Pole-changing windings for turbomechanism engines

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Abstract. The article substantiates the relevance of the development of pole-changing windings for turbo-engines. There is a review of specialized literature on the development of pole-changing windings. Two-speed motors with a 4/3 pole number ratio have one pole-changing stator winding by the method of PAM. Based on the method of “Discretely specified spatial function” a pole-changing winding is obtained for a 3/4 pole ratio with 72 stator slots. The analysis of the electromagnetic properties of the obtained winding is carried out. The correspondence of the obtained winding for use in turbo-mechanisms is revealed. As a result of the study, there were procured the stator windings at 6 and 8 poles, which enabled to change the spin speed of the motor in the fan drives without breaking the drive power circuit by the scheme ΥΥΥ/ΥΥΥ with additional branches

1. Introduction

Pumps, compressors, fans, and blowers annually consume about 25% of all-electric energy generated by the country's energy systems. The high energy consumption of these facilities attaches great economic importance to the problem of energy saving [1].

Large thermal stations, industrial enterprises, agricultural facilities of the Republic are equipped with numerous pumps, compressors, and fan units for various purposes, produced by the industry of technically developed countries in millions of pieces a year.

Large two-speed motors (TSM), now used in pumps, compressors, and fans, have two separate windings on the stator, which worsens their overall dimensions and energy parameters. The use of a single pole-changing winding (PCW) in a motor drive having two groups of terminals for each pole makes it possible to increase the useful power of these motors, i.e. more efficiently use the active part of the machine, save winding copper and insulating materials, increase energy performance, and also makes it possible to approximate TSM by weight and size indicators to conventional serial single-speed asynchronous motors (AM). The use of such engines in unregulated electric drives of pumps, compressors, and fans makes it possible to rationally use electric energy in lightly loaded operating modes [2].
Many of the developed PCW do not find practical application due to a large number of output ends, switching contacts, deteriorated electromagnetic properties, as well as the complex manufacturing technology associated with the execution of coils with different turns and different steps [3, 4, 5, 6]. Therefore, studies aimed at improving the design and the characteristics of machines of this type are important, and therefore the relevance of the development of PCW that meets the requirements of modern electrical engineering becomes obvious.

The aim of the study is the development and research of new pole-changing windings for two-speed engines with a close-ratio of rotational speeds used in pumps and fans.

2. Methods

To build a PCW for large pole ratios, Professor Kh. Karimov proposed the method of “Discretely specified spatial function” (DSSF) [7, 8, 9, 10], which was subsequently improved to build a close pole relationship [11, 12, 13].

As an example, we consider the construction of the PCW for the ratio of pairs of poles 3/4, placed in 72 stator slots of the stator using the DSSF method.

This winding has a switching circuit "three-three-phase stars with additional branches" (Figure 1). For the initial windings, we take two two-layer loop m-zone stator windings placed in 72 stator slots with the numbers of pole pairs \(2p_1=6\) and \(2p_2=8\), in increments of 1-12 (1) and 1-9 (2).

![Figure 1. Scheme of switching "YY/YY" with additional branches](image-url)
We find the ratio of coils for one and the other pole:

\[ \frac{p_1}{p_2} = \frac{3}{4} = \frac{Z_{p_1}}{Z_{p_2}} = \frac{54}{72} \]

We find the number of coils in the additional branches of each phase:

\[ \frac{Z}{m} = \frac{Z_{p_4} - Z_{p_3}}{m} = \frac{72 - 54}{3} = 6 \]

In this case, the mutual compensation of the electromotive forces (EMF) of the additional branches is carried out by connecting the coils of the additional branches in series and distributing the magnetic wires around the circumference with a lag of 120 el. degrees when placing the winding in a magnetic field with fewer poles. To do this, we place the bottom layer of each winding under each other and exclude one coil from each phase of the pole zone from the pole \(2p_1\). Accordingly, from the side of the \(2p_2\) pole it can be coils in the slots under the numbers: for phase A - 1, 2, 41, 42, 57, 58; for phase B - 9, 10, 25, 26, 65, 66; for phase C - 17, 18, 33, 34, 49, 50. These coils are brought into additional branches and, redistributing in phases, are involved in creating a magnetic field of \(2p_2\) pole.

