Study on Fractional Slot Distribution of Brushless Doubly Fed Machine

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Abstract. Brushless doubly-fed machine (BDFM) has advantages of brushless reliability and low frequency conversion capacity. It has a broad application prospect in AC speed regulation and direct drive wind power generation system. In this paper, winding arrangement and slot electromotive force star diagram of stator with different pole numbers are analyzed and studied comprehensively. When the number of slots per pole and phase is different, we get the winding wire insertion rule. These rules are of great significance for further design and application of multipole BDFM.

1. Introduction

As a new type of motor, BDFM has advantages of cage type, winding type induction motor and electric excitation synchronous motor. It can implement doubly-fed operation without brush, at this time converter is the slip power. Therefore we need the smaller converter capacity, which reduces the system operating cost. It has a broad application prospect in the field of AC motor speed regulation drive (ASD) and variable speed constant frequency power generation (VSG) [1-2]. Due to the low number of traditional BDFM poles and the low synchronous speed, gearbox is required for both the motor used in the speed regulation system and the generator used in the wind power generation system to meet the needs. The existence of gearbox not only increases the investment, but also greatly reduces the operating reliability of the system. It is of great theoretical and practical significance to make BDFM into multipole number to reduce gearbox variable ratio or even cancel gearbox (for example, brushless doubly-fed wind generator can achieve direct drive operation when the number of poles is more than 100) [3-4].

When the number of BDFM poles increases, the number of slots in each pole and each phase determine the winding arrangement appears fraction. We need to arrange the windings properly in order to generate a magnetic field close to sine in the air gap of the motor. We get winding arrangement rule when the number of slots in each pole and phase is different from each other by studying winding arrangement and slot electromotive force star diagram of stator with different number of poles.

2. Principle and structure of BDFM

BDFM stator has two sets of three-phase symmetric windings with different poles. Stator power winding has 2po poles, which is directly connected to the power grid during operation. Stator control winding has 2pq poles, which is connected to the power grid through two-way frequency converter during operation. Its structure is shown in figure 1.
3. Fractional slot arrangement of stator windings

It is necessary to use fractional slot winding arrangement in order to study the influence of design parameters on the coupling ability of BDFM.

We have learned how to arrange windings when the number of slots per pole and per phase \( q \) is integer. Now we only analyze the case where the number of slots per pole and per phase is a fraction. If the number of slots is \( Z \), the number of poles is \( 2p \), the number of phases is \( m \), and then the number of slots per pole and per phase is:

\[
q = \frac{Z}{2mp} = \frac{N}{D} = b + \frac{c}{d}
\]  

Among them, the simplest false fraction is \( \frac{N}{D} \), the integer \( b \), the simplest true fraction is \( \frac{c}{d} \).

According to the difference of \( q \), fractional slot winding can be summarized as three types: ordinary fractional slot winding of \( q > 1 \), special fractional slot winding of \( q > 1 \) and fractional slot winding of \( q < 1 \). Table 1 shows the winding connection rules under different \( Q \) conditions, which are described in detail below.

| Types of \( q \) values | General score of \( q >1 \) | Special score of \( q >1 \) | Score of \( q <1 \) |
|-------------------------|-----------------------------|-----------------------------|-----------------------------|
| slot number \( Z \)     | 72                          | 48                          | 72                          |
| phase number \( m \)    | 3                           | 3                           | 3                           |
| pole number \( 2p \)    | 20                          | 12                          | 32                          |
| Value of \( q \)        | \( \frac{1}{5} \)          | \( \frac{1}{3} \)          | \( \frac{3}{4} \)          |
| Polar phase group number| 60                          | 36                          | 96                          |
| Winding cycle rule      | 21111                       | 211 121 112                 | 1110                        |
| Coil characteristics at the pole | 5 poles make up 6 coils | Each pole coil is unequal | 4 pole make up 3 coils |
| Law of interphase connection between winding | Head-to-head, tail-to-tail connection of polar phase group coils | Head-to-head, tail-to-tail connection of polar phase group coils | 3 coils head to head, tail to tail, 0 coil head to tail, tail to head |
| Hookup                  | Figure 2.5                  | Figure 2.6                  | Figure 2.7                  |
3.1. Ordinary fractional slot winding with $q > 1$

The characteristic of this kind of winding is that $q > 1$ and $d$ is a multiple of non-3 or 3. For example, three-phase 72-slot 20-pole double-layer winding, the number of slots per pole per phase: $q = 1 \frac{1}{5}$, electrical angle $\alpha = 50^\circ$, winding distribution is shown in Table 2, short distance $y_c=3$. The characteristics of motor winding is: every 5 poles under 6 coils, can be arranged in the order of 21 11. The cell potential star diagram and the phase winding expansion diagram are shown in Figure 2.

