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Induction machine with pole-changing winding for turbomechanisms

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Abstract: This paper investigates the possibilities for developing a pole-changing winding with a pole ratio of 3:4 with improved electromagnetic properties. Such a winding can be used in two-speed induction motors for turbo mechanisms. The scheme of the new winding was obtained by using a discretely-specified spatial function method developed at the Tashkent State Technical University. A comparison of the parameters obtained for a similar winding received by the pole amplitude modulation method has been presented. Design of a new motor with a new winding is developed based on the standard induction motor. The paper presents results of laboratory tests, too.

Key words: basic scheme of winding, differential leakage factor, Görges polygone, magnetizing forces, pole-changing winding, pole amplitude modulation, winding factor

1. Introduction

Two-speed electrical machines can be built with two separate windings or with one pole-changing winding (PCW). Undoubtedly, the second kind of construction has a lot of advantages due to a smaller slot area occupied by one winding. This allows one to use the active part of the electric machine more efficiently, increase energy parameters, simplify manufacturing and repair technologies [1–5, 10].

Many scientists from different countries were engaged with the problem of PCW development and as a result of their researches, a great number of schemes for pole-changing windings with different ratios of poles and phases have been developed [1–5, 10, 15].

However, the majority of these schemes have not found industrial application, since current rules of PCW designing do not yet allow one to build a winding a wide spectrum of pole and phase ratios, coming nearer to the manufacturing technologies of conventional windings for serial induction machines.

Besides, pole-changing windings, received by the above-stated principles, have magnetizing forces (MGF) close to sinusoidal for the first pole, and for the second pole in a curve of MGFs, there are higher harmonics. The reason is the divergence of the PCW structure from the regular construction of $2m$-zone and m-zone windings.

At the same time, PCWs should have a structure close to the structures of conventional windings with a width of the phase zone of 60 and 120 degrees ($2m$-zone and m-zone windings). Here, the angle between the coils, belonging to different phases and laying in the next slots should be equal to 60 degrees ($\pi/3$) or 120 degrees ($2\pi/3$), respectively. The deviation from these values will be defined as a difference between the angles of the shift of conventional and new pole-changing windings: $|\Delta\varphi| = |\varphi_{\text{usual}} - \varphi_{\text{new}}|$. Concerning the difference $\Delta\varphi$ between angles, it is better to take it in absolute values, since the deviation from the usual shift to the left or right should be estimated equally [15].

2. New method for constructing of pole-changing windings

The development of schemes for PCWs with a structure close regular windings, i.e. with improved electromagnetic properties is possible, using the modernized method of discretely specified spatial function (DSSF). This method has been developed by the Electrical Energy Supply department at the Tashkent State Technical University [6, 7, 14, 15].

On the basis of this method, a new principle for current or phase distributions in two simple lap windings of the standard design with the number of pole pairs p_1 and p_2 and phases m_1 and m_2 can be developed. They are simultaneously used in the process of winding design. Thus, the winding scheme is not accepted as being ready and is formed in the process of construction, taking into account pictures of distribution of phase currents in slots of the machine for every pole.

The procedure for constructing a pole-changing winding according to the DSSF method consists of the following stages [6, 7, 11, 14, 15]:

1. Drawing up and joint consideration of current distributions (DSSF) corresponding to two poles;
2. Formation of the final pair of aligned DSSF;
3. Selection of the appropriate switching scheme;
4. Obtaining a table of distribution of coils by branches;
5. Analysis and comparison of options;
6. Graphic construction of the pole-changing winding.

This method was originally used to construct the electrically aligned windings of a non-contact induction machine. Subsequently, it was developed as applied to a pole-changing winding.

Proceeding from the fact that the combined windings must occupy the same number of slots, it is possible to write down the conditions:

For m-zone windings

$$Z_1 = p_1 \cdot m_1 \cdot q_1 = Z_2 = p_2 \cdot m_2 \cdot q_2\,, \tag{1}$$

where: Z_1 is the number of stator slots, p_1 and p_2 are the numbers of poles, q_1 and q_2 are the numbers of slots per pole and phase.

