Effects of Voltage Interharmonics on Cage Induction Motors

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Abstract: In a power system, the voltage waveform usually contains harmonics and sometimes interharmonics, often defined as components of frequency greater than the fundamental voltage component but not of its integer multiple. Previous studies have reported a minor effect of voltage interharmonics on a cage induction machine. This paper reveals their extraordinary harmfulness for induction motors. Namely, voltage interharmonics may cause high vibration, which can result in machine damage. In addition, interharmonics can lead to torque pulsations corresponding to the natural frequency of the first elastic mode. Consequently, possible torsional resonance may cause destruction of a power train. In this study, the results of investigations on undesirable phenomena due to interharmonics are presented for seven motors with a rated power 3 kW–5.6 MW.

Keywords: induction motors; interharmonics; power quality; power system; torsional vibration; vibration; voltage fluctuations

1. Introduction

The universal application of power electronic equipment and rapid development of renewable energy industry result in the common occurrence of voltage waveform distortions. Usually, voltage waveform distortions are restricted to voltage harmonics, although, in some power systems, voltage waveform contains interharmonics, understood in this study as components of frequencies that are greater than the fundamental harmonic but not its integer multiple. The main reason for interharmonic contamination is the work of non-linear and changeable loads, double-conversion systems and a renewable source of energy. Interharmonics are generated, among the other things, by power electronic appliances connecting two AC systems of various frequencies through a DC link [1–4], such as inverters [2–4] or HVDC [1,2]. Other sources of interharmonics are cycloconverters and loads changing over time [2], which include AC motors driving compressors [5–7], arc furnaces (especially AC types) [1,2,8,9] or laser printers [2]. Moreover, time-varying phenomena, like rapid changes of magnitude and phase, can generate interharmonics [10]. Sources of substantial interharmonics are photovoltaic plants [11–14] and wind power stations [1,2,15,16].

Interharmonics of comparatively high values, namely mains signalling voltages, can be superimposed on the fundamental voltage component for information transmission [1,17]. For the frequency range of 110–500 Hz, the standard [17] tolerates mains signalling voltages of up to 9% of the rated network voltage. It is also worth mentioning that periodic voltage fluctuations can be regarded as a superposition of interharmonics and subharmonics [18] (also called subsynchronous interharmonics—components having frequencies less than the fundamental harmonic).
Examples of interharmonic occurrences in power systems are provided in [1,3,7,13,19]. For instance, [3] reported various subharmonics and interharmonics components of value in the range 0.89–1.17%, occurring simultaneously. The voltage waveform distortions were caused by high-power variable speed drives, supplied from diesel-driven generators. Furthermore, in [19], high interharmonic contamination was reported in various industrial, urban and rural medium-voltage feeders. In some of them the average value was up to 0.9%.

Interharmonics can disturb the work of power electronic equipment, measurement and control systems [20–22], induction motors [23], and light sources, including commonly applied LEDs [24]. At the same time, power quality standards generally do not provide limitations of interharmonics. For example, the standard IEEE-519: IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems [25] presents the limits for informative purposes only. Additionally, the following comment is provided: “It is important to recognize that the suggested voltage interharmonic limits are based on lamp flicker (...) correlate with a short-term flicker severity Pst value equal to 1.0 (...). The recommended limits (...) are not based on the effects of interharmonics on other equipment and systems such as generator mechanical systems, motors, transformers, signalling and communication systems, and filters. Due consideration should be given to these effects...”. Furthermore, in the standard EN 50160 Voltage Characteristics of Electricity Supplied by Public Distribution Systems [17], the following note occurs: “Levels are under consideration, pending more experience.” In summary, imposing limitations on interharmonics requires comprehensive investigations on their impact on various elements of a power system, including induction motors.

