Design and analysis of a pole-changing winding for multi-speed induction motors operating under heavy-duty conditions

Dauletbek Rismukhamedov[1], Khusniddin Shamsutdinov[2,a)], Alim Haqberdiyev[2], Khayotullo Magdiev[3], Shakhobiddin Khusanov[1]

[1]Almalyk state technical institute, Almalyk, Uzbekistan
[2] Tashkent state technical university named after Islam Karimov, Tashkent, Uzbekistan
[3]Shakhrisabz State Pedagogical Institute, Shakhrisabz, Uzbekistan

[a)] Corresponding author: shamsutdinovh83@gmail.com

Abstract. This paper presents the design and electromagnetic analysis of a pole-changing stator winding based on the YYY/YYY base connection scheme with additional branches, intended for multi-speed induction motors operating under fan-type and heavy-duty load conditions. The proposed winding is synthesized using the method of discretely defined spatial functions and enables the realization of different pole numbers with a limited number of terminals. Particular attention is paid to the conditions ensuring the absence of circulating currents in additional branches through the vector compensation of electromotive forces. A detailed procedure for constructing slot EMF star diagrams and grouping coils into the branches of the base scheme is provided for pole combinations of $2p_1$=10 and $2p2$=8. The operating principles of the winding for different supply terminal configurations are analyzed, demonstrating complete phase symmetry and stable electromagnetic performance. The proposed winding configuration is protected by a patent of the Intellectual Property Agency of the Republic of Uzbekistan and allows the development of two-speed induction motors with an extended application range, particularly for fans, pumps, compressors, and mining machinery operating under severe conditions.

INTRODUCTION

In mining enterprises, mineral raw materials typically undergo a sequence of beneficiation stages at processing plants prior to subsequent downstream treatment. This preliminary processing is essential for achieving the required technological efficiency and product quality, as it necessitates the separation of the raw material into specific size fractions in accordance with process requirements [1].

In vibratory machines, oscillatory motion of the working elements is commonly generated by inertia-type vibration exciters. Such exciters consist of an unbalanced mass (eccentric weight) driven by an asynchronous electric motor, with the axis of the unbalance most often oriented horizontally. In the stationary state, the center of mass of the rotor is located at the lower extreme position. During operation, the electric motor must satisfy at least two fundamental conditions. First, it must provide sufficient torque to lift the center of mass of the unbalanced rotor to the upper extreme position. Second, the motor power must be adequate to compensate for friction losses in the rotor bearings and to supply the useful power required for the technological process [2].

In the majority of heavy-duty machines, the electric drive is primarily selected based on the first condition, as it represents the most stringent design criterion. Under steady-state operating conditions, each vibration cycle involves a complete conversion of kinetic energy into potential energy and, conversely, potential energy into kinetic energy. As a result, no additional energy input is required to overcome inertia forces or the forces of elastic elements.

Energy consumption is therefore associated exclusively with dissipative effects, including friction losses in the bearings, energy dissipation due to impacts of the processed material against the screening surface, as well as the energy required to transport the material along the screen [3].

In practical applications, however, the electric drive is often selected based on the starting regime. This approach typically leads to the installation of motors with power ratings 1.5–2.0 times higher than those required for steady-state operation, which is energetically inefficient [1, 4]. To lift the unbalanced mass of a vibration exciter from the lower extreme position to the upper one, the required starting torque can be determined using a numerical empirical coefficient proposed by O. P. Barsukov, and is expressed by the following relationship (for a transmission ratio i=1):

$$M \geq 0.724 \cdot m_u \cdot g \cdot e \tag{1}$$

where, m_u - is the mass of the unbalanced weight, g - is the acceleration due to gravity, and e - is the eccentricity.

Thus, it becomes possible to employ an electric drive of lower rated power that is sufficient only to maintain rotation under steady-state operating conditions. Under these circumstances, the electric drive of the vibrating screen may utilize pole-changing windings arranged within a single stator, which are characterized by a simplified manufacturing technology and the capability to vary the number of magnetic poles [5, 6].

The pole-changing winding based on the "YYY/YYY" base connection scheme (Figure 1) is implemented in a number of commercially produced electric motors and is characterized by considerable technical and economic efficiency. For example, under identical frame dimensions and the same number of poles, a 4A132M6/4UZ electric motor equipped with two independent windings delivers a useful power of 3.2 kW, whereas a 4A132M6/4UZ motor with a single pole-changing winding provides 6 kW of useful power. In comparison, a single-speed 4A132M6UZ motor of the same size develops a useful power of 7.5 kW [7, 8].