For $2m$-zone windings

$$Z_1 = 2 \cdot p_1 \cdot m_1 \cdot q_1 = Z_2 = 2 \cdot p_2 \cdot m_2 \cdot q_2\,. \tag{2}$$

For m-zone windings with $2m$-zone windings, respectively, with indices "1" and "2"

$$Z_1 = p_1 \cdot m_1 \cdot q_1 = Z_2 = 2 \cdot p_2 \cdot m_2 \cdot q_2\,. \tag{3}$$

Hence for m- or $2m$-zone windings

$$q_1 = \frac{m_2 \cdot p_2}{m_1 \cdot p_1} q_2\,. \tag{4}$$

For m-zone and $2m$-zone windings

$$q_1 = \frac{2 \cdot m_2 \cdot p_2}{m_1 \cdot p_1} q_2\,. \tag{5}$$

Usually, given p_1, p_2, m_1 and m_2, the number of slots per pole and phase (q_1 and q_2) are free, and they must take integer values.

3. Development of PCW using of new method

One of the most common speed ratios in two-speed motors used on drives of turbo mechanisms with a fan type of load is a ratio of 3:4.

At the same time, the first speed of 1 000 rpm is the main one at which the electrical machine will work in the case of full loading of the mechanism, and the second speed (750 rpm) is used to regulate performance for the responsible use of electricity and natural resources in underloading modes, and can also serve as the first stage in a step-by-step start-up [7].

With this in mind, a winding scheme of a PCW for a ratio of poles 3:4 in the number of slots 72 was developed using the new method.

In this case, two two-layer simplex lap m-zone windings of a stator are taken as initial windings, placed in 72 slots with a number of pole pairs $p_1 = 3$ and $p_2 = 4$, with steps of winding $y = 1{-}13$ and $y = 1{-}10$. DSSF and phase distribution of 6-pole and 8-pole windings are shown in Fig. 1 and Fig. 2. Here, the number of slots per pole and phase are for the first winding $q_1 = 8$ and for the second winding $q_2 = 6$.

It is clear from this DSSF that the angles of shift in these windings do not differ from ideal m-zone windings, i.e. in all slots $\|\Delta\varphi\| = 0$ [15].

These down layers of the phase distribution of 6 and 8-pole windings (Fig. 3) shall be combined. Thus, it is possible to receive a resulting combination of two windings, choosing the suitable switching scheme. The symbol "x" means that there is no conductor in one of the winding layers in this slot.

Number of slots																		Pole
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
e	e	e	e	f	f	f	f	f	f	f	f	d	d	d	d	d	d	$p_1 = 3$
d	*d*	*d*	*d*	*d*	*d*	*d*	*d*	*e*	*e*	*e*	*e*	*e*	*e*	*e*	*e*	*f*	*f*	
0°	0°	0°	0°	0°	0°	0°	0°	120°	120°	120°	120°	120°	120°	120°	120°	240°	240°	Angle of shift
0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	$\lvert\Delta\varphi\rvert$

Number of slots																		Pole
19	20	21	22	23	24	25	26	27	28	…	…	…	…	69	70	71	72	
d	d	e	e	e	e	e	e	e	e	…	…	…	…	e	e	e	e	$p_1 = 3$
f	*f*	*f*	*f*	*f*	*f*	*d*	*d*	*d*	*d*	…	…	…	…	*f*	*f*	*f*	*f*	
240°	240°	240°	240°	240°	240°	0°	0°	0°	0°	…	…	…	…	240°	240°	240°	240°	Angle of shift
0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	…	…	…	…	0°	0°	0°	0°	$\lvert\Delta\varphi\rvert$

Fig. 1. DSSF and phase distribution of 6-pole winding

Number of slots																		Pole
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
b	b	b	c	c	c	c	c	c	a	a	a	a	a	a	b	b	b	$p_2 = 4$
a	*a*	*a*	*a*	*a*	*a*	*b*	*b*	*b*	*b*	*b*	*b*	*c*	*c*	*c*	*c*	*c*	*c*	
0°	0°	0°	0°	0°	0°	120°	120°	120°	120°	120°	120°	240°	240°	240°	240°	240°	240°	Angle of shift
0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	$\lvert\Delta\varphi\rvert$

Number of slots																		Pole
19	20	21	22	23	24	25	26	27	28	19	…	…	…	69	70	71	72	
b	b	b	c	c	c	c	c	c	a	b	…	…	…	*a*	b	b	b	$p_2 = 4$
a	*a*	*a*	*a*	*a*	*a*	*b*	*b*	*b*	*b*	*a*	…	…	…	*c*	*c*	*c*	*c*	
0°	0°	0°	0°	0°	0°	120°	120°	120°	120°	0°	…	…	…	240°	240°	240°	240°	Angle of shift
0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	…	…	…	0°	0°	0°	0°	$\lvert\Delta\varphi\rvert$

Fig. 2. DSSF and phase distribution of 8-pole winding

For improving the electromagnetic properties and increasing the usability of active parts of the machine, it is advisable to use a basic scheme "Three three-phase stars with additional branches", as shown in Fig. 4. Such an arrangement is very convenient in operation, since there is no additional switching device for a changing of poles.

