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RESEARCH ARTICLE

Three-Phase Pole-Changing Winding with Ratio of Poles 4:6

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ABSTRACT: The development and analysis of a new pole-changing winding with pole ratio 2p1/2p2=4/6, as well as the experimental research of a two-speed induction motor with this winding, involved the use of modernized methods such as Discretely Specified Spatial Function (DSSF). These methods have been used to develop pole-changing winding designs for two-speed induction motors with improved electromagnetic properties, closely resembling conventional windings. The new pole-changing winding could be aviable alternative to conventional two-layer windings, as it offers similar electromagnetic properties. Furthermore, the new pole-changing winding was analyzed using ANSYS/Maxwell and tested on an induction motor built on the base of a 1,5 kW/1500 rpm induction motor in frame 4A80U3, developing 1,1 kW/0,7 kW rated power for 2p1/2p2=4/6 poles, respectively. Overall, this research demonstrates the potential for developing advanced pole-changing windings with improved electromagnetic properties and their application in practical induction motors.

Keywords: Induction motor, pole-changing winding, discretely specified spatial function, winding factor.

1. INTRODUCTION

More than 35% of the world's electricity is consumed by pumps, fans, and compressors. The International Energy Agency predicts that this consumption will double by 2040 [1]. The poles of induction motors can be changed using two primary techniques that are widely used. If one is to create a pair of independent windings on the stator (the first method involves this process), each winding can be perfectly matched to its speed.

However, with one winding running at a time, the dimensions of such induction motors are much larger than corresponding single-speed induction motors [2]. The second method is based on changing the connection of the winding parts. Although the entire winding operates at both speeds simultaneously, they have some disadvantages: additional wires are required, and the magnetic field in the gap is always significantly distorted as the speed changes [3].

The problem of designing pole-changing windings has been studied by many scientists from all over the world, and as a result of these studies, a large number of winding circuits with different pole and phase ratios have been developed [4, 5].

Two-speed induction motors with a p1/p2=1/2 pole pair ratio often utilize a pole-changing winding based on the Dahlander circuit and the Pole Amplitude Modulation (PAM) method to achieve the desired speed variation [6,7]. Two-speed induction motors with a pole ratio of p1/p2=2/3 and p1/p2=3/4 have a winding with pole changing using the Phase Modulated (PM) winding [8, 9, 10]. Some disadvantages of pole-changing windings include: inconsistent energy characteristics at different rotation speeds, leading to inefficient energy conversion; degraded electromagnetic properties, resulting in reduced performance and efficiency; complex production technology required to create windings with different numbers of turns and pitches, leading to increased manufacturing costs and production time [11].

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Pole-changing windings, designed using these principles, result in one field having a magnetomotive force (MMF) that closely resembles a sinusoidal curve. However, for another field, there are higher harmonics present in the MMF curve. This is due to the departure of the pole-changing winding structure from conventional 2m-zone and m-zone windings [12].

The article discusses a pole-changing winding with pole ratio 2p1/2p2=4/6, which is obtained using the modernized method of discretely specified spatial functions. This winding has a minimum number output terminals (6) and does not require additional contacts for switching of poles. The winding manufacturing technology is identical to the technology of conventional two-layer loop windings with the same pitch and number of turns in the coils. An analysis of the electromagnetic properties of the winding was carried out, and based on the calculated data, a prototype of a two-speed motor with a new pole-changing winding was created. The characteristics of a pole-changing motor were measured in static and dynamic modes.

2. THE DISCRETELY SPECIFIED SPATIAL FUNCTION METHOD

The modernized DSSF (discretely specified spatial function) method has opened up the possibility of creating pole-changing windings with a structure resembling conventional windings, but with improved electromagnetic properties [13, 14]. This method has led to the development of a new principle for distributing current or phase in two simple transverse windings of conventional design, which are commonly used in practice and exhibit high electromagnetic properties. These windings have differing numbers of pole pairs (p1 and p2) and phases (m1 and m2), and they are utilized simultaneously in the winding development process. As a result, the winding circuit is not pre-determined, but rather formed during the design process, taking into account the distribution patterns of phase currents in the motor's slots for each pole [15].

