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Experimental analysis of noise and vibration for large brushless doubly fed machines

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Abstract: In this study, a large-scale brushless doubly fed machine (BDFM) built in frame size D400 is tested at different operating conditions in order to examine its noise and vibration levels. A series of measurements were conducted on the machine to establish the main modes of excitation of vibration and noise developed by the machine. The harmonic spectrums of the vibration amplitudes are presented at two different rotor speeds at which the vibration level is highest, in order to determine the vibration components frequencies existed in the vibration spectrum. A harmonic analysis of the BDFM is then proposed in order to assess the sources of vibration in the machine.

1 Introduction

The brushless doubly fed machine (BDFM) shows commercial promise as both a variable speed drive and generator. As a generator, it is particularly attractive for wind power generation as a replacement for doubly-fed slip-ring generators since it offers a key advantage of variable speed operation with greater reliability, while requiring only a fractionally rated converter [1]. In addition, the BDFM is intrinsically a medium-speed machine, enabling the use of a simplified one or two-stage gearbox; hence, reducing the cost and weight of the overall drivetrain and further improving reliability [2]. A schematic of the BDFM drivetrain is shown in Fig. 1.

To date, a number of large BDFMs have been made, for example in Brazil with a 75 kW machine [3], China with the design of a 200 kW machine [4] and the 250 kW BDFM reported by Abdi *et al.* [5] and shown in Fig. 2 on test bed. The latter was built in a frame size D400 as a stepping stone towards a megawatt scale BDFM wind turbine. The acoustic noise and vibration characteristics are amongst the most important design considerations that need to be taken into account before a large-scale BDFM is constructed.

The modern BDFM concept as a variable speed drive or generator comprises two electrically separate stator windings, one connected directly to the mains, called the power winding (PW), and the other supplied from a variable voltage and frequency converter, called the control winding (CW). The pole numbers of the two stator windings are chosen so as to avoid direct coupling and a special rotor design is used to couple between the two stator windings, the nested-loop design being commonly used [1]. The machine therefore contains three magneto motive forces, the first in the stator directly supplied from the mains, the second in the stator supplied from the converter and the third induced in the rotor. The normal mode of operation of the BDFM is as a synchronous machine with the rotor rotating at a speed determined by the winding pole numbers and the mains and converter frequencies.

As with all induction type machines, the strong magnetic fields exert considerable forces on the iron parts of the machine. These cause deflections, which may be observed as vibration on the machine's surface and noise when transmitted to the surrounding air. Unlike in the induction motor which has a magnetic field dominated by a single pole number component, the BDFM has

significant field components at two different pole numbers. This is because the BDFM is fitted with two stator windings of different pole numbers and supply frequencies. The presence of the two field components causes more complex vibration patterns in the BDFM than in the induction machine, some of which are problematic in terms of vibration. The possibility of rotor eccentricity further complicates the picture by essentially modulating the waves produced by the stator windings and thus introducing further field components [6]. Other two field machines like the dual stator winding induction machine described in [7] will suffer similar problems.

In this work, the prototype 250 kW D400 BDFM was tested at different operating conditions in order to examine its actual noise and vibration levels. A series of measurements were conducted on the machine using Bruel & Kjaer vibration measurement equipment to establish the main modes of excitation of vibration and noise developed by the machine. In addition, during the modal vibration tests, the noise was measured using a single microphone placed in an appropriate position relative to the machine. Different sources of vibration were also studied based on the harmonic analysis of the BDFM. The analysis was verified by determining the main vibration components and their frequencies in the vibration spectrums obtained from the machines operating conditions with the highest vibration levels. Finally and based on the experimental results obtained, a number of design considerations are proposed for a BDFM to mitigate vibration and noise levels.

2 Previous BDFM vibration analyses

To date, only limited work has been performed on the vibration analysis of BDFMs. Logan *et al.* [8] expressed the magnitudes of the main vibration components as functions of the air-gap magnetic flux density, machine dimensions and pole numbers for an ideally built BDFM. Abdi *et al.* in [9] investigated using the finite element (FE) method the effects of parallel connections in the stator winding on vibration mitigation in the presence of rotor eccentricity. An analytical and experimental analysis of the generators vibration performance was performed in [10] showing that the vibration amplitude can be decreased if special attention is given to the choice of the BDFM power and CWs pole numbers, the number of loops in the rotor cage and the design of the laminated stator core.

