	0.005	0.002	0

Table 2.17 Electromagnetic efficiency factors k_{ef} of simple and STW with $q=4$

Winding type					
O_{14}	**P_{14}**	**R_{14}**	**O_{24}**	**P_{24}**	**R_{24}**
0.9216	0.9245	0.9292	0.9103	0.9207	0.9289

Table 2.18 Winding factors of the first and higher harmonics ($k_{w\,\nu}$) of simple and STW with $q=4$

ν–Harmonic sequence number	Winding type					
	O_{14}	**P_{14}**	**R_{14}**	**O_{24}**	**P_{24}**	**R_{24}**
1	0.885	0.899	0.912	0.829	0.855	0.904
5	–0.0786	0.00015	0	–0.1778	–0.1306	0
7	–0.1456	–0.1414	0	–0.1365	–0.0755	0
11	–0.0482	–0.0895	0	0.1092	0.0676	0
13	0.0482	0.0895	0	0.1092	0.0676	0
17	0.1456	0.1414	0	–0.1365	–0.755	0
19	0.0786	–0.00015	0	–0.1778	–0.1306	0
23	–0.885	–0.899	–0.912	0.829	0.855	0.904
25	0.885	0.899	0.912	–0.829	–0.855	–0.904

2.4 Electromagnetic Parameters of Simple and Sinusoidal Three-Phase Windings with $q = 5$

To calculate the conditional magnitudes ΔF_n related to the changes of magnetic potential difference in the slots of magnetic circuit in simple and sinusoidal three-phase windings with $q = 5$, the electrical diagram layouts of these windings presented in Figs. 1.13 and 1.25, earlier-acquired results related to the relative values of coil turn numbers listed in Tables 1.5, 1.10, 1.15, 1.20, as well as the relative values of electric current magnitudes of phase windings determined at time $t = 0$ using equation system (2.1) were used. Values of ΔF_n are calculated using formula (2.2). Calculation results for the discussed windings are listed in Table 2.19.

According to the results presented in Table 2.19, the space distributions of magnetomotive force were created for simple and sinusoidal three-phase windings at the selected point in time (Figs. 2.8b and 2.9b).

The magnetomotive force space distributions for the other maximum and short average pitch three-phase windings ($\mathbf{P_{15}}$, $\mathbf{R_{15}}$, $\mathbf{O_{25}}$, $\mathbf{P_{25}}$) are similar to those presented above. These distributions differ only in the conditional heights of the magnetomotive force rectangles F_{jr}.

Based on the results from Table 2.19 and figures presented above, the parameters of the negative half-period of rotating magnetomotive forces, which are listed in Table 2.20, were determined.

According to the results calculated using expression (2.3) and presented in Table 2.20, the harmonic analysis of the discussed windings was performed. The results of this analysis are shown in Table 2.21.

Based on the results presented in Table 2.21, the absolute relative values of ν-th harmonic amplitudes of rotating magnetomotive forces f_ν were calculated for the analyzed windings using expression (2.5) (Table 2.22).

The electromagnetic efficiency factors k_{ef} of the discussed windings (Table 2.23) were calculated on the basis of results presented in Table 2.22, using expression (2.4). These factors were determined for each winding using the relative amplitude values of rotating magnetomotive forces up to 97-th space harmonic.

Using parameters of the analyzed windings, the winding factors of the first and higher harmonics were calculated for these windings according to formulas (2.6) and (2.7) (Table 2.24).

Table 2.19 Conditional magnitudes related to the changes of magnetic potential difference in the slots of magnetic circuit (ΔF_n) in simple and STW with $q=5$ at time $t=0$

