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EFFECT OF VOLTAGE FLUCTUATIONS ON INDUCTION MOTOR CURRENTS

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Abstract: One of the types of power quality disturbances met in a power system is voltage fluctuations. Cyclic voltage fluctuations are interconnected with the presence of subharmonics and interharmonics – that is components of frequency less than the fundamental frequency or not being its integer multiple. Voltage fluctuations can be considered as practical examples of the simultaneous presence of subharmonics and interharmonics of various frequencies. This study deals with the preliminary investigations on an induction motor under voltage fluctuations of frequency greater than the supply voltage frequency. The results of the empirical investigations on currents under rectangular modulation of voltage amplitude are presented for a four-pole cage induction motor of a rated power of 4 kW.

Keywords: interharmonics, power quality, cage induction motor, subharmonics, voltage fluctuations, voltage waveform distortions.

1. INTRODUCTION

One of the voltage quality disturbances found in power systems is voltage fluctuations, understood as rapid changes in the rms voltage value [Bollen and Gu 2006; Ghaseminezhad et al. 2021a,b; Kuwałek 2021a,b; 2022; Patel and Chowdhury 2021]. Cyclic voltage fluctuations are associated with the presence of subharmonics and interharmonics, components with frequencies less than – or not being a multiple – of the fundamental harmonic frequency [Gallo et al. 2005; Bollen and Gu 2006; Tennakoon, Perera and Robinson 2008; Ghaseminezhad et al. 2021b]. Note that voltage fluctuations found in power systems should be considered as practical examples of the simultaneous existence of subharmonics and interharmonics of different frequencies [Gnaciński et al. 2024]. Voltage fluctuations and the presence of subharmonics and interharmonics are caused by the operation of non-linear loads, renewable energy sources, like wind turbines, and loads operating with variable power, like induction motors driving reciprocating compressors, and power electronic equipment [Zhang, Xu and Liu 2005; Bollen and Gu 2006; Testa et al. 2007; Xie et al. 2017; Arkkio et al. 2018; Nassif 2019; Ravindran et al. 2020; Kuwałek 2021a; Gutierrez-Ballesteros, Rönberg and Gil-de-Castro 2022]. Note that power electronic equipment can cause voltage fluctuations of up to 150 Hz [Kuwałek 2021a].

Voltage subharmonics and interharmonics interfere with the operation of various electrical equipment types, like light sources, measurement and automatic control systems, power electronic equipment, or synchronous and induction machines. In induction motors they cause, for example, excessive vibration and torsional oscillation levels, torque and speed fluctuations, local saturation of the magnetic circuit, increased power losses and overtemperature of the windings. These disturbances may even lead to a failure of the motor unit. Particularly significant vibration levels and torsional oscillations occur under resonance conditions. Torsional vibration resonance occurs when the torque pulsation frequency is close to the natural frequency of torsional vibration of a rigid or deformable body. For the natural frequency torsional vibration of a rigid body, the resonance of torsional vibrations manifests itself in the flow of current subharmonics and interharmonics of an order of up to 35% of the rated current value. For the subharmonic levels found in power systems that is about 1% [Xie et al. 2017; Nassif 2019] and can cause very strong vibrations, which can also damage the rotating machine. For the natural frequency torsional vibration of a deformable body, it results in an amplification of the torque pulsation, sometimes by more than 100 times and may lead to events like a clutch failure. The detrimental phenomena in induction motors are mainly caused by the flow of current subharmonics and interharmonics through the windings, which directly result in torque fluctuations (causing vibration, torsional oscillations and speed fluctuations) with additional power losses in the windings.