Having located the bottom row of each winding, one under the other (3), by the name of the phase in the slots with one and the other winding, one can determine the branch to which one or another coil number corresponds.

| Stator slots | 2p |
|--------------|----|
| 1 2 3 4 5 6 7 8 | 9101112131415161718192021222324252627282930313233343536 |
| - d d d d d d - f f f f f f - e e e e e - d d d d d d - f f 6 | a a a a a b b b b b c c c c c c a a a a a b b b b b b c c c c c c c |
| 373839404142434445464748495051525354555657585960616263646566676869707172 |
| f f f f - e e e e e - d d d d d d - f f f f f f - e e e e e | a a a a a b b b b b b c c c c c c a a a a a b b b b b b c c c c c |

The combination of groups of coils in the winding is carried out in accordance with the connections of the coils of the basic scheme (BS) "YYY/YYY with additional branches". For example, slot №3 at \(2p_1=6\) of the pole winding corresponds to phase \(D\), and at \(2p_2=8\) phase \(A\), therefore, belongs to the branch A-D. Based on this method, we group the coils (3) in the BS branch and put them in table 1.

| Stator slots | 2p |
|--------------|----|
| f f f f - e e e e e - d d d d d d - f f f f f f - e e e e e | a a a a a b b b b b b c c c c c c a a a a a b b b b b b c c c c c |

Table 1. Grouping coils in the branches of the winding

| No. of coils | Branches of the switching circuit "YYY/YYY with additional branches" |
|--------------|-----------------------------------------------------|
| A-D | A-E | A-F | A_add | B-D | B-E | B-F | B_add | C-D | C-E | C-F | C_add |
| 55, 56, 37, 38, 19, 20, 41, 42, 31, 32, 13, 14, 67, 67, 17, 18, 7, 8, 11, 12, 43, 44, 26, 25, 3, 4, 5, 39, 40, 21, 22, 57, 58, 51, 52, 15, 16, 69, 70, 33, 34, 27, 28, 61, 62, 45, 46, 10, 9, 6, 59, 60, 23, 24, 1, 2, 53, 54, 35, 36, 71, 72, 49, 50, 29, 30, 63, 64, 47, 48, 66, 65 |

The resulting PCW is symmetrical with respect to the power source from both poles (see tables 2, 3). Obviously, it is advisable to make the coils of the additional branches with a wire with a cross-section three times larger (the current flows three times larger in these coils) and, accordingly, with the number of turns three times smaller than in the other coils [14]. In this case, almost complete agreement of magnetic inductions in the air gap will be achieved, the condition for which is the equality:
\[ \frac{w_k \cdot \xi}{w_k \cdot \xi} = \frac{P_1}{P_2} \]  

A slight difference in the magnitude of the magnetic induction may be due to the difference in the values of the winding factors.

**Table 2.** Winding data for the pole \(2p_f=6\)

| Branches of BS «YYY/YYY with additional branches» | D-A | D-B | D-C | E-A | E-B | E-C | F-A | F-B | F-C |
|--------------------------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| E                                                | 10.4| 10.4| 10.4| 10.4| 10.4| 10.4| 10.4| 10.4| 10.4|
| \(\xi\)                                          | 0.87| 0.87| 0.87| 0.87| 0.87| 0.87| 0.87| 0.87| 0.87|
| \(\varphi\)                                      | 52.5| 52.5| 52.5| 172,| 172,| 172,| 67,5| 67,5| 67,5|