![Figure 2](image)

**Figure 2.** Doubly-layer windings arrangement of 3 phases, 20 poles and 72 slots with $q > 1$

3.2. Special fractional slot winding with $q > 1$

A special fractional slot winding with $q > 1$ is a case where $q > 1$ and $d$ is a multiple of 3. For example: $Z=48$, $2p=12$, then the number of slots per phase per pole $q = 1 \frac{1}{3}$. If the number of slots per phase per pole can be expressed as:

$$q = \frac{N_v}{D_v} \text{ (simplest formula) } \quad (2)$$

(1) When $D_v$ is a non-3-fold integer, then $Q_v=6N_v$, $x_v=D_v$;
(2) When $D_v$ is an integer of 3 multiples, then $Q_v=2N_v$, $x_v=D_v/2$. 
Among them: \(Q_v\) is the total number of vectors needed by vector star, and \(x_v\) is the displacement of each coil vector.

### Table 2. Winding assignment diagram of 48 slots and 12 poles

| Slot number | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|-------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Winding arrangement | a  | a  | -c | b  | -a | c  | c  | -b | a  | -c | b  | -a | -a | c  | -b |   |
| Slot number     |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Winding arrangement | a  | -c | -c | b  | -a | c  | b  | -b | a  | a  | -c | b  | -a | c  | -b |   |
| Slot number     |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Winding arrangement | a  | -c | b  | b  | -a | -a | c  | -b | a  | -c | -c | b  | -a | c  | -b |   |

**Figure 3.** Doubly-layer winding diagram of 3 phases, 12 poles and 48 slots with \(q>1\)

Characteristics of this motor winding: every four slots span three poles, and it is a special fractional slot arrangement. Its winding arrangement can be circulated in a manner that is not the only arrangement in 211 121 112 (That's not the only way to arrange it). Table 2 shows the distribution of the winding. Figure 3 shows the phase winding unwrapping (double-layer short distance \(y_c=3\)).

#### 3.3. Fractional slot winding with \(q<1\)

Fractional slot windings with \(q<1\) are commonly used in large wind turbines. The coupling performance analysis of the motor also needs to be used in this paper. In this case, it is difficult to divide windings by conventional understanding, so a new understanding of coil group is needed. The following are specific examples to illustrate.

An example of fractional-slot arrangement in this paper is given: the number of slots \(Z=72\), \(2p=28\), \(m=3\). It can be seen that the number of turns in series of each phase can be seen \(q = \frac{3}{4}\). That is to say, four poles span three coils, which need to be treated with the concept of "zero coils". The winding cycles are arranged as 1110, that is to say three coils and one "0" coils. In fact, "0 coils" does not exist. But when the motor winding is wired in connection, the existence must be considered as part of the winding arrangement cycle number. We think of it as part of the winding number of cycles. It also represents a set of coils. So let's think of the total number of turns as 0. The connection rules of windings are shown in table 1. The winding connection expansion diagram is shown in Figure 4.
Figure 4. Double-layer winding expansion diagram of 3-phase 32-pole 72 slot with q<1 fraction slot

4. Conclusion
When multi-pole BDFM is applied to AC speed regulation system and wind power generation system, it often occurs that the slot number of slots per pole and phase is a fraction. In order to obtain the symmetrical induced voltage in the whole period, the fractional slot winding must be arranged correctly. This paper makes a comprehensive and detailed analysis of several situations when the number of slots in each pole and phase is different and makes a reasonable distribution of windings. An example is given to illustrate the drawing of winding expansion diagram. The arrangement of these fractional slots can provide help for further design and application of multipole BDFM.

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