Scientific Journal of Gdynia Maritime University

No. 131/24, 36–47
ISSN 2657-6988 (online)
ISSN 2657-5841 (printed)
DOI: 10.26408/131.03

Submitted: 15.05.2023
Accepted: 20.12.2023
Published: 30.09.2024

EFFECT OF RECTANGULAR VOLTAGE FLUCTUATIONS ON CURRENTS OF SINGLE-PHASE INDUCTION MOTORS

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Abstract: Various power quality disturbances commonly occur in a power system, including voltage fluctuations. These can be analysed as simultaneous occurrences of voltage subharmonics and interharmonics of various frequencies – components of frequency less than the fundamental one or not being its integer multiple. This work deals with the impact of voltage fluctuations on currents of a single-phase induction motor. The results of the research on currents are presented for rectangular amplitude modulation and are compared with the investigation results under sinusoidal modulation and the appearance of a single voltage subharmonic.

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

1. INTRODUCTION

In power systems, there is always some incompatibility between the ideal voltage parameters and the actual parameters, which are defined as voltage quality disturbances. One type of these is known as voltage fluctuation [Bollen and Gu 2006; Ghaseminezhad et al. 2021a,b; Kuwałek 2021b; Patel and Chowdhury 2021], and is related to changes in its RMS voltage value [Bollen and Gu 2006; Kuwałek 2021a,b].

During voltage fluctuations, the modulating function can take different shapes, e.g. triangular, trapezoidal [Kuwałek 2021a] and, most commonly, rectangular [Kuwałek 2021a; 2022]. It should be mentioned that arbitrary cyclic voltage fluctuations can be considered as cases of the simultaneous occurrence of sinusoidal modulations with different frequencies [Ghaseminezhad 2021b]. Sinusoidal modulation, on the other hand, can be analysed as a composite of the fundamental harmonic of the voltage with a subharmonic (sub-synchronous interharmonic) and an interharmonic [Gallo et al. 2005; Bollen and Gu 2006; Tennakoon, Perera and

Robinson 2008; Ghaseminezhad et al. 2021a,b], a component with a frequency less than the fundamental component and a component with a frequency that is not an integer multiple of the fundamental component, respectively. It should be mentioned that, in the case of sinusoidal modulation, the subharmonic and interharmonic of a voltage are characterised by equal amplitudes and frequency symmetry with respect to the fundamental component of the voltage (e.g. 10 Hz subharmonic, 90 Hz interharmonic in a 50 Hz system) [Gallo et al. 2005; Bollen and Gu 2006; Tennakoon, Perera and Robinson 2008; Ghaseminezhad et al. 2021].

The direct cause of voltage fluctuations is usually current modulation [Bollen and Gu 2006]. Current modulation and the consequent occurrence of subharmonics and interharmonics in voltage waveforms is caused by the operation of renewable energy sources, e.g. wind farms, solar farms, photovoltaic cells, wave power plants [Bollen and Gu 2006; Kovaltchouk et al. 2016, Ravindran et al. 2020]; power electronic devices, e.g. frequency converters, cycloconverters [Testa et al. 2007; Nassif 2019] and equipment that consume time-varying electrical power, e.g. induction or synchronous motors driving reciprocating compressors [Arkkio et al. 2018].

Voltage fluctuations and associated voltage subharmonics and interharmonics interfere with the operation of electricity receivers, especially electrical machines [Gallo et al. 2005; Testa et al. 2007; Tennakoon, Perera and Robinson 2008; Ghaseminezhad et al. 2017a,b; 2021a,b; Gil-de-Castro, Rönnberg and Bollen 2017; Gnaciński et al. 2019b; 2022a,b; Gnaciński and Klimczak 2020; Crotti et al. 2021; Gnaciński, Muc and Pepliński 2021; Zhang, Kang and Yuan 2021; Pepliński, Adamczak and Gnaciński 2022]. In induction motors they can cause excessive vibrations and torsional oscillations, increased power losses and winding temperatures, speed fluctuations, and local saturation of the magnetic circuit [Tripp, Kim and Whitney 1993; Tennakoon, Perera and Robinson 2008; Ghaseminezhad et al. 2017a,b; 2021a,b; Gnaciński et al. 2019b; 2022a,b; Gnaciński and Klimczak 2020; Gnaciński, Muc and Pepliński 2021; Zhang, Kang and Yuan 2021; Pepliński, Adamczak and Gnaciński 2022]. In extreme cases, the considered disturbances can cause damage to the drive system [Tripp, Kim and Whitney 1993].