Undesirable phenomena due to the interharmonics’ occurrence have been discussed in numerous works [20–24,26–35]. In [26–30], induction motors under voltage fluctuations were analysed. As periodic voltage fluctuations can be considered as the superposition of subharmonics and interharmonics, the results of the research cannot be used for imposing a limitation on interharmonics occurring as a single power quality disturbance. The influence of interharmonics appearing as a single power quality disturbance on an induction motor was investigated in [18,23,31,32]. References [18,23,31,32] show that voltage interharmonics caused the flow of rather moderate current subharmonics and interharmonics and resulted in a minor increase in power losses, windings temperature and vibration, slightly exceeding its admissible level for long-term continuous machine operation [33]. It should be noted that in [23] the vibration was investigated for the interharmonics of frequencies not exceeding 70 Hz because of the speed limit of the alternator used for the generation of interharmonics. It is also worth mentioning that some of the previous works were mostly focused on the adverse effects of subharmonics [23,32] or were limited solely to them [34,35].

To sum up, previous works [18,23,31,32] have reported minor maliciousness of interharmonics on induction motors. Additionally, experimental investigations were restricted to interharmonic frequencies of up to 70 Hz. Furthermore, torque pulsations due to interharmonics occurring as single power quality disturbances were not analysed. Based on the state of the art, the goals of the paper were formulated. The first goal is to point out that interharmonics can exert extraordinarily harmful effects on induction motors. The second goal is to initiate in-depth investigations on induction motors supplied with voltage containing interharmonics. The results of these investigations should contribute to the revision of power quality standards and rules.

2. Methodology

The results of investigations are presented for seven cage induction motors with a rated power of 3 kW–5.6 MW, denoted (depending on rated power in kW and number of poles) as motor 3-p4, motor 4-p4, motor 200-p2, motor 200-p4, motor 200-p6, motor 200-p8 and motor 5M-p8. Their basic parameters are listed in Table 1. More details are provided in [34,35].
Table 1. Basic parameters of the investigated motors.

| Motor     | Type              | Rated Power (kW) | Number of Poles | Rated Speed (Rpm) | Rated Voltage (V) | Rated Current (A) |
|-----------|-------------------|------------------|-----------------|-------------------|-------------------|------------------|
| motor 3-p4 | TSG100L-4B        | 3                | 4               | 1420              | 380 ∆             | 6.9              |
| motor 4-p4 | 1LE1003-1BB22-2AA4 | 4                | 4               | 1460              | 400 Y             | 7.9              |
| motor 200-p2 | SLgm 315 ML2B    | 200              | 2               | 2982              | 400 ∆             | 335              |
| motor 200-p4 | SEE 315 L4       | 200              | 4               | 1487              | 400 ∆             | 346              |
| motor 200-p6 | 3SIE 355 ML6A    | 200              | 6               | 989               | 400 ∆             | 350              |
| motor 200-p8 | SEE 355 ML8B     | 200              | 8               | 740               | 400 ∆             | 384              |
| motor 3M-p8 | Sfw 900 HV8D      | 5 600            | 8               | 745               | 10500 Y           | 375              |

For the purpose of the paper, analysis with the finite element method (FEM) was employed. The 2D numerical computations were carried out using the MAXWELL-ANSYS environment for motor 3-p4 and the ANSYS Electronics Desktop environment (ANSYS Electromagnetics Suite 18.0.0) for the other motors. The applied Tau meshes [34] contained from 4100 to 53,596 elements. The parameters of the models were identified on the basis of constructional and experimental data. It is also worth mentioning that the motors (except motor 3-p4 and 4-p4) are produced by the company of one of the co-authors—Zakład Maszyn Elektrycznych “EMIT” S.A. Cantoni Group. Thanks to the courtesy of its management he had free access to constructional documentations and the test results of the motors. A detailed description of the used field models is presented in [34,35].