To receive an accordance between the above-stated winding and the diagram shown in Fig. 4, it is necessary to take out some coils in additional branches from the big pole, removing two coils from the $2p_1$ pole side from each phase zone.

Number of slots																		Pole
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
x	*x*	*d*	*d*	*d*	*d*	*d*	*d*	*x*	*x*	*e*	*e*	*e*	*e*	*e*	*e*	*x*	*x*	$p_1 = 3$
a	*a*	*a*	*a*	*a*	*a*	*b*	*b*	*b*	*b*	*b*	*b*	*c*	*c*	*c*	*c*	*c*	*c*	$p_2 = 4$

Number of slots																		Pole
19	20	21	22	23	24	25	26	27	28	...	...	...	...	69	70	71	72	
f	*f*	*f*	*f*	*f*	*f*	*x*	*x*	*d*	*d*	...	...	...	...	*f*	*f*	*f*	*f*	$p_1 = 3$
a	*a*	*a*	*a*	*a*	*a*	*b*	*b*	*b*	*b*	...	...	...	...	*c*	*c*	*c*	*c*	$p_2 = 4$

Fig. 3. Phase distribution in the lower layers of 8- and 6-pole windings

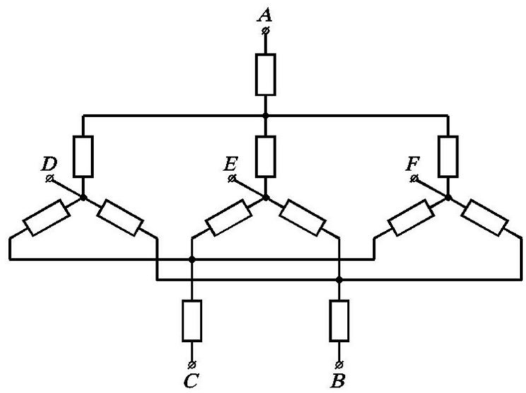


Fig. 4. Basic scheme three three-phase stars with additional branches

Accordingly, from the $2p_2$ pole side, there can be coils in slots with the following numbers: for phase a: 1, 2, 41, 42, 57, 58; for phase b: 9, 10, 25, 26, 65, 66 and for phase c: 17, 18, 33, 34, 49, 50. These coils are deduced in additional branches and, being redistributed on phases, contribute to build up a magnetic field of $2p_2$ poles [15].

At the same time, the resulting values of electromotive forces (EMFs) should be equal to zero in an additional branch from the $2p_1$ pole side, and as a whole, they should have no influence on the functioning of the motor. Mutual compensation EMF of additional branches is carried out by a consistent connection of coils of additional branches and a circular distribution of the magnet core, while the relation to each other on the corner of shift is equal to 120 electrical degrees and the winding in the magnetic field has a small number of poles.

As proved by the analysis results concerning the properties of a new winding from both poles, the corner between the phases in the given winding is equal to 120 degrees, the EMF values, induced in the parallel branches with the same name, are equal in amplitude and in phase. In the branches concerning different phases, the induced EMFs are equal in amplitude and shifted by a phase to 120 degrees. The winding is absolutely symmetric in relation to the power supply system (see Tables 1 and 1). Here, A is the amplitude of the induced EMF.

Table 1. Winding data for the pole $p_1 = 3$

	Branches of basic scheme "YYY/YYY with additional branches"								
	D–A	*D–B*	*D–C*	*E–A*	*E–B*	*E–C*	*F–A*	*F–B*	*F–C*
A, p.u.	10.46	10.46	10.46	10.46	10.46	10.46	10.46	10.46	10.46
ξ	0.872	0.872	0.872	0.872	0.872	0.872	0.872	0.872	0.872
φ, °	52.5°	52.5°	52.5°	172.5°	172.5°	172.5°	−67.5°	−67.5°	−67.5°

Table 2. Winding data for the pole $p_2 = 4$

	Branches of basic scheme "YYY/YYY with additional branches"								
	A–D	*A–E*	*A–F*	*B–D*	*B–E*	*B–F*	*C–D*	*C–E*	*C–F*
A, p.u.	19.64	19.64	19.64	19.64	19.64	19.64	19.64	19.64	19.64
ξ	0.819	0.819	0.819	0.819	0.819	0.819	0.819	0.819	0.819
φ, °	60°	60°	60°	−60°	−60°	−60°	180°	180°	180°

Diagrams of magnetizing forces created by PCWs for 6-pole and 8-pole windings are shown in Figs. 5 and 6. The diagrams of the magnetizing forces created by the PCWs from both poles are close to sinusoidal, and the winding factor is high enough.