Slot no.	Winding type					
	O_{15}	**P_{15}**	**R_{15}**	**O_{25}**	**P_{25}**	**R_{25}**
1	0	0	0	–0.0866	–0.0615	–0.01897
2	–0.0866	–0.0663	–0.0378	–0.0866	–0.0777	–0.0559
3	–0.0866	–0.0802	–0.0740	–0.0866	–0.0905	–0.0905
4	–0.0866	–0.0905	–0.1070	–0.0866	–0.0994	–0.1212
5	–0.0866	–0.0969	–0.1353	–0.0866	–0.1039	–0.1464
6	–0.1732	–0.1981	–0.1576	–0.1732	–0.1654	–0.1654
7	–0.1732	–0.1632	–0.1731	–0.1732	–0.1771	–0.1771
8	–0.1732	–0.1707	–0.1811	–0.1732	–0.1810	–0.1810
9	–0.1732	–0.1707	–0.1811	–0.1732	–0.1771	–0.1771
10	–0.1732	–0.1632	–0.1731	–0.1732	–0.1654	–0.1654
11	–0.1732	–0.1981	–0.1576	–0.0866	–0.1039	–0.1464
12	–0.0866	–0.0969	–0.1353	–0.0866	–0.0994	–0.1212
13	–0.0866	–0.0905	–0.1070	–0.0866	–0.0905	–0.0905
14	–0.0866	–0.0802	–0.0740	–0.0866	–0.0777	–0.0559
15	–0.0866	–0.0663	–0.0378	–0.0866	–0.0615	–0.01897
16	0	0	0	0.0866	0.0615	0.01897
17	0.0866	0.0663	0.0378	0.0866	0.0777	0.0559
18	0.0866	0.0802	0.0740	0.0866	0.0905	0.0905
19	0.0866	0.0905	0.1070	0.0866	0.0994	0.1212
20	0.0866	0.0969	0.1353	0.0866	0.1039	0.1464
21	0.1732	0.1981	0.1576	0.1732	0.1654	0.1654
22	0.1732	0.1632	0.1731	0.1732	0.1771	0.1771
23	0.1732	0.1707	0.1811	0.1732	0.1810	0.1810
24	0.1732	0.1707	0.1811	0.1732	0.1771	0.1771
25	0.1732	0.1632	0.1731	0.1732	0.1654	0.1654
26	0.1732	0.1981	0.1576	0.0866	0.1039	0.1464
27	0.0866	0.0969	0.1353	0.0866	0.0994	0.1212
28	0.0866	0.0905	0.1070	0.0866	0.0905	0.0905
29	0.0866	0.0802	0.0740	0.0866	0.0777	0.0559
30	0.0866	0.0663	0.0378	0.0866	0.0615	0.01897

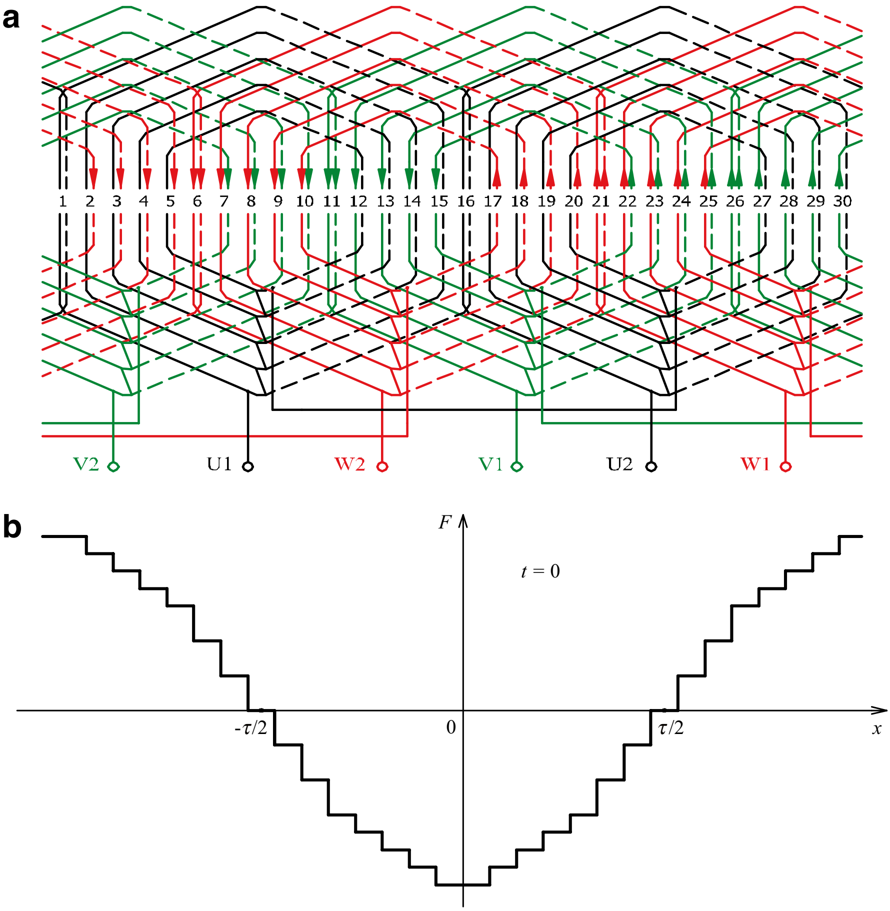

Fig. 2.8 Electrical diagram layout of the maximum average pitch concentric three-phase winding (**O**$_{15}$) with $q = 5$ (**a**) and the distribution of its rotating magnetomotive force at $t = 0$ (**b**)

