No. 111/19, 47–56
ISSN 2657-6988 (online)
ISSN 2657-5841 (printed)
DOI: 10.26408/111.05

Submitted: 14.11.2018
Accepted: 07.01.2019
Published: 23.09.2019

PRELIMINARY STUDY OF A 200-KW INDUCTION MOTOR SUPPLIED WITH VOLTAGES CONTAINING SUBHARMONICS

Piotr Gnaciński[1]*, Piotr Klimczak[2]

[1] Gdynia Maritime University, Morska 81-87, 81-225 Gdynia, Poland,
Faculty of Electrical Engineering, Department of Marine Electrical Power Engineering,
e-mail: p.gnacinski@we.umg.edu.pl, ORCID 0000-0003-3903-0453
[2] Zakład Maszyn Elektrycznych EMIT S.A. Grupa Cantoni, Narutowicza 72, 99-320 Żychlin,
ORCID 0000-0001-6757-4170
* Corresponding author

Abstract: This work deals with the preliminary investigations of a 200-kW induction cage motor with a supply voltage featuring subharmonic injection. The results of the field calculations in the MAXWELL environment are presented for subharmonics of various frequencies. It was found that subharmonics occurring in real power systems can cause overheating and premature failure of this type of machine.

Keywords: finite element method, induction motor, power quality, voltage waveform distortions, subharmonics.

1. INTRODUCTION

The voltage waveform in an electric power system is not perfectly sinusoidal. Usually, aside from the fundamental component, it also contains undesirable components. Typically these are harmonic contamination. Furthermore, in certain systems [Barros, de Apraiz and Diego 2007; Elvira-Ortiz et al. 2018] the voltage waveform also features components with a lower frequency or those which are not integer multiples of the fundamental component – subharmonics (subsynchronic interharmonics) or interharmonics. The cause of these voltage quality disturbances is the functioning of non-linear receivers, such as cycloconverters, inverters, and arc furnaces [Testa and Langella 2005; Bollen and Gu 2006; Sürgevil and Akpnar 2009; Basic 2010]. Furthermore, subharmonic and interharmonic voltages can be caused by renewable energy sources – wind farms and photovoltaic power plants [Bollen and Gu 2006; Kovaltchouk et al. 2016, Xie et al. 2017; Elvira-Ortiz et al. 2018]. It should also be noted that cyclic voltage fluctuations can be considered as the superposition of subharmonics and interharmonics [Tennakoon, Perera and

Robinson 2008]. Voltage fluctuations are frequently related to the operation high power receivers, e.g. arc furnaces, ironworking roller drives, etc. [Bollen and Gu 2006; Sürgevil and Akpnar 2009; Hsu, Chen and Lin 2011]. A similar effect can be caused by low-powered receivers [Bollen and Gu 2006].

Subharmonics are considered to be particularly harmful power quality disturbance. They cause saturation of transformer magnetic cores, light flickers and fluctuations in synchronous generator torque, among other issues [Tennakoon, Perera and Robinson 2008; Sürgevil and Akpnar 2009]. In an induction motor, they may cause local saturation of the magnetic circuit, torque and rotational speed fluctuations, increased power losses, increased winding temperatures and accelerated insulation system ageing [de Abreu and Emanuel 2002; Testa and Langella 2005; Tennakoon, Perera and Robinson 2008; Sürgevil and Akpnar 2009; Stumpf et al. 2010; Gnaciński and Pepliński 2014; Ghaseminezhad et al. 2017a,b; Zhao et al. 2014, 2017]. Despite the severe harm that voltage subharmonics cause, no limit values have been included in the relevant standards or regulations to date. According to the EN 50160 Voltage Characteristics of Electricity Supplied by Public Distribution Systems standard [EN 50160 2010], determining the acceptable subharmonic and interharmonic levels requires more experience.

