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PRELIMINARY INVESTIGATIONS OF INDUCTION MOTOR SUPPLIED WITH VOLTAGE CONTAINING SUBRHARMONICS USING FIELD AND FIELD-CIRCUIT METHODS

BADANIA WSTĘPNE SILNIKA INDUKCYJNEGO ZASILANEGO NAPIĘCIEM ZAWIERAJĄCYM SUBHARMONICZNE Z WYKORZYSTANIEM METODY POLOWEJ ORAZ POLOWO-OBWODOWEJ

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Abstract: This work is devoted to preliminary investigations concerning the effect of an inertia moment and load-speed characteristics on currents, power losses and windings temperature of an induction machine supplied with voltage containing subharmonics. The results of numerical simulations are presented for a totally-enclosed fan-cooled cage induction motor of rated power 3 kW. The computations were carried out with a field method and a hybrid field-circuit method. The results of preliminary investigations show that load properties may have significant influence on currents, power losses and windings temperature of an induction machine under considered power quality disturbances.

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

Streszczenie: Artykuł jest poświęcony wstępnym badaniom wpływu momentu bezwładności i charakterystyki obciążenia na prądy, straty mocy oraz temperaturę uzwojeń silnika indukcyjnego, zasilanego napięciem zawierającym subharmoniczne. Wyniki obliczeń numerycznych przedstawiono dla silnika indukcyjnego klatkowego budowy całkowicie zamkniętej o mocy 3 kW. Obliczenia wykonano za pomocą metody polowej oraz polowo-obwodowej. Prezentowane wyniki badań dowodzą, że właściwości obciążenia mogą mieć istotny wpływ na prądy, straty mocy oraz temperaturę uzwojeń silnika indukcyjnego w warunkach rozważanych zaburzeń.

Słowa kluczowe: metoda elementów skończonych, silnik indukcyjny, jakość napięcia, odkształcenia przebiegu napięcia, subharmoniczne.

1. INTRODUCTION

Energy consumers are exposed to impact of various power quality disturbances, like voltage deviation, voltage unbalance and voltage waveform distortions. Occurrence of voltage waveform distortions means that voltage waveform is contaminated with harmonics, and in some cases [Barros, de Apraiz and Diego 2007] also with interharmonics and subharmonics – that is components of frequency less than the fundamental one. Voltage subharmonics are caused by non-linear loads, like inverters, cycloconverters, arc furnaces etc. [Testa and Langella 2005; Bolen and Gu 2006; Sürgevil and Akpnar 2009; Basic 2010]. Another reason subharmonics occurrence is work of renewable sources of energy [Bolen and Gu 2006; Karimi et al. 2016, Kovaltchouk et al. 2016, Xie et al. 2017]. It should be noted that periodically voltage fluctuations can be considered as superposition of subharmonics and interharmonics [Tennakoon, Perera and Robinson 2008]. Voltage fluctuations are often caused by such loads like arc furnaces, railway traction, and rolling mills [Bolen and Gu 2006; Sürgevil and Akpnar 2009; Hsu, Chen and Lin 2011]. Also, low power energy receivers [Bolen and Gu 2006] can result in local voltage fluctuations.

Voltage subharmonics may significantly disturb work of light sources, synchronous generators and transformers [Langella, Testa and Emanuel 2008; Tennakoon, Perera and Robinson 2008; Sürgevil and Akpnar 2009]. They also exert negative effect on induction motors. Among the other things, voltage subharmonics cause a local saturation of magnetic circuit, speed fluctuations, an increase in magnetising and rms current, additional power losses, overheating and thermal loss of operational life [de Abreu and Emanuel 2002; Fuchs, Roesler and Masoum 2004; Testa and Langella 2005; Gnaciński, Pepliński and Szweda 2008; Tennakoon, Perera and Robinson 2008; Sürgevil and Akpnar 2009; Stumpf et al. 2010; Zhao, Ciufo and Perera 2012; 2014; Gnaciński and Pepliński 2014; Ghaseminezhad et al. 2017a, b; Zhao et al. 2017]. Although voltage subharmonics have harmful effect on generators, transformers and various energy receivers, their permissible levels are not yet specified in power quality standards. According to the standard EN 50160 Voltage Characteristics of Electricity Supplied by Public Distribution Systems [EN 50160 2010], introduction of their admissible levels requires more experience.