Previous research work on asynchronous motors under considered disturbances focuses on three-phase machines [Tripp, Kim and Whitney 1993; Tennakoon, Perera and Robinson 2008; Ghaseminezhad et al. 2017a,b; 2021a,b; Gnaciński et al. 2019b; 2022a,b; Gnaciński and Klimczak 2020; Gnaciński, Muc and Pepliński 2021; Zhang, Kang and Yuan 2021]. The subject of single-phase motors has been covered in previous work, in which the results of the tests were presented for a voltage supply containing a single subharmonic or interharmonic [Pepliński 2021] and under sinusoidal voltage fluctuations [Pepliński, Adamczak and Gnaciński 2022]. It should be mentioned that the most important task of the ongoing research work [Gnaciński et al. 2019a,b; 2022a,b; Gnaciński and Klimczak 2020; Gnaciński, Muc and Pepliński 2021; Pepliński 2021; Pepliński, Adamczak and Gnaciński 2022] is to formulate proposals to modify the voltage quality standards (e.g. [PN-EN 50160]) by introducing permissible levels of voltage subharmonics and interharmonics.

The objectives of this article are formulated taking into account the above considerations. The main objective is to study the effect of rectangular supply voltage modulation on the subharmonics and interharmonics of a single-phase motor current. The test results for rectangular voltage modulation were also compared with the results of previous analyses for sinusoidal modulation [Pepliński, Adamczak and Gnaciński 2022] and the case of supplying the motor with a voltage containing a single subharmonic or interharmonic [Pepliński 2021].

2. MEASUREMENT STATION

The measurement station consisted of the tested motor, the power supply system, a digital oscilloscope and a voltage quality analyser.

The test object was an 800 W single-phase induction motor with a permanently connected capacitor, originally part of a type JETW-B/800-50 hydrophore assembly [*Pumps and Hydrophores…*].

The nominal parameters of the hydrophore assembly are shown in Table 1. Experimental tests were carried out with the motor coupled to an unloaded DC machine of type PKBa12a/101o. In practical terms, the DC machine loaded the motor with a small resistive torque (associated with mechanical losses) and introduced an additional moment of inertia into the drive system, affecting the speed fluctuations.

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 [V]	230
Nominal frequency [Hz]	50
Pump capacity	50 l/min.
Lifting height	40 m
Insulation class	B

During the tests, the motor was powered by a programmable power supply, a Chroma 61512+A615103, which allowed the generation of voltages with programmable quality disturbances, such as voltage asymmetry, harmonics, subharmonics, interharmonics, and amplitude modulation. A Tektronix TBS 2000B digital oscilloscope was used to record the current and voltage waveforms, and a computerised power quality analyser was used for spectral analysis.

A diagram of the test station is shown in Figure 1a and a photograph (without the programmable power source located in another room) is shown in Figure 1b.

