Development of a Wound Rotor Brushless Doubly Fed Machine Based on Slot MMF Harmonics

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***Abstract*—In the rotor winding magnetomotive force (MMF) of an ac machine, there exist so-called slot harmonics which appear in pairs and the lower order harmonic of each pair rotates in the opposite direction against the fundamental component. In addition, the slot harmonics have the same winding factor as the fundamental component. Based on these properties, this paper develops a brushless doubly fed machine (BDFM) with wound rotor. The machine consists of two stator windings with p_1 and p_2 pole-pairs, respectively. The rotor has a normal symmetrical multi-phase winding, in which rotating MMFs with p_1 and p_2 pole-pairs are induced by their stator counterparts. When the number of rotor slots equals the sum of p_1 and p_2, the two MMFs rotate in opposite directions with respect to the rotor, satisfying the requirement of a BDFM. The major advantage of such a machine is that for both p_1 and p_2 pole-pair MMFs the winding factor is as high as that of the fundamental component, leading to high utilization of rotor winding and electrical efficiency.**

Keywords-brushless doubly fed machine; slot harmonic magnetomotive force (MMF); wound rotor.

I. INTRODUCTION

Brushless doubly fed machines (BDFMs) possess many advantages and hence have attracted strong interest of research and application, especially for adjustable speed drives and variable speed generators [1-4]. The BDFM has two stator windings: a power winding with p_1 pole-pairs is connected directly to the grid, and a control winding with p_2 pole-pairs is connected via a power electronic converter, as illustrated in Fig. 1. While the grid supplies the major power to the power winding, the converter only needs to supply the so-called slip power to the control winding and hence its rating can be much lower than the machine. The greatly reduced rating and cost of the converter is a significant advantage compared to the conventional variable frequency variable speed drive, where the power electronic unit must have the same rating as the machine and correspondingly it is expensive. The other advantages of a BFDM include the controllable operation in synchronous mode over a wide range, adjustable power factor, lowered total harmonic distortion, and operation as a mains fed induction machine if the converter fails [5].

The balanced multi-phase currents in the power winding and those in the control winding generate a rotating magnetomotive force (MMF) with p_1 pole-pairs and a rotating MMF with p_2 pole-pairs respectively in the air gap. The two MMFs are designed to rotate in opposite directions with reference to the rotor, so that they combine to produce a single rotor frequency as

$$f_r = \frac{p_1(n_1 - n_m)}{60} = \frac{p_2(n_m \mp n_2)}{60} \tag{1}$$

where $n_1=60f_1/p_1$ and $n_2=60f_2/p_2$ are the synchronous speeds of the air gap MMFs produced by the power winding current with f_1 frequency (mains frequency) and the control winding current with f_2 frequency, respectively, and n_m is the rotor speed. The plus/minus sign corresponds to the positive/negative sequence of the control winding with respect to that of the power winding.

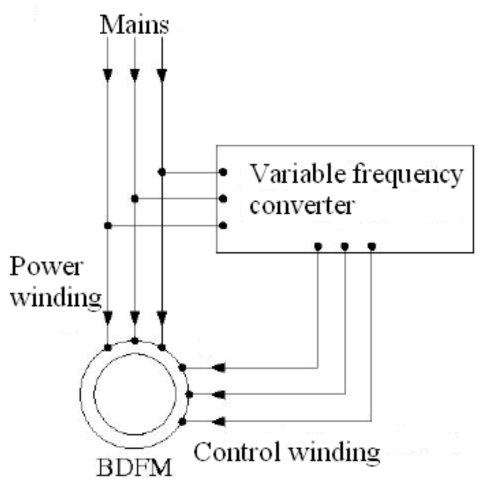

Figure 1. Configuration of a brushless doubly fed machine

The machine works in the synchronous operating mode with a constant speed, which is independent of the load. From (1), the rotor speed in rpm can be determined as

$$n_m = 60\frac{f_1 \pm f_2}{p_1 + p_2} \tag{2}$$

As the control winding is connected to the grid via the electronic converter, the rotor speed can be adjusted by varying the converter frequency, f_2, according to (2).