The DSSF method was introduced to simplify the process of designing a winding circuit by representing current distribution as a discretely specified spatial function. This method allows for a more efficient and structured approach to designing winding circuits.

The discrete element DSSF, or discretely specified spatial function, is a representation of the state of a conductor within a conventional winding. In side coil of a winding contains an ordinary conductor through which a unit current passes in one direction or the other in a slot belonging to one of the phases of the winding. These conductors are marked with letters such as a, b, and c. For example, states a, b, and c represent conductors with unit currents (or electromotive force (EMF)) of a positive direction in their respective slots (i.e., "from us"), while states -a, -b, and -c correspond to conductors with unit currents (or EMF) of a negative direction in their slots (i.e., "towards us").

The DSSF method, is a technique used in the design of pole changing windings for electric machines. The procedure involves the following steps [16]:

1. Compilation and joint consideration of current distributions (DSSF) corresponding to two poles: This step involves analyzing the current distribution for each pole and considering them together to understand their combined effect.

2. Formation of the final pair of aligned DSSF: The next step is to align and combine the DSSF for both poles to create a final pair that represents the winding design.

3. Selecting the appropriate changing scheme: This involves choosing the suitable scheme for changing the polarity or number of poles in the winding.

4. Obtaining a table of distribution of coils among branches: This step involves creating a table that outlines how coils are distributed among different branches in the winding.

5. Analysis and comparison of options: Different design options and configurations are analyzed and compared to determine the best approach for the specific application.

6. Graphic construction of the switched winding: Finally, a graphical representation of the switched winding design is constructed based on the chosen scheme and distribution of coils.

Based on the fact that the combined windings should occupy the same number of slots, we can write the conditions:

For m-zone windings,

$$Z_1 = p_1 \cdot m_1 \cdot q_1 = Z_2 = p_2 \cdot m_2 \cdot q_2 \qquad (1)$$

where Z1- number of stator slots, p1 and p2-numbers of poles, q1 and q2-numbers of slots per pole and phase. This equation shows that the number of stator slots is determined by the product of the number of poles and the number of slots per pole and phase.

For 2m-zone windings,

$$Z_1 = 2 \cdot p_1 \cdot m_1 \cdot q_1 = Z_2 = 2 \cdot p_2 \cdot m_2 \cdot q_2 \qquad (2)$$

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

$$Z_1 = p_1 \cdot m_1 \cdot q_1 = Z_2 = 2 \cdot p_2 \cdot m_2 \cdot q_2 \qquad (3)$$

Hence for m- or 2m-zone windings,

$$q_1 = \frac{m_2 \cdot p_2}{m_1 \cdot p_1} q_2 \qquad (4)$$

For m-zone and 2m-zone windings

$$q_1 = \frac{2 \cdot m_2 \cdot p_2}{m_1 \cdot p_1} q_2 \qquad (5)$$

Usually, given pole pairs (p1 and p2) and phases (m1 and m2), the number of slots per pole and phase (q1 and q2) are free, and they must take integer values. This is because the number of slots must be a whole number in order to accommodate the coils and ensure proper functioning of the motor.

3. METHODOLOGY DEVELOPMENT OF A POLE - CHANGE WINDING FOR POLE RATIO p1/p2 = 2:3

One of the most common pole ratios is p1/p2=2/3, since two-speed induction motor with this ratio can be used in turbo drives and other applications. As an example, consider the construction of a winding with a variable number of poles in Z=36 stator slots using the DSSF method. As the initial winding, you can take two double-layer stator windings of the m-zone type, placed in Z=36 slots with the number of pole pairs p1=2 and p2=3. The number of slots per pole per phase for these windings will be q1=6 and q2=4. According to the detailed diagram, the DSSF value was obtained for each winding separately (Tables 1, 2).