In addition to the FEM computations, experimental methods were applied. Because of the high power of most of the investigated machines, the empirical research (including model verification) was restricted to motor 3-p4 and motor 4-p4. The applied measurement setup was composed of an AC programmable power source, a power quality analyser, a vibration measurement system and the investigated motors. The AC programmable power source type Chroma 61512+A615103 consisted of two master/slave modules working in parallel, with a total rated power of 36 kVA. The power source enables the generation of programmable voltage subharmonics and interharmonics within the frequency range of 0.01–2400 Hz. For the measurement of current subharmonics and interharmonics, a PC-based power quality analyser was used.

The vibration was measured with a Brüel & Kjær (B&K) system, consisting of a standalone four-channel data acquisition module (B&K type: 3676-B-040), a three-axis acelerometer (B&K type: 4529-B), an accelerometer calibrator (B&K type: 4294) and a computer with the BK Connect software. The accelerometer was fixed to an additional steel stand, screwed into the aluminium motor casing (Figure 1). The accelerometer was calibrated before starting the measurements.

The investigations on vibration were performed for two newly commissioned motors 4-p4, of which one was coupled with a DC generator, and the other was uncoupled but mounted on a rigid frame (Figure 1). A simplified diagram of the measurement stand is shown in Figure 2.

In the next diagrams (Figures 3 and 4) the comparison of the results of measurements and computations is presented for motor 3-p4, supplied with the voltage containing interharmonics. The appropriate numerical and empirical experiments were performed for the uncoupled motor and the fundamental voltage component determined to achieve the nominal flux under no-load. Figure 3 shows current interharmonics vs. the frequency of voltage interharmonics, and Figure 4—current subharmonics accompanying current interharmonics. The summary of the results of measurements and FEM analysis (Figures 3 and 4) shows that the accuracy of the field calculations is acceptable.
Figure 1. Motors 4-p4 and the accelerometer (bottom left).

Figure 2. Simplified diagram of the measurement stand.

Figure 3. Measured and computed current interharmonics (related to the rated current) vs. the frequency of voltage interharmonics for motor 3-p4 and voltage containing interharmonics of value $U_{ih} = 1\% U_1$. 
Figure 4. Measured and computed current subharmonics (related to the rated current) vs. the frequency of voltage interharmonics for motor 3-p4 and voltage containing interharmonics of value $U_{ih} = 1\% U_J$.

3. Results

3.1. Preliminary Remarks

In the following subsections, the results of investigations on currents, torque pulsations and vibration are presented. Because the power quality disturbance under consideration causes fluctuations of the rotational speed [18], the impact of voltage interharmonics on induction motors significantly depends on the moment of load inertia [31]. For this reason, the FEM computations are shown for the two extreme cases: a load of a negligible moment of inertia (NMI) and the work with a constant rotational speed (CRS) due to a high moment of load inertia. For the computations, the torque load and the fundamental voltage components are assumed to be equal to its rated values. All the presented results of numerical and experimental investigations were performed for the fundamental voltage component of its rated value and voltage interharmonics equal to 1%, as similar levels are reported in [3,19].

3.2. Effect of Interharmonics on Current

Voltage interharmonics cause the flow of current interharmonics and subharmonics (CIS) through motor windings. The interaction between these current components and the rotational electromagnetic field [18] results in tangential electromagnetic forces [36] and, consequently, vibration and torsional vibration.

Below, Figures 5–9 present the computed CIS vs. the frequency of voltage interharmonics for motor 3-p4, 200-p2, motor 200-p4, motor 200-p6, motor 200-p8 and motor 5M-p8. For CRS (Figures 5 and 6), the current interharmonics did not exceed roughly 5% of the rated current ($I_{rat}$), and current subharmonics were below 1% of $I_{rat}$. Notably, maxima for motor 200-p8 and a frequency $f_{ih} \approx 60$ Hz resulted from the interference of CIS caused by voltage interharmonics and CIS caused by slots and teeth (CIS also occurs for the purely sinusoidal supply voltage). Then, for NMI (Figures 7 and 8), the highest CIS occurred for motor 200-p2 and the frequency $f_{ih} = 57–58$ Hz. Both current interharmonics and subharmonics reached approximately 9.5% of $I_{rat}$. A current spectrum for this case is given in Figure 9. In turn, the lowest CIS appeared for motor 200-p8 and motor 5M-p8, maximising at 5.5% and 4.8% of $I_{rat}$, respectively.
Figure 5. Computed current interharmonics vs. the frequency of voltage interharmonics for the various motors and the case of constant rotational speed (CRS).

