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Development of new pole-changing winding for lifting and transport mechanisms

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Abstract. In many industries, lifting and transport machines are used, particularly cranes, conveyors, and hoists. Taking into account their wide prevalence and large installed capacity, as well as the complexity of the operating mode, special attention is paid to the creation of new energy- and resource-saving electric drives that facilitate the start-up process and ensure accurate stopping of highly inertial lifting and transport mechanisms. In this direction, one of the priority tasks is the development of two-speed pole-changing motors that meet the requirements of the electric drive of lifting and transport mechanisms. Based on the method of "Discretely-given spatial functions", a pole-changing winding was obtained for a ratio of 1/5 poles at 30 slots of the stator. Analysis of the electromagnetic properties of the developed pole-changing winding showed that, compared with a close analog, the differential scattering coefficient on the p=1 side of the pole decreases from 1.7% to 1.3%, and on the p=5 side of the pole decreases from 15.9% to 9.7%, and also in the picture of the magnetomotive force, the presence of higher harmonic ones on the side of the first velocity decreases up to 6%, and from the second speed up to 20%.

1 Introduction

In many industries and warehouses, hoisting machines such as cranes, conveyors, and telphers are used to transfer and transport goods. Taking into account their widespread prevalence and the large value of the installed power, as well as the complexity of the operation mode, particular importance is attached to the problems of saving electricity and resources by improving the electric drive. In this area, special attention is paid, in particular, to the creation of new energy- and resource-saving electric drives, which make it possible to facilitate the start-up process and ensure the exact stop of highly inertial hoisting-transport mechanisms [1].

In this direction, in particular, one of the priority tasks is the development of two-speed pole-switching motors that meet the requirements of an electric drive of hoisting-transport mechanisms. Along with this, an urgent task is the development of two-speed motors of new pole-changing windings (PCHW) schemes with improved electromagnetic properties and simple manufacturing technology.

A review of literary sources showed that most of the existing methods for constructing

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PCHW circuits do not allow building windings that are close in technological and electromagnetic properties to conventional windings used in serial single-speed machines [2].

The research aims to develop and study pole-changing windings for two-speed motors of hoisting-transport mechanisms

2 Materials and Methods

To build the PCHW, Professor H.G. Karimov proposed the method of "Discretely-given spatial functions" [10], which was improved in the works of M.K.Bobojanov, D.A. Rismukhamedov and F.N. Tuychiev for constructing the PCHW for both large and close pole ratios [11]. According to this method, to simplify constructing a PCHW circuit, the concept of the current distribution of the winding is introduced, which is represented as a discrete, specified spatial function (DSSF).

As an example, consider the process of obtaining a PCHW circuit for a pole ratio of 1/5 with the number of slots Z = 30. A normal m-zone winding with the number of poles p_2=5 was taken as the initial winding, and a normal 2m-zone winding with p_1=1 was taken as a "typical" one. This winding has a «star-double star» switching scheme [15].

Here, for $2p_1$=2, the number of slots per pole and phase is q_1=5; for the number of pairs of poles $2p_2$=10, the number of slots per pole and phase is q_2=2. Then, the current distribution corresponding to the lower layers of the two windings is examined together to build the PCHW circuit. Table 1 shows the combination of the DSSF of the lower layers of the two windings.

Table 1. Combination of the lower layers of the DSSF of 2 and 10-pole windings.

1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**slots**
a	a	a	a	a	$\underline{c}$	$\underline{c}$	$\underline{c}$	$\underline{c}$	$\underline{c}$	b	b	b	b	b	p_1=1
a	a	b	b	c	c	a	a	b	b	c	c	a	a	b	p_2=5

16	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**slots**
$\underline{a}$	$\underline{a}$	$\underline{a}$	$\underline{a}$	$\underline{a}$	$\underline{c}$	$\underline{c}$	$\underline{c}$	$\underline{c}$	$\underline{c}$	$\underline{b}$	$\underline{b}$	$\underline{b}$	$\underline{b}$	$\underline{b}$	p_1=1
b	c	c	a	a	b	b	c	c	a	a	b	b	c	c	p_2=5

Table 2 shows the synthesis process of the polar coil 2p=2, where the third line contains the layer of the synthesized winding, that is, the DSSF of the PCHW belonging to the lower pole p_1=1. This is achieved by modulating the DSSF of the original winding using the DSSF of a typical winding.

Table 2. Synthesis of 2p1=2 pole winding.

