No. 119/21, 45–53
ISSN 2657-6988 (online)
ISSN 2657-5841 (printed)
DOI: 10.26408/119.04

Submitted: 27.05.2021
Accepted: 21.06.2021
Published: 30.09.2021

IMPACT OF VOLTAGE SUBHARMONICS AND INTERHARMONICS ON CURRENTS IN SINGLE-PHASE INDUCTION MOTORS

Marcin Pepliński

Gdynia Maritime University, Morska 81–87, 81–225 Gdynia, Poland, Faculty of Electrical Engineering, Department of Marine Electrical Power Engineering,
ORCID 0000-0001-5952-1028, e-mail: m.peplinski@we.umg.edu.pl

Abstract: In very low power drives, a single-phase induction motor is used. This motor, like the 3-phase induction squirrel-cage motor, requires a voltage supply with suitable parameters – of suitable quality, in practice. In energy systems, voltage quality distortions may occur in connection with the deviation of the RMS voltage and the occurrence of harmonics, subharmonics and interharmonics in its waveforms. Subharmonics and interharmonics in the voltage waveforms are particularly detrimental to induction motors. They cause, for example, additional power losses, electromagnetic torque pulsation and motor vibrations. It should be stressed that the existing publications on the impact of the considered distortions on the induction squirrel-cage motor are almost only applicable to 3-phase machines. The article presents the results of research on the influence of subharmonic and interharmonic voltage components on the single-phase induction squirrel-cage motor.

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

1. INTRODUCTION

The single-phase induction motor is very popular and used, for example, in many low power drives, such as: dishwashers, fans, washing machines, fridges, dryers, hermetic compressors, pumps, etc. The single-phase induction motor, like the 3-phase motor, requires a suitable quality voltage supply for proper operation. However, in energy systems, voltage quality distortions may occur in connection with the deviation of its RMS value and the occurrence of harmonic, subharmonic and interharmonic components in its waveforms. Subharmonics are components with frequencies lower than the basic component frequency. Subharmonics often occur in combination with voltage interharmonics, i.e. distortions with a frequency higher than the basic harmonics and not constituting its integer multiple.

The main reason for the occurrence of subharmonic and interharmonic components in the voltage waveforms are nonlinear consumers operating with variable load [Testa et al. 2007; Sürgevil and Akpnar 2009] and renewable energy sources, including: wind power plants [Bolen and Gu 2006; Testa et al. 2007; Xia et al. 2017; Yang and Bollen 2017] and photovoltaic farms [Ravindran et al. 2018; Sangwongwanich et al. 2018; Ravindran et al. 2019; Pan et al. 2020]. In addition, the distortions may also result from the operation of voltage inverters and many low power consumers supplied with single-phase voltage, such as: laser printers [Testa et al. 2007; Knockaert, Debruyne and Desmet 2019] or photocopiers.

It should be mentioned that at present there is literature confirming the particularly detrimental impact of the subharmonics and interharmonics in the voltage waveforms on the operation of the 3-phase induction motor [Abreu and Emanuel 2002; Fuchs, Roesler and Masoum 2004; Gnaciński and Pepliński 2014; Ghaseminezhad 2018; Gnaciński, Pepliński and Hallmann 2019; Gnaciński et al. 2019; Ghaseminezhad 2021; Gnaciński et al. 2021]. These distortions cause additional power losses in the motor, which result in an increase of the winding temperature. In addition, they may cause pulsation of the electromagnetic torque and excessive vibration of the motor [Gnaciński et al. 2019; Gnaciński et al. 2021]. However, the influence of the subharmonics and interharmonics on single-phase induction motors remains to be examined. It should be stressed that there are not many publications on the lowered voltage quality on the operation of the single-phase induction motor. In particular, there is a deficiency of experimental works. For example, the study [Fuchs, Roesler and Masoum 2004] proved by theoretical analysis that subharmonics, even at a low level in the voltage waveforms, at 0.5% of the basic component, significantly increase the power losses of the stator and the rotor of the motor.