Currently, the voltage quality standards [EN 50160 2010/A2:2019, IEEE 519] do not specify any acceptable levels of subharmonics and interharmonics. PN-EN 50160 [EN 50160:2010/A2:2019] *Voltage characteristics of electricity supplied by public electricity networks* includes the following provisions: “levels are under consideration, pending more experience”. *IEEE Standard for Harmonic Control in Electric Power Systems* [IEEE 519] provides a rationale for the need for permissible limit values of voltage subharmonics and interharmonics, and two alternative proposals for respective limit curves defining the permissible limit levels of the disturbances of interest. One generally limits the subharmonics and interharmonics to 0.3% and the other to 0.5%. In practice, the introduction of permissible limit levels of subharmonics and interharmonics into voltage quality standards and regulations requires in-depth studies of the effects of the disturbances of interest on various electrical equipment and, in particular, on rotating electrical machines.

The effect of voltage subharmonics and interharmonics on induction motors has been the subject of numerous research papers [Tennakoon, Perera and Robinson

2008; Ghaseminezhad et al. 2017a,b; 2021a,b; Gnaciński et al. 2019; 2022a,b; 2024; Zhang et al. 2021]. Note that the papers concerned only the case of the presence of a single subharmonic/interharmonic in the supply voltage or in the case of voltage fluctuations with a frequency less than the fundamental harmonic frequency.

It should be noted that the results of earlier work [Gnaciński et al. 2022b; 2024] demonstrate that – where voltage fluctuations are present – subharmonics and interharmonics of different frequencies can mutually amplify or attenuate their effects on the motor, e.g. on torque fluctuations and vibration.

This paper presents the results of preliminary research into an induction motor under voltage fluctuations that have a frequency greater than the fundamental harmonic frequency. The corresponding experimental tests were carried out for a 4 kW four-pole squirrel cage motor. The considerations in the paper are limited to symmetric rectangular modulation.

2. VOLTAGE FLUCTUATIONS

Sine voltage fluctuations can be considered as a composite of the fundamental voltage harmonic and the voltage subharmonic and interharmonic, according to the relation in [Gallo et al. 2005; Bollen and Gu 2006; Ghaseminezhad et al. 2021b; Gnaciński et al. 2022b]:

$$v(t) = V_{1\mathrm{A}}[\cos(2\pi f_1 t) + a\cos(2\pi f_{sh} t + \phi_{sh}) + a\cos(2\pi f_{ih} t + \phi_{ih})] \tag{1}$$

with:

- $v(t)$ – instantaneous voltage;
- V_{1A} – fundamental voltage harmonic amplitude;
- a – voltage subharmonic/interharmonic amplitude, referenced to the fundamental voltage harmonic V_{1A};
- f_1 – fundamental harmonic frequency;
- f_{sh}, f_{ih} – respectively, voltage subharmonic and interharmonic frequency;
- ϕ_{sh}, ϕ_{ih} – phase angles of the voltage subharmonic and interharmonic, where the voltage fluctuations are an amplitude modulation, phase modulation or a form between the two, depending on the phase angle.

The subharmonic and interharmonic frequencies in (1) are described by the relations [based on Gallo et al. 2005; Zhang et al. 2005; Bollen and Gu 2006; Tennakoon, Perera and Robinson 2008; Ghaseminezhad et al. 2021]:

$$f_{sh/ih} = f_1 - f_m \tag{2}$$

$$f_{ih} = f_1 + f_m \tag{3}$$

with f_m – voltage fluctuation frequency.

Note that for frequencies which are $f_m<f_1$, the subharmonic and interharmonic frequencies are symmetrical with respect to the fundamental harmonic frequency, e.g. 42 Hz and 58 Hz in 50 Hz power systems. Because they have equal amplitudes a, they are sometimes called symmetric interharmonics or symmetric subharmonics and interharmonics [Gallo et al. 2005; Gnaciński et al. 2022b]. If the frequency described by (2) has a positive value (in practice, for the frequency of voltage fluctuations which are $f_m<f_1$) then the subharmonic/interharmonic has a positive sequence [Zhang, Xu and Liu 2005]. In contrast if the frequency described by (2) has a negative value, the subharmonic/interharmonic is of negative sequence [Zhang, Xu and Liu 2005]. As demonstrated by Gnaciński et al. 2022a, both positive-sequence and negative-sequence subharmonics result in strong oscillations and torque fluctuations of a motor, while affecting induction motors in a slightly different way.

