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Voltage unbalance and harmonic distortion effects on induction motor power, torque and vibrations

Pablo Donolo[a,*], Guillermo Bossio[a], Cristian De Angelo[a], Guillermo García[a], Marcos Donolo[b]

[a] Fac. de Ingeniería, Universidad Nacional de Río Cuarto – CONICET, Ruta Nac. #36 Km 601, X5804BYA Río Cuarto, Córdoba, Argentina
[b] SEL Schweitzer Engineering Laboratories, Inc., 2350 NE Hopkins Court, Pullman, WA 99163, USA

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ABSTRACT

Voltage unbalance and harmonic voltage distortion affect the power, torque and vibrations on induction motors (IM). In this paper, we compute the frequency of the oscillations of the power, torque and vibrations due to voltage unbalance and harmonics and we present laboratory results to verify the calculations. We also show that typical values of harmonic distortion combined with the maximum levels of voltage unbalance allowed by standards are sufficient to introduce vibrations levels under which continuous operation of IMs is not recommended. This result has important implications for root-cause analysis of IM trip due to vibrations because protection engineers can rule out mechanical problems by verifying that vibrations are only present during high levels of voltage unbalance and harmonic distortion.

1. Introduction

Induction motors (IMs) are widely utilized in industrial processes. It is estimated that 75% of the electric energy generated in the US is consumed in IMs [1]. For this reason, several diagnostic techniques were developed to avoid unscheduled maintenance, reduce damage and down-time of processes that use IMs. Some of these techniques are based on the analysis of the IM currents, voltages and derived quantities such as power [2–4]. Other diagnostic techniques are based on the analysis of vibrations [5–9].

Even when these techniques have demonstrated to be effective, voltage unbalance and harmonic distortion are two common power-quality problems that lead to IMs malfunction and may interfere with vibration based diagnostics techniques [10–12].

The effect of voltage unbalance and harmonic distortion on the IM currents and their thermal overload implications are documented in detail in several works [13–17]. The effects on the IM torque are also well documented [18–21]. There is however, limited data on vibrations caused by voltage unbalance or harmonic distortion [22].

To fill this data void, we present laboratory test vibrations values cause by voltage unbalance, by harmonic distortion and by the combined effect of voltage unbalance and harmonic distortion. In this paper we also show that the combined effect of acceptable levels of voltage unbalance and harmonic distortion, leads to damaging levels of IM vibrations [23,24]. Recognizing that large vibrations may be due to power quality problems has important implications for root-cause analysis of IM trip due to vibrations because protection engineers can rule out mechanical problems by verifying that vibrations are only present during high levels of voltage unbalance and harmonic distortion.

In Section 2, we present definitions for voltage unbalance and harmonic distortion and derive mathematical expressions for the torque and active power for an IM under these power quality conditions. These expressions take into account the order and sequence of the harmonics. In Section 3, we describe our test setup and validate the mathematical expressions using experimental results. Finally, in Section 4 we present vibration measurements due voltage unbalance and harmonic distortion. Also in Section 4, we compare the measured vibration levels with the ISO 10816-1 standard vibration severity guidelines.

* Corresponding author. Tel.: +54 358 4676 255.
E-mail addresses: pdonolo@gmail.com, pdonolo@ing.unrc.edu.ar (P. Donolo), gbossio@ing.unrc.edu.ar (G. Bossio), cdeangelo@ieee.org (C. De Angelo), g.garcia@ieee.org (G. García), marcos_donolo@selinc.com (M. Donolo).

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2. Definitions and effects of power quality problems

2.1. Unbalance and harmonic distortion measurement

In this paper, we compute the voltage unbalance using [11,12];

$$\mathrm{VUF} = \frac{|\boldsymbol{v}_{1n}|}{|\boldsymbol{v}_{1p}|} \cdot 100 \quad (1)$$

where $\boldsymbol{v}_{1p}$ and $\boldsymbol{v}_{1n}$ are the fundamental positive and negative sequence components of the voltage. This definition is consistent with IEC standard 61000-4-30 [11,12].

To compute the harmonic distortion, we use the harmonic voltage factor (HVF) defined by [10]:

$$\mathrm{HVF} = \sqrt{\sum_{h=5}^{h=\infty} \frac{V_{h_{\mathrm{pu}}}^2}{h}}, \quad h = 5, 7, 11, 13, \ldots \quad (2)$$

where $V_{h_{\mathrm{pu}}}$ is the magnitude of the harmonic voltage component of order h, in per unit of the fundamental voltage magnitude. This definition is consistent with NEMA MG1 Motors and Generators [10].

