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SINGLE-PHASE INDUCTION MOTOR UNDER VOLTAGE FLUCTUATIONS

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Abstract: Some of the most common power quality disturbances are voltage fluctuations. They are interconnected with the presence of voltage subharmonics and interharmonics. Voltage fluctuations, subharmonics and interharmonics exert a negative effect on various elements of a power system, including cage induction motors. This work is devoted to the impact of voltage fluctuations on the current of a one-phase induction motor. The results of empirical investigations are presented for sinusoidal amplitude modulations of various frequencies and are compared with the effects of voltage subharmonics occurring as a single power quality disturbance.

Keywords: interharmonics, power quality, single-phase induction motor, subharmonics, voltage fluctuations.

1. INTRODUCTION

Electric power receivers are susceptible to the effects of various voltage quality disturbances, including: voltage waveform deformations, voltage asymmetry, voltage deviations from nominal values and voltage fluctuations. Voltage fluctuations are one of the most frequent, and at the same time most important disturbances [Bollen and Gu 2006; Ghaseminezhad et al. 2021a,b; Kuwałek 2021b; Patel and Chowdhury 2021]. They are usually defined as rapid changes in the effective value of voltage (voltage amplitude modulation) [Bollen and Gu 2006; Kuwałek 2021a,b 2021]. In practice, for sinusoidal voltage modulation, voltage fluctuations can be considered as a superposition of the fundamental component, a subharmonic component (i.e. a component with a frequency lower than the fundamental frequency) and an interharmonic component (a component with a frequency that is not a multiple of the fundamental component frequency) [Gallo et al. 2005; Bollen and Gu 2006; Tennakoon, Perera and Robinson 2008; Ghaseminezhad et al. 2021a,b]. The said subharmonic and interharmonic components are characterised by an identical amplitude and frequency symmetry relative to the fundamental frequency (e.g. a voltage subharmonic with a frequency of 35 Hz, occurring together with an interharmonic with a frequency of 65 Hz in an electric power system operating at 50 Hz). Depending on the phase angles of the subharmonic and interharmonic components, different cases of voltage modulation can be identified – amplitude modulation, phase modulation and intermediate cases [Gallo et al. 2005; Bollen and Gu 2006]. It should also be noted that regular voltage fluctuations with any type of modulation waveform (e.g. rectangular voltage fluctuations) can be considered a superposition of sinusoidal fluctuations at different frequencies [Ghaseminezhad et al. 2021a,b].

The main cause of voltage fluctuations are fluctuations in the current of an electric power system [Bollen and Gu 2006]. These are caused by the operation of renewable energy sources and receivers drawing variable power over time, such as metalworking roll drives and railroad conductor grid power systems [Bollen and Gu 2006; Kovaltchouk et al. 2016].

Voltage subharmonics and interharmonics are considered particularly harmful disturbances to the voltage quality. They disrupt the functioning of things like light sources, power and measurement transformers, electronic equipment, automatic systems, synchronous machines and asynchronous motors [Gallo et al. 2005; Testa et al. 2007; Tennakoon, Perera and Robinson 2008; Ghaseminezhad et al. 2017a,b; Gnaciński et al. 2019b; Gnaciński and Klimczak 2020; Crotti et al. 2021; Ghaseminezhad et al. 2021a,b; Gnaciński, Muc and Peplinski 2021; Zhang, Kang and Yuan 2021].

In asynchronous machines, they cause local saturation of the magnetic circuit, rotational speed fluctuations, increased power losses, overheating, as well as excessive vibrations and torsional vibrations [Tennakoon, Perera and Robinson, 2008; Gnaciński et al. 2019b, Ghaseminezhad et al. 2021b; Zhang, Kang and Yuan 2021].

It should be stressed that despite the significant harmfulness of the disruptions in question, no limit values have so far been introduced for them in voltage quality standards. In the PN-EN 50160 [PN-EN 50160:2010] *Power Supply Voltage Parameters in Public Electric Power Grids Standard*, the following comment can be found: "levels are under consideration, pending more experience".