The effect of voltage subharmonics on induction machines was presented in numbers of research works [de Abreu and Emanuel 2002; Fuchs, Roesler and Masoum 2004; Testa and Langella 2005; Gnaciński, Pepliński and Szweda 2008; Tennakoon, Perera and Robinson 2008; Sürgevil and Akpnar 2009; Stumpf et al. 2010; Zhao, Ciufo and Perera 2012; 2014; Gnaciński and Pepliński 2014; Ghaseminezhad et al. 2017a, b; Zhao et al. 2017]. They are devoted to analysis of currents, magnetic flux, power losses, speed fluctuations, windings temperature, operational life and developing of new machine models. It should be stressed that the effect of load parameters on currents, power losses and windings temperature has not been presented in the previous papers. For each machine the results of experimental investigations and calculations are shown for one moment of inertia and one torque-speed characteristic. Moreover, in many cases the load parameters are not taken into consideration. For example, calculations are often carried out with a transformer-type equivalent circuit [de Abreu and Emanuel 2002; Fuchs, Roesler and Masoum 2004; Gnaciński and Pepliński 2014]. In this method speed fluctuations, a moment of inertia and torque-speed characteristic are omitted.

This paper deals with preliminary investigations concerning the effect of inertia moment and load-speed characteristics on currents, power losses and windings temperature of an induction machine supplied with voltage containing subharmonic injection. The computations were carried out with a field method and a hybrid field-circuit method.

2. MACHINE MODELS

The electromagnetic calculations were performed with a finite element method (FEM), by using ANSYS Maxwell environment and a 2D model. The applied mesh (Fig. 1) consists of about 22 000 elements. The computations are based on solving of the magnetic field equation. In the general case (including machines with permanent magnets) it can be expressed as follows [ANSYS technical documentation]:

$$\nabla \times \upsilon \nabla \times A = J_s - \sigma \frac{\partial A}{\partial t} - \sigma \nabla V + \nabla \times H_c + \sigma v \times \nabla \times A \tag{1}$$

where:

- H_c – permanent magnet coercive,
- v – velocity of moving part,
- A – vector magnetic potential,
- V – electric potential,
- υ – reluctance,
- J_s – source current density,
- σ – electrical conductivity.

The model was elaborated for a totally-enclosed fan-cooled induction cage motor TSg 100L-4B type. The machine parameters are as follows: the rated power – 3 kW, the rated current – 6.9 A, the rated voltage – 380 V, the rated rotational speed – 1415 rpm, a moment of inertia – 0.0082 kg m^2, windings connection method – delta. More parameters are given in [Gnaciński 2008; Gnaciński and Pepliński 2014]. It should be noted that the machine is characterised by a comparatively strongly saturated magnetic circuit [Gnaciński 2014]. An exemplary solution of the magnetic flux density in shown in Fig. 2.

