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

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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.

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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),