Work on the issue of asynchronous motors powered by voltage containing subharmonics or interharmonics (or an asynchronous motor under voltage fluctuations [Tennakoon, Perera and Robinson 2008; Ghaseminezhad et al. 2017b; Gnaciński et al. 2019b; Gnaciński and Klimczak 2020; Ghaseminezhad et al. 2021a,b; Zhang, Kang and Yuan 2021] apply almost exclusively to three-phase motors. The single-phase motor test results are presented in a [Pepliński 2021] paper for voltage containing a single subharmonic or interharmonic. In this paper, the results found in [Pepliński 2021] are compared with measurement results under voltage fluctuations.

2. MEASUREMENT STATION

The measurement station comprises a single-phase induction motor, programmable voltage source, digital oscilloscope and voltage quality analyser.

The test single-phase induction motor with a permanently connected capacitor was part of a JETW-B/800-50 hydrophore assembly [Pumps and hydrophores...], whose nominal parameters are provided in Table 1.

Relevant measurements were performed for a decoupled motor (*Case A*) and one coupled with a PKBa12a/101 unloaded direct current motor (operating as the electricity generator) (*Case B*). The motor was powered using a Chroma 61512+A615103 programmable voltage source with a power of 36 kVA. This helps to enable the application of regular voltage fluctuations.

Due to the limitations of the programmable voltage source, the voltage-modulating sinusoidal function was approximated using 2 ms long intervals. Voltage and current waveforms were recorded using a Tektronix TBS 2000B 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 measurement station is shown in Figure 1.

Table 1. Nominal data of the JETW-B/800-50 hydrophore assembly

Assembly type: motor-pump	**JETW-B/800-50**
Motor	single-phase
Nominal power [kW]	0.8
Nominal voltage [Hz]	230
Nominal frequency [Hz]	50
Pump capacity	50 l/min.
Lifting height	40 m
Insulation class	B

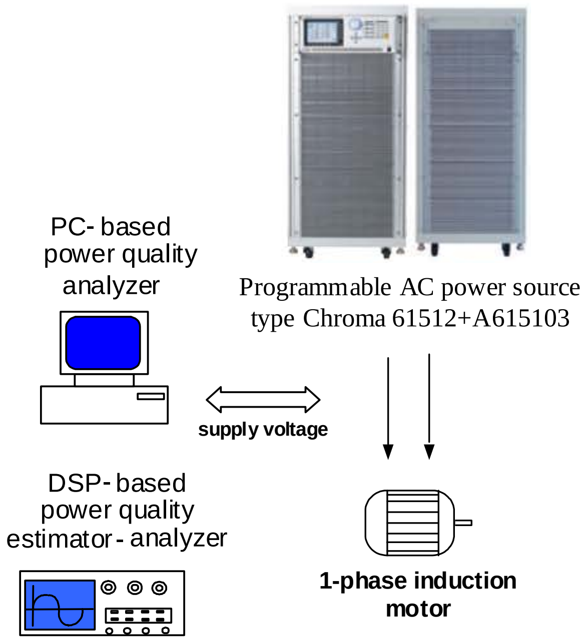

Fig. 1. Simplified diagram of the measurement station

Source: [Pepliński 2021].

3. TEST RESULTS

Below are presented the experimental results of a single-phase induction motor under sinusoidal voltage amplitude modulation, which is a special case of voltage fluctuations (see Introduction). All tests were performed for a voltage fluctuation amplitude of 2%. This corresponds to a superposition of the voltage subharmonic and interharmonic with a value of 1% of the base component and at equal frequencies (based on [Gallo et al. 2005; Bollen and Gu 2006; Tennakoon, Perera and Robinson 2008; Ghaseminezhad et al. 2021a,b]:

$$f_{sh} = f_1 - f_m \tag{1}$$

$$f_{ih} = f_1 + f_m \tag{2}$$

where:

- f_{sh} – subharmonic frequency,
- f_{ih} – interharmonic frequency,
- f_{ih} – fundamental component frequency,
- f_m – voltage modulation frequency.