2.2. Active power oscillations due to voltage unbalance

We study the effects of voltage unbalance on the active power using symmetrical components. The voltages and currents in a stationary reference frame "*q-d*" are given by [25]:

$$v_q = \hat{V}_{1p}\cos(\omega_s t + \theta_{v_{1p}}) + \hat{V}_{1n}\cos(-\omega_s t + \theta_{v_{1n}}) \quad (3)$$

$$v_d = \hat{V}_{1p}\sin(\omega_s t + \theta_{v_{1p}}) + \hat{V}_{1n}\sin(-\omega_s t + \theta_{v_{1n}}) \quad (4)$$

$$i_q = \hat{I}_{1p}\cos(\omega_s t + \theta_{i_{1p}}) + \hat{I}_{1n}\cos(-\omega_s t + \theta_{i_{1n}}) \quad (5)$$

$$i_d = \hat{I}_{1p}\sin(\omega_s t + \theta_{i_{1p}}) + \hat{I}_{1n}\sin(-\omega_s t + \theta_{i_{1n}}) \quad (6)$$

where $\hat{V}$ is the peak voltage, $\hat{I}$ is the peak current, ω_s is the angular frequency of the system and θ is the angle of the component in the "*q-d*" reference frame.

The subscript 1 refers to the fundamental component and the subscripts p and n refer to the positive and negative sequence components, respectively.

In this "*q-d*" reference frame, the instantaneous active power is calculated as follows [22,25]

$$P(t) = \frac{3}{2}(v_q i_q + v_d i_d) \quad (7)$$

By replacing the voltages and currents in (7) [22], the active power results in

$$\begin{aligned} P(t) = {} & \frac{3}{2}(\hat{V}_{1p}\hat{I}_{1p}\cos(\theta_{v_{1p}} - \theta_{i_{1p}}) + \hat{V}_{1n}\hat{I}_{1n}\cos(\theta_{v_{1n}} - \theta_{i_{1n}})) \\ & + \cdots + \frac{3}{2}(\hat{V}_{1p}\hat{I}_{1n}\cos(2\omega_s t + \theta_{v_{1p}} - \theta_{i_{1n}})) \\ & + \frac{3}{2}(\hat{V}_{1n}\hat{I}_{1p}\cos(2\omega_s t + \theta_{v_{1n}} - \theta_{i_{1p}})). \end{aligned} \quad (8)$$

The first term in (8) corresponds to the mean power P_0, while the second and third terms contains the components at $2\omega_s$ frequency, produced by voltage and current unbalance. Then, as shown in (8), the IM active power under voltage unbalance will present a pulsating component at twice the supply frequency. From these components, the first one is the greatest, since its magnitude depends on the positive sequence voltage. This component also depend on the negative sequence current, thus it will grow with the voltage unbalance. According to the rotor characteristics, this negative sequence current depends on the IM load. The third term of (8) greatly depend on the IM load, but its magnitude is usually very small, since the negative-sequence voltage is generally much lower than the positive-sequence voltage [26].

2.3. Active power oscillations due to voltage harmonics

We use a similar analysis to study the effects of voltage distortion on the instantaneous active power of the IM. In this section, we first consider the effects on the active power of the positive sequence of the harmonic voltages and then the effects of the negative sequence.

2.3.1. Positive sequence harmonics

In the "*q-d*" reference frame, voltage and currents for the fundamental and positive sequence harmonic h_p components are given by:

$$v_q = \hat{V}_{1p}\cos(\omega_s t + \theta_{v_{1p}}) + \hat{V}_{hp}\cos((h_p)\omega_s t + \theta_{v_{hp}}) \quad (9)$$

$$v_d = \hat{V}_{1p}\sin(\omega_s t + \theta_{v_{1p}}) + \hat{V}_{hp}\sin((h_p)\omega_s t + \theta_{v_{hp}}) \quad (10)$$

$$i_q = \hat{I}_{1p}\cos(\omega_s t + \theta_{i_{1p}}) + \hat{I}_{hp}\cos((h_p)\omega_s t + \theta_{i_{hp}}) \quad (11)$$

$$i_d = \hat{I}_{1p}\sin(\omega_s t + \theta_{i_{1p}}) + \hat{I}_{hp}\sin((h_p)\omega_s t + \theta_{i_{hp}}) \quad (12)$$

Using (9) and (12) in (7) we obtain:

$$\begin{aligned} P_{hp}(t) = {} & \frac{3}{2}(\hat{V}_{1p}\hat{I}_{1p}\cos(\theta_{v_{1p}} - \theta_{i_{1p}}) + \hat{V}_{hp}\hat{I}_{hp}\cos(\theta_{v_{hp}} - \theta_{i_{hp}})) \\ & + \cdots + \frac{3}{2}(\hat{V}_{1p}\hat{I}_{hp}\cos((h_p - 1)\omega_s t + \theta_{v_{1p}} - \theta_{i_{hp}})) \\ & + \frac{3}{2}(\hat{V}_{hp}\hat{I}_{1p}\cos((h_p - 1)\omega_s t + \theta_{v_{hp}} - \theta_{i_{1p}})). \end{aligned} \quad (13)$$

where the first term is the mean power and the second and third terms represent the power oscillating at $(h_p - 1)\omega_s$.