The rotor structure is a key factor affecting the performance of a BDFM, in which the rotor winding needs to be specially designed to couple the MMFs generated by both the stator power winding and control winding. Many BDFM designs have adopted the "nested loop" cage rotor, which was initially proposed by Broadway and Burbridge [6]. The simple nested loop type cage rotor is designed to produce contra rotating fields on the rotor, which were previously realized by the double-layer wound rotor. As described in [7], when a squirrel cage rotor with Z bars is subjected to a rotating magnetic field of p_1 pole pairs, the induced rotor MMF contains main slot spatial harmonics of $p_1 \pm Z$ pole pairs. When $p_1 \pm Z$ is negative, the harmonic field rotates in the opposite direction against the main field of p_1 pole pairs relative to the rotor. This is a basic requirement for the second field of p_2 pole pairs for the synchronous operation of a BDFM.

Therefore, the rotor has p_1+p_2 bars (slots). When the number of rotor bars is small, short circuited loops need to be inserted between main bars for reducing the rotor slot field leakage in practical designs. As an example, when $Z=p_1+p_2=3+1=4$, the rotor has 4 nests and each nest has 5 concentric loops as illustrated in Fig. 2. The loops in one nest can be isolated or short circuited in one end by a common end-ring.

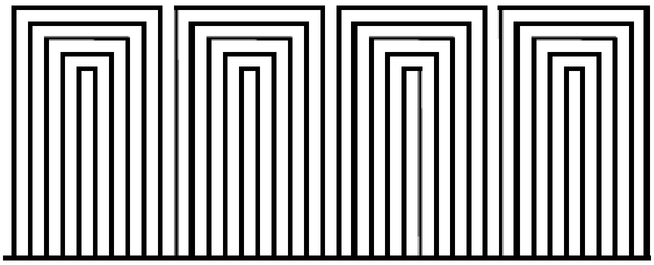

Figure 2. Nested loop design of a BDFM cage rotor

It is noted that p_1 and p_2 should be close. With a wide difference between the numbers of pole pairs, the chording factor of the short circuited loops would be small with respect to at least one of the numbers of pole pairs.

A large amount of work has been conducted on the cage rotor structure for improving the performance of BDFMs, but only limited success has been achieved so far because some of their intrinsic drawbacks have not been overcome, e.g. the rotor winding must be concentric short-circuited loops. On the other hand, the reluctance rotor has to be salient. These constraints have made the performance of BDFMs much lower than conventional AC machines, such as low utilization of rotor winding, and hence the BDFMs have not been successfully commercialized.

Despite the relatively complex winding manufacturing, the wound rotor offers flexible configuration and flexible connection. With the help of the theory on changing the number of poles, one can control and choose the major winding parameters for the optimum performance of the BDFM, such as p_1, p_2, number of rotor slots, rotational direction of MMF, winding distribution factor, and contents of harmonics. Based on these techniques, particularly the slot MMF harmonics produced by the rotor currents, this paper presents the development of a wound rotor BDFM with high performance such as high winding utilization.

II. Principle of Wound Rotor BDFM Based on Slot MMF Harmonics

The stator and rotor windings of an ac machine are commonly placed in the stator and rotor slots along the air gap, respectively. Unless the winding is sinusoidally distributed, the currents in the multi-phase windings generate an MMF with a series of harmonics besides the fundamental component. The terms with $\nu=Z/p\pm1$ orders are called the slot harmonics, where Z is the number of rotor slots and p is number of pole-pairs of the windings. In other words, the slot harmonics have pole-pairs of $Z\pm p$.

A. *Features of Slot MMF Harmonics*

For the ν-th harmonic of an integer-slot winding, the winding factor can be calculated by

$$k_{dy\nu} = k_{d\nu} k_{y\nu} \tag{3}$$

$$k_{d\nu} = \frac{\sin \nu \frac{q\alpha}{2}}{q \sin \frac{\nu\alpha}{2}} \tag{4}$$

$$k_{y\nu} = \sin \nu \frac{y\pi}{2\tau} \tag{5}$$

where $k_{dy\nu}$, $k_{d\nu}$ and $k_{y\nu}$ are the winding factor, distribution factor and chording factor, respectively, $q=Z/(2mp)$ is the number of slots per pole per phase, m is the number of phases, $\alpha=2p\pi/Z$ is the slot pitch in electrical radians, y is the chording pitch of coil in number of slots, and $\tau=Z/(2p)$ is the pole pitch.