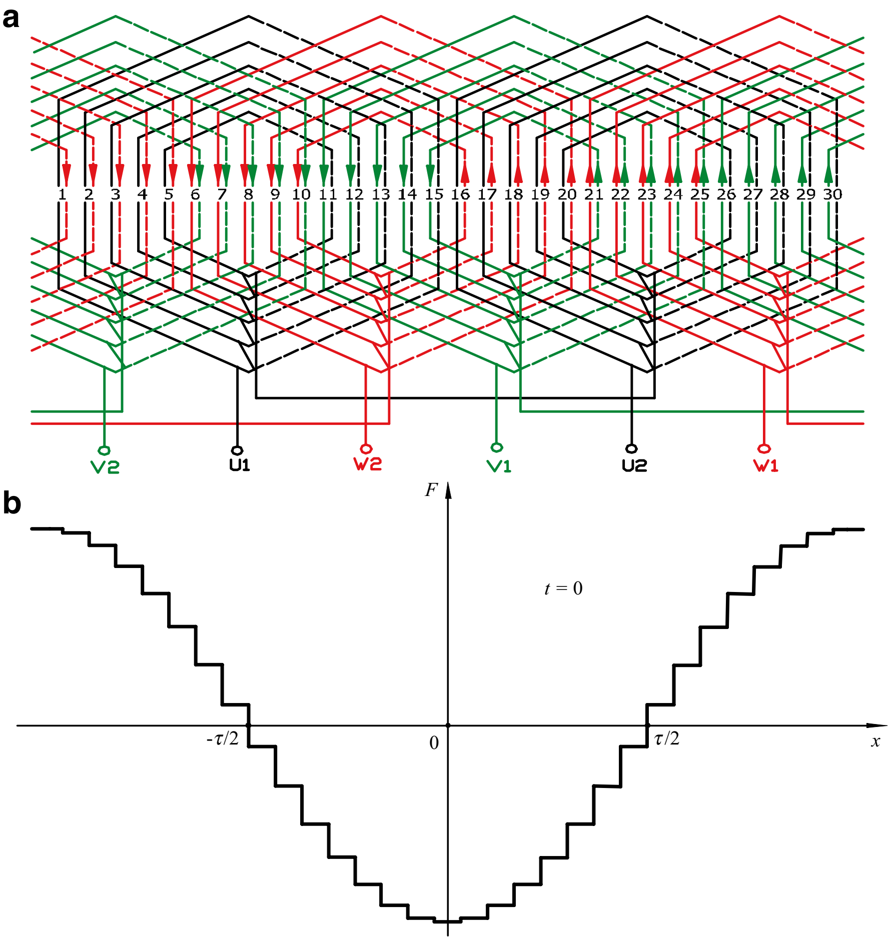

Fig. 2.9 Electrical diagram layout of the short average pitch sinusoidal three-phase winding ($\mathbf{R}_{25}$) with $q = 5$ (**a**) and the distribution of its rotating magnetomotive force at $t = 0$ (**b**)

Table 2.20 Parameters of the negative half-period of rotating magnetomotive forces for simple and STW with $q = 5$

Parameter	Winding type					
	O₁₅	**P₁₅**	**R₁₅**	**O₂₅**	**P₂₅**	**R₂₅**
k	7	7	7	8	8	8
F_{1r}	–0.1732	–0.1707	–0.1811	–0.0866	–0.0905	–0.0905
F_{2r}	–0.1732	–0.1632	–0.1731	–0.1732	–0.1771	–0.1771
F_{3r}	–0.1732	–0.1981	–0.1576	–0.1732	–0.1654	–0.1654
F_{4r}	–0.0866	–0.0969	–0.1353	–0.0866	–0.1039	–0.1464
F_{5r}	–0.0866	–0.0905	–0.1070	–0.0866	–0.0994	–0.1212
F_{6r}	–0.0866	–0.0802	–0.0740	–0.0866	–0.0905	–0.0905
F_{7r}	–0.0866	–0.0663	–0.0378	–0.0866	–0.0777	–0.0559
F_{8r}	0	0	0	–0.0866	–0.0615	–0.01897
α_1	168°	168°	168°	180°	180°	180°
α_2	144°	144°	144°	156°	156°	156°
α_3	v120°	120°	120°	132°	132°	132°
α_4	96°	96°	96°	108°	108°	108°
α_5	72°	72°	72°	84°	84°	84°
α_6	48°	48°	48°	60°	60°	60°
α_7	24°	24°	24°	36°	36°	36°
α_8	0	0	0	12°	12°	12°