Table 1: DSSF winding p_1=2 sides

Stator slots																	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
-e	-f	-f	-f	-f	-f	-f	-d	-d	-d	-d	-d	-d	-e	-e	-e	-e	-e
d	d	d	d	d	d	e	e	e	e	e	e	f	f	f	f	f	f
Stator slots																	
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
-e	-f	-f	-f	-f	-f	-f	-d	-d	-d	-d	-d	-d	-e	-e	-e	-e	-e
d	d	d	d	d	d	e	e	e	e	e	e	f	f	f	f	f	f

Table 2: DSSF winding p_2=3 sides

Stator slots																	
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	-a	-a	-a	-a	-b	-b	-b	-b	-c	-c	-c
a	a	a	a	b	b	b	b	c	c	c	c	a	a	a	a	b	b
Stator slots																	
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
-c	-a	-a	-a	-a	-b	-b	-b	-b	-c	-c	-c	-c	-a	-a	-a	-a	-b
b	b	c	c	c	c	a	a	a	a	b	b	b	b	c	c	c	c

The "YYY/YYY" circuit refers to the arrangement of coils in a three-phase winding, where each coil is connected in a Y configuration. By arranging the bottom row of each winding one below the other and indicating the phase in the groove of each winding, you can determine which branch or phase a particular coil number belongs to (Table 3).

Table 3: Distribution of windings in the stator slots

Stator slots																		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	pole
d	d	d	d	d	d	e	e	e	e	e	e	f	f	f	f	f	f	$p_1=2$
a	a	a	a	b	b	b	b	c	c	c	c	a	a	a	a	b	b	$p_2=3$
Stator slots																		
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	pole
d	d	d	d	d	d	e	e	e	e	e	e	f	f	f	f	f	f	$p_1=2$
b	b	c	c	c	c	a	a	a	a	b	b	b	b	c	c	c	c	$p_2=3$

For example, slot №1÷4 with p1=2 pole winding corresponds to phase D, and with p2=3 - phase A, therefore, belongs to branch A-D. Based on this method, we group the coils (Table 4) into branches of the basic "YYY/YYY" circuit (Fig. 1).

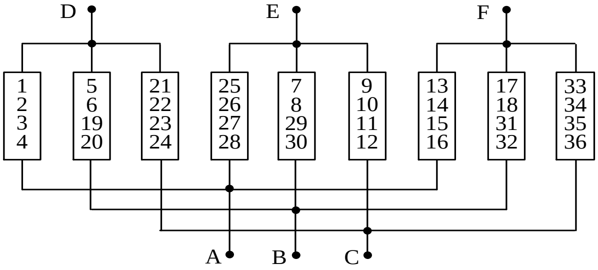


Figure 1: Branches of the basic scheme "YYY/YYY"

This type of winding is designed to ensure balanced voltage and current distribution in the machine, which is important for efficient and reliable operation. The symmetrical arrangement helps minimize the presence of harmonics and ensures that the machine operates smoothly with minimal vibration and noise. The phase shift of $2\pi/3$ radians (or 120 degrees electrical) between the branches of the same phase is a characteristic feature of a balanced three-phase system. This phase shift facilitates the generation of a rotating magnetic field which is essential for the operation of three-phase induction motors.

Table 4: Distribution of coils in the branches of the basic circuit "YYY/YYY"

Number of coils	A-D	A-E	A-F	B-D	B-E	B-F	C-D	C-E	C-F
	1, 2, 3, 4	25, 26, 27, 28	13, 14, 15, 16	5, 6, 19, 20	7, 8, 29, 30	17, 18, 31, 32	21, 22, 23, 24	9, 10, 11, 12	33, 34, 35, 36

4. RESULTS AND DISCUSSION

When evaluating the electromagnetic characteristics of pole-changing windings, it is important to analyze the harmonic content of the magnetomotive force (MMF) patterns. This analysis should take into account factors such as winding factors and differential leakage factors from both poles. By considering these factors simultaneously, a more comprehensive understanding of the electromagnetic properties of the windings can be attained.