For such windings, the winding factors, differential leakage coefficients, and, in most cases, the winding asymmetry indices remain within generally accepted limits. By varying the winding pitch, it becomes possible to slightly adjust the ratio of magnetic flux densities in the air gap corresponding to the first and second pole numbers through the associated winding factors [9].

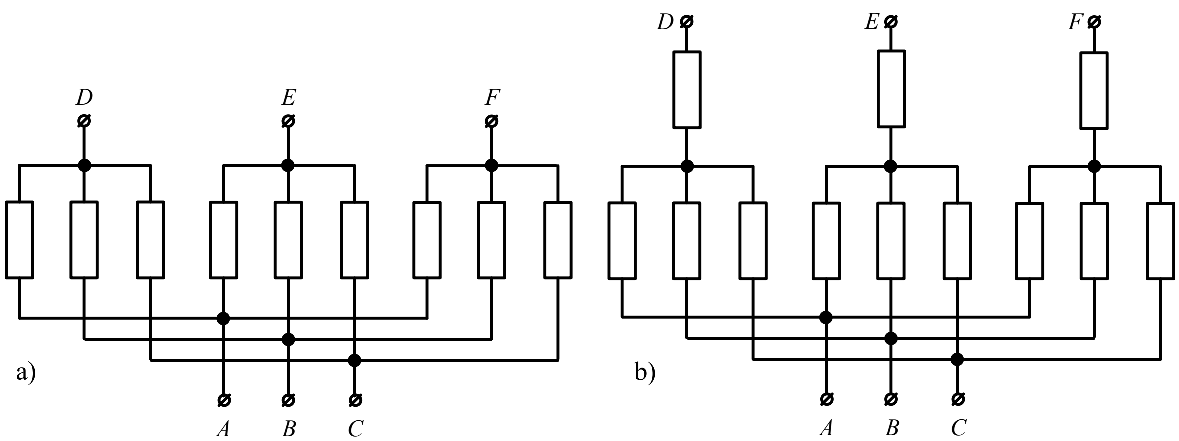

FIGURE 1. Base connection schemes of pole-changing windings: a) YYY/YYY; b) YYY/YYY with additional branches.

However, this approach becomes insufficient when a higher degree of utilization of the active part of an electric machine is required, especially in high-power machines. In such cases, it is expedient to employ pole-changing windings based on the "YYY/YYY base connection scheme with additional branches", which are particularly convenient in operation since they do not require additional switching equipment. These windings are well suited for electric motors driving mechanisms characterized by a fan-type load torque and a relatively narrow range of rotational speed control. This configuration is primarily intended for high-power electric drives [10].

In the general case, the number of additional branches in each phase of the winding is equal to n, however, in practical implementations, this number most commonly ranges from one to three (three-branch scheme). Moreover, on the basis of such windings, a pole-changing winding with a single additional branch can be readily constructed.

EXPERIMENTAL RESEARCH

When designing windings using the method of discretely defined spatial functions, a one-to-one or multiple correspondence is first established between the currents of the windings and branches of the considered base connection scheme and the individual conductors. On the basis of this correspondence, a pole-changing winding is designed. Subsequently, the circuit of the pole-changing winding is obtained by implementing electrical interconnections between its individual conductors in accordance with the similarity of conductor connections in the base scheme. It should be noted that, under conditions of one-to-one or multiple correspondence, each branch of the base connection scheme corresponds to a winding or a winding group of the pole-changing winding [11].

Based on the requirement that a pole-changing winding must occupy the same number of stator slots for both pole numbers, the following conditions can be formulated. For *m-m*-zone windings, the corresponding relationships are given as follows:

$$Z = m_1 \cdot p_1 \cdot q_1 + Z_{add} = m_2 \cdot p_2 \cdot q_2 \tag{2}$$

From this, for *m-m*-zone windings, the following relationship is obtained:

$$q_1 = \frac{m_2 \cdot p_2 \cdot q_2 - Z_{add}}{m_1 \cdot p_1} \tag{3}$$

where, m-is the number of winding phases; p-is the number of pole pairs; q-is the number of stator slots per pole per phase, where the subscript 1 corresponds to the lower pole number and the subscript 2 corresponds to the higher pole number; Z-is the total number of stator slots; Z_{add}-is the total number of stator slots occupied by the windings of the additional branches.

For the YYY/YYY base connection scheme:

$$Q = \frac{Z_1}{9} \tag{4}$$

For the YYY/YYY base connection scheme with additional branches:

$$Q = \frac{Z_1 - Z_{add}}{9} \tag{5}$$

Here, Q is the number of windings connected in series within each branch of the base connection scheme (an integer); Z_1 is the total number of stator slots; $Z_{add}=3 \cdot n \cdot h$ is the total number of stator slots occupied by the additional branches; n is the number of additional branches per phase; h-is the number of windings in the additional branches; the numbers 6, 9, and 18 represent the bases of the connection scheme and correspond to the maximum number of rays of a three-phase star connection.