It should be mentioned that the operating conditions of the magnetic circuit in the single-phase induction motor significantly differ from the operating conditions of the magnetic circuit in the 3-phase induction motor. In the single-phase motor, the magnetic field is pulsating, as in the transformer, or revolving elliptically (in a motor with a permanently connected capacitor). However, in the 3-phase induction squirrel-cage motor, there is a circle-shaped revolving magnetic field. In addition, due to the low power, and by consequence currents, single-phase motors are characterised by a relatively high winding resistance. Therefore, the results of research on 3-phase motors cannot be extrapolated to single-phase motors.

This article presents the impact of subharmonics and interharmonics on the currents of the single-phase induction motor. Since for the motor in no-load operation, a particularly negative impact of the power supply with voltage containing subharmonics and interharmonics [Gnaciński et al. 2019; Gnaciński et al. 2021] was found, the research was conducted for this operating condition of the motor.

2. MEASUREMENT STATION

The measurement station includes: a Chroma 61512+A615103 programmable alternating voltage source, a single-phase induction squirrel-cage motor with a permanently connected capacitor, a digital oscilloscope, and a computer-based electrical energy quality analyser.

The Chroma 61512+A615103 programmable power source with a rated power of 36 kVA consists of two modules, master/slave, operating in parallel. This source can generate subharmonics and interharmonics in the frequency range of 0.01–2400 Hz. The subharmonics and interharmonics content in the current was measured using a Tektronix TBS 2000B digital oscilloscope, and the computer-based electrical energy quality analyser. The subject of the study was a 4-pole single-phase induction squirrel-cage motor included in a JETW-B/800-50 motor-pressure accumulating pump assembly [*Pompy i hydrofory. Zestawy hydroforowe Webermann*...].

The rated parameters of the new assembly are included in Table 1. For research purposes, the motor and the pump were uncoupled.

Table 1. Rated parameters of the motor-pump assembly

Motor-pump assembly type	**JETW-B/800-50**
Motor	**single-phase**
Rated power [kW]	0.8
Rated voltage [V]	230
Rated frequency [Hz]	50
Capacity	50 l/min.
Lifting height	40 m
Insulation class	B

The subharmonics content in the power supply voltage and current of the examined motors were measured using the analyser-estimator of the electrical energy quality and computer-based the electrical energy quality analyser. It should be mentioned that the electrical energy analyser-estimator was designed at the Department of Marine Electrical Power Engineering of the Gdynia Maritime University and is PRS-certified [Tarasiuk 2011].

Diagram of the measurement system shown in Figure 1.

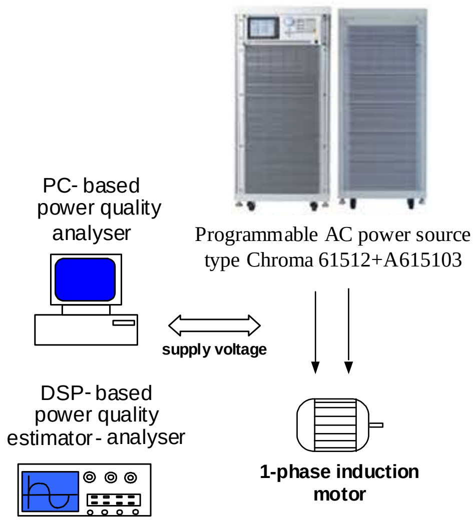

Fig. 1. Diagram of the measurement station

3. RESULTS OF EXPERIMENTAL RESEARCH

The section presents the results of experimental research on the impact of subharmonics and interharmonics with a sequence consistent with the currents of a single-phase induction motor. The relevant tests were performed during idle operation of the motor and the basic harmonic of the voltage with the rated value and amplitude of the examined subharmonics and interharmonics of 1% of the basic component of the voltage. It should be mentioned that subharmonics and interharmonics with similar values were recorded in the study [Nassif 2019].

Figure 2 shows an example waveform of the current in the examined motor for the subharmonic with the frequency of f_{sh} = 2 Hz.

Figures 3 and 4 show the subharmonic and interharmonic characteristics of the current of the stator as a function of the subharmonic frequency of the voltage. Figure 3 shows the subharmonics in the current caused directly by the subharmonics of the voltage. Figure 4 shows the interharmonic in the current of the induction motor supplied by a voltage containing subharmonics generated by fluctuations of the rotational speed [Tennakoon, Perera and Robinson 2008; Gnaciński and Pepliński 2014; Gnaciński, Pepliński and Hallmann 2019].