Sine voltage fluctuations are relatively rare in electrical power systems [Kuwałek 2021a]; however, arbitrary cyclic voltage fluctuations can be treated as a composite of sine modulations having different frequencies [Ghaseminezhad et al. 2021a,b; Gnaciński et al. 2024]. The most common voltage fluctuations are rectangular modulation with voltage step changes [Kuwałek 2021a; 2022].

An example of the modulating function waveform is shown in Figure 1 for rectangular modulation, modulating function frequency f_m = 70 Hz and a voltage change (understood as the doubled amplitude of the modulating function) equal to π%. Note that for this voltage change and symmetric rectangular modulation [Gnaciński et al. 2024], the maximum content of a single subharmonic/interharmonic in the voltage is 1% and is approximately equal to the values found in actual power systems [Xie et al. 2017; Nassif 2019]. The voltage spectrum corresponding to the modulating function of interest is shown in Figure 2. It contains the subharmonics and interharmonics corresponding to the individual harmonics of the modulating function. The first harmonic of the modulating function resulted in the presence of a subharmonic of negative sequence and frequency f_{sh} = 20 Hz along with an interharmonic of a positive sequence and frequency f_{ih} = 120 Hz and a value of 1%. The third harmonic of the modulating function corresponds to an interharmonic of a negative sequence and frequency of 160 Hz, along with an interharmonic of a positive sequence, frequency of 260 Hz and value of 0.33%. The subsequent harmonics of the modulating function correspond to frequency components no higher than 0.2%. Note that a characteristic of symmetric rectangular modulation is the absence of frequency components corresponding to the second harmonic of the modulating function, which in cases of other modulations can take on significant values.

The following section presents the preliminary results of the induction motor with a rectangular supply voltage modulation.

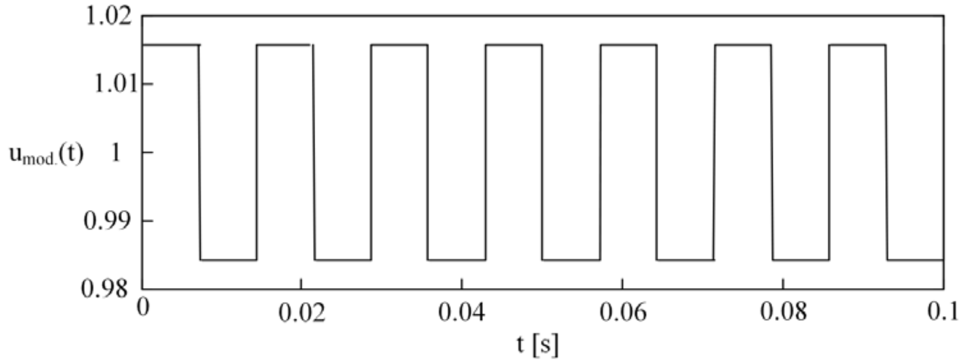

Fig. 1. Waveform of the modulating function for a voltage fluctuation frequency, f_m = 70 Hz

Source: own work.