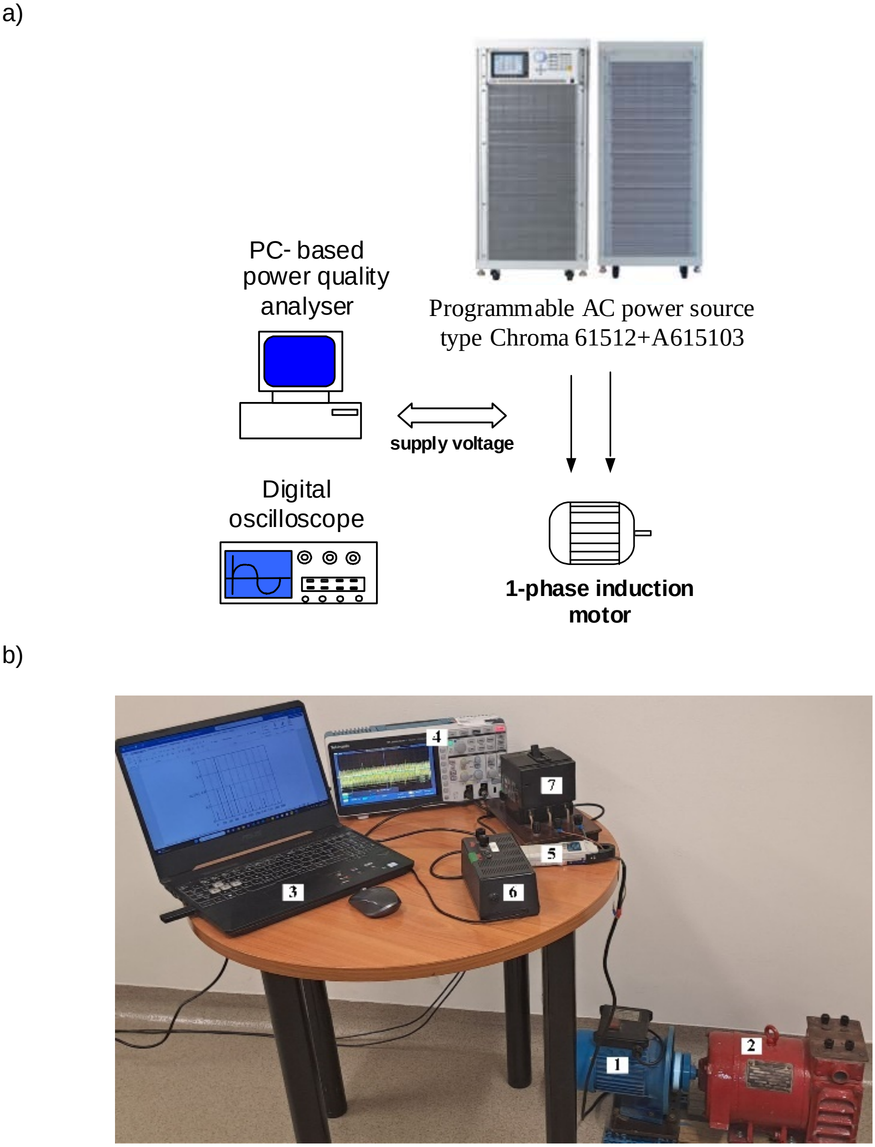

Fig. 1. Simplified diagram (a) and photo (b) of the measurement station: 1 – tested motor, 2 – load generator, 3 – computerised electricity quality analyser, 4 – digital oscilloscope, 5 – current probe, 6 – measuring transducer, 7– switch

3. TEST RESULTS

The work was carried out using symmetrical rectangular modulation, where for half of the modulation period the voltage is increased by the amplitude v_u, and for the following half it is decreased by v_u. The waveform of the modulating function is shown in Figure 2. The assumed modulation amplitude m_u = 1.57% corresponds to the maximum content of the subharmonics in the voltage, u_{sh} = 1%, which enables a direct comparison of the presented test results with previous results obtained for a voltage supply containing a single subharmonic [Pepliński 2021] and under conditions of sinusoidal voltage amplitude modulation [Pepliński, Adamczak and Gnaciński 2022].

An example of the test voltage spectrum for a modulation frequency of f_m = 20 Hz, is shown in Figure 3. The presented spectrum contains subharmonics and interharmonics corresponding to the individual harmonics of the modulating function (based on Gallo et al. 2005; Zhang, Xu and Liu 2005; Bollen and Gu 2006; Tennakoon, Perera, and Robinson, 2008; Ghaseminezhad et al. 2021a,b):

$$f_{sh/ih} = f_1 - f_{mh} \tag{1}$$

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

where:

$f_{sh/ih}$ – subharmonic/interharmonic frequency,
ff_{ih} – interharmonic frequency,
f_{ih} – fundamental frequency,
f_{mh} – frequency corresponding to the harmonic of order *h* of the voltage modulating function.