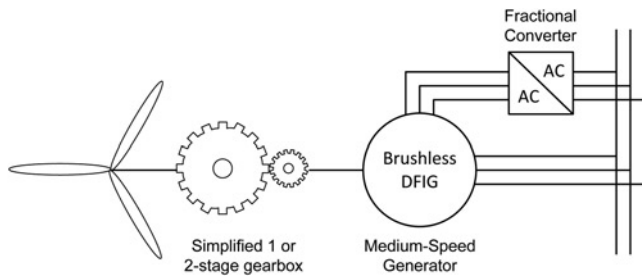


Fig. 1 BDFM drivetrain



Fig. 2 250 kW D400 BDFM (right front) on test bed

It is desirable for all induction type machines to be designed with the smallest possible air gap length in order to minimise the magnetising currents. However, this can also lead to strong magnetic fields across the air gap, which exerts considerable forces on the iron parts of the machine. These cause time-varying deflections of the machine's surface and hence transmit noise to the surrounding air. One method by which vibrations and acoustic noise may be produced is unbalanced magnetic pull, which has been shown to occur in machines with pole-pair numbers that differ by one [11]. Therefore, this source of vibration can be avoided by careful design of the pole-pair numbers.

Another source of vibration known as 'bending set up in the back iron' is shown in [8, 9] to occur in BDFMs of all pole-pair number combinations causing stator back iron deflection and leading to bending mode vibration in the BDFM.

It was shown in [8] that the deflection value in a BDFM is dominated by the term with the p_1-p_2 pole pair number and $\omega_1-\omega_2$ angular frequency. This term represents the presence of the two

Table 1 Specifications of the 250 kW D400 BDFM

frame size	400
PW pole number	4
PW rated voltage	690 V at 50 Hz (delta)
PW rated current	178 A (line)
CW pole number	8
CW rated voltage	620 V at 18 Hz (delta)
CW rated current	500 rpm \pm 36%
speed range	73 A (line)
rated torque	3670 N m
rated power	250 kW at 680 rpm
efficiency (at full load)	>95%
stack length	0.82 m

magnetic fields in the machine with different pole numbers and different frequencies. It is also shown in this paper that the vibration component with $\omega_1-\omega_2$ angular frequency makes the most contribution in machine's vibration.

As with the induction machine [12], the possibility of rotor eccentricity in imperfectly constructed machines further modulates the field patterns adding to the complication of the vibration patterns; however, these effects are not trivial to be precisely determined in analytical calculations of the machine vibration. Nevertheless, it was shown in [8] that in machines with static and dynamic eccentricities there is a mechanism by which vibration components at angular frequencies of ω_r , $\omega_1-\omega_2$, $\omega_1-\omega_2 \pm \omega_r$ are developed. The eccentricities' effects are also shown in vibration spectrums discussed in Section 6 of this paper.

The presence of stator and rotor winding time harmonics, the air gap magnetic field space harmonics and the dynamics of the mechanical system (including natural frequencies of the various components) are other important factors that can contribute to the vibration and noise of the BDFM.

3 Prototype machine considered in this study

The specifications of the 250 kW D400 BDFM are shown in Table 1. The D400 BDFM was constructed as a frame size D400 machine with the stack length of 820 mm. The stator windings were formed from copper strips. The PW was rated at 690 V, 178 A, at 50 Hz and the CW was designed for 620 V at 18 Hz and rated at 73 A. Both stator windings were connected in delta. The rotor comprises six sets of nests each consisting of a number of concentric loops [13], the conductors being solid bars with one common end ring [14]. The magnetic properties for the iron were provided by the machine manufacturer.

4 Experimental examination of vibration and noise levels in the BDFM

4.1 Vibration measurements

Vibration was measured using Bruel & Kjaer instruments from the drive end of the machine. The measured rms vibration velocity over a range of operating speeds is shown in Fig. 3.