1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**slots**
a	a	b	b	c	c	a	a	b	b	c	c	a	a	b	p_2=5 original
a	a	a	a	a	$\underline{c}$	$\underline{c}$	$\underline{c}$	$\underline{c}$	$\underline{c}$	b	b	b	b	b	p_1=1 typical
a	a	$\underline{b}$	$\underline{b}$	$\underline{c}$	$\underline{c}$	a	a	$\underline{b}$	$\underline{b}$	c	c	$\underline{a}$	$\underline{a}$	$\underline{b}$	p_1=1 synthes

16	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**slots**
b	c	c	a	a	b	b	c	c	a	a	b	b	c	c	p_2=5 original
$\underline{a}$	$\underline{a}$	$\underline{a}$	$\underline{a}$	$\underline{a}$	c	c	c	c	c	$\underline{b}$	$\underline{b}$	$\underline{b}$	$\underline{b}$	$\underline{b}$	p_1=1 typical
$\underline{b}$	c	c	$\underline{a}$	$\underline{a}$	b	b	c	c	$\underline{a}$	$\underline{a}$	b	b	$\underline{c}$	$\underline{c}$	p_1=1 synthes

The meaning of the «approximation» is to determine in each slot the sign of the state of the DSSF conductor of the synthesized winding, depending on the state of the DSSF conductor of a typical winding in this slot and based on the relative position of the vectors of phase currents in a three-phase system [9].

For example, if the position of the DSSF conductor in the original winding is equal to «b» (3-slot), and for a typical DSSF in the same phase as «a», which is known from the location of the three-phase system, currents that are close to «a» «-b», not «b» (direction of instantaneous currents corresponds), therefore, the synthesis winding is written «-b» for DSSF; if the DSSF of the original winding is «c» (6- slot), the DSSF of the typical winding is «-c», then «-c» is written in the DSSF of the synthetic winding.

Table 3. Combining the bottom layers of two windings.

1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**slots**
a	a	b	b	c	c	a	a	b	b	c	c	a	a	b	p_2=5
a	a	b	$\underline{b}$	$\underline{c}$	$\underline{c}$	a	a	$\underline{b}$	$\underline{b}$	c	c	a	$\underline{a}$	$\underline{b}$	p_1=1

16	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**slots**
b	c	c	a	a	b	b	c	c	a	a	b	b	c	c	p_2=5
$\underline{b}$	c	c	$\underline{a}$	$\underline{a}$	b	b	c	$\underline{c}$	$\underline{a}$	$\underline{a}$	b	b	$\underline{c}$	$\underline{c}$	p_1=1

Thus, the procedure for constructing the polar part of the 2p1 pole-changing winding consists in sequentially viewing the current states in each phase and recording the synthesized DPPF winding based on the above rules.

By modulation, we obtain a coil with a zone of 2m for 2p1=2 pairs of poles so that the number of coils on the branches is equal to the number of coils sitting side by side - 3 and 4, 13 and 14, 23 and 24 must have different signs. After that, these two layers are combined into the DSSF. Table 3 shows the combination of the DSSF of the lower layers of the two windings.

Table 4. Distribution of coils in the branches of the winding.

Branch name	**Number coils**	**Branch name**	**Number coils**	**Branch name**	**Number coils**
A-D	1, 2, 7, 8, 13	B-E	21, 22, 27, 28, 3	C-F	11, 12, 17, 18, 23
D-0	14, 19, 20, 25, 26	E-0	4, 9, 10, 15, 16	F-0	24, 29, 30, 5, 6

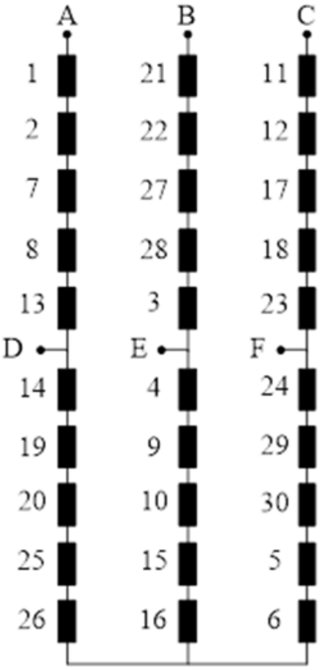


Fig. 1. Basic diagram of a pole- changing winding

Using the phase combination table, following the obtained DSSF, you can get the numbers of the coils distributed along the branches and build a schematic diagram of the connection of the PCHW. The «star-double star» scheme can be divided into the following branches: for the first phase A-D, D-0; for the second phase B-E, E-0; for the third phase C-F, F-0. Table 4 shows the distribution of the coils of the PCHW along the branches of the «star-double star» chain.