For frequencies $f_{mh}<2f_1$ the component described by relation (1) is a subharmonic, and for $f_{mh}>2f_1$ it is an interharmonic. When the frequency $f_{sh/ih}$ takes a negative value, the component in question is of the opposite order, and when it takes a positive value, then it is of the congruent order [Zhang, Xu and Liu 2005]. This is relevant in the case of three-phase motors, for which there are differences in the effects of the congruent-order and counter-order subharmonics [Gnaciński et al. 2022a]. This is due to the fact that congruent-order subharmonics generate a magnetic field in the machine that rotates in the same direction as the field from the fundamental voltage harmonic. In the case of subharmonics of the opposite order, the situation is the opposite.

In contrast, many single-phase motors often do not have a rotating field during normal operation, but a pulsating one. Alternatively, the presence of a rotating field may result from the use of a capacitor to achieve the appropriate phase shift of the currents in the motor windings. Thus in the case of single-phase motors, the order of the subharmonics and interharmonics is irrelevant. This is one of the reasons why the results for three-phase motors cannot be directly transferred to single-phase motors.

The following diagrams (Figs. 4, 5 and 6) show the spectra of the recorded motor current for frequencies $f_m = 5$ Hz, $f_m = 20$ Hz and $f_m = 40$ Hz. The first harmonic of the modulating function takes the value $I_{sh1} = 0.115$ A and the interharmonic takes $I_{ih1} = 0.028$ A. Their frequencies are $f_{sh1} = 45$ Hz and $f_{ih1} = 95$ Hz, respectively. For modulation frequency $f_m = 20$ Hz (Fig. 5), the above components take on significantly larger values: $–I_{sh1} = 0.195$ A and $I_{ih1} = 0.105$ A. On the other hand, for modulation frequency $f_m = 40$ Hz (Fig. 6), the subharmonic $I_{sh1} = 0.298$ A, and the interharmonic – $I_{ih1} = 0.0.089$ A.

Furthermore, the above spectra contains harmonics as well as subharmonics and interharmonics caused by the harmonics of the voltage modulating function. It should be mentioned that voltage modulation causes an increase in the third harmonic current – for a fully sinusoidal supply its value is 0.361 A, while for modulation with frequency $f_m = 40$ Hz it is 0.427 A. This can be explained by the local saturation of the magnetic circuit caused by the subharmonics [Ghaseminezhad et al. 2017b].

Figure 7 shows the subharmonic and interharmonic current characteristics corresponding to the first harmonic of the modulating function. The subharmonic I_{sh1} increases monotonically with frequency f_m, from 0.115 A to 0.304 A, while the interharmonic I_{ih1} assumes its highest value for $f_m = 20$ Hz.

Compared to sinusoidal modulation with the same amplitude [Pepliński, Adamczak and Gnaciński 2022], for symmetric rectangular modulation, there are higher values of subharmonic I_{sh1} for modulation frequencies around 35–45 Hz, and lower for frequencies around 25 Hz.

For the other modulation frequencies, the numerical results obtained are comparable, although the respective curves (Fig. 7) [Pepliński, Adamczak and Gnaciński 2022] differ significantly in shape.

It should also be mentioned that the maximum values of the subharmonic currents in Figure 7 approximately correspond to analogous maximum values for the supply voltage containing a single subharmonic [Pepliński 2021]. It should also be mentioned that the I_{sh1} component assumes the highest values among all components with subharmonic and interharmonic frequencies.

Figure 8 shows the characteristics of the components corresponding to the third harmonic of the modulating function. The subharmonic/interharmonic with the frequency described by relation (1) is denoted as $I_{sh/ih3}$, while the interharmonic with the frequency described by relation (2) is denoted as I_{ih3}. The $I_{sh/ih3}$ component reaches its highest value ($I_{sh/ih3} = 0.128$ A) for modulation frequency $f_m = 10$Hz, and the interharmonic I_{ih3} – for $f_m = 45$Hz ($I_{ih3} = 0.034$ A).

Although the above components are apparently insignificant, they can cause torque pulsations at resonant frequencies. It should be emphasised that, under resonance conditions, even a minimal subharmonic content in the supply voltage can cause excessive oscillations [Gnaciński et al. 2019b].