According to the VDI 2056 standard of evaluation for mechanical vibrations of electrical machines, for a 250 kW Class M machine, the following can be concluded:

- For the operating conditions with rotor speed between 540 and 680 rev/min, the rms values of vibration velocity remain within the allowable range of 2.87–4.01 mm/s, but close to the standard limit;
- For the operating speed range of 320–520 rev/min, the measured vibration rms values stay between 5.15 and 12.70 mm/s, which is above tolerable limit for the whole speed range.

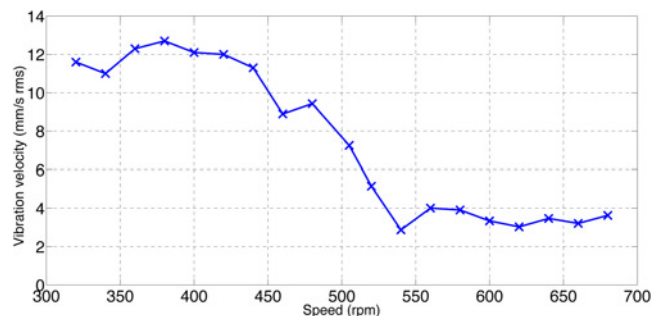


Fig. 3 Vibration velocity at a range of operating speeds

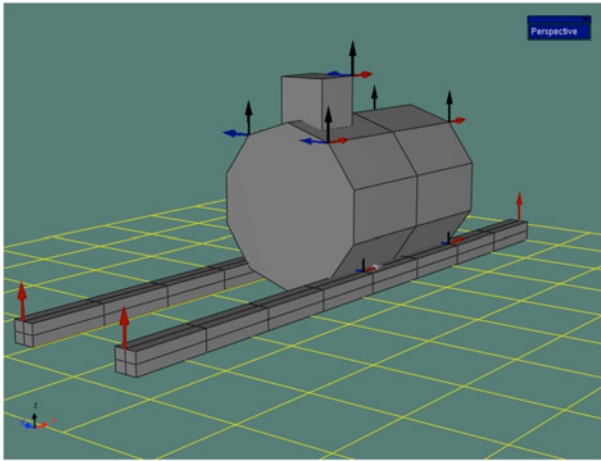


Fig. 4 Location of accelerometers for vibration modal analysis tests

A series of measurements was conducted on the machine to establish the main modes of excitation of vibration and noise developed by the machine. The machine was instrumented with a number of accelerometers positioned on the bedplate, frame and terminal box of the machine, as shown in Fig. 4, and the machine was operated at a range of speeds from 320 to 620 rev/min.

Displacement, velocity and acceleration values were extracted from the accelerometers as interpolated motion diagrams based on the location of the accelerometers. The interpolated modal motion diagrams were extracted for the following rotational speed modes, 1st, 3rd, 5th, 7th, 9th and 12th.

- The source of the vibration is primarily motion at the centre of the main core of the machine, coupled to its cast frame, and therefore originates primarily from the air gap field;
- However, there is significant motion of the fabricated parts, bolted to the cast frame, namely the sheet metal instrumentation extension and fan enclosure at the non-drive end (NDE) and the fabricated terminal box at the drive end;
- The results all confirm that the vibration excitation is more severe at lower speeds from 320 rev/min rising to a peak at around 400 rev/min, then falling from that speed to 620 rev/min, as was observed also in the vibration measurements shown in Fig. 3;
- When considering the contributions to the measured vibration velocity the modal images showed that the most significant contribution to the vibration velocity came from the following orders, in descending order of importance: 3rd, 5th, 1st, 7th, 12th and 9th.

4.2 Noise measurement

Noise was initially considered qualitatively and noise levels were high, particularly close to or below the natural speed, 500 rev/min. The noise radiated from the sheet metal components of the machine notably the main terminal box, auxiliary terminal box and the NDE ventilation cowl was significant, in fact from the latter a resonance was noted at low speed ~350 rev/min.