Figures 2–3 show a sample test voltage waveform with a spectrum, for modulation frequency $f_m = 20$ Hz. The corresponding current waveform and its spectrum are shown in Figure 4 and Figure 5 for *Case A*. The current waveform spectrum (Fig. 5) contains a subharmonic with frequency $f_{sh} = 30$ Hz, effective value $I_{sh} = 0.3$ A and an interharmonic with frequency $f_{ih} = 70$ Hz and effective value $I_{ih} = 0.16$ A. The next figure, Figure 6, shows the current subharmonic and interharmonic characteristics of a function of voltage modulation frequency for *Case A*. Current subharmonics reach their maximum ($I_{sh} = 0.34$ A) for modulation frequency $f_m = 25$ Hz, while interharmonics do so for frequency $f_m = 20$ Hz. As has been mentioned, a previous paper by one of the authors [Pepliński 2021] presented the test results for the same motor powered by voltage containing a single subharmonic with a value of 1% of the fundamental component. In comparison with the test results published in [Pepliński 2021], current subharmonics for sinusoidal modulation of voltage amplitude reach similar values as for single voltage subharmonics. Current interharmonics for modulation frequencies $f_m \geq 20$ Hz, on the other hand, are much lower than observed in the [Pepliński 2021] study. For $f_m < 20$ Hz, however, current interharmonics have comparable or slightly higher values than in [Pepliński 2021].

The differences stem from the fact that for sinusoidal modulation of voltage (amplitude or phase modulation, or intermediate cases), current components generated independently by voltage subharmonics or interharmonics amplify or attenuate each other, depending on the phase angles [Gallo et al. 2005] of the voltage subharmonics and interharmonics. As a result, for some motors and sinusoidal voltage amplitude modulation, current subharmonics can reach much lower values than for single voltage subharmonics. Relevant test results will be presented in a separate paper on three-phase motors.

The next figure (Fig. 7) shows the characteristics of current subharmonics and interharmonics as a function of voltage modulation frequency for *Case B*. Current subharmonics reach their maximum value $I_{sh} = 0.32$ A for modulation frequency $f_m = 25$ Hz. Current interharmonics reach their maximum ($I_{sh} = 0.1$ A) for modulation frequency $f_m = 20$ Hz. The differences between *Case A* (decoupled motor) and *Case B* (motor coupled with a direct current machine) result from the effect of the moment of inertia of the powered direct current machine. Specifically, voltage subharmonics and interharmonics cause rotation speed fluctuations, the result of which is increased current subharmonics and interharmonics for specific frequencies [Gnaciński et al. 2019a; Gnaciński and Klimczak 2020]. As a result, increasing the rotating mass moment of inertia (*Case B*) caused a drop in current interharmonics and a slight reduction in subharmonics.

It should be noted, however, that for a three-phase induction motor, even a slight increase in rotating mass moment of inertia can result in a significant reduction in current subharmonics [Gnaciński et al. 2019a; Gnaciński and Klimczak 2020]. It must also be mentioned that the above phenomena do not occur for a motor working under a load with a moment of inertia much higher than the motor's moment of inertia. For such cases, further increases in moment of inertia (above a certain threshold value) no longer affect the current subharmonic values [Gnaciński et al. 2019a; Gnaciński and Klimczak 2020]. Furthermore, if certain conditions are met [Gnaciński et al. 2019a, Gnaciński and Klimczak 2020], a motor powered with a voltage containing subharmonics can be analysed using an equivalent transformer-type diagram.

To summarise, for the test motor, voltage amplitude modulation and voltage subharmonics cause a flow of current subharmonics with similar values. Comparable levels of current subharmonics are observed for *Case A* and *Case B*.