For the subharmonic frequency of the voltage (Fig. 3) fluctuating in the range of f_{sh} = 2 Hz to f_{sh} = 27 Hz, the current subharmonic RMS value fluctuates slightly in the range of I_{sh} = 0.307 A to 0.323 A (on average in this range, it is approx. 0.32 A, which is approx. 17.3% I_{1o} of the basic harmonic measured at idle speed). In the frequency range of f_{sh} = 27 Hz to f_{sh} = 45 Hz, a nonlinear drop of the subharmonic current amplitude to I_{sh} = 0.071 A occurs. The occurrence of the fixed current subharmonics for a frequency of up to f_{sh} = 27 Hz is related to the high resistance of the stator winding. Only at a frequency higher than f_{sh} = 27 Hz, the reactance of the stator winding becomes so high that it causes significant attenuation of the amplitude corresponding to this subharmonic in the current.

In turn, the amplitude of the current interharmonics generated from the voltage subharmonics (Fig. 4) with the range of f_{sh} = 2 Hz to f_{sh} = 27 Hz constitutes an increasing function and varies from I_{sh} = 0.073 A to I_{sh} = 0.187 A. A frequency increase above f_{sh} = 27 Hz, to f_{sh} = 45 Hz, causes a nonlinear drop of the interharmonic current amplitude to I_{sh} = 0.053 A.

Figures 5 and 6 show the subharmonic and interharmonic characteristics of the current of the stator as a function of the interharmonic frequency of the voltage. Figure 5 shows the interharmonics in the current generated directly from the interharmonics in the voltage. Figure 6 shows the subharmonics in the current generated from the interharmonics in the voltage.

For the interharmonic frequency of the voltage (Fig. 5) changing in the range of f_{ih} = 55 Hz to f_{ih} = 65 Hz, the amplitude of the current interharmonics drops from I_{ih} = 0.054 A to I_{ih} = 0.024 A. The frequency increase from f_{ih} = 65 Hz to f_{ih} = 85 Hz causes a nonlinear increase of the amplitude of the current interharmonic to I_{ih} = 0.086 A. However, in the range of f_{ih} = 85 Hz to f_{ih} = 99 Hz, the amplitude of the interharmonic drops to I_{ih} = 0.073 A.

In turn, the amplitude of the current subharmonics generated from the voltage interharmonics (Fig. 6) with the range of f_{ih} = 55 Hz to f_{ih} = 70 Hz constitutes an increasing function from I_{sh} = 0.046 A to I_{sh} = 0.083 A. A frequency increase above f_{sh} = 70 Hz, to f_{sh} = 99 Hz, causes a nonlinear drop of the interharmonic current amplitude, until complete disappearance (f_{ih} = 99 Hz).

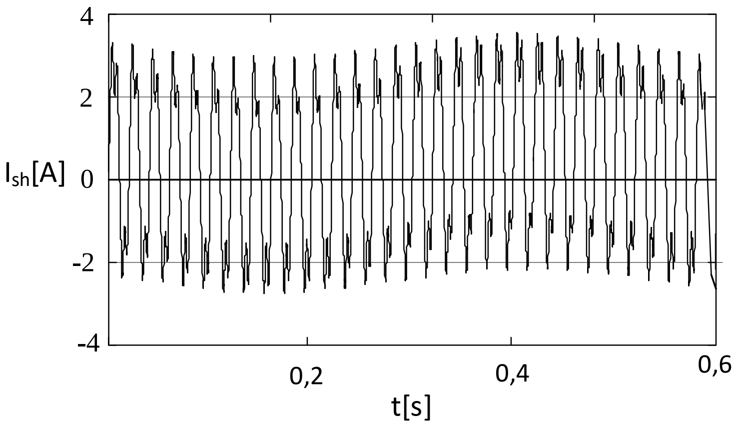

Fig. 2. Experimentally determined waveform of the current drawn by the motor for the supply voltage with a subharmonic with a compliant sequence, frequency of f_{sh} = 2 Hz and amplitude of u_{sh} = 1% of the basic harmonic amplitude