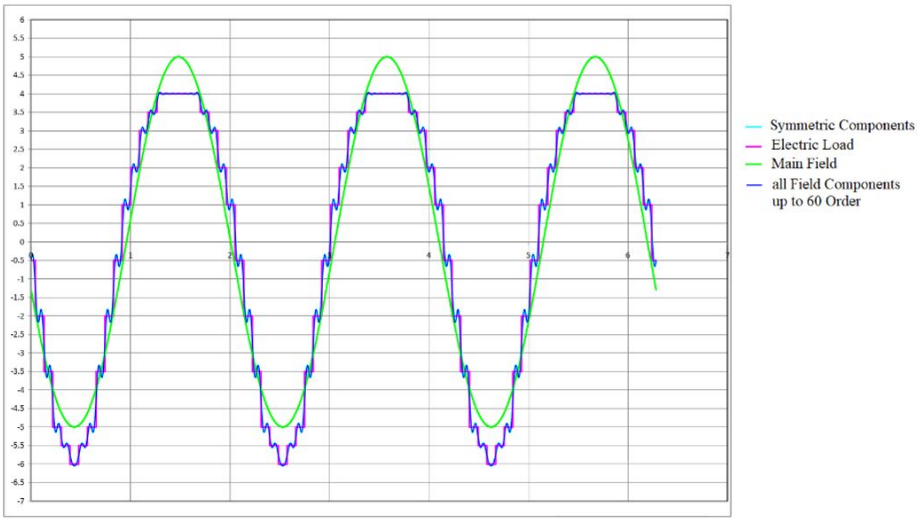


Fig. 5. Diagrams of magnetizing forces created by PCWs for a 6-pole winding

For the coils of additional branches, it is expedient that the wire has a three times larger cross-section and accordingly a three times fewer number of turns than in other coils. In this case,

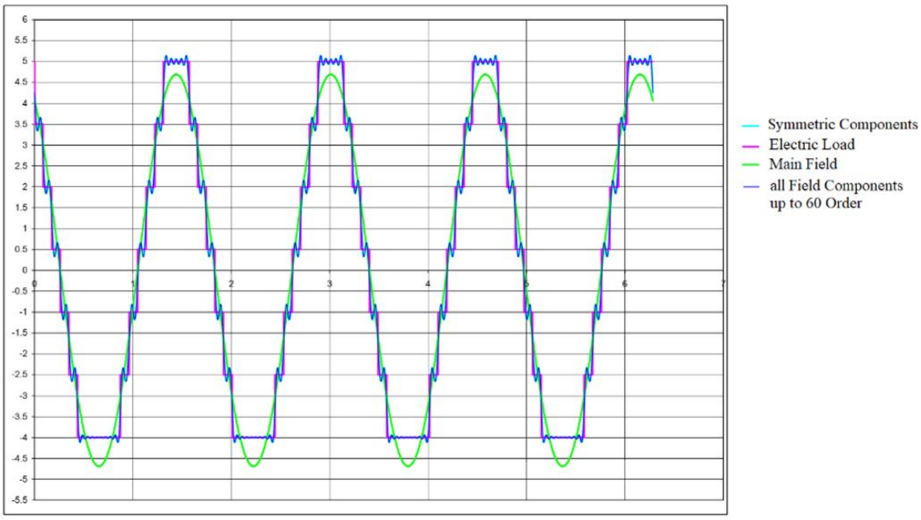


Fig. 6. Diagrams of magnetizing forces created by PCWs for 8-pole windings

practically full coordination of the magnetic inductance in the air gap is achieved by gaining the same performance:

$$\frac{w_1 \cdot \xi_1}{w_2 \cdot \xi_2} = \frac{p_1}{p_2} = \frac{3}{4}, \tag{6}$$

where: ξ_1, ξ_2 are the winding factors from the side of poles p_1 and p_2.