For the slot MMF harmonics, $\nu=Z/p\pm1=2mq\pm1$, then (4) and (5) can be expressed as

$$k_{d\nu} = \frac{\sin(2mq\pm1)\frac{q\alpha}{2}}{q\sin\frac{(2mq\pm1)\alpha}{2}} = \frac{\sin(q\pi \pm \frac{q\alpha}{2})}{q\sin(\pi\pm\frac{\alpha}{2})} = \pm k_{d1} \tag{6}$$

$$k_{y\nu} = \sin(2mq\pm1)\frac{y\pi}{2\tau} = \sin(y\pi \pm \frac{y\pi}{2\tau}) = \pm k_{y1} \tag{7}$$

Therefore, $k_{dy\nu}=k_{dy1}$, i.e. the winding factor of the slot MMF harmonics equals that of the fundamental component. Similarly, one can show that all the harmonics with $\nu= 2mkq\pm1$ (k=1, 2, 3…) have the same winding factor as the fundament component. However, the higher the harmonic order is, the less effect the harmonic has on the machine performance.

For the v-th MMF harmonic,

$$f_{Av} = F_{\phi v} \cos v\theta \cos \omega t$$
$$f_{Bv} = F_{\phi v} \cos v(\theta - \frac{2}{3}\pi) \cos(\omega t - \frac{2}{3}\pi) \quad (8)$$
$$f_{Cv} = F_{\phi v} \cos v(\theta - \frac{4}{3}\pi) \cos(\omega t - \frac{4}{3}\pi)$$

where f_{Av}, f_{Bv} and f_{cv} are the pulsating MMFs produced by three phase currents respectively. When v=1, the combination of three phase MMFs is

$$f_1(t,\theta) = \frac{3}{2} F_{\phi 1} \cos(\omega t - \theta) \quad (9)$$

It is a well-known conclusion that when the symmetrically distributed three phase windings are excited by balanced three phase currents, the superposition of three pulsating phase-MMFs results in a rotating MMF with constant speed and constant magnitude.

The slot MMF harmonics appear in pairs, e.g. $v=2mq\pm1$. For the lower order harmonic, $v=2mq-1$, we have

$$f_v(t,\theta) = \frac{3}{2} F_{\phi v} \cos(\omega t + (2mq - 1)\theta) \quad (10)$$

Comparing (9) and (10), we can conclude that the slot harmonic MMF with order of $v=2mq-1$ rotates in the opposite direction against the fundamental component. Similarly, one can show that the slot MMF harmonic with order of $v=2mq+1$ and the fundamental component rotate in the same direction.

B. BDFM Based on the Slot MMF Harmonics

From the above analysis, it can be seen that the slot MMF harmonics have two noticeable features: (1) The winding factor equals that of the fundamental component; (2) The lower order of each pair rotates in the opposite direction against the fundamental component. These features can be employed for developing new rotor structure BDFMs.

According to the operation principle of a BDFM, the rotor winding should be able to produce two MMFs with different pole-pairs (p_1 and p_2) and the two MMFs rotate in different directions. Therefore, the design procedure of windings can be: (1) Select the pole-pair (p_1) of the power winding according to the desired base speed; (2) Select the pole-pair (p_2) of the control winding considering the speed range; and (3) Select the number of rotor slots (Z) satisfying the requirement for symmetrical rotor winding and $Z=p_1+p_2$.

It can be seen that the rotating MMF with p_2 pole-pair is always a slot harmonic when the fundament component is of p_1 pole-pair, or the rotating MMF with p_1 pole-pair is always a slot harmonic when the fundament component is of p_2 pole-pair. As the winding factor of the slot harmonic is the same as that of the fundament, one can design the rotor winding by considering the stator power winding only. That is, if the winding is designed to have a high winding factor with respect to p_1 pole-pair MMF component, the p_2 pole-pair component will certainly have a high winding factor. For example, when the rotor winding is a regular 3-phase 60^o phase-belt winding with respect to p_1, naturally it is so with respect to p_2. Therefore, such a rotor winding has high utilization for both stator power winding and stator control winding fields.

