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DERATING OF AN INDUCTION MACHINE UNDER VOLTAGE AND FREQUENCY DEVIATION

OBCIĄŻALNOŚĆ MOCĄ SILNIKA INDUKCYJNEGO W WARUNKACH WYSTĘPOWANIA ODCHYLENIA NAPIĘCIA I CZĘSTOTLIWOŚCI

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Abstract: One of the most frequently appearing power quality disturbances is voltage deviation. In addition in autonomic power systems, e.g. in ships, frequency deviation often occurs. It causes additional power losses and increase in thermal loads of induction machines. This paper deals with an effect of voltage and frequency deviation on derating.

Keywords: electric machines, induction motors, heating.

Streszczenie: Jednym z najczęściej występujących zaburzeń jakości napięcia jest odchylenie jego wartości skutecznej. Ponadto w autonomicznych systemach elektroenergetycznych, np. na statkach, występują często odchylenia częstotliwości. Zaburzenia te powodują w silnikach indukcyjnych dodatkowe straty mocy i zwiększenie ich obciążalności cieplnej. Artykuł dotyczy wpływu odchyleń wartości skutecznej napięcia i częstotliwości na obniżenie wartości dopuszczalnej mocy i momentu silnika indukcyjnego.

Słowa kluczowe: maszyny elektryczne, silnik indukcyjny, nagrzewanie.

1. INTRODUCTION

An induction cage machine is one of the most widespread electrical receiver in the industrial applications. It is estimated that over 2/3 all electric receivers in civil power systems are asynchronous motors. In ships power systems induction motors are commonly used as prime movers of auxiliary machines in an engine room, thrusters and in some cases – screw propellers.

An asynchronous motor has simple construction and high reliability but it needs appropriate quality of supply voltage. Feeding induction machines with a voltage of lowered quality results in additional power losses. Consequently it causes higher windings temperature leading to faster aging of insulation system and significant reduction of the machine reliability and operational life [Fuchs, Roester and Kovacs 1986; de Abreu and Emanuel 2002; Gnaciński 2008a, b; 2009; Baptista et al. 2010].

According to rules of ship classification societies, the voltage deviation should not exceed +6%, -10%, and frequency deviation – ±5% [IEEE Std. 86-1987; Det Norske Veritas 2001; PN-EN 61000-2-4:2003; American Bureau of Shipping 2014; Mindykowski 2014; Lloyd's Register of Shipping 2018]. The effect of lowered voltage quality on induction machine significantly depends on machine properties, especially of – on properties of magnetic circuit. For example, 10% overvoltage may cause considerable overheating of a machine with a strongly saturated magnetic circuit and reduction in windings temperature of a motor with a weakly saturated magnetic circuit [Gnaciński 2008a, b; 2009]. Furthmore, for motors with a strongly saturated circuit an increase in magnetizing current under voltage subharmonics causes additional machine heating [Gnaciński and Pepliński 2014].

There are different methods to protect induction motor under lowered voltage quality. One of them is derating – appropriate reduction of the load [Gnacinski 2009; 2014]. An induction machine supplied with voltage of lowered quality is a subject of numerous works, dealing mostly with the effect of voltage deviation, voltage unbalance and voltage waveform distortion. The impact of frequency deviation on an induction motor is shown in [Gnaciński 2009; 2014; Budziłowicz and Gnaciński 2018].

This paper is devoted to the effect of frequency and voltage deviation on load-carrying capacity of a cage induction motor with comparatively weakly saturated magnetic circuit. It is worth mentioning that this work is an extension of analogous investigations [Budziłowicz and Gnaciński 2018] performed for machine with a comparatively strongly saturated magnetic circuit.

2. THE HEAT PHENOMENA IN AN INDUCTION MACHINE

Thermal processes in an induction motor are very complicated. The temperature distribution inside a machine is heterogeneous because of non-uniform power losses occurrence and interactions between neighbouring elements inside a motor. It should be noted that an asynchronous motor consists of many elements with completely different basic physical characteristics, e.g. specific heat and conductivity. The heat exchange in an induction motor takes place through conduction, convection and radiation. Heat conducting is the process of kinetic energy transmission from oscillating molecules with bigger energy to neighbouring molecules with lower energy. The heat transfer in solid anisotropic materials can be described by equation [Latek 1973; 1979]:

$$c\gamma \frac{\partial \Theta}{\partial t} - q_v = \left(\lambda_x \frac{\partial^2 \Theta}{\partial x^2} + \lambda_y \frac{\partial^2 \Theta}{\partial y^2} + \lambda_z \frac{\partial^2 \Theta}{\partial z^2} \right) \tag{1}$$

where:

c – average specific heat,
γ – average specific gravity,
Θ – temperature,
t – time,
q_v – heat transfer per time unit and volume unit,
$\lambda_x, \lambda_y, \lambda_z$ – resultant heat conductivity in axis direction x, y, z.