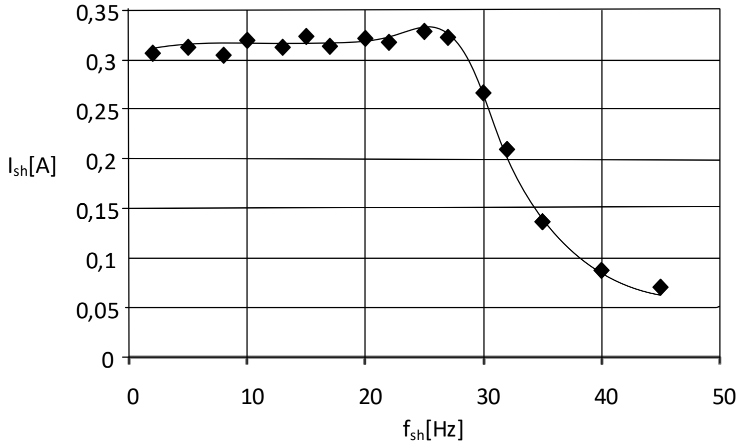

Fig. 3. Experimentally determined RMS values of the current subharmonics of the motor as a function of the subharmonic voltage frequencies

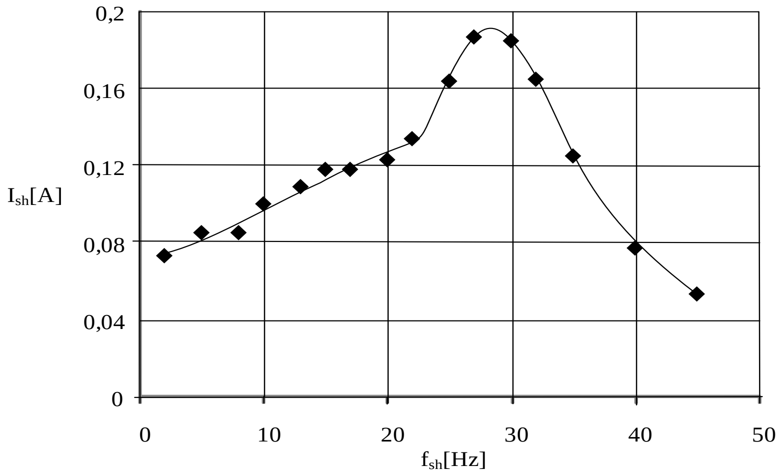

Fig. 4. Experimentally determined RMS values of the current interharmonics of the motor as a function of the subharmonic voltage frequencies

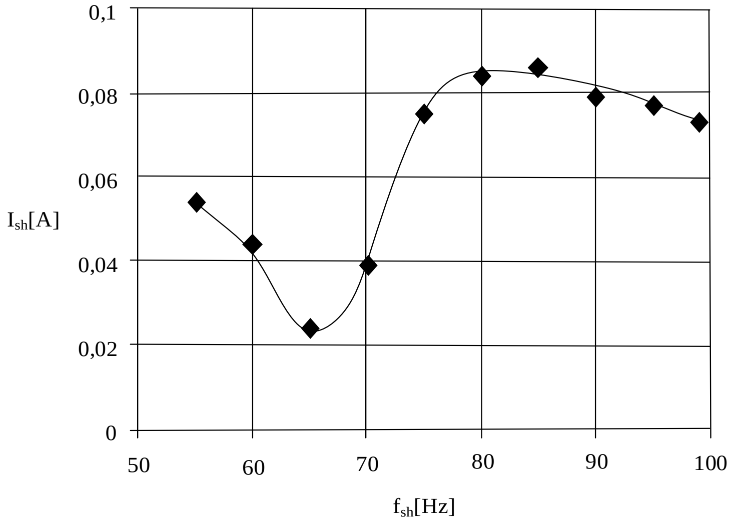

Fig. 5. Experimentally determined RMS values of the current subharmonics of the motor as a function of the interharmonic voltage frequencies