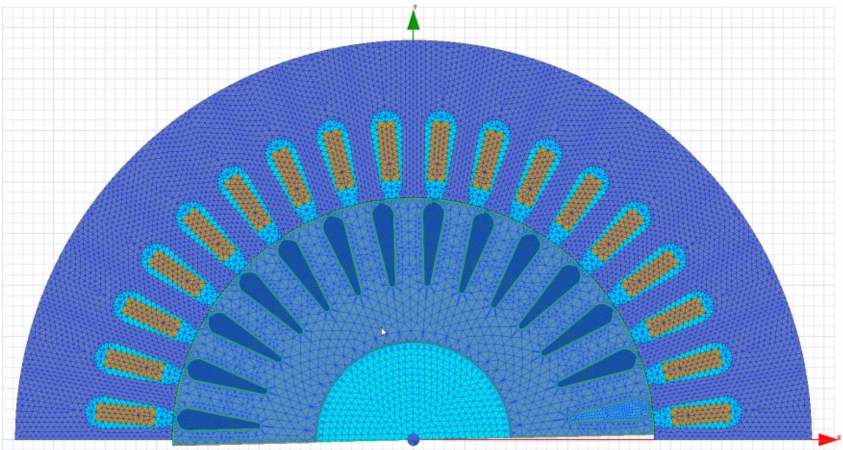

Fig. 1. Applied mesh

Rys. 1. Zastosowana siatka podziału

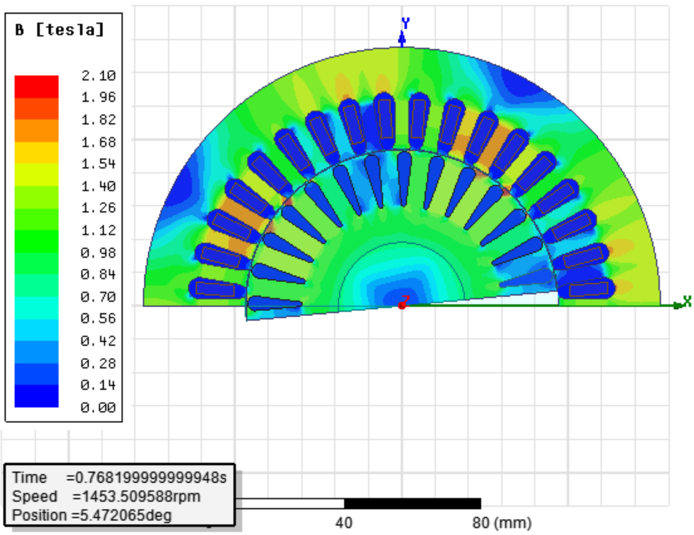

Fig. 2. Magnetic flux density for the constant load torque of the rated value, moment of load inertia equal to 50% of motor inertia and supply voltage containing subharmonic of value U_{sh} = 1.5% U_{rat}, frequency f_{sh} = 20 Hz

Rys. 2. Rozkład indukcji magnetycznej dla stałego momentu obciążenia o wartości znamionowej, momentu bezwładności obciążenia równej 50% momentu bezwładności silnika oraz napięcia zasilania zawierającego subharmoniczną o wartości U_{sh} = 1,5% U_{rat} i częstotliwości f_{sh} = 20 Hz

Source: own study.

Power losses determined with the field model are used as input data for thermal calculations performed with a circuit method. It should be noted that Joule losses are recalculated for the actual windings temperature. The applied thermal model – equivalent thermal network – is presented in Fig. 3. In the network capacities correspond to thermal capacities in the machine, resistances – to thermal resistances, voltages – to temperatures, currents – to heat flow. More detailed description of the equivalent thermal network is given in [Gnaciński 2008; Gnaciński 2014].

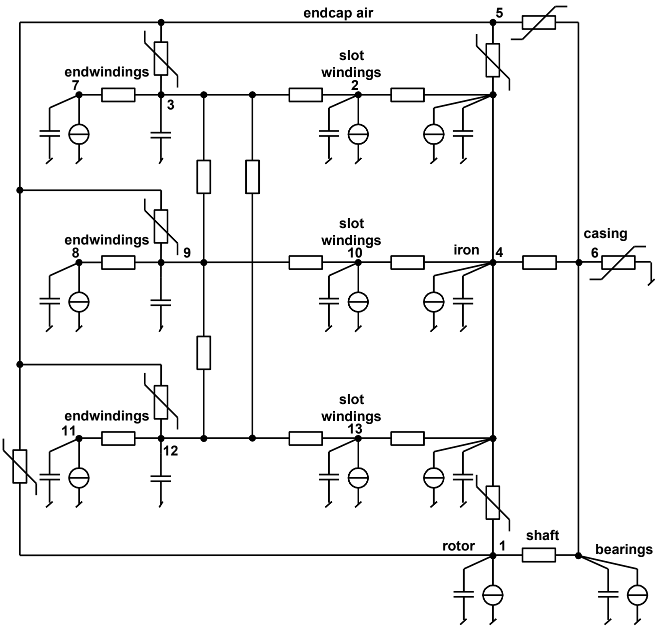

Fig. 3. Equivalent thermal network of an induction machine

Rys. 3. Zastępczy schemat cieplny silnika indukcyjnego

Source: [Gnaciński 2008].

3. RESULTS OF INVESTIGATIONS

Below there are presented the results of preliminary research on the effect on the properties of load on currents, power losses and windings temperature.