The effects of the subharmonics on the functioning of an induction motor are discussed, for example, in [de Abreu and Emanuel 2002; Testa and Langella 2005; Tennakoon, Perera and Robinson 2008; Sürgevil and Akpnar 2009; Stumpf et al. 2010; Gnaciński and Pepliński 2014; Ghaseminezhad et al. 2017a,b; Zhao et al. 2014, 2017]. However, it must be noted that in most of these papers, the relevant calculations were performed using methods based on the dq transform and on the induction motor transformer type equivalent circuit. The above methods have limited application in analysing induction motors with voltage supplies containing subharmonics, which in some cases may lead to erroneous results [Gnaciński and Pepliński 2014; Ghaseminezhad et al. 2017a]. The results of evaluating induction motors with voltage supplies containing subharmonics, obtained from field tests or experimental methods, are included in the literature [Gnaciński and Pepliński 2014; Ghaseminezhad et al. 2017a,b], although it should be noted that they only concern low-power motors. This paper presents the results of the preliminary tests of a 200 kW motor, obtained using the finite elements method.

2. MODELLING THE MOTOR

The paper presents the results of simulation tests on a 3SIE355ML6A type squirrel-cage induction motor with a rated power of 200 kW, produced by Zakład Maszyn Elektrycznych EMIT (Z.M.E. EMIT), Cantoni Group. The rated parameters of the motor in question are shown in table 1. The motor had delta connected stator windings.

Table 1. Rated parameters of the 3SIE355ML6A type motor

Rated power	**200 kW**
Rated voltage	400 V (delta)
Rated frequency	50 Hz
Rated current	350 A
Power factor	0.86
Rated efficiency	95.8%
Rated speed	989 rpm

Source: Engineering documentation for 3SIE355ML6A type motors designed and produced by Zakład Maszyn Elektrycznych EMIT S.A., Cantoni Group in Żychlin.

The motor field model in question was created in the ANSYS Maxwell environment. The 2D model was generated from the RMxprt model after entering all the geometric dimensions of the motor, either known or determined on the basis of the engineering documentation. In the 2D model, the parameters of the materials used to produce the motor were also specified. Based on the motor heating test, performed at Z.M.E. EMIT, a winding resistance corresponding to the actual operating temperature was assumed. A standard Tau mesh (Fig. 1) available in Maxwell 18.0.0 was used for the calculations, as it allowed a mesh to be created comprising triangular elements with side dimensions no greater than 4.35 mm for the motor winding, 4.85 mm for the stator winding, and 16 mm for other elements. The integration step was assumed at 0.1 ms.

To verify the model, the calculation results were compared to the motor heating test results. A constant rotational speed of 990.5 rpm was assumed for the calculation, as measured during the test, and the voltage RMS value of 397 V, corresponding to the effective voltage value during the test. A summary of the measurement and calculation results is shown in Table 2. Based on the obtained calculation results, it was decided that the motor model prepared in the Maxwell environment was consistent with the motor, factory number 159932, used as the object of testing at Z.M.E. EMIT.

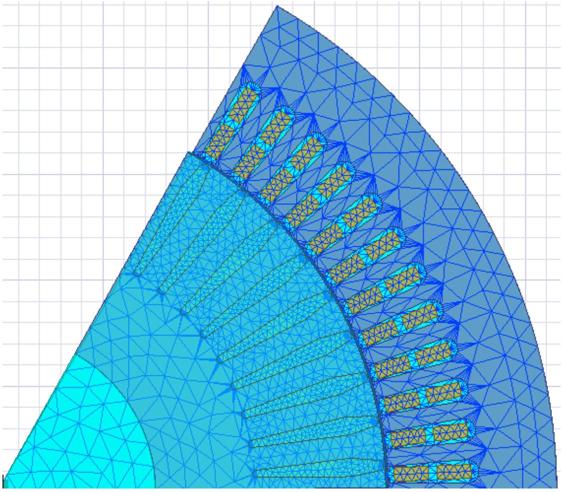

Fig. 1. Mesh segments

Source: original study.

Table 2. Comparison of 2D model calculations with the motor test results

Parameter	**Test result value**	**Calculated value**
Motor current	356.7 A	357.4 A
Power factor cos φ	0.853	0.858
Power losses	9150 W	9105 W

Source: Report no. 2/NZ/17 concerning tests of a 3SIE355ML6A type motor made by Zakład Maszyn Elektrycznych EMIT S.A., and the original study.

3. TEST RESULTS

The results of the preliminary testing of the effects of voltage subharmonics on the currents and motor power losses are presented below. The calculations were made for the fundamental component of the power supply voltage and for the rated rotation speed. In practice, assuming a constant rotational speed is component with operation under a load having a moment of inertia significantly higher than the motor's moment of inertia. For all cases analysed, the voltage subharmonic value was equal to 1% of the fundamental constituent. It should be noted that a subharmonic of a similar value was observed in the [Elvira-Ortiz et al. 2018] study.