2.3.2. Negative sequence harmonics

In the "*q-d*" reference frame, the voltages and currents with negative sequence harmonics are given by:

$$v_q = \hat{V}_{1p}\cos(\omega_s t + \theta_{v_{1p}}) + \hat{V}_{hn}\cos(-(h_n)\omega_s t + \theta_{v_{hn}}) \quad (14)$$

$$v_d = \hat{V}_{1p}\sin(\omega_s t + \theta_{v_{1p}}) + \hat{V}_{hn}\sin(-(h_n)\omega_s t + \theta_{v_{hn}}) \quad (15)$$

$$i_q = \hat{I}_{1p}\cos(\omega_s t + \theta_{i_{1p}}) + \hat{I}_{hn}\cos(-(h_n)\omega_s t + \theta_{i_{hn}}) \quad (16)$$

$$i_d = \hat{I}_{1p}\sin(\omega_s t + \theta_{i_{1p}}) + \hat{I}_{hn}\sin(-(h_n)\omega_s t + \theta_{i_{hn}}) \quad (17)$$

Using (14) and (17) in (7) we obtain the IM's instantaneous active power in terms of negative-sequence harmonic voltages.

$$\begin{aligned} P_{h2}(t) = {} & \frac{3}{2}(\hat{V}_{1p}\hat{I}_{1p}\cos(\theta_{v_{1p}} - \theta_{i_{1p}}) + \hat{V}_{hn}\hat{I}_{hn}\cos(\theta_{v_{hn}} - \theta_{i_{hn}})) \\ & + \cdots + \frac{3}{2}(\hat{V}_{1p}\hat{I}_{hn}\cos((h_n + 1)\omega_s t + \theta_{v_{1p}} - \theta_{i_{hn}})) \\ & + \frac{3}{2}(\hat{V}_{hn}\hat{I}_{1p}\cos((h_n + 1)\omega_s t + \theta_{v_{hn}} - \theta_{i_{1p}})). \end{aligned} \quad (18)$$

The first term in (18) represents the mean active power of the IM. In this case, the term $\hat{V}_{hn}\hat{I}_{hn}\cos(\theta_{v_{hn}} - \theta_{i_{hn}})$ represents the mean power generated by the harmonic components of negative sequence. The second and third term of (18) represent the power oscillations at frequency $(h_n + 1)\omega_s$, where h_n is the order of the negative-sequence harmonic component.

According to (13), the interaction between V_{1p} and I_{hp} generates power oscillations at a frequency given by $(h - 1)\omega_s$ [21]. Similarly, the interaction between I_{1p} and V_{hp} generates active power oscillations at a frequency $(h - 1)\omega_s$. On the other hand, according to (18), the interaction between V_{1p} and I_{hn} generates power oscillations at a frequency $(h+1)\omega_s$ [21]. Similarly, the interaction between I_{1p} and V_{hn} generates active power oscillations at a frequency $(h+1)\omega_s$ [21]. For this reasons, larger active power oscillations may appear when the power oscillations due to positive- and negative-sequence harmonics coincide in frequency and phase [21].

3. Active power and electromagnetic torque oscillations measured on IMs

3.1. Test bench

Fig. 1 shows the test bench we used to test a 5.5 kW IM. The bench consists of a three-phase programmable source to create voltage supply conditions including voltage unbalance and harmonic distortion.

Fig. 1 also shows the IM under test connected to a second IM used as a load. This IM is fed by a variable speed drive (VSD) so that the load on the IM under test may be adjusted.

We record two line voltages and two phase currents into the IM under test using a four-channel recorder (3.2 s, 40 kS). The remaining voltage and current are obtained adding the measured values. A vibration analyzer is used to measure the vibrations in the frame of the IM.

During the tests, we keep the positive sequence of fundamental voltage at nominal value. We introduce voltage unbalance by increasing the negative sequence component of the fundamental voltage. To generate harmonic voltage distortion, we introduced 5th and 7th harmonics keeping the magnitude of the 7th harmonic at 0.7 that of the 5th harmonic. According to [11] this ratio between the 5th and 7th harmonic is the most common in electric power system. Further, the 5th harmonic component was found to be of negative sequence and the 7th harmonic of positive sequence [21].

We measure the instantaneous active power using the voltages and currents supplied to the IM. We use the stator voltage, current and resistance to estimate the linked stator flux [25] and then we use the currents and the flux to estimate the electromagnetic torque as in [25].

3.2. Oscillations generated by voltage unbalance

During ideal voltage supply conditions, the instantaneous active power and torque of the IM are constant. Fig. 2(a) shows the frequency spectrum of the instantaneous active power and Fig. 2(b) the spectrum of the electromagnetic torque on an IM at 75% load under ideal supply conditions. The mean power component (0 Hz), and some smaller magnitude components that may due to the IM's characteristics or to small asymmetries in the voltage supply can be appreciated.