Fig. 4–7 show spectrums of the supply motor current, for voltage containing subharmonic of value U_{sh} = 1.5% U_{rat} and frequency f_{sh} = 20 Hz. It should be noted that similar values of voltage subharmonics were observed for a short period of time during subharmonic resonance of a wind farm [Xie et al. 2017] and that the motor under investigation is especially susceptible for subharmonics of this frequency.

The results of calculations presented in Fig. 4, 5, 6 correspond to the relative moment of load inertia (related to the moment of motor inertia) equal $j = 0.5$, and in Fig. 6 – to $j = 15$. The investigations were carried out for the following torque-speed characteristics [Gross 2007]:

- constant load torque – Fig. 4;
- linear load torque (load torque proportional to the rotational speed) – Fig. 5, 7;
- parabolic load torque (load torque proportional to the squared rotational speed) – Fig. 6.

Additionally, in Fig. 8, 9 are presented waveforms of the testing voltage and motor current for $j = 0.5$ and constant load torque.

For $j = 0.5$ in the motor current occurs a subharmonic of value $I_{sh} = 32.8\%\ I_{rat}$, $I_{sh} = 34.4\%\ I_{rat}$ and $I_{sh} = 32\%\ I_{rat}$ for the constant load torque (Fig. 3, 4), linear load torque (Fig. 4, 5) and parabolic load torque (Fig. 6), correspondingly. Because of rotational speed fluctuations, the current subharmonics are accompanied with interharmonics of frequency equal $2f_1 - f_{sh}$, that is 80 Hz (on the basis of [Tennakoon]). Their values are $I_{ih} = 9.4\%\ I_{rat}$, $I_{ih} = 9.3\%\ I_{rat}$ and $I_{ih} = 9\%\ I_{rat}$, respectively. Further, for $j = 15$ and linear load torque (Fig. 6, 7) the current subharmonic and interharmonic are $I_{sh} = 22.3\%\ I_{rat}$ and $I_{ih} = 1\%\ I_{rat}$, It should be noted that analogous computations were carried out also for the other torque-speed characteristics, but the disparities are inconsiderable.

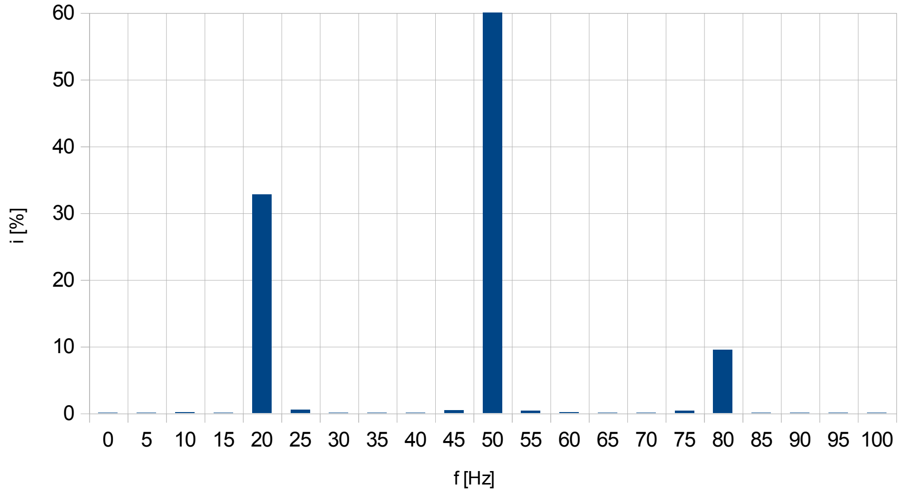

Fig. 4. Current spectrum for constant load torque, the relative moment of inertia $j = 0.5$ and voltage subharmonic of value $U_{sh} = 1.5\%\ U_{rat}$, frequency $f_{sh} = 20$ Hz

Rys. 4. Widmo prądu dla stałego momentu obciążenia, względnego momentu bezwładności $j = 0{,}5$ oraz subharmonicznej napięcia o wartości $U_{sh} = 1{,}5\%\ U_{rat}$ i częstotliwości $f_{sh} = 20$ Hz

Source: own study.