There might be a small deviation in the magnetic inductance, which can be provoked by differing winding factors.

The construction of windings with a number of additional branches in each phase $n \geq 2$ is complicated, because of the necessity of leveling currents elimination in additional branches. An absence of these currents is connected with the fulfillment of the following conditions:

1) Vectors of all EMF branches coincide in value and direction for windings placed in a magnetic field with the high number of poles $2p_2$;

2) Vectors of all EMF branches also coincide in value and direction for windings placed in the field with smaller numbers of poles $2p_1$;

3) EMF vectors of one half of the coil of each branch in the field $2p_1$ poles are opposite to the vectors of the other half, and the total EMF of a branch is equal to zero;

4) EMF vectors of coil groups of each branch in the field $2p_1$ poles are directed to the beams' m-phase star, and the total EMF for a branch is equal to zero.

Simultaneously, two conditions, i.e. the first and any of the others, should be satisfied: The fulfillment of conditions 1) and 2) is possible at parities $p_1/p_2 = ½, ¼, \ldots$, which; however, cannot be received for three-phase (from both parties) windings of the considered type. Conditions 1) and 3), 1) and 4) are carried out, if there are $2m$-zone windings, i.e. windings with the dispersed phase zones, at the heart of the combined windings.

According to conditions 1) and 3), coils which are taken out in additional branches, should be simultaneously removed in an even number of times τ_2 and an odd number of times τ_1, i.e. p_1 should be odd and p_2 even. The number of slots for which the coils are removed, is common both τ_1 and for τ_2. More often, this number is equal to $Z/2$. Obviously, for a choice of the number of stator slots Z, in addition to the conditions for the choice of the numbers of slots of the combined windings, one more condition should be satisfied:

$$\frac{z - 3nh}{9} = \text{integer}, \tag{7}$$

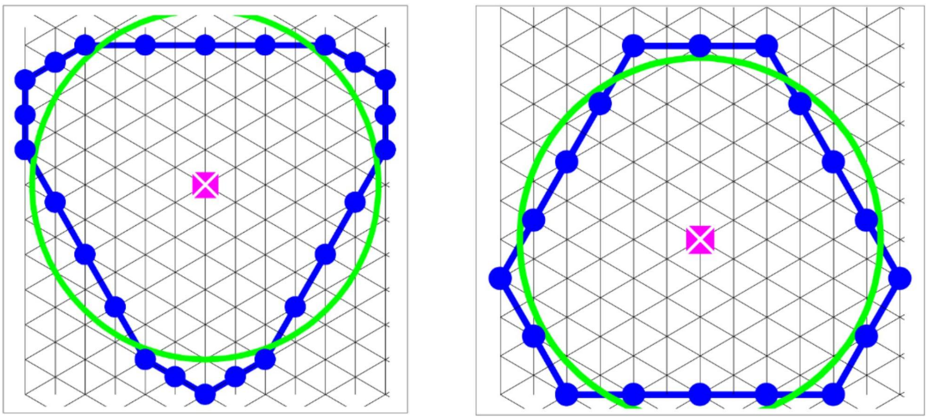
where: n is the number of additional branches in one phase; h is the number of coils in an additional branch; τ_1 is the pole division from the p_1 pole side; τ_2 is the pole division from the p_2 pole side.

Thus, the number of slots in a pole and the phase q can be fractional. In this case, the construction of the winding can be made in the following order. At first, DSSF (current distribution) will be compiled for one layer of the pole-changing winding from the pole side $2p_2$. Then, depending on the required number of turns in the phase from the first and second poles w_1 and w_2, the number of additional branches is determined, as well as the number of turns in the coils.

4. Comparison with other windings

In order to study the properties of a new winding and comparing them to a similar winding received by the method of pole-amplitude modulation (PAM), a special program – WET (Winding Design Tool, in German: Wicklungs-Entwurfs-Tool) – developed at the Institute for Drive System and Power Electronics of Leibniz University Hannover, has been carried out.

Figure 7 shows the Görges polygons of new 6- and 8-pole windings, the differential leakage factor σ_d and the winding factors ξ of the main field.



