New pole-changing winding for electric drive of ball mills

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Abstract. The article substantiates the expediency of using a controlled electric motor in grinding mechanisms in electric drives instead of an unregulated asynchronous motor. The problem of facilitating the start-up of ball mills and ensuring accurate stop of the neck of ball mills using the lowest speed is considered. As the review of the literature showed, speed control in electric drives using two-speed motors is a simple, cheap and reliable option. In many existing two-speed motors, two independent windings are placed in the stator slots; for this reason, the motor magnetic circuit is not effectively used, in turn, the use of one pole-changing winding improves the energy performance of the motor and saves winding copper and insulating materials. Based on the analysis of the operating modes of grinding mechanisms, in terms of facilitating start-up and resource saving (increase the operating time of the engine itself), the expediency of creating a two-speed motor with a pole-changing winding with a pole ratio of 2:5 and improving existing electric drive systems with its use is substantiated.

1 Introduction

In many technological and production processes of mining and processing and ceramic factories, dust preparation systems of thermal power plants, house-building plants, chemical plants, mechanisms for grinding various materials are widely used, which include ball drum mills of periodic action [1].

The presence of large inertial masses and an unbalanced load complicates the acceleration and positioning of the ball mill drum. The maximum value of the load moment is observed when the drum rotates from the vertical axis by 90°, which can lead to its stop if the engine torque is insufficient. In this case, the mill is started by the operator by swinging the drum for 7-10 switching on and off, which leads to rapid wear of the engine and mechanical transmission elements, which determines significant economic losses and requires modernization of the electric drive [2].

2 The current state of the investigated problem

By replacing the single-speed asynchronous motor in this mill with a two-speed pole-changing motor, which has a simple preparation technology mounted on a single stator, it can facilitate the starting process and ensure accurate stopping, as well as drastically reduce the number of mill switching per operation cycle. In this case, the mill is started with a step start, that is, during the start-up process, it is started from the side of low speed and after a full turn of the drum, it is switched to the side of high speed. During mill stop, precise stop is ensured by switching from high speed to low speed.

To build a pole-changing winding at the Tashkent State Technical University, a new method “Discrete-specified spatial functions” was developed. On the basis of this method, many schemes of pole-changing windings were developed for a wide range of pole and phase ratios, close in their properties to serial windings [3].

The basis of the method is a method in which two windings of normal design are taken (one of them is original, the other is typical) with a given number of poles ($2p_1$, $2p_2$) and phases (m_1, m_2) and are simultaneously used in the process of constructing a pole-changing winding, according to the principle approximation of the current distribution and the pattern of the magnetomotive forces of the synthesized winding to the current distribution and the picture of the magnetomotive forces of a typical winding, where each layer of conductors distributed over the grooves with conditional currents is replaced by a discrete element of the winding [4]. A discretely given spatial function of a conventional winding is the state of the conductor and is assigned to the coil side with one conditional conductor, through which a single current of one direction or another flows in a slot belonging to one of the phases and designated identically with this phase [5].

The construction of pole-changing windings is based on special basic circuits that have two groups of terminals and when switching power from one group of terminals to another (Fig. 1), the number of pairs of poles changes (in relation to one group of terminals they are $2p_1$-pole, and in relation to another - $2p_2$-pole) [6].

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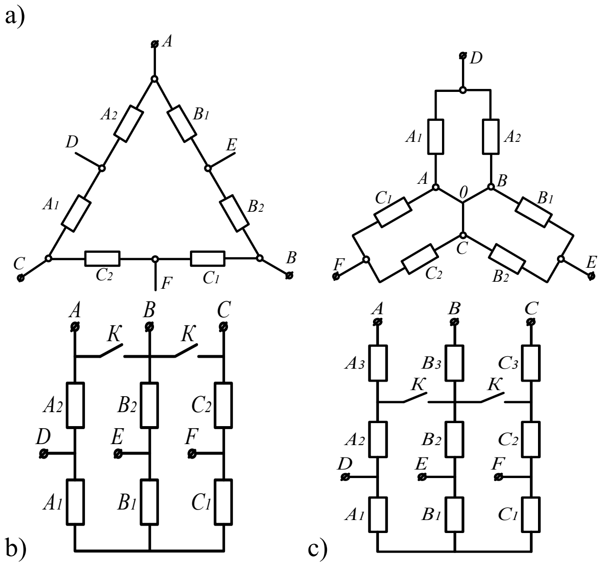