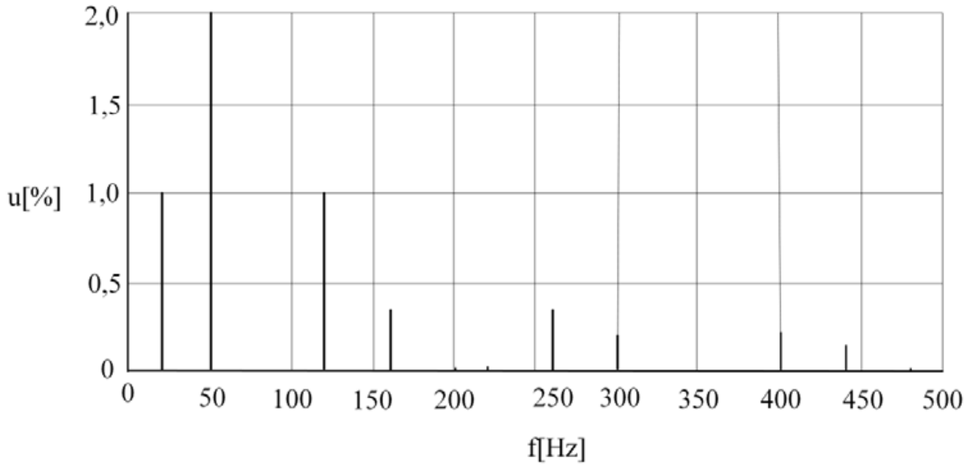

Fig. 2. Spectrum of the voltage waveform for rectangular modulation and fluctuation frequency, f_m = 70 Hz

Source: own work.

3. DESCRIPTION OF THE TEST RIG

The test rig included a programmable voltage source, a three-phase squirrel cage induction motor and a power quality analyser with an oscilloscope. The Chroma 61512+A615103 programmable voltage source used comprised two master and slave modules, with a total capacity of 36 kVA. It enabled the generation of programmable voltage quality disturbances, like voltage fluctuations, harmonics, sub-harmonics, inter-harmonics, amplitude and voltage asymmetry, etc. A four-pole induction motor of type 1AV3112B with an output of 4 kW was coupled to an unloaded DC generator. Selected parameters of the test motor are shown in Table 1. Power supply voltage and motor current waveforms were recorded using a Tektronix TBS2000B digital oscilloscope, and the contents of the subharmonics and interharmonics were determined using a computer analyser of electric energy quality. A simplified diagram of the test rig is shown in Figure 3.

Table 1. Ratings of the tested motor type 1AV3112B

Nominal power [kW]	4
Rated voltage [V]	400
Rated current [A]	7.9
Rated power factor [-]	0.82
Weight [kg]	34
Rated speed [rpm]	1460
Rated efficiency [%]	88.6
Efficiency class	IE3
Insulation class	F
Winding connection system	star
Manufacturer	SIEMENS

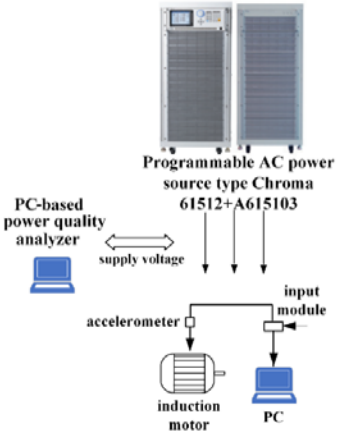

Fig. 3. Simplified diagram of the test rig

Source: [Gnaciński et al. 2024].

4. RESULTS

Preliminary results for the effect of rectangular supply voltage modulation on a squirrel-cage induction motor are presented below. Since voltage fluctuations, sub-harmonics and inter-harmonics cause the largest oscillations in idling motors, the results are shown for an unloaded motor. The corresponding experimental tests were performed for a voltage change of 3.14% (see Section 2 for the rationale). All values of current frequency components were related to the rated current value (I_{rat}).

Figure 4 shows the measured motor current waveform for modulation at a frequency of f_m = 70 Hz (the modulating function waveform and voltage spectrum are shown in Fig. 1 and Fig. 2), and the current waveform spectrum is shown in Figure 5. In addition to the fundamental component and harmonics caused by the magnetic circuit properties of the rotating induction machine, the motor contained subharmonics and interharmonics corresponding to the individual harmonics of the modulating function (see Section 2). The first harmonic of the modulating function corresponds to a subharmonic with a frequency of f_{sh} = 20 Hz and I_{sh} = 10.4% I_{rat} and an interharmonic of f_{ih} = 120 Hz and I_{ih} = 3.99% I_{rat}. The current interharmonics corresponding to the third harmonic of the modulating function take on much smaller values. The component at f_{ih} = 160 Hz is equal to I_{ih} = 0.46% I_{rat}, wheras the component at f_{ih} = 260 Hz is equal to I_{ih} = 0.24% I_{rat}.