The winding factors are often expressed for each space harmonic [17].

$$E_{i\nu} = Ee^{j\gamma i\nu} - Ee^{j\gamma(i+)\nu} \tag{6}$$

where E - unit EMF amplitude; i - coil number; ◎=360p/Z -angle per slot; Z - number of slots; y - coil pitch; ν - harmonic number.

The resulting amplitude of the EMF of series-connected n coils:

$$E_{res\,\nu} = \sum_{i=1}^{n} E_{n\nu_i} \tag{7}$$

where n - number of coils in a phase or branch.

The winding factor is determined by the expression

$$\xi_\nu = \frac{E_{res\,\nu}}{2n} \tag{8}$$

Winding factors data are given in Table 5.

The differential leakage factor of the new pole-changing winding for the ratio of poles 2p1/2p2=4/6 in Z1=36 stator slots from the side p1=2 poles with a step y=7 (1-8) is equal to σ0=5,1%, and from the side p2=3 poles - σ0=4,9% (Fig. 2).

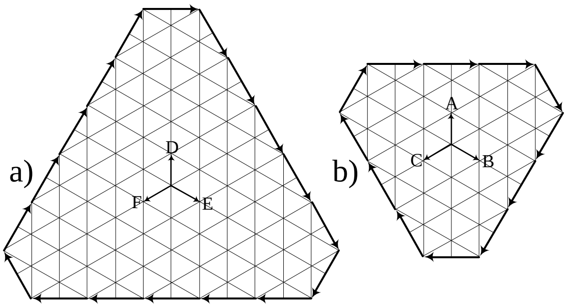
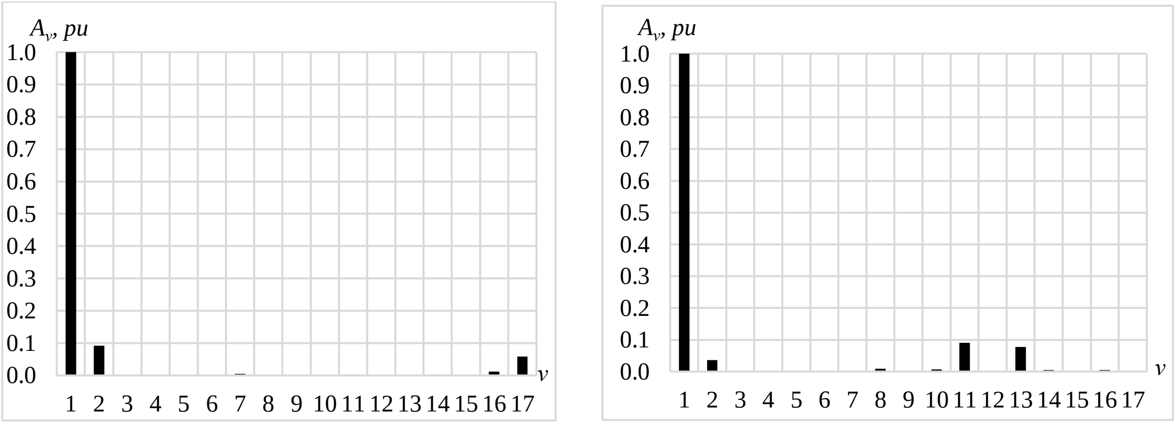


Figure 2: Görges polygon pole-changing winding: a) from the side p1=2, b) from the side p2=3.

In the image of the DSSF of a pole winding with 2p1=4 poles with a winding pitch y=7 (1-8), in addition to the first harmonic, there are the second, fifth, seventh, eighth, eleventh, fourteenth, sixteenth and seventeenth harmonics, their amplitude in relative units is A2=9%, A5=0,1%, A7=0,5%, A8=0,1%, A11=0,3%, A14=0,3%, A16=1,2%, A17=5,9% respectively. A pole winding with 2p2=6 poles with a winding pitch y=7 (1-8), in addition to the first harmonic, contains the second, fifth, seventh, eighth, tenth, eleventh, thirteenth, fourteenth and sixteenth harmonics, their amplitude in relative units is A2=3,6%, A5=0,1%, A7=0,1%, A8=0,9%, A10=0,7%, A11=9,1%, A13=7,7%, A14=0,5%, A16=0,4% respectively.