When the number of stator slots is not a multiple of the base value, the application of additional branches becomes expedient. For example, for the “YYY/YYY” base connection scheme, such cases include Z_1=24, 30, 48, 60 and similar values [12]. In addition, auxiliary branches may be employed to improve electromagnetic characteristics, to optimize the ratio of magnetic flux densities in the air gap, to enhance symmetry, and for related purposes. The number of coils assigned to the additional branches may account for approximately 17–50% of the total number of winding coils.

Typically, coils that are insufficiently effective in forming the resultant phase electromotive force (EMF) on the lower-pole side are transferred to the additional branches. The coils of the auxiliary branches are distributed in accordance with the mutual compensation condition, since, when the supply source is connected from the pole side without additional branches, induced EMFs arise that lead to the appearance of circulating equalizing currents within these branches [13].

Using the method of discretely defined spatial functions, a number of windings with close pole-number ratios of 3/4, 5/6, 8/6, and 10/12 have been developed. These windings can be applied in two-speed electric motors with smaller dimensions and a relatively large number of stator slots [2, 14].

A number of pole-changing windings with close pole ratios of 3/4, 5/6, 8/6, and 10/12 have been developed using the method of discretely defined spatial functions. These windings can be applied in two-speed electric motors with either a small or a large number of stator slots [2, 15].

Despite the considerable number of winding designs developed to improve the electric drives of vibratory screens, the issues related to the design of pole-changing winding schemes with a pole ratio of 4:2 for electric drives of ventilation system fans have not yet been sufficiently investigated. In this dissertation, the use of three-speed asynchronous motors with pole-changing windings is proposed, along with the implementation of an automatic control system for the electric drive of ventilation systems in poultry farms [2].

RESEARCH RESULTS

As an illustrative example, the construction of a pole-changing winding based on the most practically relevant pole-pair ratio of 5/4 is considered in the following.

As the initial windings, two double-layer lap-type m-zone stator windings are selected. These windings are arranged in 60 stator slots and correspond to pole-pair numbers p_1=5 and p_2=4, with coil pitches of y_1=1-7 and y_2=1-9, respectively. In accordance with the developed winding layout, the discretely defined spatial functions of each winding are determined separately and presented in Table 1 and Table 2.

Since the number of coils connected in series within the branches of the base connection scheme depends on the number of stator slots, the pole-changing winding designed on the basis of this scheme must satisfy the same requirement. According to equation (4), for the "YYY/YYY" base connection scheme (Figure 1 (a)) with the number of stator slots Z_1=60, this quantity must be an integer.

TABLE 1. The discretely defined spatial function corresponding to the pole side with p_1=5 is given below.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	slots
-e	-e	-f	-f	-f	-f	-d	-d	-d	-d	-e	-e	-e	-e	-f	-f	-f	-f	-d	-d	-d	-d	-e	-e	-e	-e	-f	-f	-f	-f	p_1=5
d	d	d	d	e	e	e	e	f	f	f	f	d	d	d	d	e	e	e	e	f	f	f	f	d	d	d	d	e	e	

31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	slots
-d	-d	-d	-d	-e	-e	-e	-e	-f	-f	-f	-f	-d	-d	-d	-d	-e	-e	-e	-e	-f	-f	-f	-f	-d	-d	-d	-d	-e	-e	p_1=5
e	e	f	f	f	f	d	d	d	d	e	e	e	e	f	f	f	f	d	d	d	d	e	e	e	e	f	f	f	f	

TABLE 2. The discretely defined spatial function corresponding to the pole side with p_2=4 is given below.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	slots
-b	-b	-b	-c	-c	-c	-c	-c	-a	-a	-a	-a	-a	-b	-b	-b	-b	-b	-c	-c	-c	-c	-c	-a	-a	-a	-a	-a	-b	-b	p_2=4
a	a	a	a	a	b	b	b	b	b	c	c	c	c	c	a	a	a	a	a	b	b	b	b	b	c	c	c	c	c	

31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	slots
-b	-b	-b	-c	-c	-c	-c	-c	-a	-a	-a	-a	-a	-b	-b	-b	-b	-b	-c	-c	-c	-c	-c	-a	-a	-a	-a	-a	-b	-b	p_2=4
a	a	a	a	a	b	b	b	b	b	c	c	c	c	c	a	a	a	a	a	b	b	b	b	b	c	c	c	c	c	

That is, the condition Z_1=60 is not satisfied. In this case, the grouping of coils into the winding is carried out in accordance with the coil connections of the "YYY/YYY base connection scheme with additional branches".