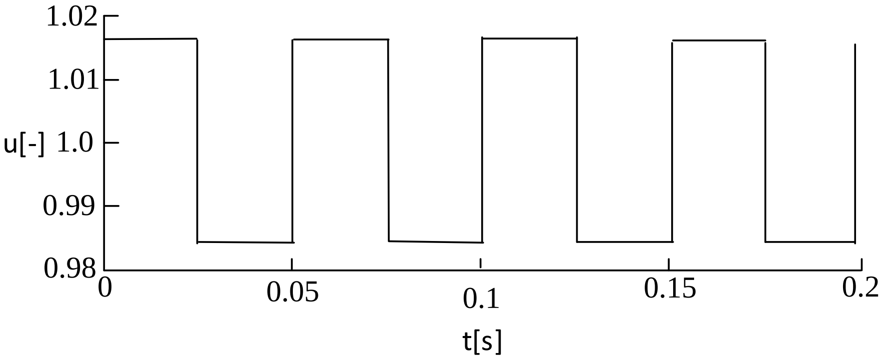

Fig. 2. Example waveform of the modulating function

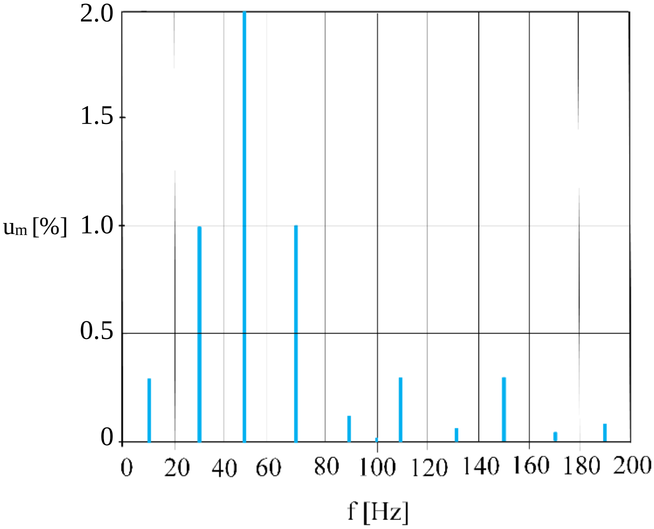

Fig. 3. Supply voltage spectrum for modulation with frequency f_m = 20 Hz

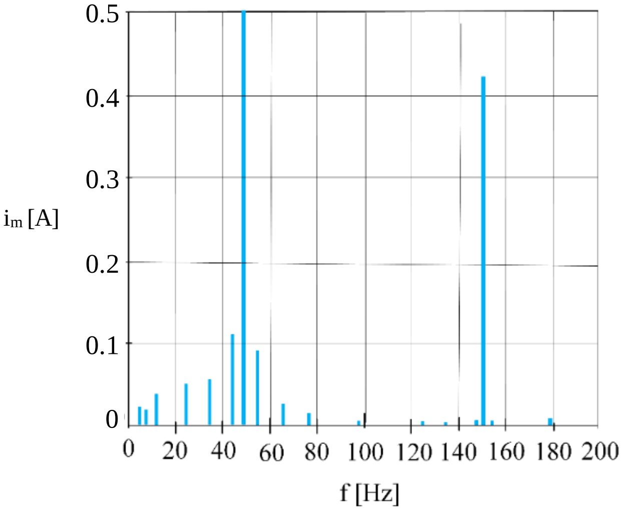

Fig. 4. Supply current spectrum of the motor for modulation with frequency f_m = 5 Hz

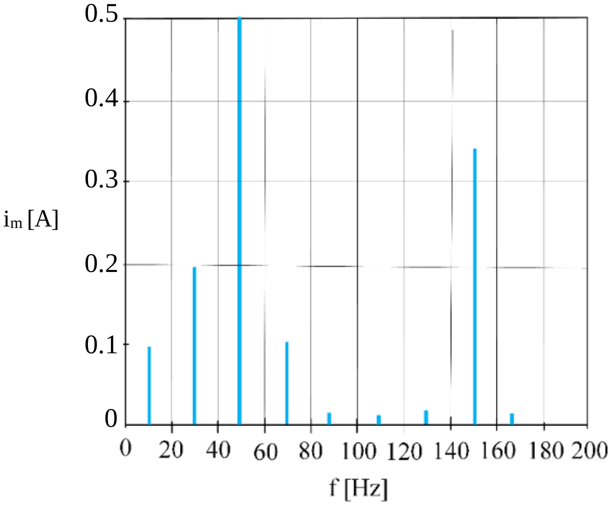

Fig. 5. Supply current spectrum of the motor for modulation with frequency f_m = 20 Hz