Table 5: Harmonic content of MMF.

Z	2p		Number of harmonic, ν																
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
36	4	ξ	0,87	0,46	0,21	0,13	0,01	0,21	0,21	0,05	0	0,05	0,2	0,21	0,01	0,13	0,21	0,46	0,87
		A,	4,47	0,77	0	0	0,03	0	0,09	0,03	0	0,02	0,06	0	0,01	0,09	0	0,09	0,26
		A, %	100	9	0	0	0,1	0	0,5	0,1	0	0	0,3	0	0	0,3	0	1,2	5,9
	6	ξ	0,808	0,21	0	0,21	0,05	0	0,05	0,21	0	0,21	0,808	0	0,808	0,21	0	0,21	0,05
		A	3,08	0,41	0	0	0,04	0	0,03	0,10	0	0,08	0,28	0	0,23	0,05	0	0,05	0,01
		A, %	100	3,6	0	0	0,1	0	0,1	0,9	0	0,7	9,1	0	7,7	0,5	0	0,4	0



a) b)

Figure 3: Harmonic component of MMF: a) for $2p_1$=4, b) for $2p_2$=6

In the image of the DSSF of a pole winding with 2p1=4 poles with a winding pitch y=7 (1-8), in addition to the first harmonic, there are the second, fifth, seventh, eighth, eleventh, fourteenth, sixteenth and seventeenth harmonics, their amplitude in relative units is A2=9%, A5=0,1%, A7=0,5%, A8=0,1%, A11=0,3%, A14=0,3%, A16=1,2%, A17=5,9% respectively. A pole winding with 2p2=6 poles with a winding pitch y=7 (1-8), in addition to the first harmonic, contains the second, fifth, seventh, eighth, tenth, eleventh, thirteenth, fourteenth and sixteenth harmonics, their amplitude in relative units is A2=3,6%, A5=0,1%, A7=0,1%, A8=0,9%, A10=0,7%, A11=9,1%, A13=7,7%, A14=0,5%, A16=0,4% respectively.

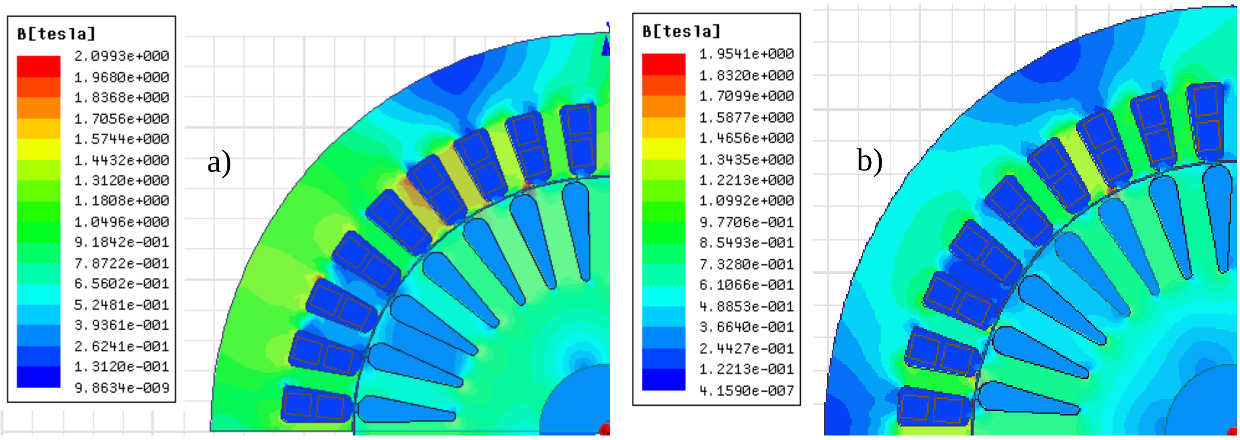


Figure 4: Flux density distribution: a) for $2p_1=4$, b) for $2p_2=6$.