In general, the number of additional branches per phase is equal to n; however, in most practical cases, it ranges from one to three. The number of coils in the additional branches of each phase may be either even or odd. The design of such windings is complicated by the necessity to eliminate circulating (equalizing) currents in the additional branches. When the winding is supplied from the lower-pole side, the directions of the induced electromotive forces in the additional branches must be selected so as to ensure their mutual compensation; otherwise, circulating currents will arise [2, 16].

The absence of circulating currents is ensured provided that the following conditions are satisfied:

1. When the winding is placed in the magnetic field of the higher pole number $2p_1$, the resultant phase electromotive force vectors of the additional branches are identical in both magnitude and direction.
2. For n=3 and odd values of i, when the winding is placed in the magnetic field of the lower pole number $2p_2$, the resultant phase EMF vectors of the additional branches are identical in both magnitude and direction.
3. For n=1…z and even values of i, when the winding is placed in the magnetic field of the lower pole number $2p_2$, the EMF vectors of each individual branch are equal in magnitude and opposite in direction.
4. For n=1…z and i≥3, when the winding is placed in the magnetic field of the lower pole number $2p_2$, the EMF vectors of each individual branch have identical magnitudes and are phase-shifted relative to each other by an electrical angle of $(2\pi)/i$.

To ensure the absence of circulating currents, at least two of the above conditions must be satisfied simultaneously, namely, the first condition together with any one of the remaining conditions.

The first and second conditions can be satisfied for pole ratios of p_1/p_2=1/2 and 1/4. However, these ratios cannot be realized for the considered type of three-phase windings operating on both pole sides.

According to the first and third conditions, the coils assigned to the additional branches must be positioned simultaneously at distances corresponding to an even multiple of $\tau 2$ (the diametral pitch) and an odd multiple of $\tau 1$. This implies that p_1 must be odd and p_2 even, while the number of stator slots occupied by the coils must be divisible by both $\tau 1$ and $\tau 2$. In most cases, this number is equal to $Z/2$.

The first and fourth conditions are satisfied when the coils (or coil groups) of the same phase assigned to the additional branches are spaced at intervals equal to Z/i (most commonly $Z/3$). In this case, p_1 may be odd and p_2 even, or vice versa.

Under these conditions, the number of stator slots per pole per phase, denoted by q, may take either integer or fractional values.

The number of coils in the common part of the base connection scheme, that is, the number of coils corresponding to the base scheme, is determined to be a multiple of nine, which corresponds to the number of rays of three-phase star connections. Accordingly, this number may take values such as 54, 45, 36, and so forth.

Starting from the maximum value, the ratio of the number of coils on both pole sides is then determined as follows:

$$\frac{p_2}{p_1} = \frac{4}{5} = \frac{Z_{p=4}}{Z_{p=5}} = \frac{54}{60}; \; Z_{add} = Z_{p=4} - Z_{p=5} = 60 - 54 = 6.$$

The number of coils in the additional branches of each phase is determined as follows:

$$\frac{Z_{add}}{m} = \frac{Z_{p=5} - Z_{p=4}}{m} = \frac{60 - 54}{3} = 2$$

In this case, the main part of the base connection scheme consists of 54 coils, and two coils are allocated to the additional branches of each phase. The ratio of the numbers of coils connected in series in each phase is equal to 8 for the pole side with p_1=5 and 6 for the pole side with p_2=4. However, the electromotive forces (EMFs) induced in the coils of the additional branches do not mutually compensate when these branches are placed in the magnetic field corresponding to the pole number p_2=4. As a result, during motor operation, parasitic EMFs are generated that produce an opposing torque, adversely affecting the machine performance.

Furthermore, for the following value, the ratio of the numbers of coils on both pole sides is determined as follows:

$$\frac{p_2}{p_1} = \frac{4}{5} = \frac{Z_{p=4}}{Z_{p=5}} = \frac{45}{60}; \; Z_{add} = Z_{p=5} - Z_{p=4} = 60 - 45 = 15.$$

The number of coils in the additional branches of each phase is determined as follows:

$$\frac{Z_{add}}{m} = \frac{Z_{p=5} - Z_{p=4}}{m} = \frac{60-45}{3} = 5.$$

In this case, the main part of the base connection scheme consists of 45 coils, while five coils are assigned to the additional branches of each phase. Under these conditions, the ratio of the numbers of coils connected in series in each phase is equal to 10 for the pole side with p_1=5 and 5 for the pole side with p_2=4. In accordance with Condition 4, mutual compensation of the electromotive forces (EMFs) in the additional branches is achieved when the coils of the additional branches are connected in series and, when placed in the magnetic field corresponding to the lower pole number, are distributed around the magnetic circuit with a relative phase displacement of 120 electrical degrees.