(a) (b)

Fig. 7. Görges polygons of DSSF: (a) 6-pole winding with $\sigma_d = 4.16\%$ and $\xi = 0.872$; (b) 8-pole winding with $\sigma_d = 2.18\%$ and $\xi = 0.819$

For comparison, we analyzed the structures of similar pole-changing windings received by the method of pole-amplitude modulation (PAM) for a ratio of poles 3:4 and 72 slots. DSSF (current distribution) for these 6- and 8-pole windings is shown in Fig. 3.

As can be seen from the analysis of the winding structure, it strongly differs from a usual winding (in this case $2m$-zone windings), where the number of slots per pole and phase from $p_1 = 3$ should be 4, and for the second pole $p_2 = 4$, the number of slots per pole and phase should be 3. The diagrams of the magnetizing forces created for the PAM winding are shown in Figs. 8 and 9.

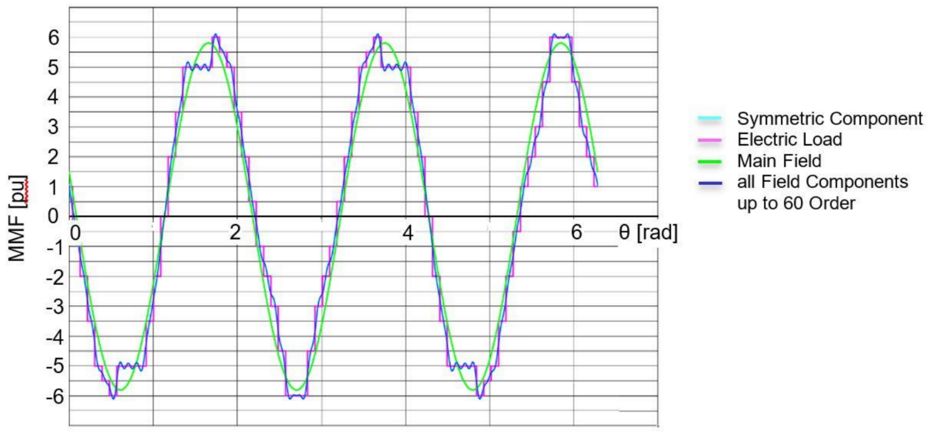


Fig. 8. Diagrams of magnetizing forces created for 6-pole PCWs

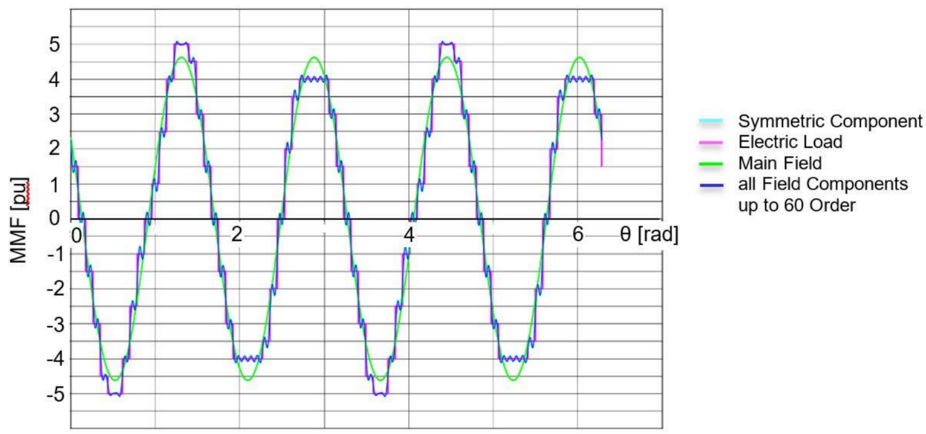
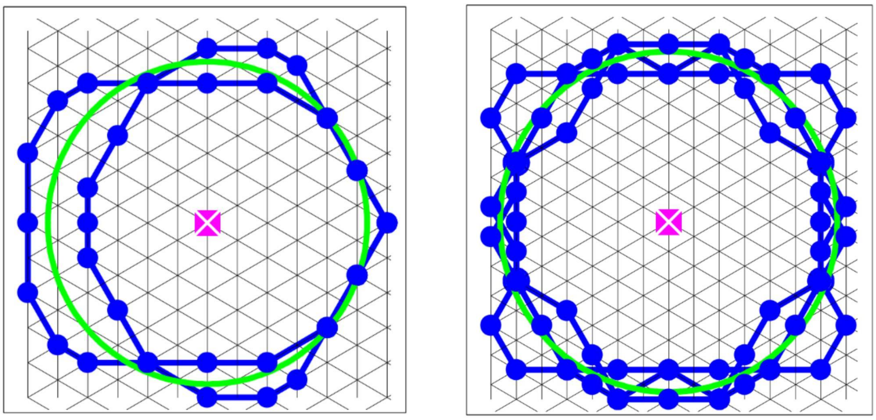


Fig. 9. Diagrams of the magnetizing forces created for 8-pole PCWs

Görges polygons of 6- and 8-pole windings created by using the PAM method are shown in Fig. 10.