Fig 1. Basic schemes of pole-changing windings: a) Δ/YY; b) Y/YY; c) Y/YY with additional branches

The basic scheme may consist of a general and additional parts. In this case, the common part of the basic circuit serves as the basis of the pole-changing winding and participates in the creation of a magnetic field from both poles, and the additional part participates in the creation of a field of only one pole.

Two-speed pole-changing windings are built on the basis of a joint consideration of two multi-phase two-layer loop windings, which are most widely used in the practice of electrical engineering [7, 8].

The development of pole-switchable winding circuits with a fractional pole ratio based on existing basic circuits has its own characteristics, for example, to mitigate the effect of winding fractionality on the pattern of magnetomotive forces of the pole-changing winding according to the basic “Y/YY” or “Δ/YY” circuit, it is advisable to perform windings 2m-2m -zonal, which makes it possible to improve the vibroacoustic characteristics of the engine. In addition, 2m-2m-zone windings have the smallest composition of higher harmonics, which makes it possible to use them in engines with a busy operating mode, in particular, electric drives for grinding mechanisms for step start [9].

When obtaining a pole-changing winding based on the “Y/YY” or “Δ/YY” schemes, it is necessary to synthesize a discretely given spatial function corresponding to one of the poles [10].

As an example, consider the process of obtaining a pole-changing winding circuit for a pole ratio of 2/5 with the number of slots Z=30. In Table 1, a normal 2m-zone winding with the number of poles p_2=5 is taken as the “initial” winding, and a normal 2m-zone winding with p_1=2 is also taken as a “typicalA” winding [11].

Let us write the discretely given spatial function of one layer of these windings under each other:

Table 1. Synthesizing 2p1=4 pole winding

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	groove
a	$\underline{c}$	b	$\underline{a}$	c	$\underline{b}$	a	$\underline{c}$	b	$\underline{a}$	c	$\underline{b}$	a	$\underline{c}$	b	p_2=5 initial.
a	a	a	$\underline{c}$	$\underline{c}$	b	b	b	$\underline{a}$	$\underline{a}$	c	c	c	$\underline{b}$	$\underline{b}$	p_1=2 typical
a	$\underline{c}$	$\underline{b}$	a	$\underline{c}$	b	$\underline{a}$	$\underline{c}$	b	$\underline{a}$	c	$\underline{b}$	$\underline{a}$	c	$\underline{b}$	p_1=2 synt.

16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	groove
$\underline{a}$	c	$\underline{b}$	a	$\underline{c}$	b	$\underline{a}$	c	$\underline{b}$	a	$\underline{c}$	b	$\underline{a}$	c	$\underline{b}$	p_2=5 initial.
a	a	$\underline{c}$	$\underline{c}$	$\underline{c}$	b	b	$\underline{a}$	$\underline{a}$	$\underline{a}$	c	c	$\underline{b}$	$\underline{b}$	$\underline{b}$	p_1=2 typical
a	$\underline{c}$	b	a	$\underline{c}$	b	$\underline{a}$	c	b	$\underline{a}$	c	$\underline{b}$	a	c	$\underline{b}$	p_1=2 synt.

The discretely given space function of the synthesized winding is obtained by “modulating” the discretely given space function of the original winding with the help of the discretely given space function of the typical winding. This process is based on the principle of approximation of the current distribution to the picture of the magnetomotive force of the pole-changing winding from the pole side 2p1 to the current distribution and picture of the magnetomotive force of a typical winding. The meaning of “approximation” is to determine in each slot the sign of the state of the conductor of a discretely given spatial function of the synthesized winding, depending on the state of the conductor of a discretely given spatial function of a typical winding in this groove and based on the relative position of the phase current vectors in a three-phase system [12].