During the modal vibration tests the noise was measured using a single microphone placed at the NDE 1 m from the machine at a height of approximately 1 m. The machine was accelerated smoothly from 320 to 620 rev/min over a period of 70 s and the noise level measured using this microphone, with results shown in Fig. 5. An acceptable noise level for the machine would be 85–90 dBA and the results shown in Fig. 5 confirm the qualitative results above, namely that:

- The measured noise level ranged from 86 to 105 dBA;
- There was a peak noise level of 105 dBA at 400 rev/min, confirming the vibration results above. This noise level would be unacceptable on a commercially produced machine;

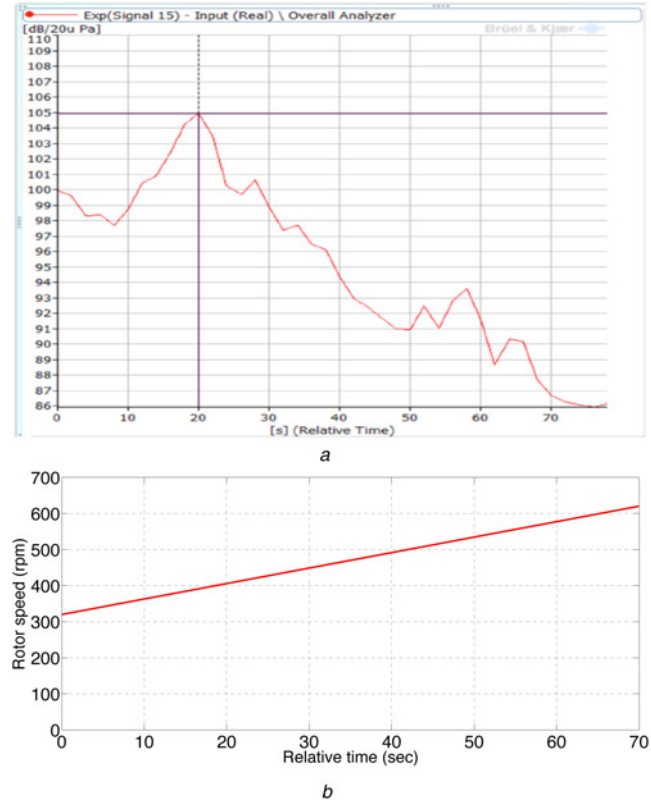


Fig. 5 Noise versus speed analysis

- a Measured noise at a range of rotor speed between 320 and 400 rev/min
- b Variation of rotor speed with time during measurement

- The machine was noisier at lower speeds with noise levels rising from 320 to 400 rev/min;
- The machine noise then fell steadily from 400 to 630 rev/min.

5 Harmonic analysis of the BDFM

In order to study the potential harmonics content in a BDFM and their contributions in the machine's vibration, the prototype machine was run in synchronous mode of operation with PW and CW supplied at frequencies of 50 and 18 Hz, respectively, resulting in the rotor speed of 680 rpm. The PW active power and reactive power were set to be –183 kW and 100 kVAR. The harmonic contents of PW current, PW active power and the machine torque are examined in this section and different sources of harmonics were investigated based on the BDFM harmonic analysis proposed in the literature, e.g. [15, 16]. Fig. 6 shows the spectrum of the PW current, PW active power and the machine torque at the aforementioned operating condition.

5.1 PW and CW time harmonics

A 50 Hz three-phase system will have no third-order harmonics but with –5, +7, –11, 13 time harmonics. The PW time harmonics due to PW supply can be obtained from

$$f_h = n \times f_{pw} \quad (1)$$

The observed harmonic frequencies in PW current spectrum are –250 and 350 Hz also calculated from (1) by substituting n with –5 and 7. Similarly, the CW has also its high-order harmonics,