Table 2.21 Harmonic analysis results of rotating magnetomotive forces of simple and STW with $q = 5$

ν—Harmonic sequence number	Winding type					
	O₁₅	**P₁₅**	**R₁₅**	**O₂₅**	**P₂₅**	**R₂₅**
1	–0.835	–0.851	–0.869	–0.791	–0.816	–0.864
5	–0.019	–0.005	0	–0.033	–0.025	0
7	–0.020	–0.018	0	–0.018	–0.010	0
11	0.001	0.005	0	–0.008	–0.005	0
13	–0.005	–0.007	0	–0.007	–0.004	0
17	0.004	0.005	0	–0.005	–0.003	0
19	–0.001	–0.003	0	–0.005	–0.003	0
23	0.006	0.005	0	–0.005	–0.003	0
25	0.004	0.001	0	–0.007	–0.005	0
29	0.029	0.029	0.030	–0.027	–0.028	–0.030
31	–0.027	–0.027	–0.028	0.026	0.026	0.028
35	–0.003	–0.001	0	0.005	0.004	0

Table 2.22 Absolute relative values of ν-th harmonic amplitudes of rotating magnetomotive forces (f_ν) for simple and STW with $q=5$

ν—Harmonic sequence number	Winding type					
	O$_{15}$	**P**$_{15}$	**R**$_{15}$	**O**$_{25}$	**P**$_{25}$	**R**$_{25}$
1	1	1	1	1	1	1
5	0.023	0.006	0	0.042	0.031	0
7	0.024	0.021	0	0.023	0.012	0
11	0.001	0.006	0	0.010	0.006	0
13	0.006	0.008	0	0.009	0.005	0
17	0.005	0.006	0	0.006	0.004	0
19	0.001	0.004	0	0.006	0.004	0
23	0.007	0.006	0	0.006	0.004	0
25	0.005	0.001	0	0.009	0.006	0
29	0.035	0.034	0.035	0.034	0.034	0.035
31	0.032	0.032	0.032	0.033	0.032	0.032
35	0.004	0.001	0	0.006	0.005	0

Table 2.23 Electromagnetic efficiency factors k_{ef} of simple and STW with $q=5$

Winding type					
O$_{15}$	**P**$_{15}$	**R**$_{15}$	**O**$_{25}$	**P**$_{25}$	**R**$_{25}$
0.9340	0.9394	0.9448	0.9237	0.9346	0.9447

Table 2.24 Winding factors of the first and higher harmonics ($k_{w\,\nu}$) of simple and STW with $q=5$

ν—Harmonic sequence number	Winding type					
	O$_{15}$	**P**$_{15}$	**R**$_{15}$	**O**$_{25}$	**P**$_{25}$	**R**$_{25}$
1	0.874	0.891	0.910	0.829	0.855	0.905
5	–0.100	–0.0256	0	–0.1732	–0.1285	0
7	–0.1462	–0.1305	0	–0.1294	–0.0704	0
11	–0.01144	–0.0572	0	0.0948	0.0605	0
13	0.0684	0.0910	0	0.0885	0.0526	0
17	0.0684	0.0910	0	–0.0885	–0.0526	0
19	–0.01144	–0.0572	0	–0.0948	–0.0605	0
23	–0.1462	–0.1305	0	0.1294	0.0704	0
25	–0.100	–0.0256	0	0.1732	0.1285	0
29	0.874	0.891	0.910	–0.829	–0.855	–0.905
31	–0.874	–0.891	–0.910	0.829	0.855	0.905

2.5 Electromagnetic Parameters of Simple and Sinusoidal Three-Phase Windings with $q = 6$

To calculate the conditional magnitudes ΔF_n related to the changes of magnetic potential difference in the slots of magnetic circuit in simple and sinusoidal three-phase windings with $q = 6$, the electrical diagram layouts of these windings presented in Figs. 1.15 and 1.27, earlier-acquired results related to the relative values of coil turn numbers listed in Tables 1.6, 1.11, 1.16, 1.21, as well as the relative values of electric current magnitudes of phase windings determined at time $t = 0$ using equation system (2.1) were used. Values of ΔF_n are calculated using formula (2.2). Calculation results for the discussed windings are listed in Table 2.25.

According to the results presented in Table 2.25, the space distributions of magnetomotive force were created for simple and sinusoidal three-phase windings at the selected point in time (Figs. 2.10b and 2.11b).