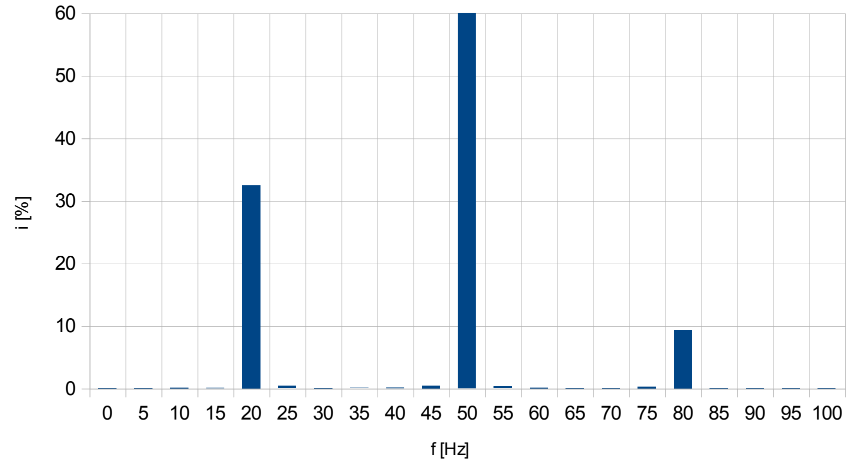

Fig. 5. Current spectrum for linear load torque, the relative moment of inertia *j* = 0.5 and voltage subharmonic of value U_{sh} = 1.5% U_{rat}, frequency f_{sh} = 20 Hz

Rys. 5. Widmo prądu dla momentu obciążenia o charakterystyce liniowej, względnego momentu bezwładności *j* = 0,5 oraz subharmonicznej napięcia o wartości U_{sh} = 1,5% U_{rat} i częstotliwości f_{sh} = 20 Hz

Source: own study.

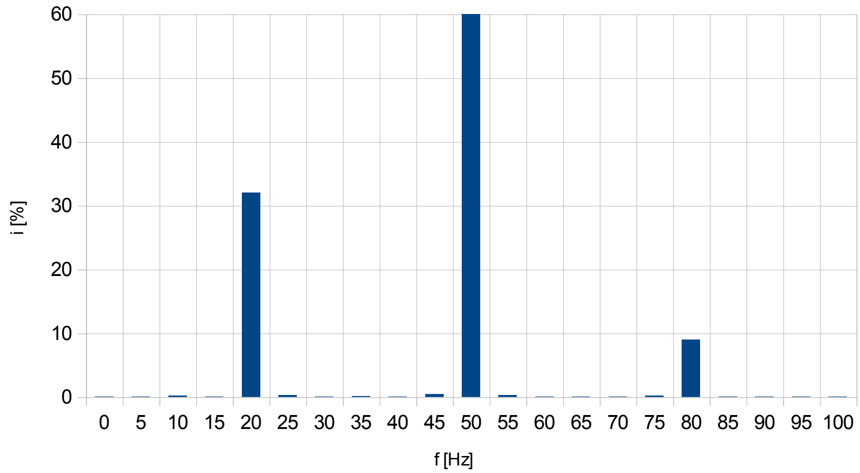

Fig. 6. Current spectrum for parabolic load torque, the relative moment of inertia *j* = 0.5 and voltage subharmonic of value U_{sh} = 1.5 % U_{rat}, frequency f_{sh} = 20 Hz

Rys. 6. Widmo prądu dla momentu obciążenia o charakterystyce parabolicznej, względnego momentu bezwładności *j* = 0,5 oraz subharmonicznej napięcia o wartości U_{sh} = 1,5% U_{rat} i częstotliwości f_{sh} = 20 Hz

Source: own study.