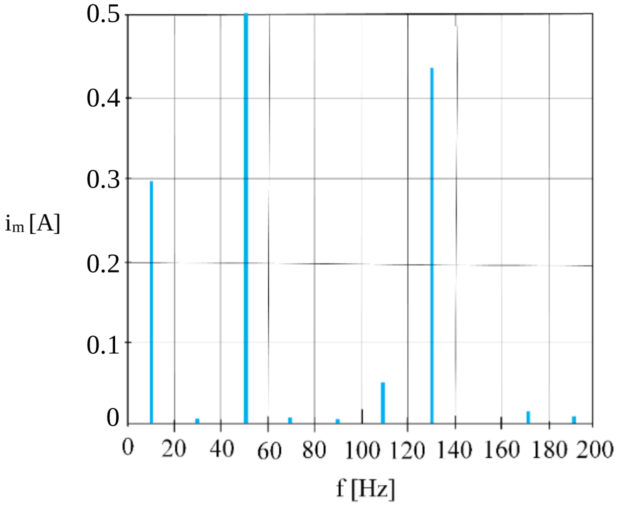

Fig. 6. Supply current spectrum of the motor for modulation with frequency f_m = 40 Hz

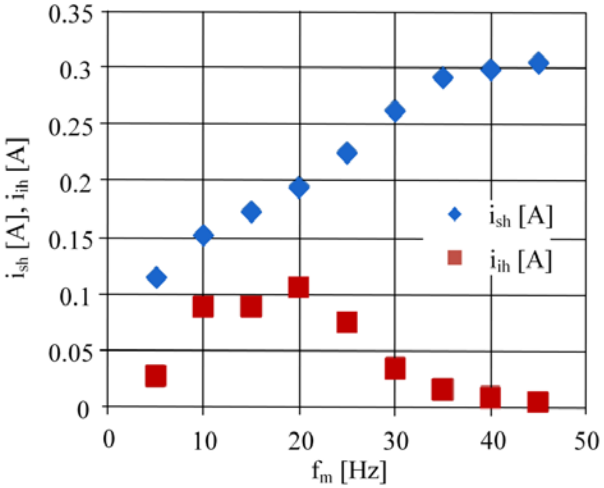

Fig. 7. Subharmonic and interharmonic of the motor supply current corresponding to the first harmonic of the modulating function

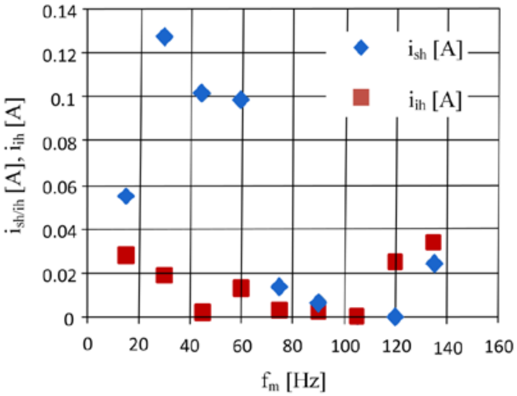

Fig. 8. Subharmonic/interharmonic and interharmonic of the motor supply current corresponding to the third harmonic of the modulating function

4. CONCLUSIONS

In the case of rectangular modulation, the voltage waveform contains subharmonics and interharmonics due to the harmonics of the modulating function. Their presence causes additional current components to flow in the motor windings. The voltage modulation method significantly influences the shape of the current subharmonic characteristics as a function of modulation frequency. For the tested motor and rectangular sinusoidal modulation [Pepliński, Adamczak and Gnaciński 2022], supplying the motor with a voltage containing single subharmonics [Pepliński 2021], the maximum values of current subharmonics reached similar values, although the mentioned characteristics significantly differ in shape. Moreover, voltage modulation can cause a significant increase in the third harmonic of the current drawn by the motor. An in-depth explanation of the phenomena occurring in an induction motor under voltage fluctuations, including the load level of the motor, shall be the subject of further research by the authors.

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