The next stage of designing the pole-changing winding is carried out in accordance with the ratio Z_1=60 and Z_{add}=15.

The extraction of coils into the additional branches is performed according to the following ratio: Z_I/Z_{add}=60/15=4, that is, by uniformly selecting every fourth coil.

For this purpose, the lower layers of each winding are arranged beneath one another (Table 3), and one coil from each phase of the pole zone is removed from the $2p_1$ pole side. Accordingly, on the $2p_2$ pole side, the coils located in the following stator slots may be selected: for phase D—slots 1, 13, 25, 37, and 49; for phase E—slots 5, 17, 29, 41, and 53; and for phase F—slots 9, 21, 33, 45, and 57 (these coils are underlined in Table 3). These coils are transferred to the additional branches and redistributed among the phases, thereby participating in the formation of the magnetic field with $2p_1$ poles.

Based on Table 3, taking into account the extracted coils and the phase designation of each slot for both windings, it is possible to determine the branch to which a given coil number corresponds. For example, the coil located in slot 1 corresponds to phase D of the pole winding for p_1=5, whereas for p_2=4 it does not correspond to any phase; therefore, it is assigned to the additional D1–D branch. The coils located in slots 2, 3, and 4 correspond to phase D of the pole winding for p_1=5 and to phase A for p_2=4; consequently, they are assigned to the A–D1 branches.

TABLE 3. Extraction of coils into additional branches.

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

31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	slots
e	e	f	f	f	f	d	d	d	d	e	e	e	e	f	f	f	f	d	d	d	d	e	e	e	e	f	f	f	f	p_1=5
a	a	x	a	a	b	x	b	b	b	x	c	c	c	x	a	a	a	x	a	b	b	x	b	b	c	x	c	c	c	p_2=4

Following this procedure, the coils are grouped into the branches of the base connection scheme, as summarized in Table 4.

TABLE 4. Branches of the YYY/YYY base connection scheme with additional branches.

A-D1	B-D1	C-D1	D1-D	A-E1	B-E1	C-E1	E1-E	A-F1	B-F1	C-F1	F1-F
2, 3, 4, 50, 51	26, 38, 39, 40, 52	14, 15, 16, 27, 28	1, 13, 25, 37, 49	6, 18, 19, 20, 32	7, 8, 54, 55, 56	30, 31, 42, 43, 44	5, 17, 29, 41, 53	34, 35, 36, 47, 48	10, 11, 22, 23, 24	12, 46, 58, 59, 60	9, 21, 33, 45, 57

Operation of the winding. When a three-phase supply is connected to terminals A, B, and C (with terminals D, E, and F left open), an eight-pole rotating magnetic field is formed in the air gap (see Figure 2). In this operating mode, 45 coils are connected in the circuit. The phase electromotive force vectors are equal in magnitude and phase-shifted by 120°, indicating that the winding is completely symmetrical with respect to the supply source on the $2p_2$=8 pole side [11, 17].

When a three-phase supply is connected to terminals D, E, and F (with terminals A, B, and C interconnected), a ten-pole rotating magnetic field is generated (see Figure 2). In this case, all 60 coils are connected in the circuit. Due to differences in the EMF vectors between the D–E branches (equal to 2.36 electrical degrees) and between the E–F branches (equal to 3.52 electrical degrees), circulating (equalizing) currents arise. These currents are equal in magnitude and phase-shifted by 120° and are mutually compensated by interconnecting terminals A, B, and C at a common point. As a result, they do not affect the operation of the electric motor (see Figure 2).

The construction of windings and the interconnection of coils can be performed using the electromotive force vector diagram of the stator slots. For this purpose, the electrical angle between adjacent slots is first determined:

for the pole side with p_1=4: $\alpha_1 = \frac{360 \cdot p_1}{Z} = \frac{360 \cdot 4}{60} = 24°$;

for the pole side with p_2=5: $\alpha_2 = \frac{360 \cdot p_2}{Z} = \frac{360 \cdot 5}{60} = 30°$

For the pole side with p_1=4, the construction of the slot EMF star diagram is carried out as follows. A vertical vector 1 is taken as the EMF vector of the upper layer of the first stator slot, and the star vectors are labeled by numbers. The vector adjacent to the first one in the clockwise direction, denoted as vector 2, is positioned at an angle of 24° relative to the first vector. This vector corresponds to the EMF of the winding associated with the second stator slot. Subsequently, the third vector is placed at an additional 24° angular displacement from the second vector, and the remaining vectors are arranged sequentially in the same manner.