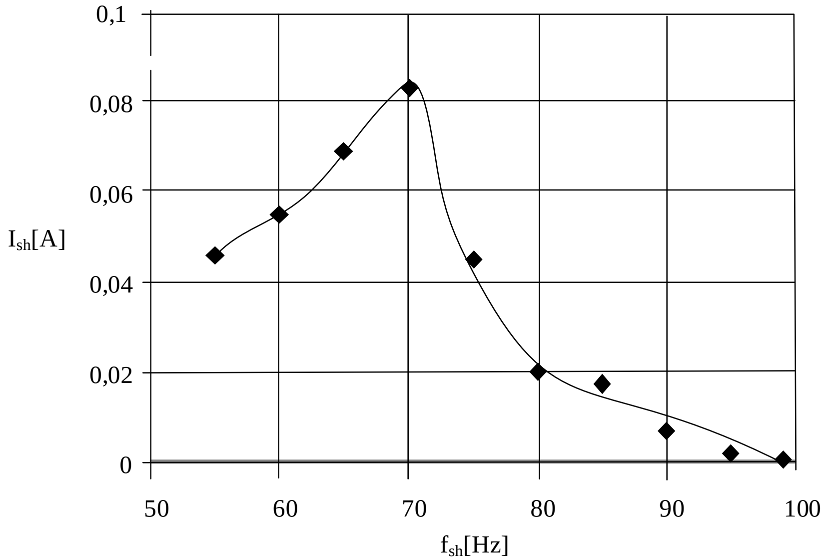

Fig. 6. Experimentally determined RMS values of the current interharmonics of the motor as a function of the interharmonic voltage frequencies

4. CONCLUSIONS

The presented relationships between the RMS subharmonic and interharmonic values in the current waveforms of the single-phase motor on the frequency show a significant difference relative to the analogical relationships determined for 3-phase motors. Firstly, in the examined motor, at $f_{sh} < 27$ Hz, the voltage subharmonics frequency influences the subharmonic value of the current. Secondly, in a 3-phase motor, a significant impact on the considered characteristics is exerted by resonance phenomena [Gnaciński et al. 2019; Gnaciński et al. 2021] that is not found in the examined single-phase motor.

REFERENCES

Abreu de, J.P.G., Emanuel, A.E, 2002, *Induction Motor Thermal Aging Caused by Voltage Distortion and Imbalance: Loss of Useful Life and Its Estimated Cost*, IEEE Transactions on Industry Applications, vol. 38, no. 1, pp. 12–20.

Bolen, M.H.J., Gu, I.Y.H., 2006, *Origin of Power Variations Quality. Processing of Stationary Signals. In Signal Processing of Power Quality Disturbances,* Wiley, New York, NY, USA, pp. 41–276.

Fuchs, E.F., Roesler, D.J., Masoum, M.A.S., 2004, *Are Harmonics Recommendations According to IEEE and IEC Too Restrictive?* IEEE Transactions on Power Delivery, vol. 19, no. 4, pp. 1775–1786.

Ghaseminezhad, M., Doroudi, A., Hosseinian, S.H., Jalilian, A., 2018, *Investigation of Increased Ohmic and Core Losses in Induction Motors Under Voltage Fluctuation Conditions*, Iran. J. Sci. Technol. Trans. Electr. Eng., vol. 43, pp. 1–10.

Ghaseminezhad, M., Doroudi, A., Hosseinian, S.H., Jalilian, A., 2021, *Analytical Field Study on Induction Motors Under Fluctuated Voltages*, Iran. J. Electr. Electron. Eng., vol. 17, no. 1.

Gnaciński, P., Hallmann, D., Klimczak, P., Muc, A., Pepliński, M., 2021, *Effects of Voltage Interharmonicson Cage Induction Motors*, Energies, vol. 14, pp. 12–18.

Gnaciński, P., Klimczak, P., 2020, *High-Power Induction Motors Supplied with Voltage Containing Subharmonics*, Energies, vol. 13, pp. 58–94.

Gnaciński, P., Peplinski, M., 2014, *Induction Cage Machine Supplied with Voltage Containing Subharmonics and Interharmonics,* IET Electric Power Applications, vol. 8, pp. 287–295.

Gnaciński, P., Pepliński, M., Hallmann, D., 2019, *Currents and Power Losses of Induction Machine Under Voltage Interharmonics*, Proceedings of the 2019 21st European Conference on Power Electronics and Applications (EPE'19 ECCE Europe), Genova, Italy, 3–5 September.