**Table 3.** Winding data for the pole \(2p_f=8\)

| Branches of BS «YYY/YYY with additional branches» | A-D | A-E | A-F | B-D | B-E | B-F | C-D | C-E | C-F |
|--------------------------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| E                                                | 19.64| 19.64| 19.64| 19.64| 19.64| 19.64| 19.64| 19.64| 19.64|
| \(\xi\)                                          | 0.819| 0.819| 0.819| 0.819| 0.819| 0.819| 0.819| 0.819| 0.819|
| \(\varphi\)                                      | 60   | 60   | 60   | -60  | -60  | -60  | 180  | 180  | 180  |

Pictures of the magnetomotive forces (MMF) of the obtained PCW are presented in Figures 2 and 3.
3. Results and discussion

Most of the existing PCW schemes are limited in widespread use due to the influence of factors such as complex manufacturing technology (a large number of leads, coil design with different turns and different steps), poor electromagnetic properties, asymmetry of parallel branches and phases (difference amplitudes and angles of the shift of EMF) [15, 16, 17, 18]. Therefore, an analysis of the properties of PCW is necessary to identify the most optimal schemes of PCW that meet the requirements for the manufacture of electrical machines.

When analyzing the electromagnetic properties of the PCW, the calculated data of the harmonic composition of the MMF patterns are simultaneously considered taking into account the winding factors and the differential leakage factors from both poles at three possible steps from both poles. By analyzing the obtained calculation data given in tables 4÷6, it is necessary to determine the optimal winding pitch that would satisfy the requirements of both poles, while the indicators in terms of both electromagnetic and technological should be the highest [19, 20].

In the MMF PCW picture (table 4) from the side of 6 poles with a winding pitch of y=9, in addition to the first harmonic, there are 2nd, 5th, 7th, 10th and 11th harmonic, their amplitude in percentage ratio is 27.29%, 1.78%, 2.35%, 1.46%, 0.50%, respectively, and taking into account winding factors (table 5), their influence decreases to 14.9%, 0.16%, 0.39%, 0.21%, 0.03%. The differential leakage factor (table 6) is equal to $\sigma=8.39\%$.

At a step y=10 from the side of the 6 poles (table 4), harmonic waves of the same order have amplitudes of 18.46%, 1.15%, 0.63%, 0.99%, 1.20%, respectively, but taking into account winding factors (table 5) their value is greatly reduced, i.e. - 6.82%, 0.07%, 0.03%, 0.10%, 0.16%. The differential leakage factor (table 6) is $\sigma=4.16\%$.

With a step y=11 from the side of the 6 poles (table 4), harmonic waves of the same orders have amplitudes of 9.31%, 3.43%, 1.44%, 1.86%, 0.16%, respectively, and taking into account their winding factors (table 5) their value is greatly reduced, i.e. - 1.73%, 0.59%, 0.15%, 0.35% and 0.00%. The differential leakage factor (table 6) is equal to $\sigma=1.73\%$.

In the MMF PCW picture from the side of 8 poles with a step of y=9, in addition to the first harmonic, there are 5th, 7th and 11th harmonic (table 4), their amplitude is 4.53%, 2.64%, and 1.68%,
respectively, and taking into account winding factors (table 5) - 1.03%, 0.49%, and 0.31%. The differential leakage factor (table 6) is \( \sigma = 1.46\% \).

With a step \( y = 10 \) from the side of the 8 poles, in addition to the first harmonic, there are the 2nd, 5th, 7th, 8th, 10th and 11th harmonics (table 4), their amplitude is 8.82%, 2.96%, 0.92%, 2.20%, 1.76% and 0.58%, respectively, and taking into account winding factors (table 5) - 1.56%, 0.44%, 0.06%, 0.39%, 0.31% and 0.04%. The differential leakage factor (table 6) is equal to \( \sigma = 2.18\% \).

With a step of \( y = 11 \) from the side of the 8 poles (table 4), harmonics of the same orders have amplitudes of 17.37%, 0.84%, 2.15%, 0.80%, 0.64% and 1.37%, respectively and taking into account winding factors (table 5) - 6.03%, 0.04%, 0.32%, 0.05%, 0.04% and 0.21%. The differential leakage factor (table 6) is \( \sigma = 2.18\% \).