Figure 6. Computed current subharmonic vs. the frequency of voltage interharmonics for the various motors and the case of CRS.

Figure 7. Computed current interharmonics vs. the frequency of voltage interharmonics for the various motors and the case of negligible moment of inertia (NMI).
The shape of the characteristics presented in Figures 7 and 8 results from the occurrence of rigid-body resonance, similar to that observed for voltage subharmonics [34,35]. Namely, current interharmonics cause torque pulsations and fluctuations of the rotational speed, whose frequency is defined as the following (based on [18]):

\[ f_p = f_{ih} - f_1 \]  

where \( f_{ih} \) and \( f_1 \) are the frequencies of current interharmonics and the fundamental voltage component, respectively. Speed fluctuations lead to the flow of current subharmonics of frequency \( f_{sh} \) (based on [5,6,18]):

\[ f_{sh} = f_1 - f_p \]  

For the frequency \( f_p \) close to the natural frequency of the rigid-body mode \( f_{Nr-b} \) [5], CIS imposed torque pulsations and, consequently, speed fluctuations. The fluctuations are illustrated in Figure 10. For motor 3-p4 the speed fluctuations are as high as about 1.9%, and for the other motors up to about 0.7%. The magnified speed fluctuations additionally increased CIS (based on [5,6]). Consequently, in Figures 7 and 8, current peaks occurred around the frequency corresponding to the rigid body resonance. Contrastingly, for a high moment of load inertia, the speed fluctuations were negligible and, as a result, CIS were comparatively low (Figures 5 and 6). The natural frequency \( f_{Nr-b} \) depends on machine size; the frequencies \( f_{Nr-b} \) are tens of Hz for small machines and a few Hz for large machines [5,6,18]. For the reason, for motor 3-p4 the characteristics in Figures 7 and 8 reach
the maximum for the frequency \( f_{ih} \) closed to 80 Hz, while for the other motors it is about 54–63 Hz.

![Figure 10](https://example.com/image10)

**Figure 10.** Computed amplitude of speed fluctuation (related to rated speed) vs. the frequency of voltage interharmonics for the various motors and the case of NMI.

The flow of CIS caused a minor increase in power losses [31] as well as more harmful phenomena—torque pulsations and vibrations, which are analysed in the next subsections.

### 3.3. Effect of Interharmonics on Torque Pulsations

The results of research on electromagnetic torque pulsations are presented in Figures 11–13. In Figure 11, exemplary torque waveforms are shown for motor 200-p2 and for two supply cases. The first case concerns the purely sinusoidal voltage supply, and the second case is for the supply with voltage containing interharmonics of a frequency corresponding to the rigid-body resonance. For both cases, the torque waveform contains pulsating components due to the presence of slots and teeth. Additionally, for the latter case, the main alternating component is caused by the interharmonic injection, with an amplitude of approximately 20% of the rated torque \( T_{rat} \) and frequency \( f_p = 7 \) Hz—see (1).