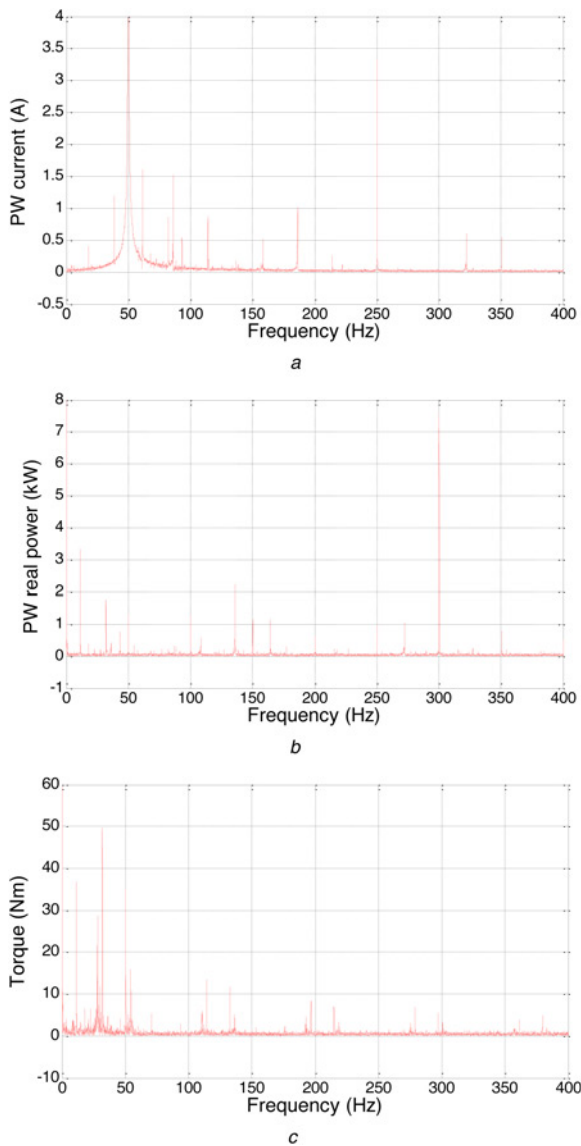


Fig. 6 Spectrum of the PW current, active power and the machine torque in synchronous mode of operation with $f_{pw} = 50$ Hz, $f_{cw} = 18$ Hz and rotor speed of 680 rpm
a Spectrum of the PW current
b Spectrum of the PW active power
c Spectrum of the machine torque

which affect the PW via the rotor. The CW time harmonic frequencies can be obtained from

$$f_h = (p_1 + p_2)f_r - n \times f_{cw} \quad (2)$$

where n is an integer number. The harmonics component with the frequency of 158 Hz observed in PW current and machine torque can be obtained from (2) when $n = -5$.

It was also observed in PW current spectrum that the CW fundamental frequency has a direct coupling to the PW with the CW supply frequency of 18 Hz.

5.2 Space harmonics

The BDFM rotor flux contains space harmonics, which cause additional PW time harmonics with the frequencies of

$$f_h = f_{pw} \pm n \times f_r \quad (3)$$

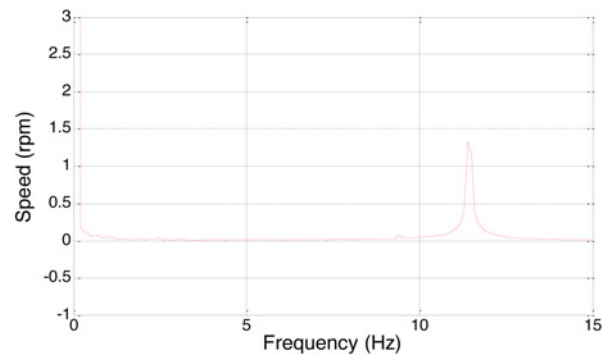


Fig. 7 Spectrum of the rotor speed in synchronous mode of operation with $f_{pw} = 50$ Hz, $f_{cw} = 18$ Hz and rotor speed of 680 rpm

The frequencies of 86, 186, 222 and 322 Hz in the PW current spectrum were observed, these can also be calculated from (3) when n is substituted by 12 and 24. In addition, the time harmonics of the PW (-250 and 350 Hz) will add to the space harmonics of (3) creating other space harmonic frequencies as

$$f_h = m \times f_r \pm n \times f_{cw} \quad (4)$$

The observed harmonic frequencies of 114 and 214 Hz correspond to the frequencies obtained from (4) if (m, n) are replaced by $(-5, 12)$ and $(7, 12)$, respectively.

5.3 Speed variation

The variation of the rotor speed will cause harmonics. The speed spectrum is given in Fig. 7. The rotor speed has an 11.3 Hz harmonic component representing the rotor frequency f_r . The resultant harmonic components in PW current can be obtained from

$$f_h = f_{pw} \pm n \times f_r \quad (5)$$

The harmonic components observed in PW current spectrum due to speed ripple are 38.7, 61.3, 83.9 and 95.5 Hz, and can be obtained from (5). In addition of the harmonics induced in PW current, speed ripples have created considerable harmonic content in the torque spectrum with the frequencies obtained from

$$f_h = \pm n \times f_r \quad (6)$$

The observed frequencies correspond to f_h from (6) when n is substituted by 1, 2, 3, 4, 6 and 8.