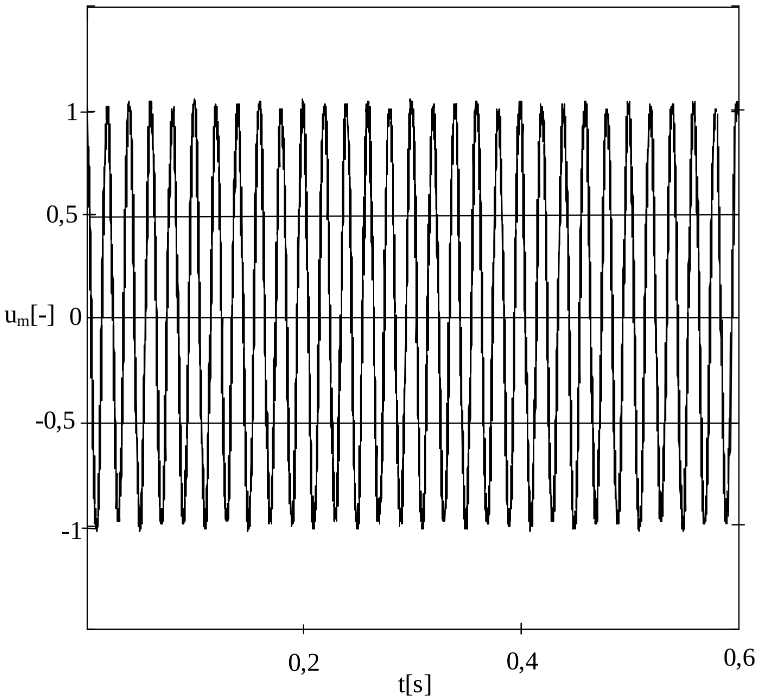

Fig. 2. Recorded test voltage waveform for voltage modulation at frequency f_m = 20 Hz

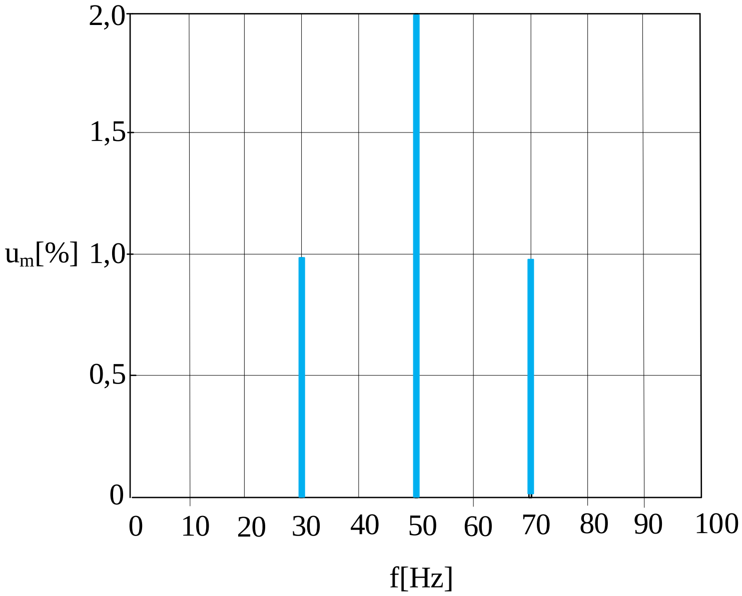

Fig. 3. Waveform spectrum for the voltage shown in Figure 2

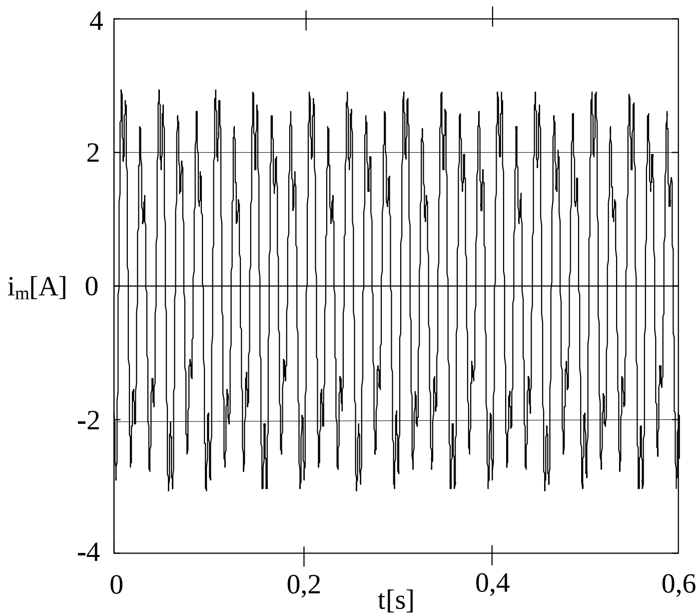

Fig. 4. Recorded waveform of current drawn by the motor for *Case A* and voltage modulation at frequency f_m = 20 Hz