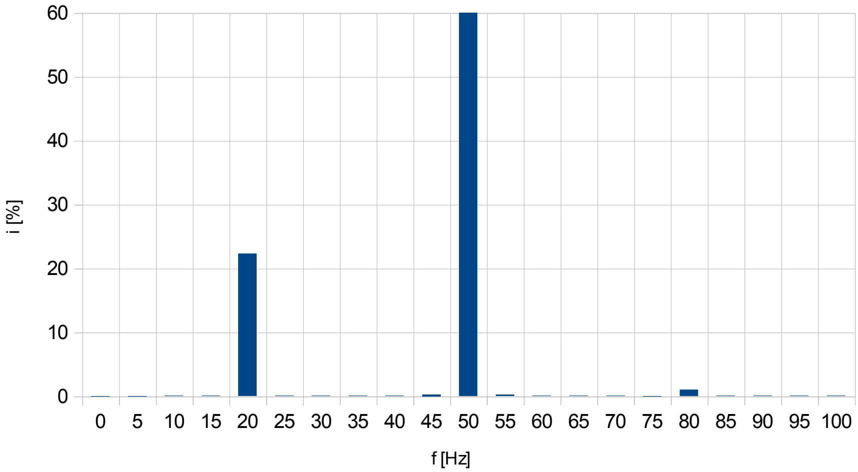

Fig. 7. Current spectrum for linear load torque, the relative moment of inertia j = 15 and voltage subharmonic of value U_{sh} = 1.5% U_{rat}, frequency f_{sh} = 20 Hz

Rys. 7. Widmo prądu dla liniowego momentu obciążenia, względnego momentu bezwładności j = 15 oraz subharmonicznej napięcia o wartości U_{sh} = 1,5% U_{rat} i częstotliwości f_{sh} = 20 Hz

Source: own study.

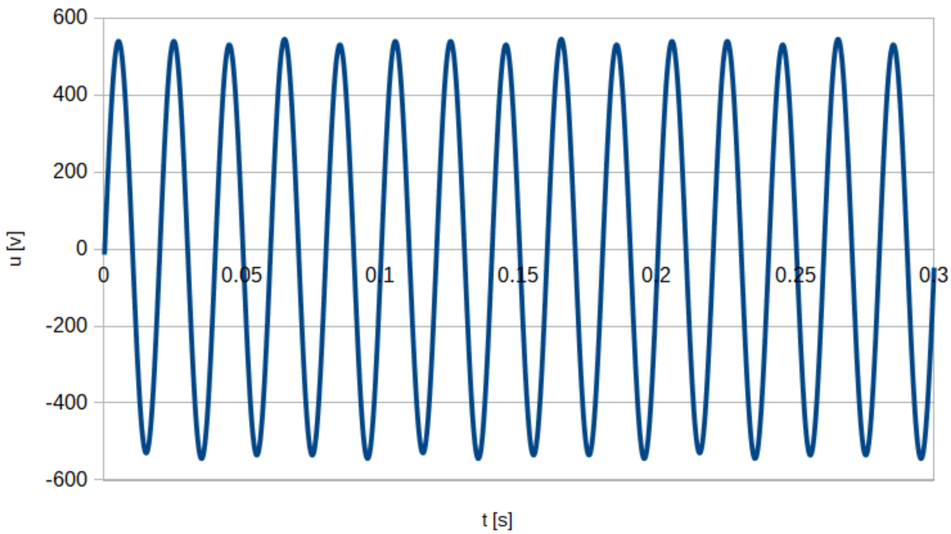

Fig. 8. Waveform of the testing voltage

Rys. 8. Przebieg napięcia testowego

Source: own study.

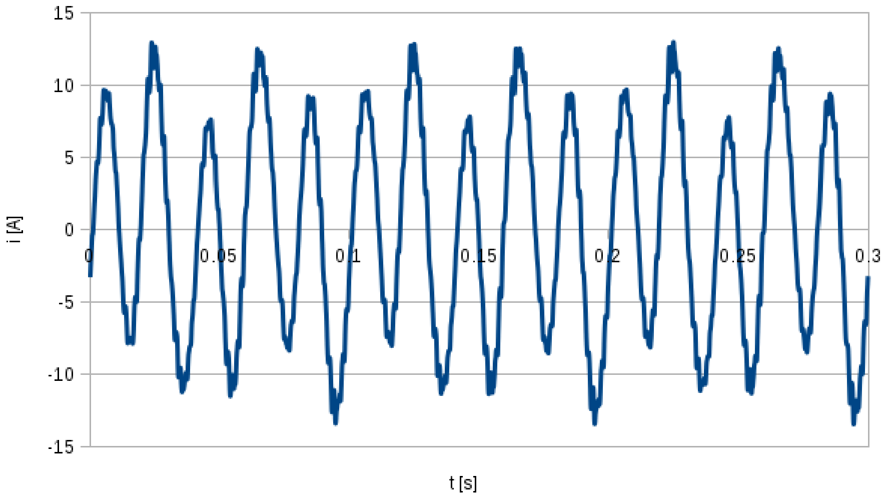

Fig. 9. Current waveform for constant load torque, the relative moment of inertia *j* = 0.5 and voltage subharmonic of value U_{sh} = 1.5% U_{rat}, frequency f_{sh} = 20 Hz