Based on the calculated data, a prototype of a two-speed induction motor with a winding of a variable number of poles was manufactured based on the magnetic circuit of a serial machine of type 4A80B4U3 with the number of stator slots Z1=36 and the rotor stator Z2=28. The induction motor is made on a magnetic circuit with an outer stator diameter 131 mm, an inner stator diameter 84 mm, a stator package length 98 mm, an air gap 0.25 mm. A two-speed induction motor was modeled and studied using the Ansys/Maxwell software module. The flux density distribution for excitation p1=2 and p2=3 is shown in Figures 5 and 6, respectively. The graphs show that in the case of p1=2, the maximum flux density occurs in the stator teeth.

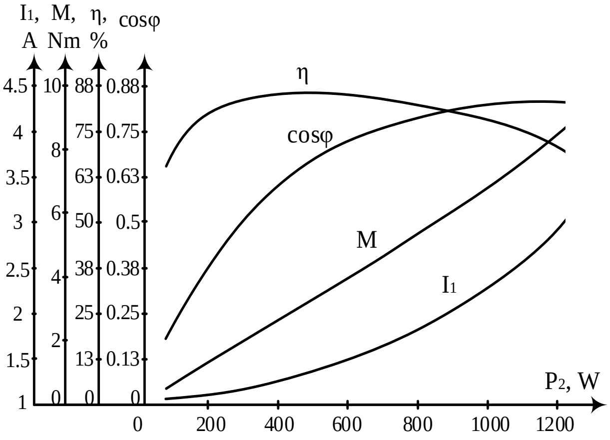


Figure 5: Characteristic curves of an induction motor from p1=2 side.

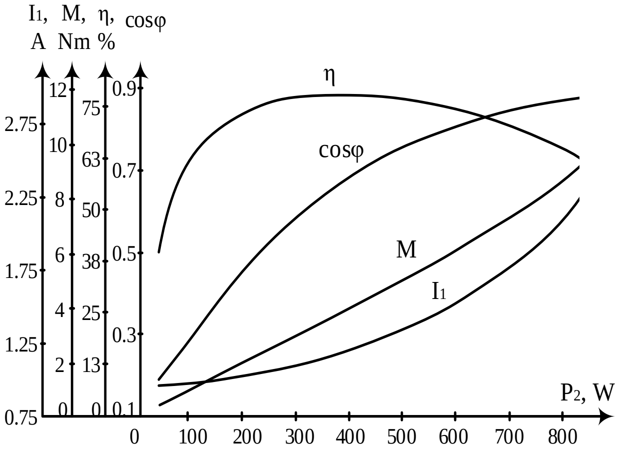


Figure 6: Characteristic curves of an induction motor from p2=3 side.

The induction motor can reach a useful active power of 1,1 kW with an efficiency of 75%, a power factor of 0,83, and a stator current of 2,7 A when operated with p1=2 pairs of poles. When operated with p2=3 pairs of poles, it can develop an active power of 0,7 kW at an efficiency of 71%, a power factor of 0.87, and a stator current of 1,7 A (Table 6).

Fig. 7. illustrates the torque-speed properties of a two-speed induction motor featuring a pole-changing winding 4A80B4/6U3. The graph depicts smooth mechanical characteristics, with a starting torque of 7.1 Nm from the 4 pole side (p1=2) and 4.6 Nm from the 6 pole side (p2=3). Furthermore, the maximum starting torque is recorded at 12.5 Nm for the 2p1=4 pole side and 9.5 Nm for the 2p2=6 pole side.