As a result, a 15-ray slot EMF star corresponding to slots 1 through 15 is obtained. The coil sides corresponding to slots 16–30, 31–45, and 46–60 follow the same 15-ray EMF star pattern as that of slots 1–15. The neutral points (marked by crosses) do not participate in this construction (see Figure 3).

In an analogous manner, the EMF vector diagram is constructed for the pole side with p_2=5. A vertical vector 1 is taken as the EMF vector of the upper layer of the first stator slot, and the star vectors are numbered accordingly. The vector adjacent to the first one in the clockwise direction, denoted as vector 2, is positioned at an angle of 30° relative to the first vector. This vector corresponds to the EMF of the winding associated with the second stator slot. Subsequently, the third vector is placed after an additional rotation of 30°, and the remaining vectors are arranged sequentially in the same manner.

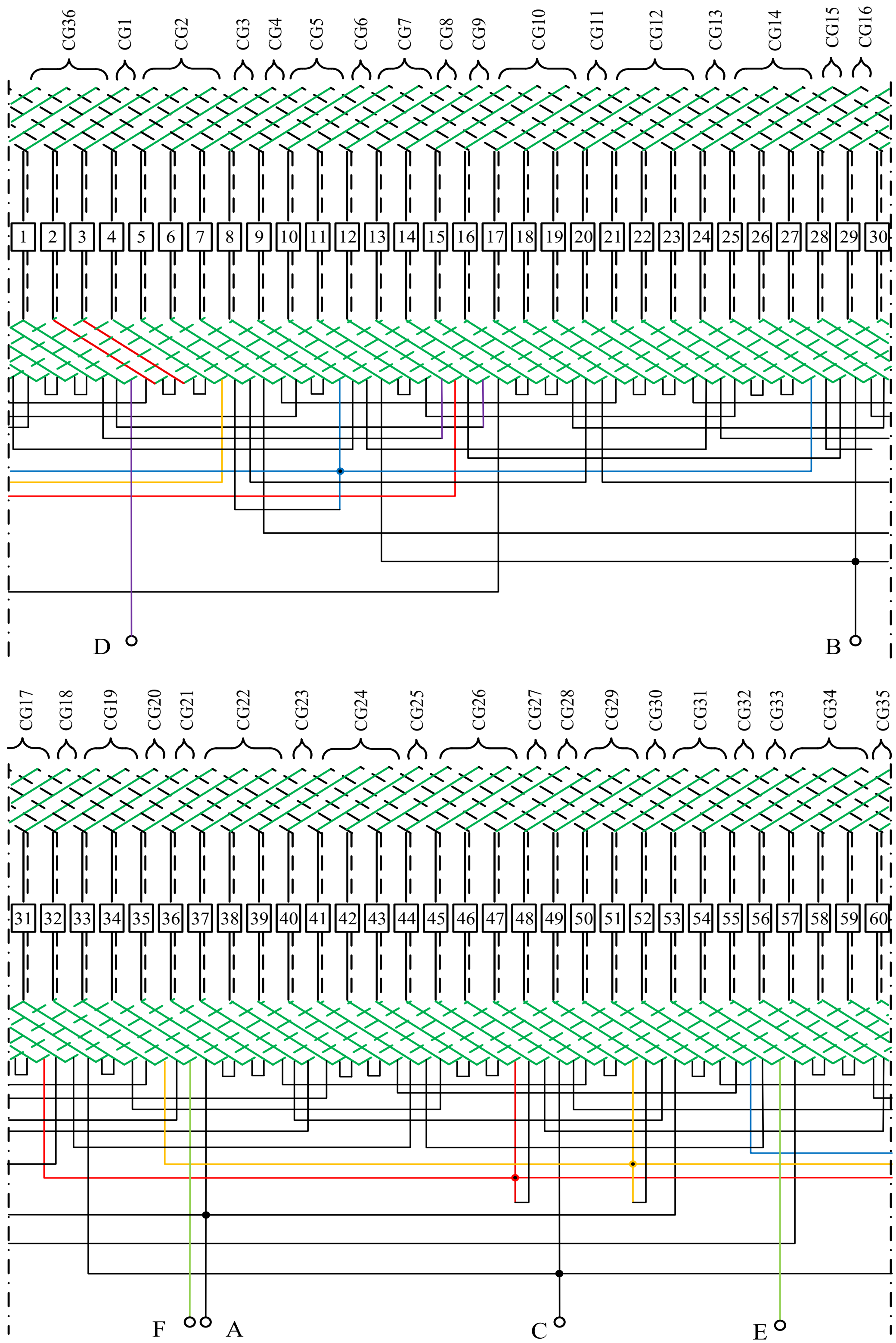

FIGURE 2. Developed diagram of a pole-changing winding.