Voltage unbalance generates active power and electromagnetic torque oscillations at two times the fundamental frequency. Fig. 3 shows the frequency spectrum of the instantaneous active power (a) and the electromagnetic torque (b) for a VUF = 3% condition.

Two main frequency components appear in Fig. 3, the DC components due to the mean power and the 100 Hz (50 Hz system) component due to the voltage unbalance.

The figure also shows that under these conditions (75% load 3% VUF) the magnitude of the 100 Hz component of the active power is about one third (1.7 kW) of the nominal power of the IM (5.5 kW). Similarly, the 100 Hz frequency component of the electromagnetic torque represents one quarter (8.9 N m) of the nominal torque of the IM.

The amplitude of the 100 Hz frequency components depends on negative sequence currents on the IM. The negative sequence currents depend on the characteristics of the IM, the voltage unbalance, and the loading level of the IM [26,27]. Fig. 4 shows that the amplitude of the 100 Hz frequency component grows linearly with the voltage unbalance. It must be noted that this component can reach 80% of the nominal power and up to 60% of the rated torque for 7% VUF condition.

3.3. Oscillations generated by voltage harmonic distortion

As described in Section 3.1, the 5th and 7th order harmonics in the supply voltage appear as oscillations in the IMs instantaneous active power and torque at a frequency equal to that of the 6th order harmonic.

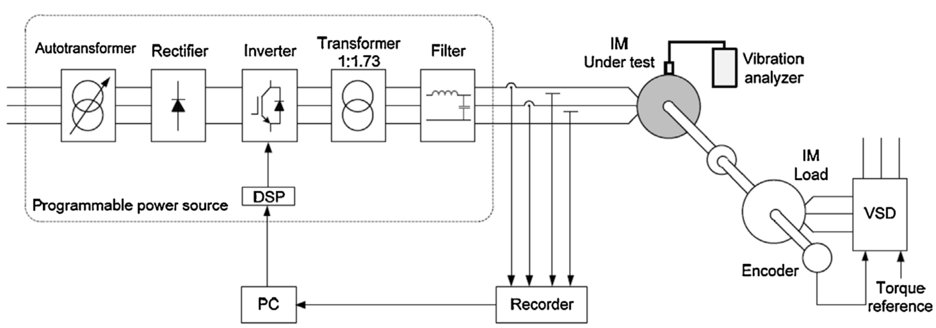


Fig. 1. Test bench used to measure power, torque and vibrations.

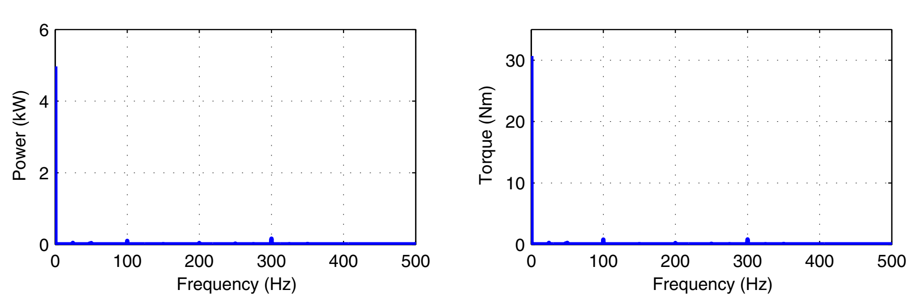


Fig. 2. Frequency spectrum of the active power (a) and torque (b) of the IM. Ideal supply.

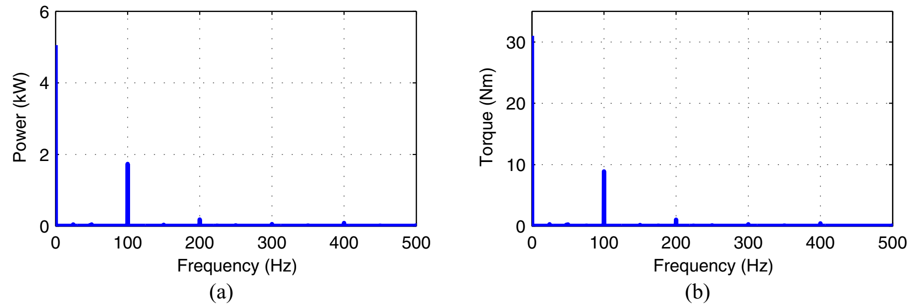


Fig. 3. Frequency spectrum of the active power (a) and torque (b) of the IM. VUF = 3%.