5.4 Load machine's control drive

The load induction machine was supplied by an ABB converter with a direct torque control algorithm, which will cause additional harmonics because of the stochastic variation of voltage zero-crossing points. A test was done by running the ABB machine at 680 rev/min while the BDFM system was shut-down. Several significant harmonics can be observed in the torque spectrum, e.g. 29, 53.5, 111, 136 and 193 Hz.

6 Discussion and conclusions

The spectrum of vibration amplitudes for the D400 BDFM is shown in Fig. 8 at the operating conditions where the machine's vibration velocity is at its highest level. The main vibration frequencies are also shown in the figures with different colours each representing a harmonic source of vibration studied in Section 5. Table 2 describes those harmonic sources allocated to each colour. From

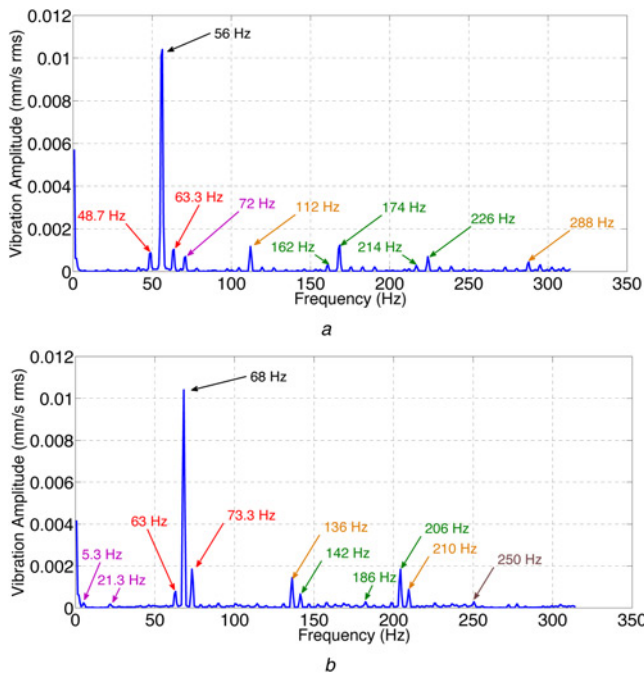


Fig. 8 Vibration amplitude spectrum at machine drive end at 0 kW, 100 kVAr
a 440 rpm rotor speed
b 320 rpm rotor speed

Table 2 Associated colours to each source of vibration frequency in Fig. 8

Source of vibration	Associated colours in Fig. 8
bending set up in the back iron	black
rotor eccentricity	red
PW and CW time harmonics	brown
space harmonics	green
speed variation	purple
load machine's control drive	orange

Fig. 8, it is obvious that the vibration frequency with highest amplitude is generated from the bending set up in the back iron due to the presence of two stator-winding fields with different frequencies and pole numbers.

The second most important vibration component belongs to 'rotor eccentricity'. There is a degree of rotor eccentricity due to imperfect construction of the rotor in induction typed machines. Abdi *et al.* showed in [8] that by careful parallel connections of stator winding coils, the back iron deflection can be reduced significantly.

Other sources of vibration inherently with harmonic natures have been studied in Section 5 showing that these effects exacerbate the vibration and noise levels. Therefore, special considerations such as rotor design optimisation and use of magnetic wedges in rotor slot openings can be used to reduce the harmonic effects.

It is clear from the measurements above that for a totally enclosed fan-cooled BDFM, where the stator core is closely coupled to the stator frame, the noise and vibration levels can reach higher levels than it is acceptable. This is specially the case when the

BDFM is operating close to its natural speed (500 rev/min). The origin of the vibration and noise appears to be the electromagnetic forces due to the complex air-gap magnetic field of the BDFM, rotor eccentricity and air gap harmonics content, although other sources of vibration may also make contribution. Therefore, future machine designs will need to mitigate the high vibration and noise level by the possible introduction of one or more of the following:

- Increasing the air gap length;
- Introduction of damping in the rotor winding;
- Introduction of damping in the stator winding with parallel paths;
- Isolation of the stator frame from the stator core.

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