As a result, a 12-ray EMF star corresponding to slots 1 through 12 is obtained. The coil sides associated with slots 13–24, 25–36, 37–48, and 49–60 follow the same 12-ray EMF star pattern as that of slots 1–12.

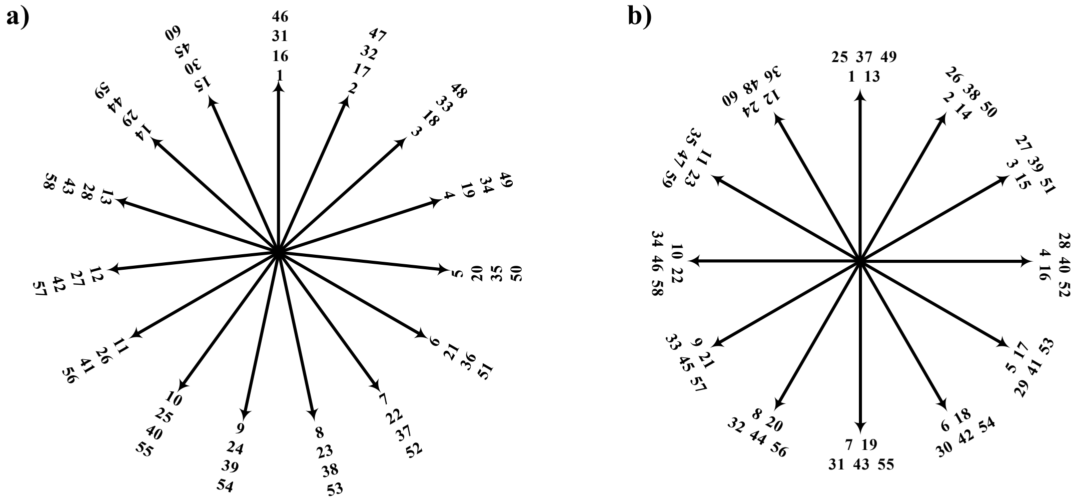

FIGURE 3. Slot EMF star diagrams: a) for p_1=4; (b) for p_2=5.

It is well known that, on the pole side with $2p_2$=8, the winding consists of three star connections:

the first star (A–D1, B–D1, C–D1), the second star (A–E1, B–E1, C–E1), and the third star (A–F1, B–F1, C–F1).

Similarly, on the pole side with $2p1$=10, the winding also comprises three star connections:

the first star (D–A, E–A, F–A), the second star (D–B, E–B, F–B), and the third star (D–C, E–C, F–C) [18].

The D–A branch consists of the vectors with ordinal numbers 1, 13, 25, 37, 49, 2, 3, 4, 50, and 51 connected in series.

The D–B branch consists of the vectors 1, 13, 25, 37, 49, 26, 38, 39, 40, and 52 connected in series.

The D–C branch consists of the vectors 1, 13, 25, 37, 49, 14, 15, 16, 27, and 28 connected in series.

The E–A branch consists of the vectors 5, 17, 29, 41, 53, 6, 18, 19, 20, and 32 connected in series.

The E–B branch consists of the vectors 5, 17, 29, 41, 53, 7, 8, 54, 55, and 56 connected in series.

The E–C branch consists of the vectors 5, 17, 29, 41, 53, 30, 31, 42, 43, and 44 connected in series.

The F–A branch consists of the vectors 9, 21, 33, 45, 57, 34, 35, 36, 47, and 48 connected in series.

The F–B branch consists of the vectors 9, 21, 33, 45, 57, 10, 11, 22, 23, and 24 connected in series.

The F–C branch consists of the vectors 9, 21, 33, 45, 57, 12, 46, 58, 59, and 60 connected in series (Figure 4, a).

On the $2p_2$=8 pole side, the A–D1 branch consists of the vectors 2, 3, 4, 50, and 51 connected in series;

the A–E1 branch consists of the vectors 6, 18, 19, 20, and 32;

the A–F1 branch consists of the vectors 34, 35, 36, 47, and 48;

the B–D1 branch consists of the vectors 26, 38, 39, 40, and 52;

the B–E1 branch consists of the vectors 7, 8, 54, 55, and 56;

the B–F1 branch consists of the vectors 10, 11, 22, 23, and 24;

the C–D1 branch consists of the vectors 14, 15, 16, 27, and 28;

the C–E1 branch consists of the vectors 30, 31, 42, 43, and 44;

and the C–F1 branch consists of the vectors 12, 46, 58, 59, and 60 connected in series (Figure 4, b).