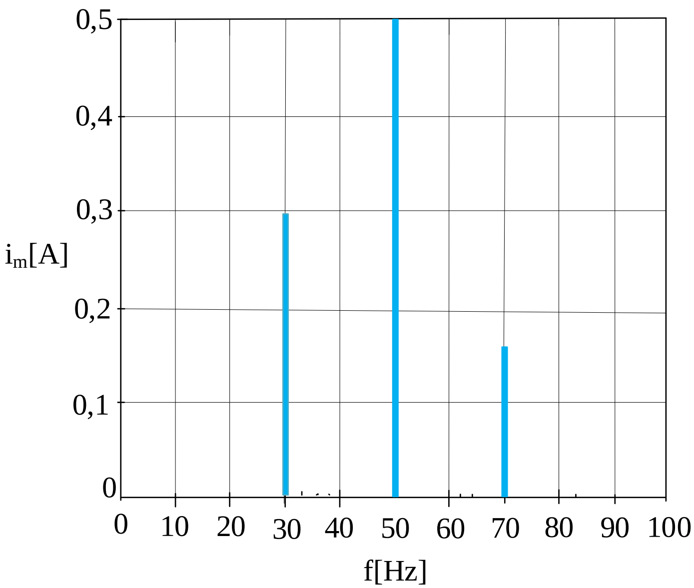

Fig. 5. Waveform spectrum for the current shown in Figure 4

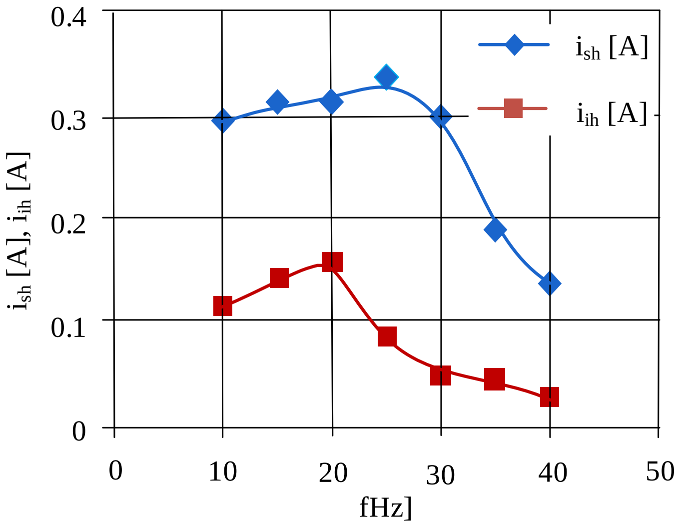

Fig. 6. Current subharmonics and interharmonics for *Case A* as a function of voltage modulation frequency

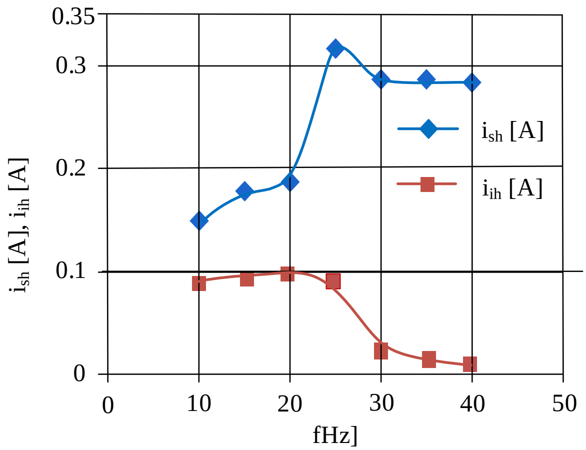

Fig. 7. Current subharmonics and interharmonics for *Case B* as a function of voltage modulation frequency

4. CONCLUSIONS

This paper presents the results of a single-phase induction motor under sinusoidal voltage amplitude modulation, which is a special case of voltage fluctuations. For the test motor, subharmonic voltages, occurring as a single voltage quality disturbance, and the voltage amplitude modulation result in the flow of current subharmonics with comparable values. On the other hand, the observed current interharmonics were generally much lower than the current subharmonics, and for modulation frequency $f_m \geq 20$ Hz they were also much lower than current interharmonics caused by voltage subharmonics occurring as a single disturbance [Pepliński 2021]. Furthermore, increasing the moment of inertia of rotating masses has a minor impact on current subharmonics. The presented test results may not be generalised to cover other cases of voltage fluctuations, such as phase modulation.

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