(a) (b)

Fig. 10. Görges polygons of PAM winding: (a) for $p_1 = 3$ with $\sigma_d = 2.61\%$ and $\xi = 0.7532$; (b) for $p_2 = 4$ with $\sigma_d = 5.61\%$ and $\xi = 0.806$

As can be seen from the above-stated comparison that the new winding has improved parameters compared to windings received by the PAM method. Görges polygons of the new winding are closer to a circle.

It means that the DSSF winding has less high harmonic contents than PAM windings.

It is necessary to notice, that with the above-stated winding constructed by the DSSF method, it is possible to receive slot numbers that are multiple of 36. This winding also possesses similar properties as previously achieved for 72 slots.

5. Development and test of new two-speed induction machines

At the Tashkent State Technical University (TSTU), a sample model of a new two-speed machine was designed, having a PCW with a speed ratio of 1 000/750 rpm. It is based on a magnetic core of a common 6-pole squirrel-cage motor AGM100L6 with an output power of 1.5 kW, a nominal speed of 925 rpm, efficiency 79% and $\cos\varphi = 0.66$.

The change of the stator current I_1 and the torque on the motor shaft M during start can be determined by the following formulas:

$$I_1 = \frac{U}{\sqrt{\left(R_1 + \frac{R_2'}{s}\right)^2 + \left(x_1 + x_2'\right)^2}}, \tag{8}$$

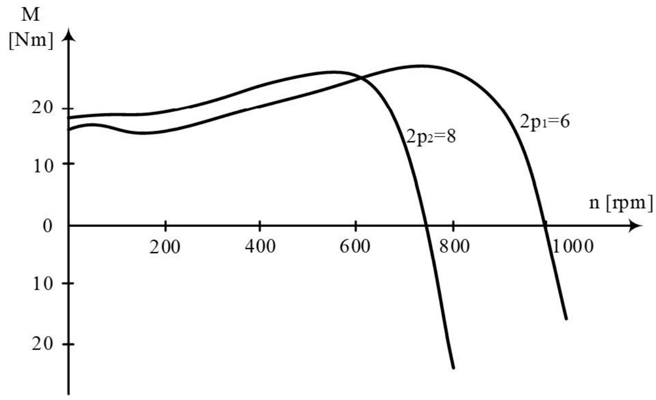
$$M = \frac{mU^2 R_2' s}{\omega\left(\left(sR_1 + R_2'\right)^2 + s^2 x_k^2\right)}, \tag{9}$$

where: U is the voltage on the stator; m is the number of phase; R_1 is the active resistance of the stator; R_2' is the reduced active resistance of the rotor; s is the slip; ω_1 is the angular frequency; x_k is the short circuit inductive resistance.

This machine was tested in the electromechanical laboratory of the Electrical Energy Supply department at the TSTU. The results of experimental research on the new machine in motor duty have shown the following: for 6 poles, the useful power of the new motor reaches 1 200 W, efficiency and $\cos\varphi$ corresponding to this power amount to 76.9% and 0.722, the nominal stator current is equal to 3.7 A, and the slip s is equal to 3.9%.

For 8 poles, the value of useful power for the two-speed motor almost amounts to 982 W, the values for efficiency, the power factor and the slip corresponding to this power are equal to 73%, 0.663 and 5.6%.

Figure 11 presents the torque curves of the new motor AGM100L6/8.



$2p_1 = 6$ $M_{start} = 16.817$ Nm $I_{start} = 15.89$ A
$2p_2 = 8$ $M_{start} = 18.516$ Nm $I_{start} = 11.73$ A

Fig. 11. Torque curve of the new electrical machine AGM100L6/8 with PCW

As can be seen from the drawing, the curves have a smooth appearance. The starting torque for 8 poles is higher and the starting current is less than for 6 poles, which allows using such motors for drives with heavy conditions during start-up and in areas with a weak power line. Due to a low starting current, the power line loaded by a starting current will be low.