For the proposed winding, a patent for invention has been granted by the Intellectual Property Agency of the Republic of Uzbekistan. Owing to the specific interconnection scheme of its sections and coils, the winding is implemented with six terminals and enables the realization of windings with pole numbers differing by a factor of five. This feature significantly broadens the application range of the proposed winding. In particular, two-speed electric motors equipped with such windings can be effectively employed in mechanisms with fan-type loads (fans, pumps, and compressors), as well as in mining machinery and equipment, where electric motors are required to operate under heavy-duty operating conditions [1, 19, 20].

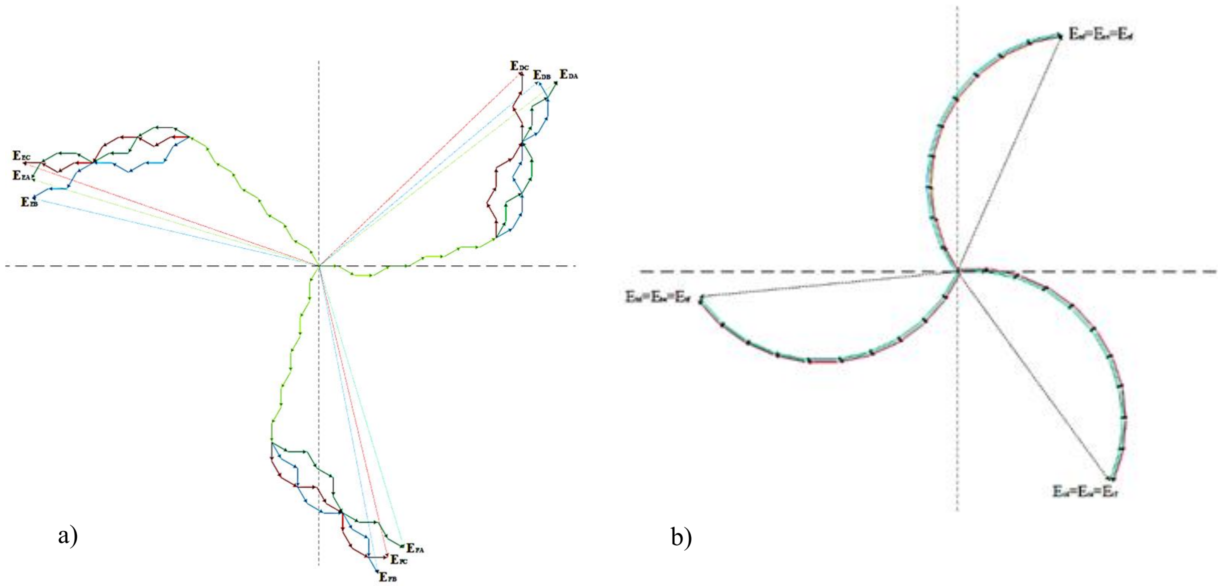

FIGURE 4. EMF vectors: a) for the $2p_1$=10 pole side; b) for the $2p_2$=8 pole side.

CONCLUSIONS

Based on the performed theoretical analysis, electromagnetic modeling, and synthesis of the pole-changing winding, the following conclusions can be drawn:

1. A pole-changing stator winding based on the YYY/YYY base connection scheme with additional branches has been developed for multi-speed induction motors intended to operate under heavy-duty and fan-type load conditions.

2. The application of the method of discretely defined spatial functions enabled a systematic synthesis of the winding, including the construction of slot EMF star diagrams, coil grouping, and branch interconnections for different pole numbers, while ensuring electromagnetic symmetry.

3. The conditions ensuring the absence of circulating (equalizing) currents in the additional branches have been analytically substantiated. For the considered pole combinations $2p_1$=10 and $2p_2$=8, vector compensation of electromotive forces has been shown to be achieved.

4. The proposed winding configuration provides stable operation for different supply terminal arrangements, forming rotating magnetic fields with different pole numbers and maintaining equal phase EMF magnitudes with a 120° phase displacement.

5. The developed winding allows the realization of multi-speed induction motors with a limited number of terminals, which simplifies the electric drive structure and improves manufacturability.

6. The practical feasibility and novelty of the proposed solution are confirmed by a patent granted by the Intellectual Property Agency of the Republic of Uzbekistan, demonstrating its industrial relevance.

7. The proposed pole-changing winding significantly expands the application range of multi-speed induction motors, making them suitable for use in fans, pumps, compressors, and mining machinery operating under heavy-duty conditions.

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