![Figure 11](https://example.com/image11)

**Figure 11.** Computed torque waveform of motor 200-p2, supplied with (a) purely sinusoidal voltage and (b) voltage containing interharmonic of frequency \( f_{ih} = 57 \) Hz and the case of NMI.
The amplitudes of the torque-pulsating component of the frequency described with (1) is denoted as $\Delta T_{ih}$. Its characteristics vs. the frequency of voltage interharmonics are given in Figures 12 and 13. For CRS (Figure 12), the amplitude $\Delta T_{ih}$ is nearly 6.6%. For motor 200-p8, the characteristic curve shows a maximum for the frequency $f_{ih}$ of about 60 Hz, which was caused by the interaction of torque pulsations due to voltage interharmonics and torque pulsations from slots and teeth (even for the purely sinusoidal supply, the torque waveform contains pulsating components of frequency close to 10 Hz). In turn, for NMI (Figure 13), the maximal value of the amplitude $\Delta T_{ih}$ is roughly 18% and 20% of $T_{rat}$ for motor 3-p4, motor 200-p2, respectively, and the frequencies $f_{ih} = 57$ Hz and $f_{ih} = 80$ Hz. The lowest amplitudes appeared for motor 5M-p8 and motor 200-p8—up to 9.3% and 12.5% of $T_{rat}$, respectively.

It should be stressed that the frequency of torque pulsations due to interharmonics $f_{ih}$—see (1)—may correspond to the natural frequency of the first elastic-mode $f_{N1e}$. According to [37], the natural frequency $f_{N1e}$ is typically below the network frequency for large and medium two-pole or four-pole motors driving turbomachinery. For example, for induction motors with rated powers of 6.1 MW and 500 hp, driving a compressor and a fan, the natural frequencies $f_{N1e}$ were reported as 17, 24 and 28.5 Hz (depending on coupling stiffness) [37,38]. In the authors’ previous study [34], similar frequencies $f_{N1e}$ were determined with an analytical method for the high-power motors under consideration. Appropriate calculations were carried out for the exemplary moment of load inertia equal to 500% of the motor moment and clutches of a sample manufacturer. The frequencies $f_{N1e}$ are shown in Table 2 (based on [34]).
Table 2. Natural frequencies of the first elastic mode.

| Motor   | Motor 200-p2 | Motor 200-p4 | Motor 200-p6 | Motor 200-p8 | Motor 5M-p8 |
|---------|--------------|--------------|--------------|--------------|-------------|
| Natural frequency (Hz) | 30           | 32.5         | 31           | 30           | 14          |

The amplitudes $\Delta T_{ih}$ presented in Figures 11–13 are rather moderate. However, under elastic mode resonance [37,38], torque pulsations can be amplified 50 times [38]. Notably, excessive torsional vibration can cause mechanical failures, such as a crack in the shaft or coupling [37,38]. For this reason, voltage interharmonics should be regarded a considerably more harmful power quality disturbance than the previous works [18,23,31,32] have indicated. Another detrimental effect of torque pulsations due to interharmonics is vibration.

3.4. Effect of Interharmonics on Vibration

The highest vibration due to subharmonics and interharmonics is expected under no load (based on [23]). Therefore, for the demonstration of extraordinary harmfulness of voltage interharmonics, the case of idle running was chosen. It should be noted that idling for most of the operational period might correspond to the standard work S6 15% [39].

Recommendations concerning acceptable vibration levels are provided in the standard ISO 10816-1:2001 Mechanical Vibration—Evaluation of Machine Vibration by Measurements on Non-rotating Parts—Part 1: General Guidelines [33] and its updated version [40]. The standard [40] does not univocally specify the acceptable levels; so, in this study, the measured vibrations are referred to the recommendations included in [33], similarly as in [23].

The broad-band vibration velocity component vs. interharmonic frequency $f_{ih}$ is given in Figure 14 for motor 4-p4 coupled with the unloaded DC generator (see Section 2). For comparison, Figure 15 presents the measured CIS. The highest vibration velocity—5.59 mm/s—occurred in the horizontal direction for the frequency $f_{ih} = 85$ Hz (Figure 14), which is the approximate frequency corresponding to the greatest CIS in Figure 15. For the uncoupled motor (see Section 2), the vibration level was much less than for the presented case. Equally of note, for supply voltage without interharmonic injection, the measured vibration velocity was roughly 0.87 mm/s and 0.34 mm/s for the coupled and uncoupled motor, respectively.