### Table 4. Harmonic structure of MMF

| Z | 2p | \( \xi \) | Amplitude of harmonic, \( \% \) relative to the first harmonic |
|---|----|---|--------------------------------------------------|
| 9 | 10 | 100.0 | 27.29 0.00 0.00 1.78 0.00 2.35 0.00 0.00 1.46 0.50  |
| 6 | 10 | 100.0 | 18.46 0.00 0.00 1.15 0.00 0.63 0.00 0.00 0.99 1.20  |
| 72 | 10 | 100.0 | 9.31 0.00 0.00 3.43 0.00 1.44 0.00 0.00 1.86 0.16  |
| 8 | 10 | 100.0 | 8.82 0.00 0.00 2.96 0.00 0.92 2.20 0.00 1.76 0.58  |
| 11 | 100.0 | 17.37 0.00 0.00 0.84 0.00 2.15 0.00 0.00 0.64 1.37  |

### Table 5. Harmonic structure of MMF taking into account winding factors

| Z | 2p | \( \xi \) | Amplitude of harmonic, \( \% \) |
|---|----|---|----------------------------------|
| 9 | 10 | 100.0 | 27.29 0.00 0.00 1.78 0.00 2.35 0.00 0.00 1.46 0.50  |
| 6 | 10 | 100.0 | 18.46 0.00 0.00 1.15 0.00 0.63 0.00 0.00 0.99 1.20  |
| 72 | 10 | 100.0 | 9.31 0.00 0.00 3.43 0.00 1.44 0.00 0.00 1.86 0.16  |
| 8 | 10 | 100.0 | 8.82 0.00 0.00 2.96 0.00 0.92 2.20 0.00 1.76 0.58  |
| 11 | 100.0 | 17.37 0.00 0.00 0.84 0.00 2.15 0.00 0.00 0.64 1.37  |

### Table 6. Differential leakage factors

| Stator slots | Winding pitch | \( \sigma_0 \), % at 2p=6 | \( \sigma_0 \), % at 2p=8 |
|-------------|--------------|----------------|----------------|
| 9 | 8.39 | 1.46 |
| 72 | 10 | 4.16 | 2.18 |
| 11 | 1.73 | 4.87 |

As can be seen from the analysis from the side of 6 poles at step \( y = 11 \), the content of higher harmonics is minimal (even harmonic ones do not occur) and, accordingly, the value of the differential leakage factors is minimal.

However, from the side of 8 poles in the MMF picture, there are even harmonic amplitudes with large amplitudes (for example, the amplitude of the 2nd harmonic, taking into account the winding factor with respect to the amplitude of the first harmonic, is 6.03%) and the differential leakage factors is 4.87%.

Since in TSM of pumps, compressors, and fans, the electromagnetic properties of the PCW on both sides should be optimal. An analysis of the electromagnetic properties of the developed PCW from the...
side of both poles at different steps showed that the optimal step of the winding at 72 stator slots is a step equal to y=10 (1→11).

4. Conclusions
1. Using the method of “Discretely specified spatial function”, a new PCW was developed based on the basic scheme “YYY/YYY with additional branches” for a 3/4 pole ratio in the number of stator slots equal to 72.
2. The study and theoretical analysis of the properties of a new pole-switched winding showed that this winding from the side of both poles has the usual phase distribution of the coils, the EMF values induced in parallel branches of the same name are equal in amplitude and phase, and in branches belonging to different phases, EMFs are induced, which are equal in amplitude and phase-shifted by 120°, i.e. the winding is completely symmetrical with respect to the power source and has sufficiently high winding factors.
3. From a technological point of view, the developed pole-switched winding is an ordinary two-layer winding, consisting of equal-pitch coils of equal pitch evenly distributed over the grooves, which allows for the industrial applicability of the proposed winding, since two-speed motors with such a winding can find the application on numerous centrifugal pumps and fans, where it is necessary to adjust the rotation speed according to the technological process or in order to save energy.

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