Figures 6, 7 and 8 show the spectra of the motor supply current for a voltage modulation frequency of f_m = 60 Hz, f_m = 80 Hz and f_m = 90 Hz, respectively. The current subharmonics corresponding to the first harmonic of the modulating function are I_{sh} = 15.7% I_{rat} (Fig. 6), I_{sh} = 7.2% I_{rat} (Fig. 7), I_{sh} = 6% I_{rat} (Fig. 8), whereas for the current interharmonics, I_{ih} = 4.9% I_{rat} (Fig. 6), I_{ih} = 3.4% I_{rat} (Fig. 7), and I_{ih} = 2.5% I_{rat} (Fig. 8). The interharmonics corresponding to the successive harmonics of the modulating function are much smaller, as in the case of modulation with f_m = 70 Hz (Fig. 4 and Fig. 5). As an example, for the third harmonic of the modulating function, the interharmonic current does not exceed 0.5% I_{rat}. This is due both to the small value of the voltage interharmonics corresponding to the successive harmonics of the modulating function (see Section 1) and to the relatively strong attenuation of the current interharmonics at a frequency of a few hundred Hertz by the winding inductance.

As mentioned in Section 1, the direct effects of the current subharmonics and interharmonics flowing through the motor windings include torque fluctuations, causing vibration and torsional oscillation [Gnaciński et al. 2019; 2022; 2024]. The individual torque pulse components caused by the current subharmonics and interharmonics are in practice proportional to the values of the current subharmonics and interharmonics. Consequently, considering the current spectra shown in Figures 5 to 8, it should be considered that the torque components caused by the harmonics of the modulating function are significantly smaller than those caused by the first harmonic of the modulating function.

The individual current subharmonics and interharmonics correspond to specific frequencies of the torque pulse components. For positive-sequence subharmonics and interharmonics, they are equal respectively (based on [Tennakoon, Perera and Robinson 2008):

$$f_p = f_1 - f_{sh} \tag{4}$$

$$f_p = f_{ih} - f_1 \tag{5}$$

In turn, subharmonics and interharmonics of negative sequence generate the torque ripple component with a frequency of [Gnaciński 2022a]:

$$f_p = f_{sh/ih} + f_1 \tag{6}$$

In practice, for the current subharmonics and interharmonics present in the spectra in Figures 5 to 8, the frequency of the torque pulse components is $f_p \geq 60$ Hz. At the same time, for high-powered electrical machines, the natural frequency of rigid-body torsional vibration is of the order of single Hertz, while for low-powered machines it is of the order of single tens of Hertz [Arkkio et al. 2018; Gnaciński, Muc and Pepliński 2021; Gnaciński et al. 2022a,b; 2024]. For example, for none of the motors studied by the authors, did the natural frequency exceed 35 Hz. Consequently, for the voltage modulation of interest, there is practically no risk of rigid-body torsional vibration resonance.

In summary, for the motor under study, the current interharmonics corresponding to the higher harmonics of the voltage modulating function are significantly smaller than the subharmonics and interharmonics corresponding to the first harmonic of the modulating function. Furthermore, for the modulation of interest, there is virtually no risk of rigid-body torsional resonance.

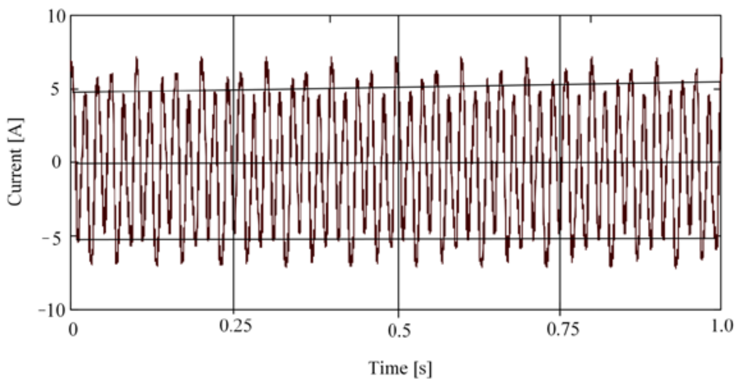

Fig. 4. Measured motor supply current waveform for a voltage fluctuation frequency, $f_m = 70$ Hz

Source: own work.