The magnetomotive force space distributions for the other maximum and short average pitch three-phase windings ($\mathbf{P_{16}}$, $\mathbf{R_{16}}$, $\mathbf{O_{26}}$, $\mathbf{P_{26}}$) are similar to those presented above. These distributions differ only in the conditional heights of the magnetomotive force rectangles F_{jr}.

Based on the results from Table 2.25 and figures presented above, the parameters of the negative half-period of rotating magnetomotive forces, which are listed in Table 2.26, were determined.

According to the results calculated using expression (2.3) and presented in Table 2.26, the harmonic analysis of the discussed windings was performed. The results of this analysis are shown in Table 2.27.

Based on the results presented in Table 2.27, the absolute relative values of ν-th harmonic amplitudes of rotating magnetomotive forces f_ν were calculated for the analyzed windings using expression (2.5) (Table 2.28).

The electromagnetic efficiency factors k_{ef} of the discussed windings (Table 2.29) were calculated on the basis of results presented in Table 2.28, using expression (2.4). These factors were determined for each winding using the relative amplitude values of rotating magnetomotive forces up to 97-th space harmonic.

Using parameters of the analyzed windings, the winding factors of the first and higher harmonics were calculated for these windings according to formulas (2.6) and (2.7) (Table 2.30).

Table 2.25 Conditional magnitudes related to the changes of magnetic potential difference in the slots of magnetic circuit (ΔF_n) in simple and STW with $q=6$ at time $t=0$

Slot no.	Winding type					
	$\mathbf{O_{16}}$	$\mathbf{P_{16}}$	$\mathbf{R_{16}}$	$\mathbf{O_{26}}$	$\mathbf{P_{26}}$	$\mathbf{R_{26}}$
1	0	0	0	–0.0722	–0.0500	–0.01316
2	–0.0722	–0.0535	–0.0263	–0.0722	–0.0617	–0.0391
3	–0.0722	–0.0638	–0.0518	–0.0722	–0.0714	–0.0638
4	–0.0722	–0.0721	–0.0758	–0.0722	–0.0790	–0.0866
5	–0.0722	–0.0783	–0.0974	–0.0722	–0.0842	–0.1068
6	–0.0722	–0.0820	–0.1160	–0.0722	–0.0869	–0.1237
7	–0.1443	–0.1666	–0.1313	–0.1443	–0.1368	–0.1368
8	–0.1443	–0.1355	–0.1424	–0.1443	–0.1458	–0.1458
9	–0.1443	–0.1421	–0.1492	–0.1443	–0.1503	–0.1504
10	–0.1443	–0.1443	–0.1515	–0.1443	–0.1503	–0.1504
11	–0.1443	–0.1421	–0.1492	–0.1443	–0.1458	–0.1458
12	–0.1443	–0.1355	–0.1424	–0.1443	–0.1368	–0.1368
13	–0.1443	–0.1666	–0.1313	–0.0722	–0.0869	–0.1237
14	–0.0722	–0.0820	–0.1160	–0.0722	–0.0842	–0.1068
15	–0.0722	–0.0783	–0.0974	–0.0722	–0.0790	–0.0866
16	–0.0722	–0.0721	–0.0758	–0.0722	–0.0714	–0.0638
17	–0.0722	–0.0638	–0.0518	–0.0722	–0.0617	–0.0391
18	–0.0722	–0.0535	–0.0263	–0.0722	–0.0500	–0.01316
19	0	0	0	0.0722	0.0500	0.01316
20	0.0722	0.0535	0.0263	0.0722	0.0617	0.0391
21	0.0722	0.0638	0.0518	0.0722	0.0714	0.0638
22	0.0722	0.0721	0.0758	0.0722	0.0790	0.0866
23	0.0722	0.0783	0.0974	0.0722	0.0842	0.1068
24	0.0722	0.0820	0.1160	0.0722	0.0869	0.1237
25	0.1443	0.1666	0.1313	0.1443	0.1368	0.1368
26	0.1443	0.1355	0.1424	0.1443	0.1458	0.1458
27	0.1443	0.1421	0.1492	0.1443	0.1503	0.1504
28	0.1443	0.1443	0.1515	0.1443	0.1503	0.1504
29	0.1443	0.1421	0.1492	0.1443	0.1458	0.1458
30	0.1443	0.1355	0.1424	0.1443	0.1368	0.1368
31	0.1443	0.1666	0.1313	0.0722	0.0869	0.1237
32	0.0722	0.0820	0.1160	0.0722	0.0842	0.1068
33	0.0722	0.0783	0.0974	0.0722	0.0790	0.0866
34	0.0722	0.0721	0.0758	0.0722	0.0714	0.0638
35	0.0722	0.0638	0.0518	0.0722	0.0617	0.0391
36	0.0722	0.0535	0.0263	0.0722	0.0500	0.01316