Figure 1 shows a schematic electrical diagram of the proposed three-phase pole-switchable winding, consisting of six parts: coils numbered 1, 2, 7, 8, 13, connected in series according to sections A-D; coils with numbers 14, 19, 20, 25, 26, connected in series according to sections D-0; coils numbered 21, 22, 27, 28, 3, connected in series according to sections B-E; coils with numbers 4, 9, 10, 15, 16, connected in series according to sections E-0; coils with numbers 11, 12, 17, 18, 23, connected in series according to sections C-F; coils with numbers 24, 29, 30, 5, 6, connected in series according to sections F-0. The pictures of the magnetomotive forces of the obtained PCHW are presented in figure 2.

3 Result and Discussion

The resulting winding is symmetrical concerning the power source on the side of both poles. The vectors of the electromotive forces of the branches of the same name of each phase are mutually symmetric to each other; that is, they are equal in amplitude and shifted at an angle of 2π/3 el.rad. in phase.

One of the main indicators of the developed PCHW is the winding ratio. The winding coefficient can be calculated separately for each harmonic using the generalized method [16] and the matrix method [7].

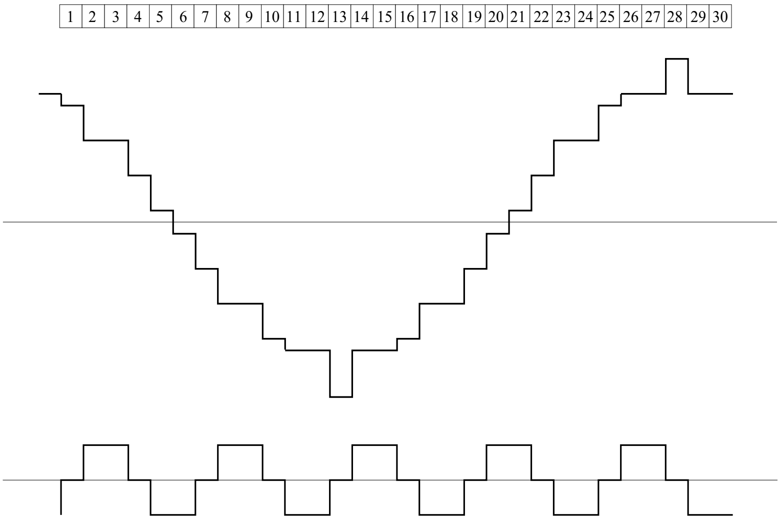


Fig. 2. Pictures of the magnetomotive force of the obtained PCHW.

The geometric sum of electromotive forces

$$E_{iv} = E \cdot e^{j\gamma iv} - E \cdot e^{j\gamma(i+y)v} \tag{1}$$

where, *E* is the amplitude of the electromotive force, conventionally assumed to be equal to one; *i* is coil number;*γ* is spatial angle between grooves; $\gamma = 360p/Z$, *Z* is the number of slots in the stator; *y* is winding step; *v* is harmonic number.

If *N* is the number of coils connected in series, the amplitude of the resulting electromotive force is determined as follows:

$$E_{res.v} = \sum_{i=1}^{N} E_{nv_i} \tag{2}$$

where, *N* is number of coils in a phase or branches.

Considering the above, the winding v is harmonic distortion

$$k_{win.v} = \frac{E_{res.v}}{2N} \tag{3}$$

The winding coefficient for $2p_1$ and $2p_2$ is k_{win1}=0.633 and k_{win2}=0.866, respectively, with a winding step *y* = 15 (see tables 5 and 6).

Table 5. Winding data for pole p_1=1.

Branches of the base scheme Y/YY						
	A-D	*D-**	*B-E*	*E-**	*C-F*	*F-**
A	6.33	6.33	6.33	6.33	6.33	6.33
k_{win}	0.633	0.633	0.633	0.633	0.633	0.633
φ	240	240	120	120	0	0

Table 6. Winding data for pole p_2=5

Branches of the base scheme Y/YY			
	*A-**	*B-**	*C-**
A	17.32	17.32	17.32
k_{win}	0.866	0.866	0.866
φ	30	150	270

The coefficient of differential dissipation for any electrical machine does not depend on the geometric dimensions of the stator and rotor packages. The differential scattering coefficient is determined using the Gerges diagram (figure 3) as follows [17]:

$$\sigma_0 = \left(\frac{R_g}{R_1}\right)^2 - 1 \tag{4}$$

where, R_g is radius of gyration, R_1 is fundamental harmonic radius.

If the value of σ_0 is small, the lower the composition of the higher harmonics and the better the winding parameters.