Table 6: Experimental data of the new two-speed induction motor

№	P_2	I_1	$cos\varphi$	η	M	P_2	I_1	$cos\varphi$	η	M
	W	**A**		**%**	**Nm**	**W**	**A**		**%**	**Nm**
	for p_1=2					for p_2=3				
1	200	1,1	0,34	79	1,3	100	0,9	0,26	59	0,9
2	400	1,2	0,57	84	2,5	200	1	0,42	72	1,9
3	600	1,5	0,71	84	2,9	300	1,1	0,55	77	2,9
4	700	1,7	0,75	83	4,6	400	1,2	0,66	78	3,9
5	800	1,9	0,78	82	5,3	500	1,3	0,74	76	5
6	900	2,1	0,81	80	6	600	1,4	0,8	74	6,1
7	1000	2,3	0,82	78	6,7	700	1,7	0,84	71	7,2
8	1100	2,7	0,83	75	7,7	800	2,1	0,87	65	8,5
9	1200	3,1	0,83	71	8,3	900	2,9	0,88	52	10,3

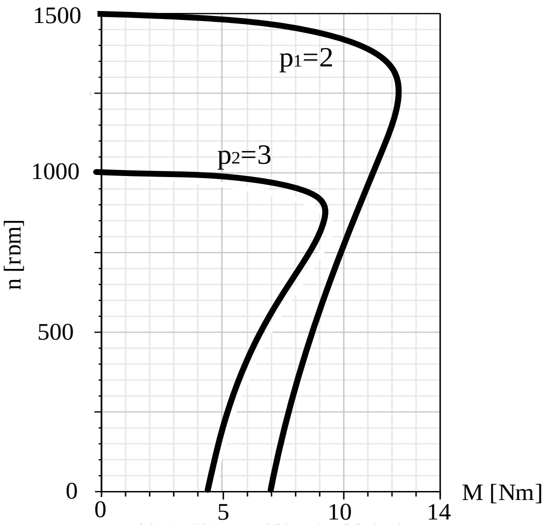


Figure 7: Torque-speed characteristics of a two-speed induction motor

The study involved the detailed analysis of the operation of a new electric drive system featuring a two-speed induction motor with a pole ratio of p1/p2=2/3. The research focused on dynamic modes and was conducted on a fan drive of the VSUN 160x74-0.55-4 type. (Fig. 8). The investigation of the new pole-changing induction motor included an analysis of its dynamic modes of operation, such as startup, steady-state operation and transient response [18].

In Fig. 9, the curve indicates that the induction motor takes 200 ms to reach a steady state of operation when starting from the p1=2 pole side, with a starting current reaching 13,53 A.

In Fig. 10, when starting from the p2=3 pole side, the induction motor reaches steady-state operation after 120 ms, with a starting current of 10,87 A.

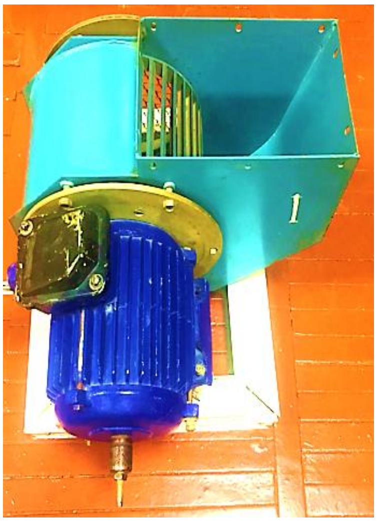


Figure 8: New two-speed induction motor driving the fan.