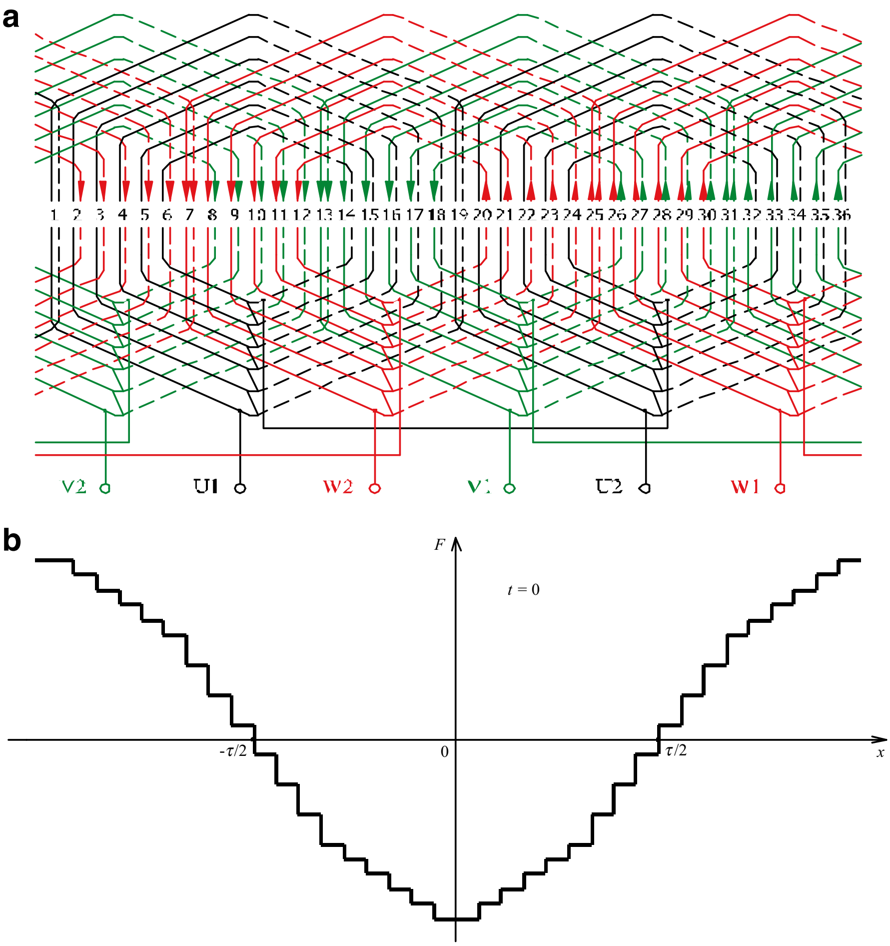

Fig. 2.10 Electrical diagram layout of the maximum average pitch concentric three-phase winding ($\mathbf{O_{16}}$) with $q = 6$ (**a**) and the distribution of its rotating magnetomotive force at $t = 0$ (**b**)