The radius of gyration and the radius of the fundamental harmonic in the formula (4) are determined as follows.

$$R_g = \left(\frac{J_p}{Z_N}\right)^{\frac{1}{2}}, \; R_1 = \frac{Z \cdot k_{win}}{p \cdot \pi} \tag{5}$$

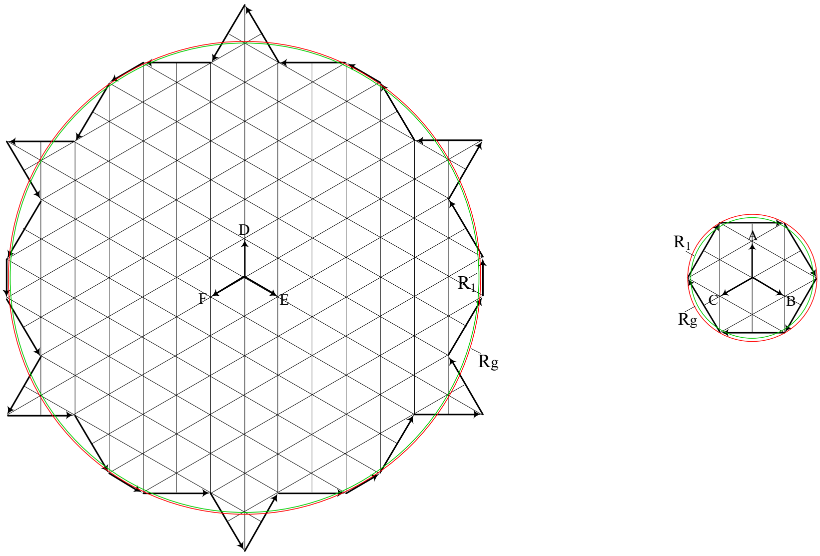
where, J_p is polar moment of inertia, k_{win} is winding coefficient of the fundamental harmonic.

When analyzing the electromagnetic properties of the PCHW, the calculated data from the side of both poles are simultaneously considered at different winding steps. By analyzing the calculated data obtained, it is necessary to determine the optimal winding step that satisfies the requirements on both poles' sides.

Table 7. Differential scattering coefficient.

Number of slots	Basic schema	Winding step	σ₀, %	
			2p=2	2p=10
30	Y/YY	14	1.53	21.8
		15	1.3	9.7
		16	1.53	21.8

In the picture of the magnetizing forces of the PCHW for a ratio of 1:5 with the basic scheme «Y/YY» in 30 slots of the stator (figure 4) from the side 2p=2 poles with a step of y=14, in addition to the first harmonic, there are the 2nd, 5th, 7th, 8th, 10th, 11th, 13th, 14th, 16th and 17th harmonic, their amplitude as a percentage of the total harmonic is ν_2=1.42%, ν_5=2.34%, ν_7=0.37%, ν_8=3.09%, ν_{10}=2.03%, ν_{11}=2.17%, ν_{13}=0.48%, ν_{14}=1.29%, ν_{16}=1.14%, ν_{17}=0.37%, respectively, and taking into account the winding coefficients (table 9), their influence decreases ν_2=0.05%, ν_5=3.07%, ν_7=0.15%, ν_8=0.98%, ν_{10}=1.62%, ν_{11}=0.66%, ν_{13}=0.05%, ν_{14}=0.29%, ν_{16}=0.27%, ν_{17}=0.02%. The differential scattering coefficient is σ_0 = 1.53%.



(a) *(b)*

Fig. 3. Gerges diagrams: a) for 2p1=2 sides σ0 = 1.3%; b) for 2p2 = 10 sides σ0 = 9.7%

At step *y*=15, in addition to the first harmonic, the 5th, 7th, 11th, 13th, and 17th harmonic are present; their amplitude as a percentage of the total harmonic is ν_5=2.75%, ν_7=0.50%, ν_{11}=5.42%, ν_{13}=2.39%, ν_{17}=1.83% respectively, and taking into account the winding coefficients (table 9), their influence decreases ν_5=3.92%, ν_7=0.35%, ν_{11}=3.85%, ν_{13}=0.87%, ν_{17}=0.68%. The differential scattering coefficient is σ_0 = 1.3%.

When the winding is lengthened by one more slot, that is, at a step of *y* = 16, the harmonic composition of the magnetizing forces and the winding coefficients of the same orders have the same values at a step of *y*=14, the differential scattering coefficient also has the same value.