Fig. 2 shows the motor current waveform for a subharmonic with a frequency f_{sh} = 5 Hz, and Fig. 3 shows the current waveform for a subharmonic with a frequency f_{sh} = 45 Hz.

The spectra for the waveforms in question are shown in Fig. 4. The voltage subharmonic with a frequency f_{sh} = 5 Hz caused the flow of a current subharmonic with an amplitude of I_{sh} = 143 A, which is 49.2% of the fundamental component. For a voltage subharmonic with a frequency f_{sh} = 45 Hz, the value of the current subharmonic was much lower, at I_{sh} = 13.7 A, i.e. 4.7% of the fundamental component. Furthermore, both spectra contain interharmonics of lower values.

The current subharmonic amplitude as a function of frequency is shown in Fig. 5.

The next figure (Fig. 6) presents the characteristic of the ratio of effective motor current value to rated value, as a function of voltage subharmonic frequency. The highest increase in current, of 12%, occurs for the 5Hz subharmonics. It results in additional power losses in windings.

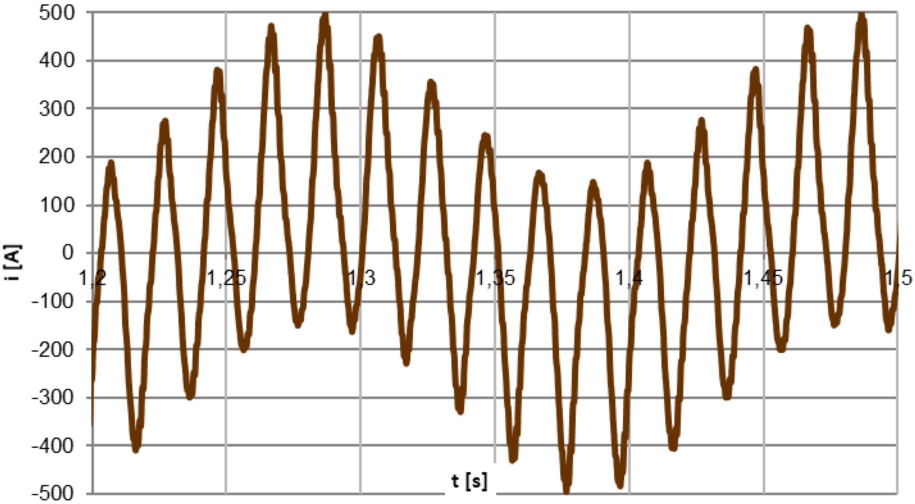

Fig. 2. Motor current waveform for a voltage subharmonic of U_{sh} = 1.0% U_{rat}, frequency f_{sh} = 5 Hz

Source: original study.

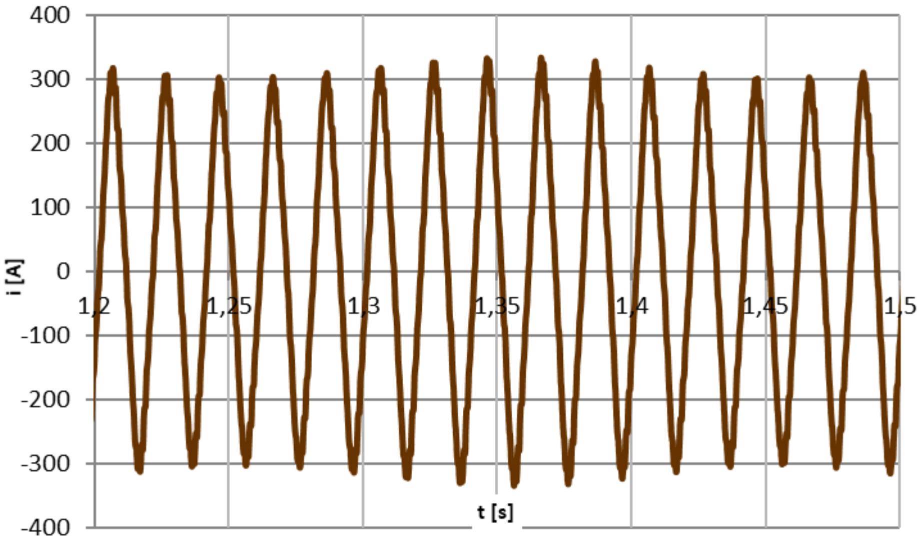

Fig. 3. Motor current waveform for a voltage subharmonic of U_{sh} = 1.0% U_{rat}, frequency f_{sh} = 45 Hz

Source: original study.