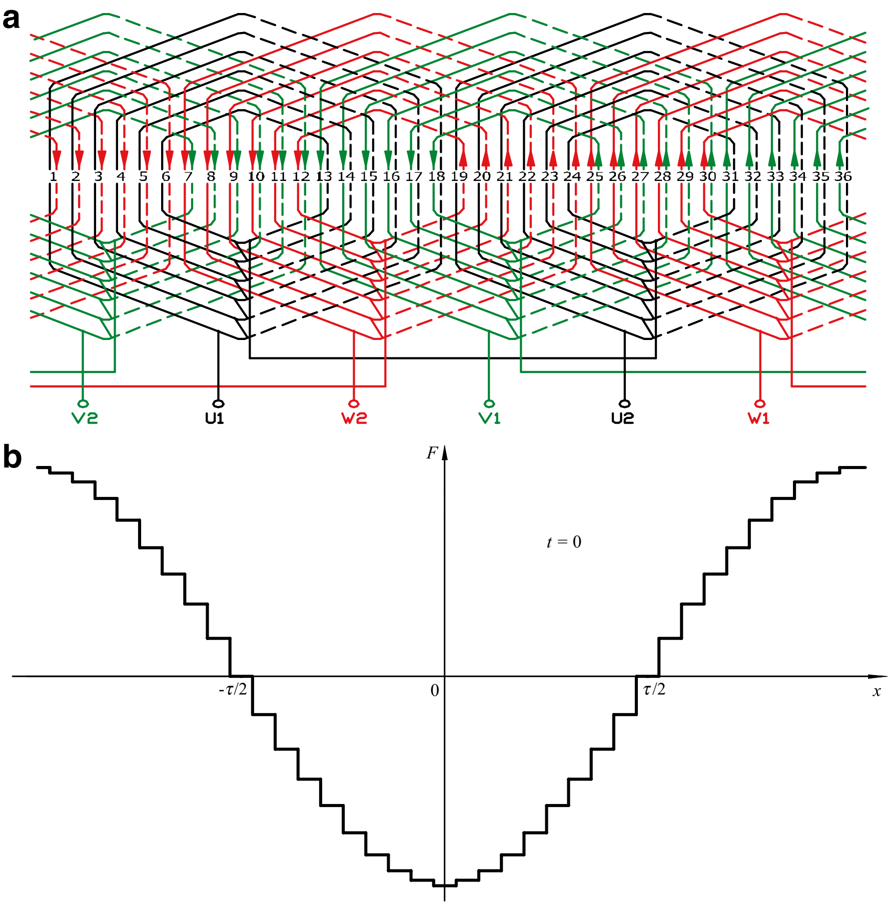

Fig. 2.11 Electrical diagram layout of the short average pitch sinusoidal three-phase winding (**R₂₆**) with $q = 6$ (**a**) and the distribution of its rotating magnetomotive force at $t = 0$ (**b**)

Table 2.26 Parameters of the negative half-period of rotating magnetomotive forces for simple and STW with $q=6$

Parameter	Winding type					
	O$_{16}$	**P$_{16}$**	**R$_{16}$**	**O$_{26}$**	**P$_{26}$**	**R$_{26}$**
k	9	9	9	9	9	9
F_{1r}	–0.0722	–0.0722	–0.0758	–0.1443	–0.1503	–0.1504
F_{2r}	–0.1443	–0.1421	–0.1492	–0.1443	–0.1458	–0.1458
F_{3r}	–0.1443	–0.1355	–0.1424	–0.1443	–0.1368	–0.1368
F_{4r}	–0.1443	–0.1666	–0.1313	–0.0722	–0.0869	–0.1237
F_{5r}	–0.0722	–0.0820	–0.1160	–0.0722	–0.0842	–0.1068
F_{6r}	–0.0722	–0.0783	–0.0974	–0.0722	–0.0790	–0.0866
F_{7r}	–0.0722	–0.0721	–0.0758	–0.0722	–0.0714	–0.0638
F_{8r}	–0.0722	–0.0638	–0.0518	–0.0722	–0.0617	–0.0391
F_{9r}	–0.0722	–0.0535	–0.0263	–0.0722	–0.0500	–0.01316
α_1	180°	180°	180°	170°	170°	170°
α_2	160°	160°	160°	150°	150°	150°
α_3	140°	140°	140°	130°	130°	130°
α_4	120°	120°	120°	110°	110°	110°
α_5	100°	100°	100°	90°	90°	90°
α_6	80°	80°	80°	70°	70°	70°
α_7	60°	60°	60°	50°	50°	50°
α_8	40°	40°	40°	30°	30°	30°
α_9	20°	20°	20°	10°	10°	10°

Table 2.27 Harmonic analysis results of rotating magnetomotive forces of simple and STW with $q=6$

ν—Harmonic sequence number	Winding type					
	O$_{16}$	**P$_{16}$**	**R$_{16}$**	**O$_{26}$**	**P$_{26}$**	**R$_{26}$**
1	–0.828	–0.846	–0.868	–0.791	–0.816	–0.865
5	–0.022	–0.008	0	–0.033	–0.024	0
7	–0.020	–0.017	0	–0.017	–0.009	0
11	–0.001	0.003	0	–0.008	–0.005	0
13	–0.006	–0.006	0	–0.006	–0.003	0
17	0.002	0.004	0	–0.004	–0.002	0
19	–0.002	–0.003	0	–0.004	–0.002	0
23	0.003	0.004	0	–0.003	–0.002	0
25	0	–0.001	0	–0.003	–0.002	0
29	0.005	0.004	0	–0.004	–0.002	0
31	0.003	0.001	0	–0.005	–0.004	0
35	0.024	0.024	0.025	–0.023	–0.023	–0.025
37	–0.022	–0.023	–0.023	0.021	0.022	0.023
41	–0.003	–0.001	0	0.004	0.003	0
43	–0.003	–0.003	0	0.003	0.002	0