Rys. 9. Przebieg prądu dla stałego momentu obciążenia, względnego momentu bezwładności *j* = 0,5 oraz subharmonicznej napięcia o wartości U_{sh} = 1,5% U_{rat} i częstotliwości f_{sh} = 20 Hz

Source: own study.

It is also worth adding that the case of *j* = 15 and linear load torque corresponds to the investigated machine loaded with a DC generator type PKM a44a/101, and the results of field calculations are generally in accordance with experimental ones [Gnaciński and Pepliński 2014]. A comparison of measured and calculated current subharmonics and increases in windings temperatures for various frequencies of voltage subharmonics will be presented in a separate paper. Additionally, for *j* = 15 the current subharhamonic value calculated with FEM is approximately equal to its value determined with a transformer-type equivalent scheme [Gnaciński and Pepliński 2014]. As it was mentioned above, it is frequently used for analysis of an induction machine under subharmonics. However, taking into account that in this computation method speed fluctuations are omitted, its applications should be restricted for motors driving loads of high inertia moment. More detailed recommendations concerning this method will be presented in a separate paper.

One of negative effects caused by voltage subharmonics is an increase in power losses and windings temperature of an induction motor. The results of preliminary investigations concerning the undesirable phenomena are presented in Tab. 1 for a voltage subharmonic of value U_{sh} = 1.5% U_{rat}, frequency f_{sh} = 20 Hz and the considered inertia moments and load-speed characteristics. For *j* = 0.5 the increase in total power losses (related to its value in the nominal work conditions) occurring in the investigated motor is 14.4%, 14.2% and 13.8% for the constant load torque, linear load torque and parabolic load torque, respectively. The increase in end-windings temperature is equal to 18.5 K, 18.3 K and 17.7 K, correspondingly. Further, for j = 15 and linear load torque, the increase in power losses is 5.6% and in end-windings temperature – 7 K. It is also worth mentioning that the highest differences in power losses and windings temperature for various moments of inertia occur for frequency $f_{sh} \approx 20$ Hz. Detailed research on the considered issue will be presented in a separate paper.

The differences in current subharmonics, interharmonics, power losses and windings temperature for various moments and load-speed are probably caused by fluctuations of the rotational speed. For high moment of load inertia or parabolic load torque the fluctuations are suppressed, and consequently – the negative phenomena due to voltage subharmonics are less intense than for low moment of inertia and constant load torque.

In summary, the moment of load inertia has considerable influence on undesirable phenomena appearing in an induction machine under subharmonics. The load torque-speed characteristics have much less effect on currents, power losses and windings temperature.

Table 1. Relative increase in power losses (related to its value in the nominal work conditions) and increase in windings temperature caused by voltage subharmonic of U_{sh} = 1.5% U_{rat}, frequency f_{sh} = 20 Hz

Tabela 1. Względny wzrost strat mocy (odniesiony do strat w warunkach znamionowych) oraz wzrost temperatury uzwojeń spowodowany przez subharmoniczną o wartości U_{sh} = 1,5% U_{rat} i częstotliwości f_{sh} = 20 Hz

Case	Relative moment of load inertia [-]	Torque-speed characteristic	Relative increase in power losses [%]	Increase in windings temperature [K]
1	0.5	constant load torque	14.4	18.5
2	0.5	linear load torque	14.2	18.3
3	0.5	parabolic load torque	13.8	17.7
4	15	linear load torque	5.6	7

Source: own study.

4. CONCLUSIONS

The results of preliminary investigations show that the impact of a single voltage subharmonic on an induction machine considerably depends on loads properties. For a small moment of load inertia and constant load torque, a current subharmonic, power losses and an increase in windings temperature may be significantly greater than for a load of high inertia moment. Detailed investigations concerning the issue under consideration will be shown in a separate paper.

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