From the side 2p=10 poles in the picture of magnetizing forces with a step of *y*=14, in addition to the first harmonic, there are the 2nd, 5th, 7th, 8th, 10th, 11th, 13th, 14th, 16th, and 17th harmonic, their amplitude as a percentage of the total harmonic is ν_2=13.97%, ν_5=9.67%, ν_7=6.93%, ν_8=3.48%, ν_{10}=2.81%, ν_{11}=4.4%, ν_{13}=3.72%, ν_{14}=2%, ν_{16}=1.76%, ν_{17}=2.84% respectively, and taking into account the winding coefficients, their influence decreases ν_2=8.98%, ν_5=10.78%, ν_7=7.67%, ν_8=2.26%, ν_{10}=1.81%, ν_{11}=4.91%, ν_{13}=4.16%, ν_{14}=1.3%, ν_{16}=1.1%. The differential scattering coefficient is σ_0 = 21.8%.

At step *y*=15, in addition to the first harmonic, the 5th, 7th, 11th, 13th and 17th harmonic are present, their amplitude as a percentage of the total harmonic is ν5=12.76%, ν7=9.09%, ν11=5.78%, ν13=4.89%, ν17=3.74% respectively, taking into account the winding coefficients, their influence is reduced ν5=14.42%, ν7=5.19%, ν11=3.33%, ν13=2.77%, ν17=2.12%. The differential scattering coefficient is *σ0*=9.7%.

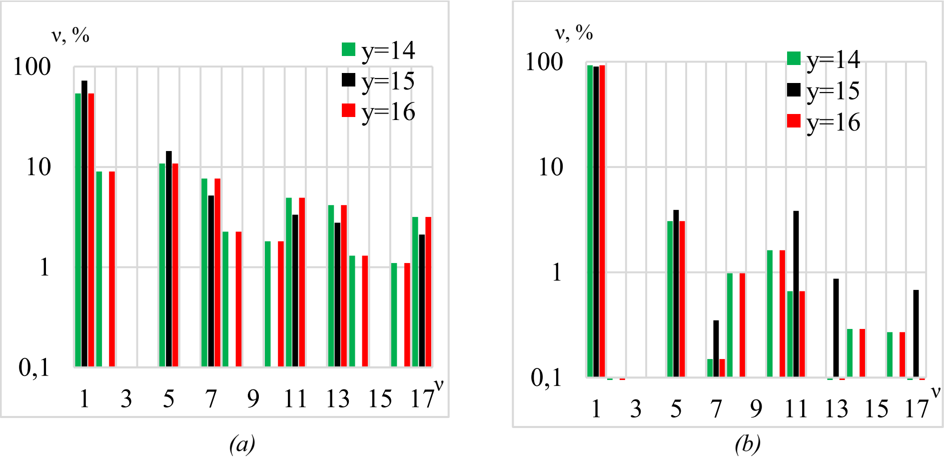


Fig. 4. Higher harmonic diagram: a) for side p_1=1; b) for side p_1=5.

As can be seen from the above analysis of the PCHW for a ratio of 1:5 with the basic scheme «Y/YY» in 30 stator slots from the side of 2p=2 poles with a step of *y*=15, the content of higher harmonic is minimal (even harmonics do not take place) and accordingly, the value of the differential scattering coefficient is the smallest.

Since both speeds are equivalent in these two-speed motors, the electromagnetic properties of the PCHW on both sides must be optimal. Therefore, we choose to step *y*=15 as the optimal step.

4 Conclusion

1. Based on studying the operating modes of electric drives of hoisting-and-transport mechanisms operated at industrial enterprises and analyzing the literature in this area, the need to improve the motors on the drive of these mechanisms is substantiated. As a result, the need to develop two-speed asynchronous motors for a large speed ratio with one winding with improved electromagnetic properties and simple manufacturing technology was identified.

2. Using the DPPF method, a new PCHW with a pole ratio of 1:5 was developed based on the «Y/YY» scheme with the number of stator slots equal to 30, with improved electromagnetic properties and simple manufacturing technology.

3. Analysis of the harmonic composition of the magnetomotive forces of the new developed PPO showed that for $2p_1$=2 and $2p_2$=10 of the pole side, in addition to the first harmonic, there are 5-, 7-, 11-, 13-, 17-harmonics, whose amplitude corresponds to the percentage of the total harmonic: 2.75%, 0.50%, 5.42%, 2.39%, 1.83%, respectively.

4. Analysis of the electromagnetic properties of the developed PCHW showed that, in comparison with a close analog, the coefficient of differential scattering of the PPO from the side p=1 decreases from 1.7% to 1.3%, and from the side p=5, it decreases from 15.9% to 9.7%, and also in the picture of magnetomotive forces, the presence of higher harmonic forces from the side of the first speed decreases to 6%, and from the side of the second speed to 20%.

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