According to the obtained discretely given spatial function, it is possible to group the coils into the BS branches (Table 2).

Table 2. Grouping coils in the branches of the basic circuit “Δ/YY”

Branches	**Coil number**
A1	-4, 7, 13, -16, 25
A2	19, -22, -28, 1, -10
B1	-24, 27, 3, -6, 15
B2	9, -12, -18, 21, -30
C1	-14, 17, 23, -26, 5
C2	29, -2, -8, 11, -20

Table 3. Winding data from side p_1=2

Branches of the basic circuit Δ /YY			
Branches	***A-D***	***D-0***	***B-E***
A	6,44	6,44	6,44
k_{win}	0,644	0,644	0,644
φ	42	42	162
Branches	***E-0***	***C-F***	***F-0***
A	6,44	6,44	6,44
k_{win}	0,644	0,644	0,644
φ	162	282	282

Table 4. Winding data from side p_2=5

	Branches of the basic circuit Δ /YY		
	A	***B***	***C***
A	17,32	17,32	17,32
k_{win}	0,866	0,866	0,866
φ	0	120	240

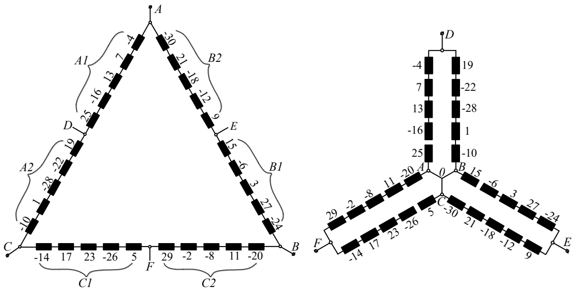

Fig 2. Electric circuit of the pole-switched winding according to the basic circuit "Δ/YY

The resulting winding (Fig. 2) is completely symmetrical with respect to the power source from both poles, the vectors of the electromotive forces of the same branches of each of the phases are symmetrical to each other, i.e. equal in amplitude and shifted in phase by an angle of $2\pi/3$ el. rad., at y=8, the winding coefficients from $2p_1$ and $2p_2$ of the pole side are respectively equal to k_{win1}=0.644 and k_{win2}=0.866 (Table 3 and Table 4) [11].

The resulting pole-changing winding works as follows: When a three-phase power supply is connected to terminals D, E, F (pins A, B, C are combined into a common point), a four-pole rotating magnetic wave occurs in the air gap, all 30 coils are included in the circuit, the electromotive force vectors of each phase are equal in amplitude and shifted along phase by 120^0, that is, the winding on the side of $2p_1$=4 poles is completely symmetrical with respect to the power source.

When a three-phase power supply is connected to terminals A, B, C (terminals D, E, F are free), a ten-pole rotating magnetic wave, all 30 coils are included in the circuit, the electromotive force vectors of each phase are equal in amplitude and shifted in phase by 120^0, that is, the winding on the side of the pole pairs, it is perfectly symmetrical with respect to the power source.

The creation of a two-speed engine, approaching conventional single-speed engines in terms of their energy and weight and size indicators, is one of the urgent problems. The development of such motors makes it possible to improve the existing electric drive with two-speed motors and replace some single-speed motors with two-speed motors in order to save electricity and natural resources in lightly loaded modes, as well as to facilitate the process of starting powerful motors [13].

It should be noted that the task of designing a two-speed motor with one winding is a complex process and can be compared with the simultaneous design of two single-speed motors that have interconnected parameters and cannot be changed unilaterally [14, 18].

3 Results and discussion

Based on the calculated data, «ENERGY MOTORS» LLC manufactured experimental models of a two-speed motor with a developed pole-changing winding (No. IAP 06203, 03/20/2020) for a pole ratio of 4/10 at BS "Δ/YY" based on magnetic cores of serial machines of the АИР112М4 and АИР225L4.