Furthermore, the design according to slot harmonic MMFs meets the general requirement of BDFM, e.g. that p_1 and p_2 are not equal for avoiding direct transformer coupling between the power winding and the control winding, and that the difference between p_1 and p_2 must be larger than 1 for avoiding unbalanced magnetic pull on the rotor. The slot harmonic MMFs of the same pair feature a difference of 2 between the numbers of pole-pairs.

III. Design Example

A slot harmonic BDFM has been designed and analyzed. The power winding has 7 pole-pairs and the rotor employs regular 3-phase 60^o phase-belt symmetrical winding. The number of pole-pairs of the control winding is chosen as 5, so the number of rotor slots is 12.

To achieve a 3-phase regular 60^o phase-belt winding for Z=12 and p_1=7, the slot-number phase diagram is plotted as shown in Fig. 3(a), from which the slot numbers for each phase are determined as shown in Fig. 3(b). It can be seen that the slots (winding conductors) of each phase is within 60^o phase-belt and the distribution factor can be computed as 0.9659.

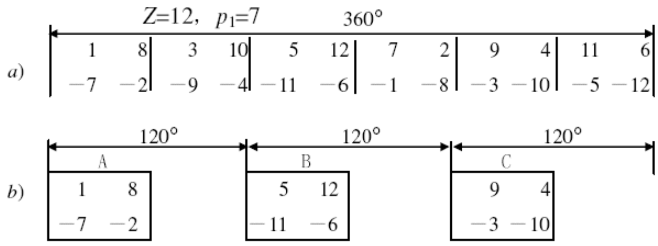

Figure 3. (a) Slot-number phase diagram (Z=12, p_1=7), (b) determination of slot numbers for 3 phases

Fig. 4(a) shows the slot-number phase diagram for Z=12 and p_2=5, in which the slot numbers of each phase, determined by Fig. 3(b), are re-plotted. It can be seen that the slots of each phase is also within 60^o phase-belt and the distribution factor is 0.9659. This agrees with the property of slot harmonics.

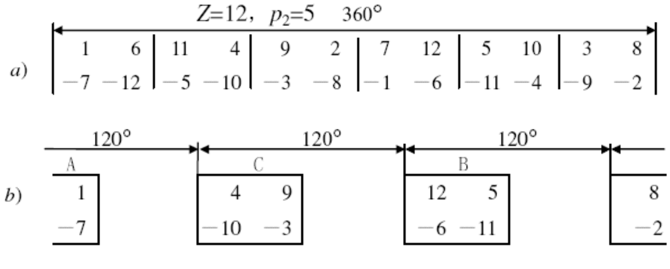

Figure 4. (a) Slot-number phase diagram (Z=12, p_2=5), (b) Distribution of the slot numbers of 3 phases in Fig. 1(b)

Comparing Fig. 3(b) with Fig. 4(b) reveals that the phase sequence for p_1=7 is in the order of A-B-C-A-, and the phase sequence for p_1=5 is in A-C-B-A-. In other words, the phase sequences for p_1=7 and p_2=5 are opposite; this satisfies the condition for BDFM operation.

Table 1 lists the harmonic analysis of the resultant MMF produced by the three phase currents when the coil span is chosen as 1 slot (*y*=1). The chording factor for both p_1=7 and p_2=5 is equal to 0.9659, resulting in a high winding factor of 0.9330. This implies that the rotor winding has high utilization rate, a unique feature for the proposed design method based on the slot MMF harmonics.

TABLE I. HARMONIC ANALYSIS OF THE RESULTANT ROTOR MMF

Pole-pair	Distribution factor	Chording factor	Winding factor	Resultant MMF (%)	
				Fv+	Fv-
1	0.2588	0.2588	0.0670	35.8984	0
5	0.9659	0.9659	0.9330	0	100
7	0.9659	0.9659	0.9330	71.4286	0
11	0.2588	0.2588	0.0670	0	3.2635
13	0.2588	0.2588	0.0670	2.7614	0
17	0.9659	0.9659	0.9330	0	29.4118
19	0.9659	0.9659	0.9330	26.3158	0
23	0.2588	0.2588	0.0670	0	1.5608
25	0.2588	0.2588	0.0670	1.4359	0

From Table I, it can be seen that the harmonics with $Z+p_2$=17 and $Z+p_1$=19 pole-pairs have also high winding factor of 0.9330. Compared to the p_1=7 and p_2=5 pole-pair components, the 17 and 19 pole-pair harmonics have considerably higher number of pole-pairs and lower magnitude so their effect on the machine performance is not significant. As to the component of 1 pole-pair, although its magnitude seems high (35.8984%), it does not affect greatly the machine performance. This is the common feature of low order components (v<1).