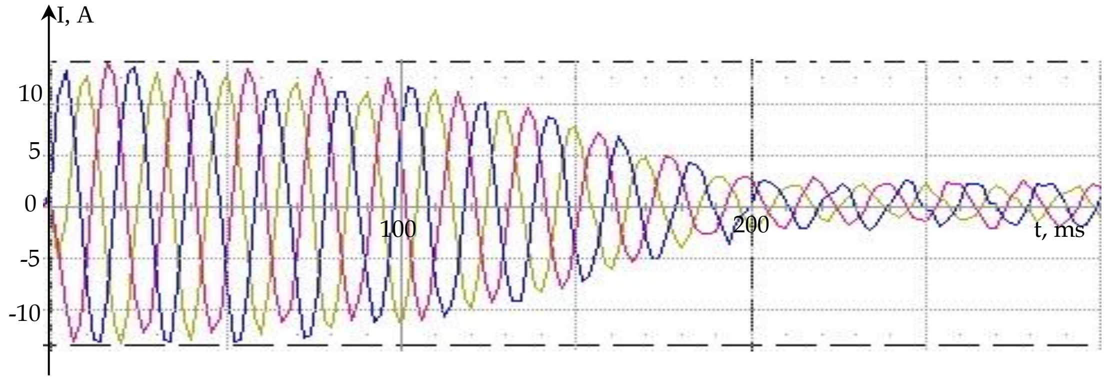


Figure 9: Curves of stator currents changes from the side p_1=2.

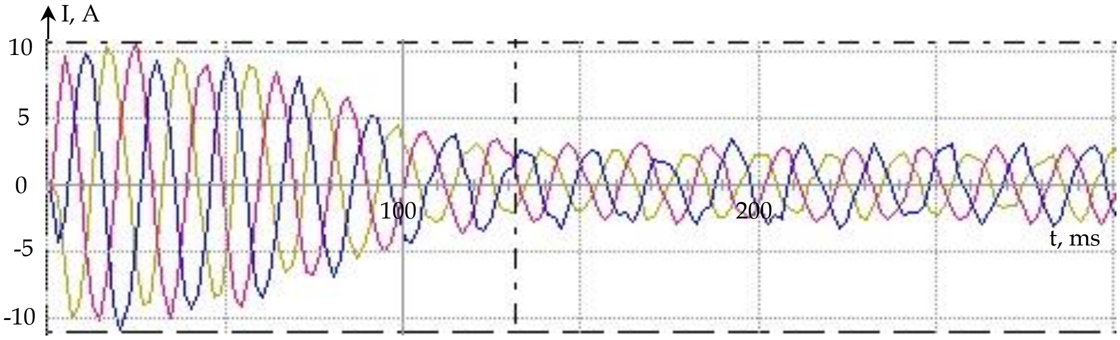


Figure 10: Curves of stator currents changes from the side p_2=3.

The figures (Fig. 9 and Fig. 10) illustrate the curves of stator current versus time for both scenarios, providing visual representations of the induction motor's performance during startup.

It appears that the tests conducted on operating installations in industrial conditions have shown that electric drives of fans based on a two-speed induction motor with a pole-changeable winding meet all the fundamental requirements for fan electric drives. This suggests that the induction motor's performance and characteristics align with the necessary criteria for effectively driving fans in industrial settings [19, 20].

5. CONCLUSIONS

The analysis of the new pole-changing winding using ANSYS/Maxwell software has revealed that its electromagnetic properties closely resemble those of conventional two-layer windings. The winding was tested on a 1,5 kW/1500 rpm induction motor in frame 4A80B4U3, where the height of the axis is 80 mm, producing 1,1 kW/0,7 kW rated power for 2p1/2p2=4/6 poles, respectively.

The results indicate that the new pole-changing winding demonstrates balanced air gap flux density at both speeds, leading to almost constant torque. As a result, it can be used in various general applications where speed regulation is required to optimize energy and resource usage due to changes in load on the shaft based on seasonal and time-of-day variations.

Furthermore, the new two-speed induction motor is suitable for use in drives for turbo mechanisms and other installations that demand speed regulation to achieve energy and resource savings. Overall, the findings suggest that the new pole-changing winding offers promising potential for enhancing induction motor performance and efficiency in diverse operational scenarios.

Author Contributions: Makhsud Bobojanov, Coordinating the work of the scientific group and the group of authors during research work, the results of which are presented in this article; Dauletbek Rismukhamedov, developing a pole change winding scheme for a pole pair ratio of 2/3 with a number of stator slots of 36; Furkat Tuychiev, analysis of the properties of the new winding by Fourier series expansion, using of Goerges diagrams, and also the Ansys Maxwell program; Doctor Khusniddin Shamsutdinov -

Preparation of the text of the article and translation into English.

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