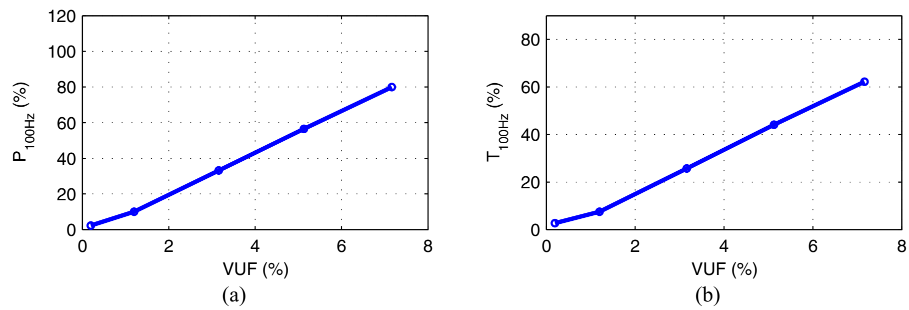


Fig. 4. Oscillations of the active power (a) and torque (b) at twice supply frequency for unbalanced voltage. IM at full load.

Fig. 5 shows the frequency spectrum of the instantaneous active power (Fig. 5(a)) and the electromagnetic torque (Fig. 5(b)) of the IM at 75% load with a typical value of voltage harmonic distortion (HVF = 0.06).

In this test, the 6th order harmonic frequency component in the active power spectrum has a magnitude of 2.8 kW which represents 51% of the nominal power of the IM. Similarly, the 6th order harmonic frequency component in the torque spectrum has a magnitude of 13.9 N m which represents 39% of the nominal torque of the IM.

Fig. 6 shows that the magnitude of the 300 Hz frequency component grows linearly with the harmonic voltage distortion.

3.4. Oscillations generated by unbalanced and distorted voltages

In this section we show the combined effect of voltage unbalance and harmonic distortion on the active power and torque of the IM.

Fig. 7 shows the frequency spectrum of the active power and the electromagnetic torque, for a 3% voltage unbalance and a harmonic distortion of HVF = 0.06 while the IM load is 75%.

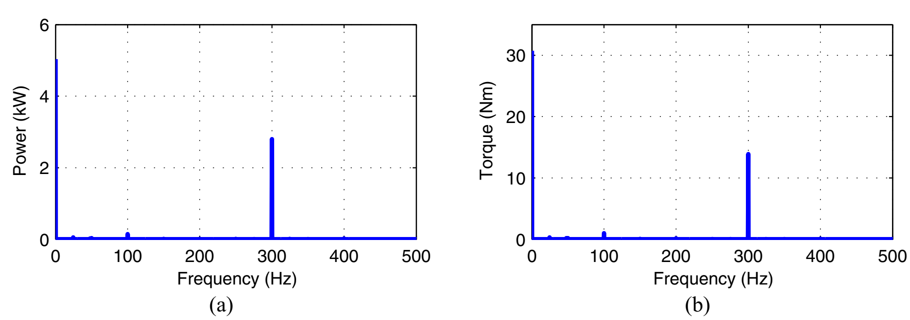


Fig. 5. Effect of voltage harmonic distortion on the active power (a) and torque (b) of the IM.

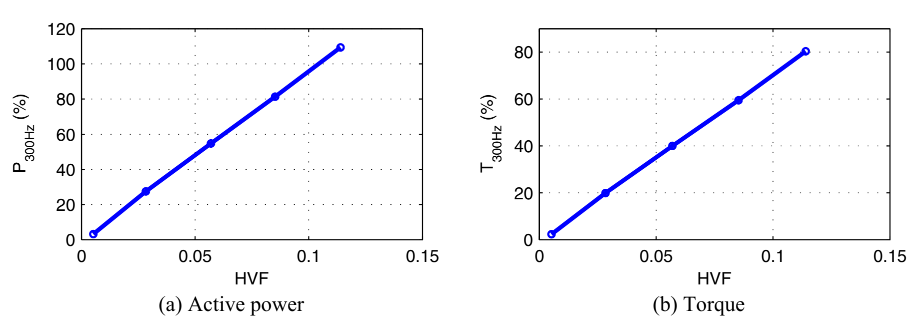


Fig. 6. Oscillations at six times supply frequency of the active power (a) and torque (b) for harmonic voltage distortion. IM at full load.

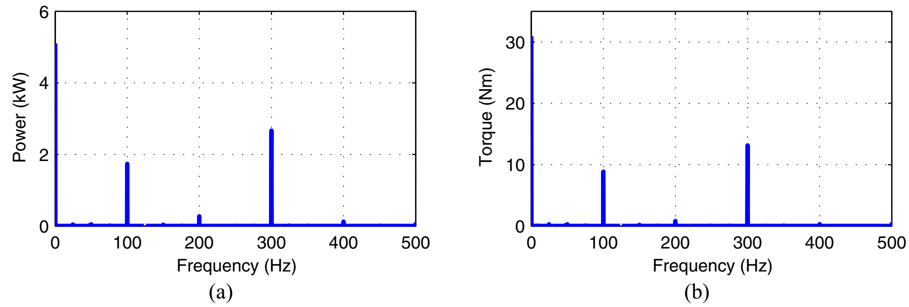


Fig. 7. Frequency spectrum of the active power (a) and torque (b) of the IM. VUF = 3% and HVF = 0.06.