In the research laboratory "Energy-saving technologies in power supply systems" of the Tashkent Technical University, experimental tests were carried out in static modes to determine the losses of idling and short circuit (see tables 5 and 6), as well as the operating and mechanical characteristics of a new two-speed motor with pole-changing winding for the ratio of pairs of poles 2/5 type АИР112М4.

Table 5. Idle experience data

U_1	**from p_1=4**				
	I_0	P_0	$\cos\varphi_0$	P_{el}	$P_{be}+P_{mag}$
V	**A**	**W**		**W**	**W**
60	0,9	145	0,62	5,95	139,05
80	1	147	0,43	7,35	139,65
100	1,21	150	0,3	10,76	139,24
140	1,65	160	0,17	20,01	139,99
180	2,2	180	0,11	35,57	144,43
220	3,18	261	0,08	84	177
	from p_2=10				
60	0,95	144	0,4	14,86	126,13
80	1,24	158	0,25	30,44	127,55
100	1,57	176	0,18	48,8	127,19
140	2,3	232	0,12	94,74	137,25
180	3,5	411	0,11	242,5	168,45
220	5,3	780	0,1	556,2	223,8

Table 6. Short circuit experience data

from p_1=4			
U_{1K}	P_K	I_{1K}	$\cos\varphi_K$
V	W	A	
30	160	3,4	0,52
40	280	4,8	0,49
50	440	6,2	0,47
60	650	7,7	0,47
70	940	9,4	0,48
80	1250	10,9	0,48
from p_2=10			
40	240	2,1	0,551
60	420	2,8	0,501
70	525	3,2	0,452
80	650	3,5	0,447
90	790	4	0,423
110	1000	4,6	0,381

The operating characteristics of the electric motor were obtained in the direct load mode (Fig. 3). A DC generator with independent excitation was used as a load machine.

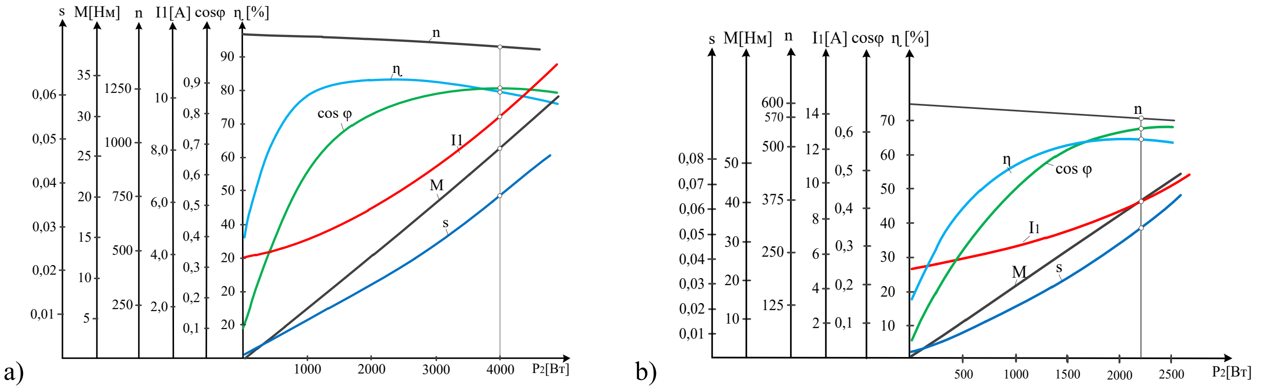

Fig 3. Performance characteristics of a new two-speed motor: a) for p_1=2 poles; b) for p_2=5 poles

The mechanical characteristics of the new two-speed motor are shown in fig. 4

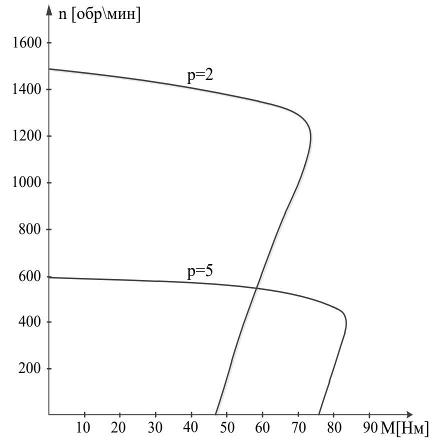

Fig 4. Mechanical characteristics of the new two-speed motor

In connection with the widespread use of motors with a squirrel-cage rotor for ball mills, the behavior of motors during start-up is of great interest.