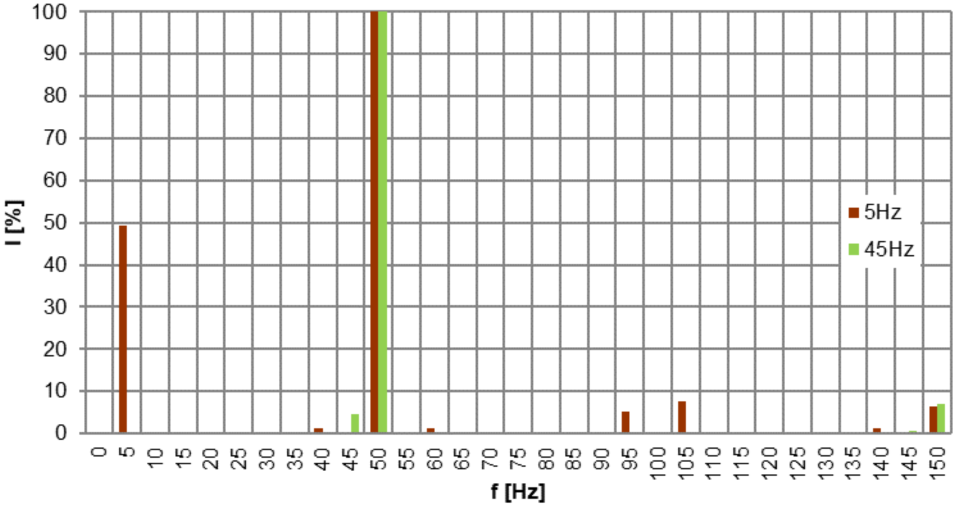

Fig. 4. Motor current spectra for a voltage subharmonic of U_{sh} = 1.0% U_{rat}, frequency f_{sh} = 45 Hz

Source: original study.

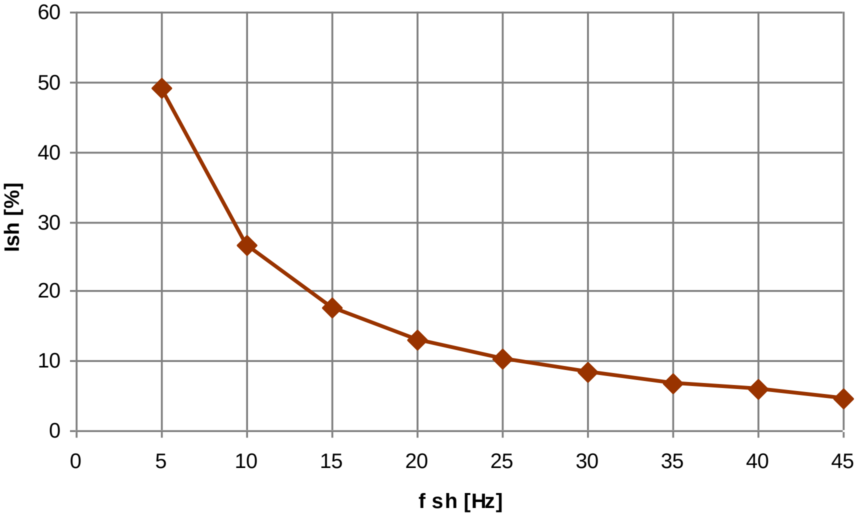

Fig. 5. Percentages of subharmonic currents vs subharmonic voltage frequency

Source: original study.