Comparing Fig. 7 with Figs. 3 and 5, we conclude that:

- The magnitude of the frequency component associated to the voltage unbalance (100 Hz), is not influenced by the voltage harmonic distortion (Figs. 3 and 7).
- The magnitude of the frequency component associated with voltage harmonic distortion (300 Hz) is not influenced by voltage unbalance (Figs. 5 and 7).

The combined effect of voltage unbalance and harmonic distortion generates moderate active power and torque oscillations at 4 and 8 times the fundamental frequency (200 Hz and 400 Hz).

The frequency component at 4 times the fundamental frequency is generated by the interaction between I_{3n} and V_{1p} and the interaction between V_{3n} and I_{1p}. The interaction between I_{5p} and V_{1p} and the interaction between V_{5p} and I_{1p} also generate active power oscillation at 4 times the fundamental frequency. The frequency component at 8 times the fundamental frequency is generated by the interaction between I_{7n} and V_{1p} and the interaction between V_{7n} and I_{1p}.

While smaller than the components at 2 and 6 times the fundamental frequency, the components at 4 and 8 times the fundamental frequency are greatly amplified by the combined effect of voltage unbalance and harmonics as shown in Table 1.

4. Measured vibrations on IMs

Fig. 8 shows the frequency spectrum of the speed of vibrations on the stator of the IM while operating with sinusoidal, balanced voltages at 75% load.

The frequency component close to 25 Hz corresponds to the IM rotor speed (f_r). This rotor speed component and its multiples appear in the spectrum due to normal asymmetries in the rotor such as mass unbalance, eccentricity, and misalignments [5]. The frequency component at 4 times the speed of the IM is very close to 2 times the supply frequency (f_s).

The RMS value of vibrations is often used to assess the general health of rotating equipment [23,24]. The ISO 10816-1 and the IEC 60034-14 standards establish tolerable levels of vibrations on IMs for different power ratings, foundation and load type [23,24]. According to the ISO 10816-1 standard, for this IM (power <15 kW), vibration velocities between 0 and 0.71 mm/s (zone A) correspond to machines just put into service. Values between 0.71 and 1.8 mm/s (zone B) correspond to equipment which can operate continuously without any restrictions. Finally, values between 1.8 and 4.5 mm/s (zone C) indicate that the condition is acceptable only for a limited period of time [24].

According to the IEC 60034-14 for IMs with no special vibration requirements (IMs class A) and frame sizes between 56 and 132, vibration velocities should be less than 1.3 mm/s for rigid foundation and 1.6 mm/s for free suspension. For IMs with special vibration requirements (IMs class B) and frame sizes between 56 and 132, vibration velocities should be less than 0.7 mm/s for free suspension [23].

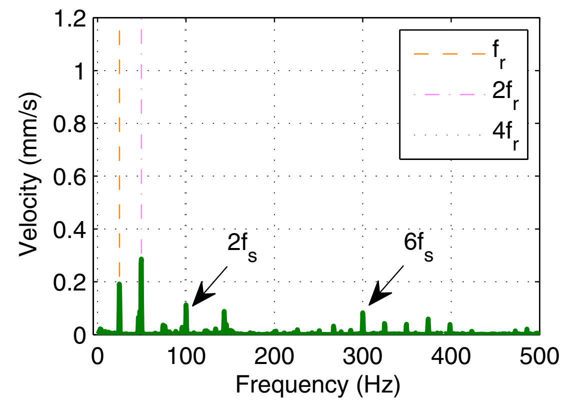


Fig. 8. Frequency spectrum of the vibrations of the IM. Ideal supply voltage.

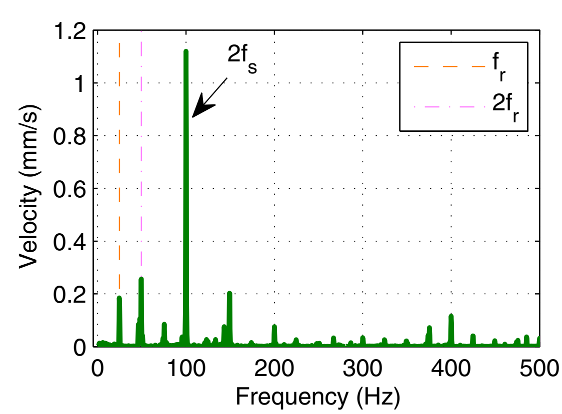
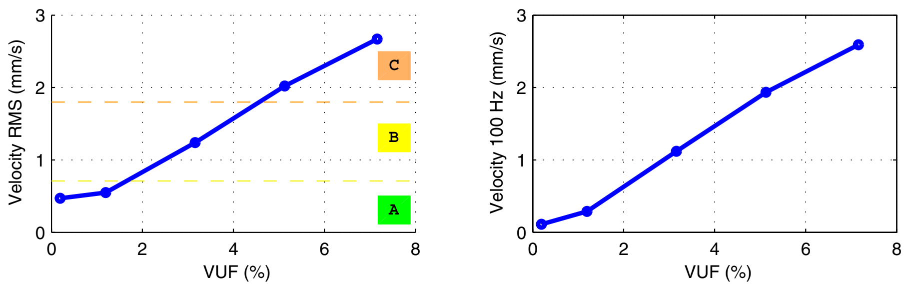