The experimental tests of the new machine in generator duty were carried out at direct connection of the two-speed induction machine to the network, and in an independent mode with connection to condenser batteries.

Figures 12 and 13 present waveforms at the output of an induction machine with a pole-changing winding from both sides.

As can be seen from these curves, the form of the voltage obtained is close to a sinusoidal wave, the harmonic content in a voltage curve changes minimally, i.e. the form of the voltage is very close to a sinusoidal wave.

By analyzing the received experimental test results, it is possible to say that the new two-speed induction generator has weight-dimensional and power parameters similar to the parameters of the usual one-speed induction generators.

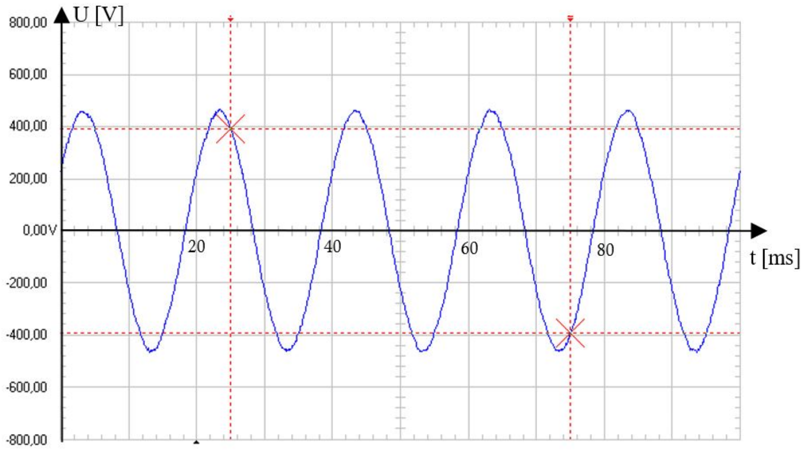


Fig. 12. Waveform at the output of induction machine with PCW from side $2p = 6$

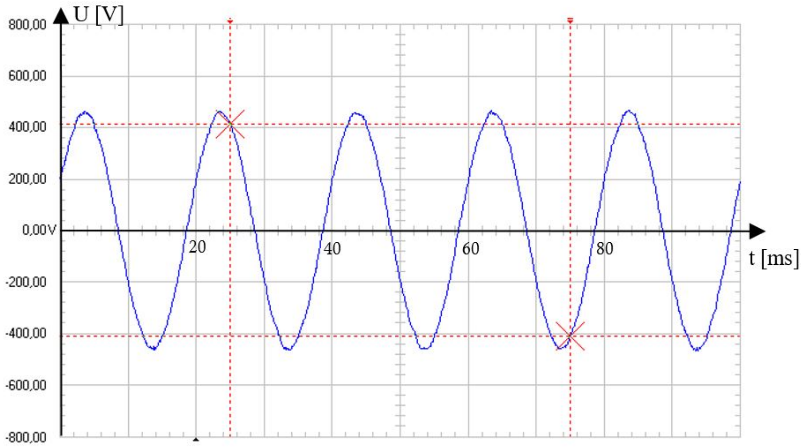


Fig. 13. Waveform at the output of induction machine with PCW from side $2p = 8$

Thus, there is a real opportunity of creating new types of compact and reliable induction generators which can be used in wind installations or in separately standing hydro stations.

Reducing the weight of wind devices, from saving material means, would simplify processes of manufacturing, transportation and installation of wind installations.

As a whole, it can be noticed that thanks to new PCWs with improved electromagnetic properties, it is possible to build two-speed machines having weight-dimension and power parameters as close to the parameters of one-speed electrical machines as possible [12, 13, 15].

The use of such machines as motors allows one to modernize existing electric drives with two-speed motors and to replace some conventional one-speed motors by two-speed pole-changing motors for the purpose of energy saving in small loading duty, in connection with technological or seasonal changes of loading and also to facilitate start-up processes for powerful motors.

Currently, scientific research is being conducted to create a double-fed induction machine with a pole-changing winding on the stator [8, 9].

6. Conclusions

The new method allows the design of PCWs in terms of different ratios of pole pairs and phase numbers, not differing in manufacturing and repairing technology from usual two-layer windings. The offered PCWs do not have switching devices and possess improved electromagnetic characteristics and energy parameters in comparison with windings obtained by other methods. Two-speed electrical machines with PCWs differ only marginally from usual serial one-speed induction machines and can perfectly substitute them with respect to energy saving.

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