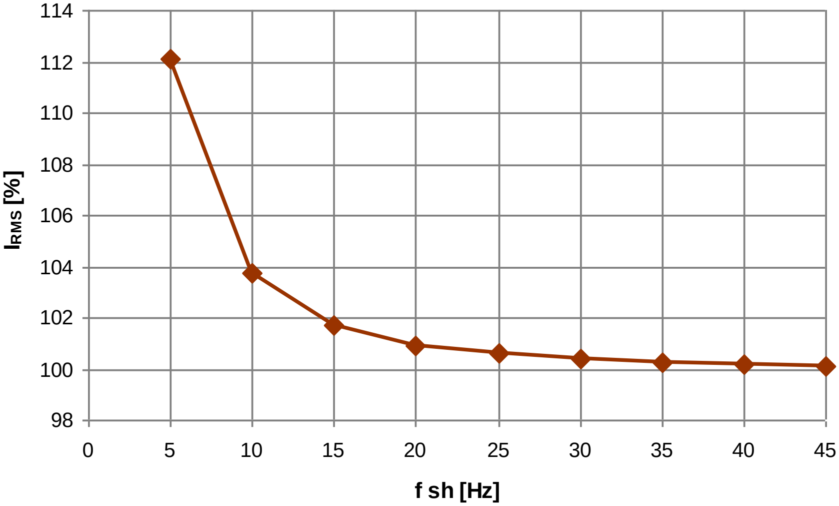

Fig. 6. Percentage effective motor current values vs subharmonic voltage frequency

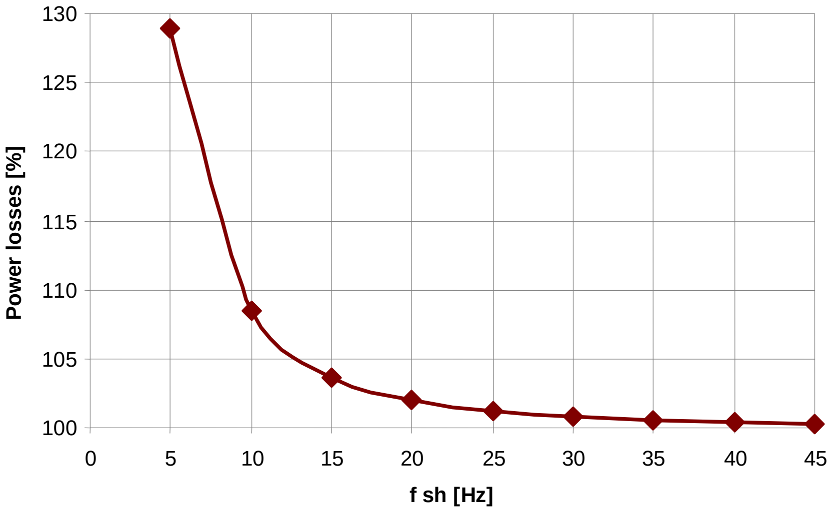

Fig. 7. Percentage power loss values vs subharmonic voltage frequency

Source: original study.

Fig. 7 shows the total losses in the motor (relative to the value of losses under rated conditions) as a function of the voltage subharmonics. For a frequency of 5 Hz, the power losses is 28.9%, while for frequencies higher than approx. 30 Hz they are practically negligible.

For a coarse motor heating analysis it can be assumed that the winding temperature increase is approximately proportional to the power losses in the machine. For the 10 Hz subharmonic, the motor power losses increase causes an estimate temperature rise of approx. 5 K, while for the 5 Hz subharmonic the temperature increase is as much as 18 K. For the studied motor, the temperature increase during the heating test was 61.3 K [Report no. 2/NZ/17 by Z.M.E. EMIT], while for a motor without a heat reserve, accelerated heat ageing of the insulation system may occur. For this reason, additional analysis is necessary of high-power motors powered by voltages containing low-frequency subharmonics.

4. CONCLUSIONS

The calculation results indicate a particularly significant increase in effective motor current value and power losses for subharmonics at frequencies below 10 Hz. In practice, the low-frequency subharmonics that occur in actual electric power systems [Elvira-Ortiz et al. 2018] could lead to overheating and premature failure of machines with similar parameters. It should also be noted that the motor in question was much more susceptible to voltage subharmonics than low-power engines, the results for which are shown in [Gnaciński and Pepliński 2014]. Consequently, it is advisable to conduct further studies on the effects of voltage subharmonics on high- and extremely high-powered motors. Further studies should include testing of engines with powers ranging from 200 kW to 5.6 MW using field test methods.

REFERENCES

de Abreu, 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.

Barros, J., de Apraiz, M., Diego, R.I., 2007, *Measurement of Subharmonics in Power Voltages*, Power Tech IEEE Conference, Lausanne, Switzerland, 1–5 July, pp. 1736–1740.