Fig. 9. Frequency spectrum of the vibrations of the IM. VUF = 3%.

Table 1
200 Hz and 400 Hz active power components for different test cases.

VUF (%)	HVF	200 Hz component (W)	400 Hz component (W)
0.19	0.005	33.4	2.96
3.16	0.004	171.5	81.0
0.20	0.057	27.0	25.3
3.16	0.054	270.1	114.1



(a) (b)

Fig. 10. Vibration velocity as a function of the voltage unbalance. (a) RMS and (b) 100 Hz component. IM load 75%.

4.1. *Vibrations on IMs due to unbalanced voltage supply*

Voltage unbalance generates vibrations at two times the fundamental frequency. Fig. 9 shows the frequency spectrum of the IMs vibrations for a VUF = 3% condition. Comparing Fig. 8 with Fig. 9, we see that voltage unbalance caused the magnitude of the 100 Hz component to grow 10 times.

Fig. 10(a) shows the RMS value of the vibrations velocity for different values of voltage unbalance. The figure also shows the vibration thresholds defined by the ISO 10816-1 standard. As the voltage unbalance goes from 0% VUF to 7% VUF, the RMS values of the vibrations velocity grows as a result of the increase in the 100 Hz component of the vibration's velocity (see Fig. 10(b)).

For voltage unbalance factors less than 1%, the vibration level corresponds to machines recently brought into service (zone A of the ISO 10816-1 standard). On the other hand, for voltage unbalance ratios greater than 4.5, the vibration levels exceed the threshold of vibrations acceptable under continuous operations (zone C of the standard).

4.2. *Vibrations on IMs due to harmonics voltage distortion*

Fig. 11 shows the frequency spectrum of the velocity vibrations on the frame of an MI with the same load level as before but when the harmonic voltage distortion is set to HVF = 0.06.

The figure shows vibration velocity component at 6 times the fundamental frequency due to the harmonic distortion.

Fig. 12(a) shows the RMS value of the velocity vibration for different values of voltage harmonic distortion. In this case, the growth in the RMS value corresponds to the increase of the 300 Hz component of the vibrations as shown in Fig. 12(b). Note that the additional vibrations caused by the harmonic voltage distortion moved the IM condition from zone A to zone B of the ISO 10816-1 standard.

Figs. 4 and 6 show that the active power and electromagnetic torque are more susceptible to changes in harmonic distortion than

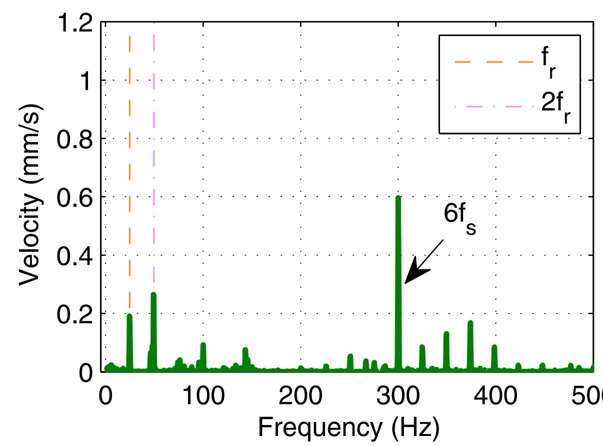


Fig. 11. Frequency spectrum of the vibrations of the IM. HVF = 0.06.

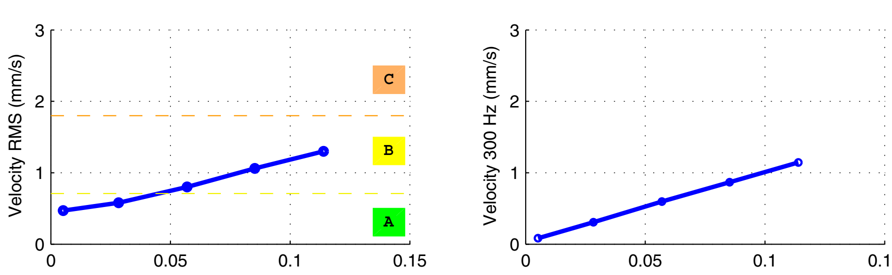
to changes in voltage unbalance. Figs. 10 and 12, show, contrary to what could be expected, that vibrations are more affected by changes in voltage unbalance than to changes in harmonic distortion.