![Figure 14. Measured broad-band vibration velocity in the horizontal (H), vertical (V) and longitudinal (L) direction vs. interharmonic frequency for motor 4-p4 coupled with the DC generator.](image-url)
The highest vibration level in Figure 14 (5.59 mm/s) corresponds to Zone D specified in the standard [33] (vibration velocity greater than 4.5 mm/s in the case of small electric motors). According to [33], “vibration values within this zone are normally considered to be of sufficient severity to cause damage to the machine” [33]. For some other frequencies, the vibrations are also excessive. For the frequencies $f_{ih}$ around 51, 60 and 110 Hz, the vibration levels exceed the boundaries of Zone C—1.8 mm/s [33]. For this zone, “vibration values are normally considered unsatisfactory for long-term continuous operation” [33].

In summary, voltage interharmonics reported in real power systems can cause unacceptable vibration. Comprehensive investigations of the vibration of induction motors under interharmonics will be presented in a separate paper. The study includes a comparison of motors of various rated powers and number of poles as well as the admissible level of voltage interharmonics, determined according to the criterion of induction motor vibration.

4. Discussion

As mentioned in Section 1, previous studies have indicated a minor impact of voltage interharmonics on an induction cage machine (the term interharmonics in this work include components of frequency greater than the fundamental voltage component but not of an integer multiple). The reported impact [18,23,31,32] was generally limited to speed fluctuations, small increases in power losses and winding temperature, and moderate vibrations—slightly exceeding the lower boundaries of Zone C. Consequently, from the point of view of induction motors, interharmonics could be regarded as a slightly noxious power quality disturbance.

The results of the current research reveal that voltage interharmonics can exert extraordinarily harmful effect on induction motors. Voltage interharmonics of levels reported in real power systems may cause vibration “of sufficient severity to cause damage to the machine” [33]. To compound the problem, interharmonics may result in torque pulsations corresponding to the natural frequency of the first elastic mode of power trains with medium- and high-power induction motors. For the investigated high-power motors and the negligible moment of load inertia, the observed amplitude of torque pulsations was up to 20% of $T_{int}$. This value apparently does not seem especially detrimental. However, under the elastic mode resonance, torque pulsations can be amplified dozens of times [38]. Consequently, the potential occurrence of the torsional resonance may lead to the destruction of a clutch or a motor shaft.

At the same time, power quality standards and rules should provide effective protection for any electrical equipment against potential malfunction due to excessive power quality disturbances. Thus, limitations on voltage interharmonics are urgently needed. In practice, this task requires the determination of admissible levels for various components.
of a power system, including induction motors. Therefore, in-depth research on induction motors under considered power quality disturbances is required.

5. Conclusions

The presented results of investigations have revealed extraordinarily harmful effect of voltage interharmonics on induction motors. It was found out that they can cause unacceptable vibration. Additionally, voltage interharmonics lead to pulsations of the rotational torque, whose frequency may correspond to the natural frequency of the first elastic mode. Under resonance the torque pulsations may be magnified dozens of times, which could result in the destruction of the power train. Consequently, voltage interharmonics should be regarded as much more detrimental power quality disturbance than the previous works [18,23,31,32] have indicated.

The results of the research also prove there is a necessity to impose limitations on voltage interharmonics. From the point of view of induction motors, the admissible levels of interharmonics (except subsynchronous ones, which are not covered by this study) should be determined according to the criterion of the allowable longitudinal and torsional vibration. Additionally, separate limits should be determined according to the criterion of the correct work of other electric equipment, like for example power electronic appliances, measurement and control systems or modern light sources. The lowest of the above limits should be included in the power quality standards as the admissible levels of voltage interharmonics.

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