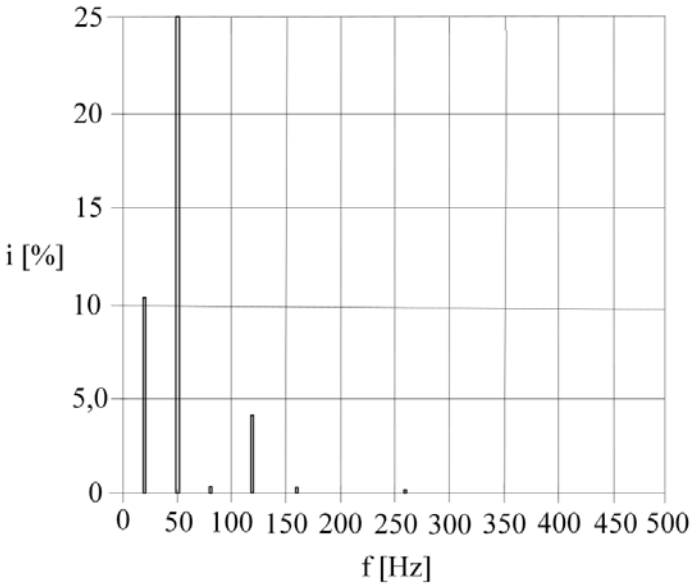

Fig. 5. Motor supply current spectrum for a voltage fluctuation frequency, f_m = 70 Hz

Source: own work.

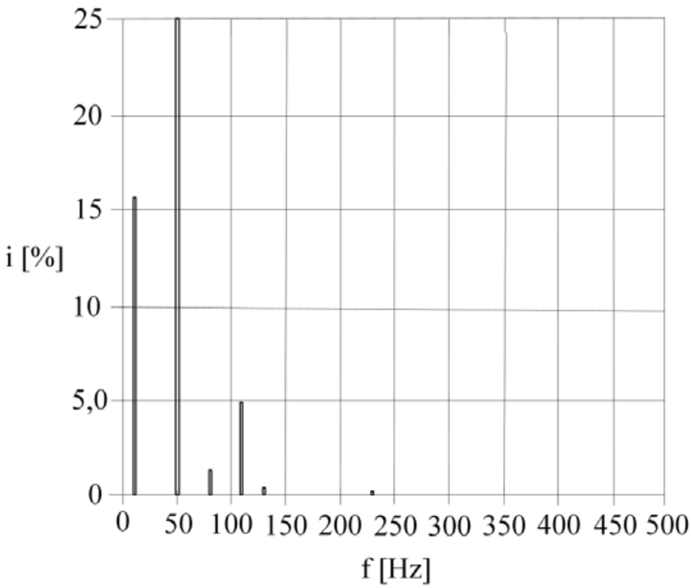

Fig. 6. Motor supply current spectrum for a voltage fluctuation frequency, f_m = 60 Hz

Source: own work.