The connection diagram of the 3 phase windings is illustrated in Fig. 5.

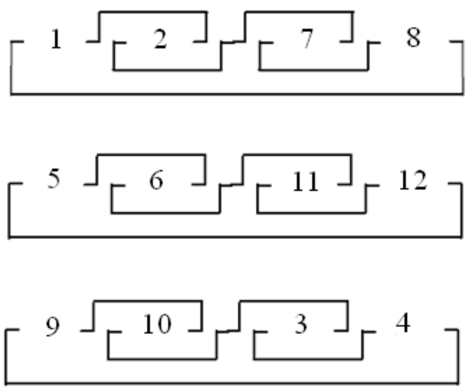

Figure 5. Winding connection of a wound rotor (12 slots, 7/5 pole-pairs)

The machine (Z_1=12, *y*=1) has a uniform air gap but it acts as a salient rotor. Therefore, the coil manufacturing is very simple, which is an important factor for low speed high power machines. This is the advantage of the slot harmonics method in the aspect of rotor structure.

Although theoretically the selection of p_2 and Z is quite arbitrary (only if the relation of $p_1=Z-p_2$ is satisfied), we normally choose $p_2<p_1$, in order to reduce the rating of the control winding.

IV. BDFM PROTOTYPE

The designed rotor winding has been wound in an YZR112 induction machine. The stator has 36 slots, in which two 3-phase windings of p_1=7 and p_2=5 pole-pairs are separately placed. The rotor has 24 poles and its winding connection diagram is shown in Fig. 6, where *y*=2.

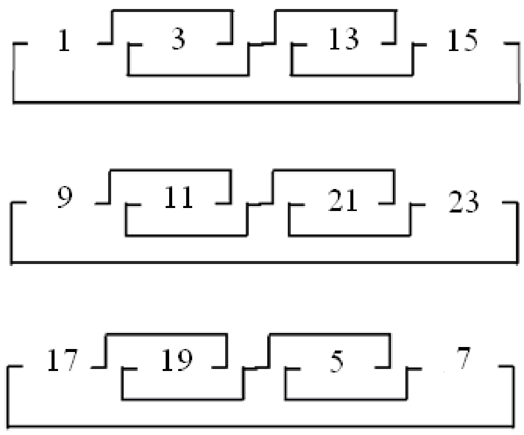

Figure 6. Winding connection of a wound rotor (24 slots, 7/5 pole-pairs, y=2)

The prototype has been tested at no-load. The power winding (p_1=7) is directly connected to the grid with a voltage of 150 V. The control winding (p_2=5) is connected via a varying voltage varying frequency power converter (*U*/*f*=200/50). The experimental results are listed in Table 2, showing that the slot harmonic wound rotor BDFM can effectively adjust the machine speed by varying the frequency of electronic converter of the control winding.

TABLE II. NO-LOAD SPEED VARYING TEST

Converter frequency (Hz)	Rotor speed (r/min)	Power winding current (A)	Control winding current (A)
2	260	2.70	0.40
4	270	2.70	0.50
6	280	2.70	0.65
8	290	2.65	0.85
10	300	2.65	1.00
12	310	2.65	1.15
14	320	2.60	1.30
16	330	2.60	1.45
18	340	2.60	1.60
20	350	2.55	1.73
21	355	2.55	1.80
23	365	2.55	1.88
25	375	2.50	1.98
27	385	2.50	2.10
29	395	2.47	2.19
31	405	2.45	2.27
35	425	2.40	2.40

V. Conclusion

This paper presents a preliminary investigation on developing a brushless doubly fed machine based on the theory of slot harmonics of magnetomotive force, aiming to achieve high winding factor and power efficiency. Preliminary analysis and experiment show that the motor can vary speed smoothly as expected. Detailed theoretical analysis and experimental study are being carried out.

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