In the Research and Production Association for the Production of Rare Metals and Hard Alloys of Almalyk MMC JSC, the operation of a ball mill electric drive with a new two-speed motor of the AIR225M10/4 type was studied in the following modes: start-up, operation at a constant speed, switching to the second speed (deceleration) and stop (further all currents are indicated in the amplitude value).

On fig. 5 shows the curve of the stator current as a function of time when starting from standstill on the p_1=2 polarity side. As can be seen from this curve, the onset of the steady state operation of the engine occurs in 800 ms, the starting current is 385 Amperes.

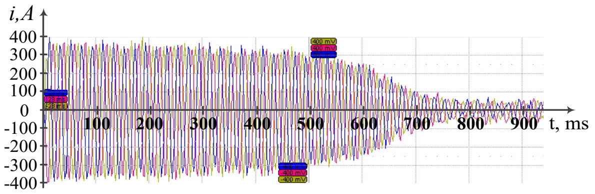

Fig. 5. The curve of the stator current change depending on the time when starting from the state of rest of the electric motor type АИР225M10/4 from the side p_1=2 poles

On fig. 6 shows the curve of the stator current as a function of time when starting from standstill on the p2=5 polarity side. As can be seen from this curve, the onset of the steady state operation of the engine occurs in 400 ms, the starting current is 185 Amperes.

When switching directly from high to low speed, large dynamic torques occur in the drive, which are much higher than the rated torque and can exceed the critical torques in motoring mode. To reduce the dynamic moments in the drive when switching from high to low speed, it is necessary to disconnect the motor from the mains for the duration of braking and, at the moment the synchronous speed corresponding to the low-speed winding is reached, reapply mains voltage to the motor.

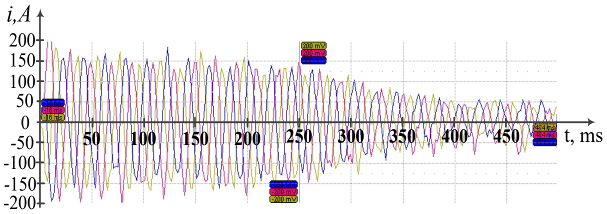

Fig. 6. Curve of stator current change depending on time at starting from a state of rest of an electric motor of the type АИР225M10/4 from the side p_2=5 poles

This method is simpler, but requires a speed or crank angular position sensor with a fairly wide measurement range. During the transition to low speed it is necessary to control the speed of the motor, because due to the variability of the load, it is not possible to pre-calculate the deceleration path, and therefore the free coast of the motor and the switching of the contactors.

On fig. 7 shows the curve of the stator current versus time when starting from standstill on the p_1=2 pole side and switching a two-speed motor to p_2=5 pole. As can be seen from this curve, the onset of the steady state operation of the engine occurs within 800 ms, the starting current is 376 Amperes.

After 2.15 s after the steady state operation on the side p_1=2 poles, the electric motor was switched to p_2=5 poles. As can be seen from this curve, the steady state of the engine operation occurs in 140-150 ms, the starting current is 245 Amperes.