Basic, D., 2010, *Input Current Interharmonics of Variable-Speed Drives Due to Motor Current Imbalance*, IEEE Transactions on Power Delivery, vol. 25, no. 4, pp. 2797–2806.

Bollen, M.H.J., Gu, I.Y.H., 2006, *Signal Processing of Power Quality Disturbances*, Wiley, New York, USA.

Dokumentacja konstrukcyjna silnika typu 3SIE355ML6A zaprojektowanego i wykonanego w Zakładzie Maszyn Elektrycznych EMIT S.A. Grupa Cantoni w Żychlinie

Elvira-Ortiz, D.A., Osornio-Rios, R.A., Morinigo-Sotelo, D., Rostro-Gonzalez, H., Romero-Troncoso, R.J., 2018, *Power Quality Monitoring System under Different Environmental and Electric Conditions*, 18th International Conference on Harmonics and Quality of Power (ICHQP), Ljubljana, Slovenia.

EN 50160, 2010, *Voltage characteristics of electricity supplied by public distribution network*.

Ghaseminezhad, M., Doroudi, A., Hosseinian, S.H., Jalilian, A., 2017a, *Analysis of Voltage Fluctuation Impact on Induction Motors by an Innovative Equivalent Circuit Considering the Speed Changes*, IET Generation, Transmission & Distribution, vol. 11, no. 2, pp. 512–519.

Ghaseminezhad, M., Doroudi, A, Hosseinian, S.H., Jalilian, A., 2017b, *An Investigation of Induction Motor Saturation under Voltage Fluctuation Conditions*, Journal of Magnetics, vol. 22, no. 2, pp. 306–314.

Gnaciński, P., Pepliński, M., 2014, *Induction Cage Machine Supplied with Voltage Containing Subharmonics and Interharmonics*, IET Electric Power Applications, vol. 8, no. 8, pp. 287–295.

Hsu, C.T., Chen, C.S., Lin, C.H., 2011, *Electric Power System Analysis and Design of an Expanding Steel Cogeneration Plant*, IEEE Transactions on Industry Appl., vol. 47, no. 4, pp. 1527–1535.

Kovaltchouk, T., Armstrong, S., Blavette, A., Ahmed H.B., Multon B., 2016, *Wave Farm Flicker Severity: Comparative Analysis and Solutions*, Renewable Energy, vol. 91, pp. 32–39.

Sprawozdanie nr 2/NZ/17 z próby silnika 3SIE355ML6A Zakładu Maszyn Elektrycznych EMIT S.A.

Stumpf, P., Varga, Z., Sepsi, T.D., Jardan, R.K., Nagy, I., 2010, *Ultrahigh Speed Induction Machine Overheated by Subharmonics of PWM Inverter*, Proc. IEEE, 36th Annual Conference on Industrial Electronics Society, Glendale, AZ, USA, pp. 1754–1759.

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

Tennakoon, S., Perera, S., Robinson, D., 2008, *Flicker Attenuation—Part I: Response of Three-Phase Induction Motors to Regular Voltage Fluctuations*, IEEE Transactions on Power Delivery, vol. 23, no. 2, pp. 1207–1214.

Testa, A., Langella, R., 2005, *Power System Subharmonics,* Power Engineering Society General Meeting, San Francisco, CA, USA, pp. 2237–2242.

Xie, X., Zhang, X., Liu, H., Li, Y., Zhang, C., 2017, *Characteristic Analysis of Subsynchronous Resonance in Practical Wind Farms Connected to Series-Compensated Transmissions*, IEEE Transactions on Energy Conversion, vol. 32, no. 3, pp. 1117–1126.

Zhao, K., Cheng, L., Zhang, C., Nie, D., Cai, W., 2017, *Induction Motors Lifetime Expectancy Analysis Subject to Regular Voltage Fluctuations,* IEEE In Electrical Power and Energy Conference (EPEC), Saskatchewan, Canada, pp. 1–6.

Zhao, K., Ciufo, P., Perera, S., 2014, *Performance of Adjustable Speed Drives Subject to Regular Voltage Fluctuations*, IEEE 16th International Conference Harmonics and Quality of Power (ICHQP), Bucharest, Romania, pp. 253–257.