This behavior is due to rotating inertias filtering out higher frequency components.

4.3. *Vibrations on IMs due to unbalance and harmonics voltage supply*

Fig. 13 shows the combined effect of voltage unbalance VUF = 3% and harmonic distortion HVF = 0.06, on the frequency spectrum of the vibrations velocity of an IM with 75% of load. Note the increased magnitude values of frequency components at multiples of the fundamental frequency, especially at 100 Hz due to voltage unbalance, and at 300 Hz due to voltage harmonics at 250 Hz and 350 Hz.

Fig. 14 shows the combined effect of voltage unbalance and harmonic distortion on the RMS value of the velocity vibration. For



(a) (b)

Fig. 12. Velocity vibration as a function of the voltage distortion. (a) RMS and (b) 300 Hz component. IM load 75%.

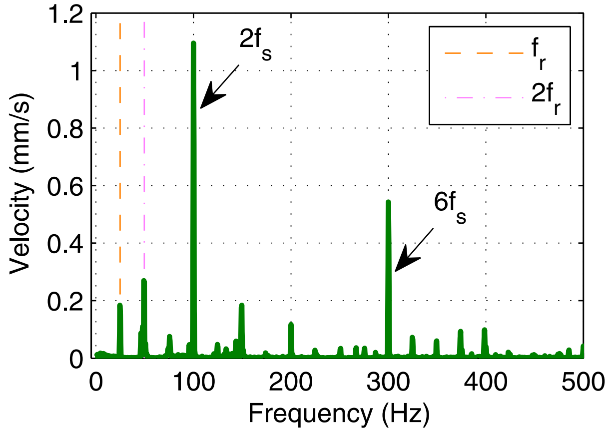


Fig. 13. Frequency spectrum of the vibrations of the IM. VUF = 3% and HVF = 0.06.

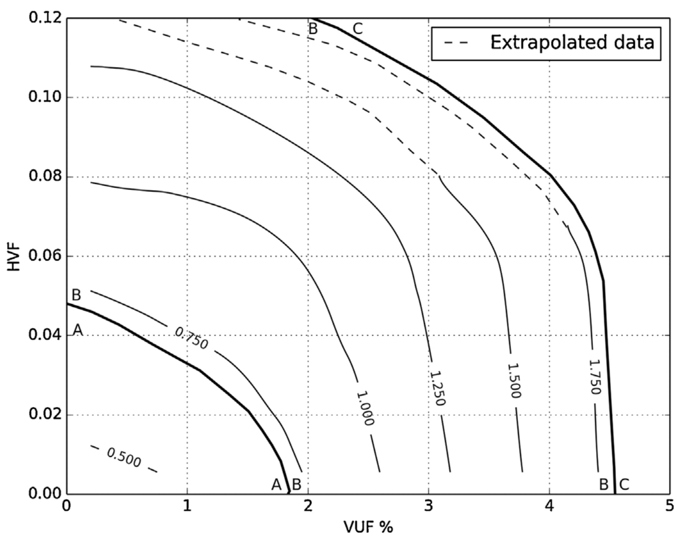


Fig. 14. Vibration velocity as a function of the unbalance and voltage distortion.

example 1 mm/s – rms vibration values are obtained at HVF = 0.08 for no voltage unbalance conditions and at VUF = 2.5% for no harmonic distortion. When both harmonic voltage distortion and voltage unbalance are combined, the 1 mm/s – rms vibration level is obtained at HVF = 0.06 and VUF = 2%.

5. Conclusions

In this paper, we studied the effects of voltage unbalance and harmonic distortion on IMs instantaneous power, torque and vibrations.

From this study, we showed that voltage unbalance generates a power oscillation at twice the supply frequency. This oscillation generates, in turn, torque oscillations and additional IM vibrations. This component of the instantaneous power grows almost linearly with the voltage unbalance, reaching 60% the rated IM power for 5% voltage unbalance. Voltage unbalance can also produce a significant increase of the IM vibrations, may even reach values where the IM continuous operation is not recommended according to standards.

We also demonstrated that the 5th and 7th voltage harmonics produce active power oscillations and torque oscillations at 6 times the supply frequency. The component of the instantaneous power grows almost linearly with the voltage distortion, reaching 80% the rated IM power for HVF = 0.09. Finally, we showed that the combined effect of acceptable levels of voltage unbalance and harmonic distortion, leads to unacceptable levels of IM vibrations.

Another way of looking at these results is that voltage unbalance and harmonic distortions can be determined by the presence of large components at 2 and 6 times the fundamental frequency in the spectrum of vibrations. For example, following a trip due to vibrations, mechanical problem can be ruled out if the frequency spectrum of vibrations is dominated by the 2nd and 6th harmonics of the fundamental frequency.

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