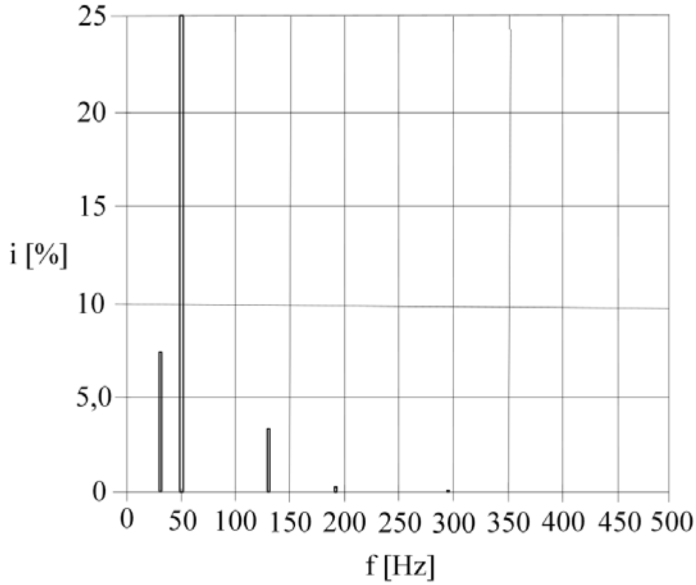

Fig. 7. Motor supply current spectrum for a voltage fluctuation frequency, f_m = 80 Hz

Source: own work.

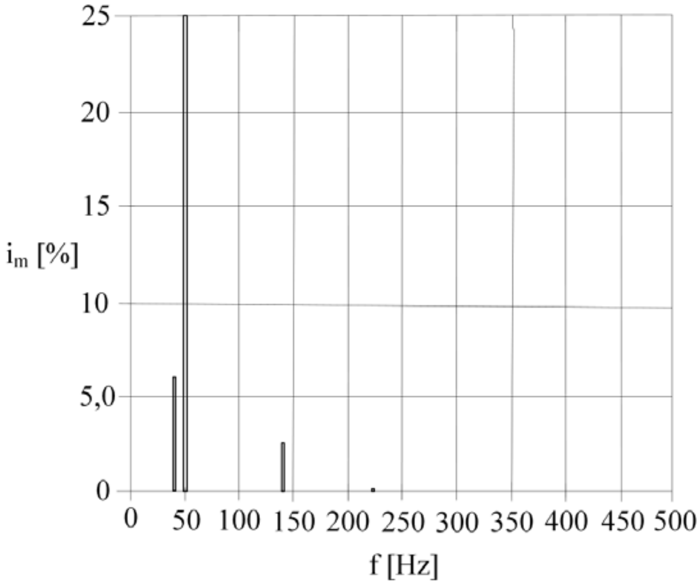

Fig. 8. Motor supply current spectrum for a voltage fluctuation frequency, f_m = 90 Hz

Source: own work.

5. CONCLUSIONS

The individual harmonics of the voltage modulating function corresponded to the subharmonics and interharmonics of the motor supply current, at a specific frequency and in a specific sequence – either positive or negative. For the tested motor and symmetrical rectangular modulation with a frequency in the range of 60 to 90 Hz, the current interharmonics corresponding to the subsequent harmonics of the modulating function were significantly smaller than the current subharmonics and interharmonics corresponding to the first harmonic of the modulating function. Consequently, the torque pulse components corresponding to the subsequent harmonics of the modulating function were significantly smaller than those corresponding to the first harmonic. Furthermore, for the modulation of interest in this work, the frequency of the torque pulse components, corresponding to the individual current subharmonics and interharmonics, was higher than the natural frequency of the rigid-body torsional vibration. Consequently, there was virtually no risk of rigid-body torsional vibration.

However, as demonstrated in [Gnaciński et al. 2022b; 2024] (the research was limited to voltage fluctuations with a frequency less than the supply voltage frequency), the effect of a single voltage subharmonic on an induction motor was, in some cases, different from the effect of voltage fluctuations. The different effect was due to the presence of symmetrical subharmonics and interharmonics with a synergy of subharmonics and interharmonics at different frequencies in presence of voltage fluctuations. Given this, the authors believe that it is reasonable to continue research on the induction motor under voltage fluctuations with a frequency higher than the supply voltage frequency. Future research work will include analyses of motor supply current and motor torque using field and experimental methods, with vibration measurements of induction motors of different powers. A comparison of the test results under voltage fluctuations and the presence of a single voltage subharmonic is planned.

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