Table 2.28 Absolute relative values of ν-th harmonic amplitudes of rotating magnetomotive forces (f_ν) for simple and STW with $q=6$

ν–Harmonic sequence number	Winding type					
	O_{16}	**P_{16}**	**R_{16}**	**O_{26}**	**P_{26}**	**R_{26}**
1	1	1	1	1	1	1
5	0.027	0.009	0	0.042	0.029	0
7	0.024	0.020	0	0.021	0.011	0
11	0.001	0.004	0	0.010	0.006	0
13	0.007	0.007	0	0.008	0.004	0
17	0.002	0.005	0	0.005	0.002	0
19	0.002	0.004	0	0.005	0.002	0
23	0.004	0.005	0	0.004	0.002	0
25	0	0.001	0	0.004	0.002	0
29	0.006	0.005	0	0.005	0.002	0
31	0.004	0.001	0	0.006	0.005	0
35	0.029	0.028	0.029	0.029	0.028	0.029
37	0.027	0.027	0.026	0.027	0.027	0.027
41	0.004	0.001	0	0.005	0.004	0
43	0.004	0.004	0	0.004	0.002	0

Table 2.29 Electromagnetic efficiency factors k_{ef} of simple and STW with $q=6$

Winding type					
O_{16}	**P_{16}**	**R_{16}**	**O_{26}**	**P_{26}**	**R_{26}**
0.9417	0.9487	0.9563	0.9326	0.9450	0.9561

Table 2.30 Winding factors of the first and higher harmonics ($k_{w\,\nu}$) of simple and STW with $q=6$

ν—Harmonic sequence number	Winding type					
	O_{16}	**P_{16}**	**R_{16}**	**O_{26}**	**P_{26}**	**R_{26}**
1	0.867	0.885	0.909	0.828	0.855	0.906
5	–0.1131	–0.0423	0	–0.1708	–0.1273	0
7	–0.1448	–0.1217	0	–0.1258	–0.0679	0
11	0.00887	–0.0373	0	0.0881	0.0569	0
13	0.0753	0.0873	0	0.0796	0.0463	0
17	0.0354	0.0650	0	–0.0725	–0.0441	0
19	–0.0354	–0.0650	0	–0.0725	–0.0441	0
23	–0.0753	–0.0873	0	0.0796	0.0463	0
25	–0.00887	0.0373	0	0.0881	0.0569	0
29	0.1448	0.1217	0	–0.1258	–0.0679	0
31	0.1131	0.0423	0	0.1708	–0.1273	0
35	–0.867	–0.885	–0.909	0.828	0.855	0.906
37	0.867	0.885	0.909	–0.828	–0.855	–0.906
41	–0.1131	–0.0423	0	0.1708	0.1273	0
43	–0.1448	–0.1217	0	–0.1258	0.0679	0

2.6 Conclusions

- The fundamental (first) space harmonics of rotating magnetomotive forces in the maximum and short average pitch sinusoidal three-phase windings with optimized pulsating and rotating magnetomotive forces are practically in all cases larger than the same harmonics of the corresponding double-layer concentric windings.
- The higher space harmonics of rotating magnetomotive forces (except for slot ripples) in the maximum and short average pitch sinusoidal three-phase windings with optimized pulsating and rotating magnetomotive forces are significantly reduced compared with the same magnetomotive force harmonics of the corresponding double-layer concentric windings.
- Slot ripples of rotating magnetomotive forces in the maximum and short average pitch sinusoidal three-phase windings with optimized pulsating and rotating magnetomotive forces remain of the same magnitude as in the double-layer concentric windings.
- Higher space harmonics (except for slot ripples) of rotating magnetomotive forces in the maximum and short average pitch sinusoidal three-phase windings with optimized rotating magnetomotive forces are reduced to zero.
- The electromagnetic efficiency factors of the maximum and short average pitch sinusoidal three-phase windings with optimized pulsating and rotating magnetomotive forces are higher than the same factors of the corresponding double-layer concentric windings.
- When the number of coils in their groups is increased in the analyzed three-phase windings, the electromagnetic efficiency factors are noticeably increased.
- The calculated winding factors of the double-layer concentric and sinusoidal three-phase windings reflect the results of harmonic analysis of the stair-shaped functions of the instantaneous rotating magnetomotive forces generated in these windings.
- According to their electromagnetic properties, the short average pitch sinusoidal three-phase windings with optimized pulsating and rotating magnetomotive forces almost equals the maximum average pitch sinusoidal three-phase windings; furthermore, because of shortened coil endings the used of these windings results in savings of nonferrous metals.

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