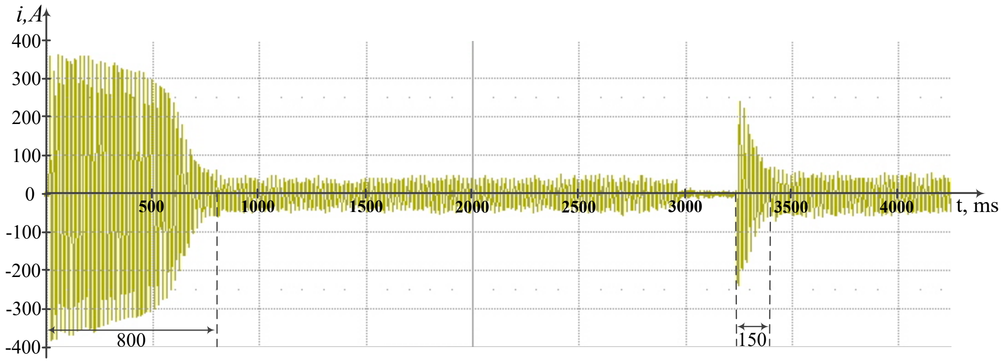

Fig. 7. The curve of the stator current change depending on time when starting from a standstill state of the electric motor of the type АИР225M10/4 from the p_1=2 poles and switching to p_2=5 poles

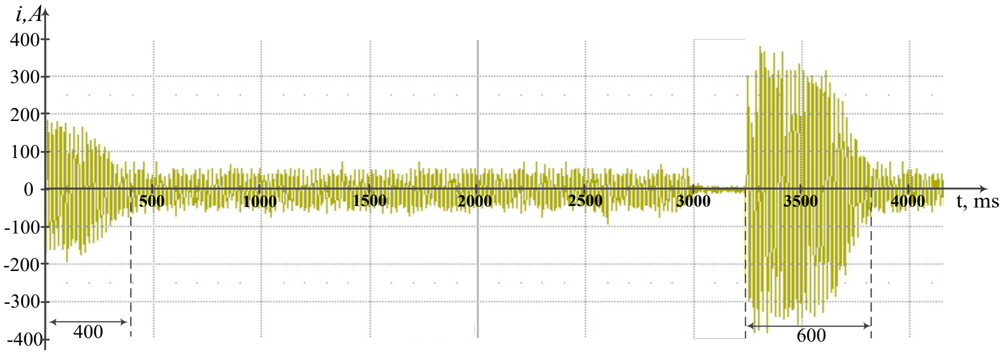

Fig. 8. Curve of stator current change depending on time when starting from a state of rest of an electric motor of the type АИР225M10/4 from p_2=5 poles and switching to p_1=2 poles

On fig. 8 shows the curve of the stator current versus time when starting from standstill on the p_2=5 pole side and switching a two-speed motor to p_1=2 pole

As can be seen from this curve, the onset of the steady state operation of the engine occurs within 400 ms, the starting current is 190 Amperes.

After 2.65 s after the steady state operation on the p2=5 pole side, the electric motor was switched to p1=2 pole. As can be seen from this curve, the steady state of the engine operation occurs within 600 ms, the starting current is 385 Amperes.

Thus, with a direct start, the electric motor reaches a steady state in 800 ms at a starting current of 400 Amperes, and with a stepped start in 600 ms at a starting current of 385 Amperes.

4 Conclusion

As you can see, with a stepped start, the electric motor at a lower starting current reaches the steady state faster, thereby facilitating start-up and resource saving (increasing the operating time of the motor itself and current-carrying parts) due to the lower amount of heat generated by the starting current, and also slows down the process of wear of the mechanical parts of the ball the mill, in addition, it provides an accurate stop of the mechanism without multiple starts, which also affects resource saving in general.

Based on the study of the operating modes of ball mills used in the crushing of various materials in mining, construction, and also in chemical enterprises, it was justified the need to improve the electric drives of these mechanisms by using two-speed electric motors with pole-changing windings.

Using the method of discrete given spatial functions based on the basic circuit “Δ/YY”, a new circuit of a pole-changing winding with a pole ratio of 2:5 with high electromagnetic properties was developed and the invention was protected in the form of a patent by the Intellectual Property Agency under the Ministry of Justice of the Republic of Uzbekistan.

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