Gnaciński, P., Pepliński, M., Hallmann, D., Jankowski, P., 2019, *The Effects of Voltage Subharmonics on Cage Induction Machine,* Int. J. Electr. Power Energy Syst., vol. 111, pp. 125–131.

Gnaciński, P., Pepliński, M., Murawski, L., Szeleziński, A., 2019, *Vibration of Induction Machine Supplied with Voltage Containing Subharmonics and Interharmonics*, IEEE Transactions on Energy Conversion, vol. 34, no. 4, pp. 1928–1937.

Knockaert, J., Debruyne, C., Desmet, J., 2019, *Interharmonics and LED Flicker, An assessment by CFD*, Proceedings of the 25th International Conference on Electricity Distribution, Madrid, Spain, 3–6 June.

Nassif, A.B., 2019, *Assessing the Impact of Harmonics and Interharmonics of Top and Mudpump Variable Frequency Drives in Drilling Rigs*, IEEE Transactions Industry Applications, vol. 55, pp. 5574–5583.

Pan, Y., Sangwongwanich, A., Yang, Y., Blaabjerg, F., 2020, *A Phase-Shifting MPPT Method to Mitigate Interharmonics from Cascaded H-Bridge PV Inverters*, Proceedings of the 2020 IEEE Applied Power Electronics Conference and Exposition (APEC), New Orleans, LA, USA, 15–19 March, pp. 157–163.

Pompy i hydrofory. Zestawy hydroforowe Webermann, http://www.superhosting.com.pl/ko-lanko/technika/pompy4.php.

Ravindran, V., Busatto, T., Rönnberg, S.K., Meyer, J., Bollen, M.H., 2019, *Time-Varying Interharmonics in Different Types of Grid-Tied PV Inverter Systems*, IEEE Transactions Power on Delivery, vol. 35, pp. 483–496.

Ravindran, V., Rönnberg, S.K., Busatto, T., Bollen, M.H., 2018, *Inspection of Interharmonic Emissions from a Grid-Tied PV Inverter in North Sweden*, In Proceedings of the 18th International Conference on Harmonics and Quality of Power (ICHQP), Ljubljana, Slovenia, 13–16 May, pp. 1–6.

Sangwongwanich, A., Yang, Y., Sera, D., Soltani, H., Blaabjerg, F., 2018, *Analysis and Modeling of Interharmonics from Grid-Connected Photovoltaic Systems*, IEEE Transactions Power Electronics, vol. 33.

Sürgevil, T., Akpnar, E., 2009, *Effects of Electric Arc Furnace Loads on Synchronous Generators and Asynchronous Motors*, Proceedings of International Conference on Electrical and Electronics Engineering ELECO 2009, Bursa, 5–8 November, pp. I-49–I-53.

Tarasiuk, T., 2011, *Estimator-Analyzer of per Quality: Part I – Methods and Algorithms*', Journal of the International Measurement Confederation, vol. 44, no. 1, pp. 238–247.

Tennakoon, S., Perera, S., Robinson, D., 2008, *Flicker Attenuation – Part I: Response of Three-Phase Induction Motors to Regular Voltage Fluctuations*, IEEE Transactions Power on Delivery, vol. 23, pp. 1207–1214.

Testa, A., Akram, M.F., Burch, R., Carpinelli, G., Chang, G., Dinavahi, V., Hatziadoniu, C., Grady, W.M., Gunther, E., Halpin, M., Lehn, P., 2007, *Interharmonics: Theory and Modeling*, IEEE Transactions Power on Delivery, vol. 22, pp. 2335–2348.

Xia, Q., Wang, Z., Liu, F., Li, Y., Peng, Y., Xu, Z., 2017, *Study on Power Quality Issues of Wind Farm*, Proceedings of the 2017 36th Chinese Control Conference (CCC), Dalian, China, 26–28 July, pp. 10 490–10 494.

Yang, K., Bollen, M.H., 2017, *Interharmonic Currents from a Type-IV Wind Energy Conversion System*, Electricity Power System Restoration, vol. 143, pp. 357–364.