In practice during heat transfer analyses in electric machines some simplifications are assumed, e.g. that heat is exchanged through a flat wall, made of homogeneous material of constant specific conductivity without heat sources. Then the temperature drop in time unit while passing through wall layer can be expressed as follows [Latek 1973]:

$$\Delta\Theta = \frac{Q_t}{\lambda S}\delta \tag{2}$$

where:

Q_t – heat flow;
S – surfaces of walls layer;
δ – thickness of walls.

If we consider heat transfer through homogeneous cylinder of constant thermal conductivity, the temperature drop can be expressed as:

$$\Delta\Theta = \frac{Q_t}{2\pi\lambda l} ln \frac{r_2}{r_1} \tag{3}$$

where:

l – cylinder length,
r_1 – internal diameter of the cylinder,
r_2 – outside diameter of the cylinder.

Transmission of the heat flux through radiation is strictly related to geometric dimensions of the motor, material emissivity and properties of machine ambience. The heat transmission through radiation can be omitted e.g. for totally enclosed fan cooled induction motor working with rated speed. However, when motor works with reduced speed, heat transmission through radiation has significant contribution to the overall thermal balance.The heat flux radiated can be described by Stefan-Boltzman low [Latek 1973]:

$$q_p = k_p v_p \left(T^4 - T^4{}_{am}\right) \tag{4}$$

where:

q_p – heat radiated from considered surface within one second,
T – absolute temperature of surface in [K],
T_{am} – the ambient absolute temperature in [K],
k_p – constant for radiation from a black body 5.77·10-12 W/cm²·K,
v_p – relative radiation body per radiation from a black body.

The third way to heat transmission is convection, the heat transfer based on macroscopic matter motion of substance. Two types of convection can be distingnished: natural and forced. The natural convection is observed when medium surrounding cooling surface is not set in motion by external factors, e.g. ventilating equipment. The forced convection requires medium in motion toward cooling surface. The mechanism of heat transfer by convection is very complicated and heat transfer coefficient depends on many variables such as: heat exchange surface, shape of cooling surface, viscosity etc. Therefore the heat transfer is often assessed by the following expression [Latek 1973]:

$$q_k = c_k \sqrt{\delta_w}\, \Delta\vartheta^{1,25} \tag{5}$$

where:

q_k – heat transmission per surface unit of a natural convection per time unit,
c_k – coefficient value within the limits specified in 2.79..3.39 W/m²·K,
δ_w – the relative humidity of the air.

For forced cooling the heat transmission is much more intense than for natural cooling. The forced convection heat transfer mechanism is very complicated as it is for natural convection and depends on many variables such as: cooling factors (e.g. the air, hydrogen), flow of the coolant character (laminar, turbulent, transitional), the dimensions and cross sections of ventilation ducts etc. While considering the flow phenomena we define no dimension „criteria" which are different combination of characteristic parameters of the cooling medium. These parameters are called criteria of similarity and they allow to estimate character of the flow of the coolant in electric machines. One of these criterion is the Reynolds number expressed as:

$$Re = \frac{v\, l}{v_{kin}} \tag{6}$$

where:

v – air speed in a cross-section ducts,
l – linear dimension characterising air duct cross-section,
v_{kin} – air kinematic viscosity.

Reynolds number Re specifies similarity of hydrodynamic flows. Two flows with different kinematic viscosities and speeds in ducts of diameters d_1 i d_2 are similar when Reynolds number describing them are the same. The flow is laminar when Reynolds number is lower than critical Reynolds number, which according to work [L1] is R_{ekr} = 2010..3000. For bigger value of Reynolds number flow become turbulent.

3. SIMULATION MODEL OF AN INDUCTION MACHINE

The heat process in an induction motor can be examined with various methods. One of commonly used is a method of equivalent thermal network [Mellor and Turner 1988; Mellor, Roberts and Turner 1991; Boglietti, et al. 2003; 2005a, b; Gnaciński 2008a, b]. It is based on analogy between mathematical description of heat phenomena and the current flow in electrical circuits.

An analysis by this method requires using equivalent thermal network in the form of electrical scheme. For the purpose of elaboration of equivalent thermal network, a machine is divided into basic parts, such as: end-windings, slots windings, rotor core, etc. Every element in real machine corresponds to a node in equivalent scheme.The relevant potentials in particular nodes correspond to average or maximal temperatures in each part of the motor.

Thermal resistants beetwen each part of machine correspond to resistants in equivalent thermal network, while thermal capacity of particular parts of motor corresponds to electric capacity in the electric scheme. Current in equivalent scheme is an analogue of heat flow in the machine.The heat sources inside machines correspond to current sources.

The parameters of equivalent scheme can be determined with both theoretical and experimental way. The machine thermal equivalent network is usually formulated on the grounds of various assumptions, e.g. such as: machine is fully symmetrical, the influence of ambient conditions (ambient air temperature, pressure and relative humidity) on machine heating are omitted.

For the paper purpose the equivalent network presented in Fig. 1 is applied. Power losses are calculated with an equivalent circuit type T shown in Fig. 2. Detailed description and validation of the models are given in [Gnaciński 2009].

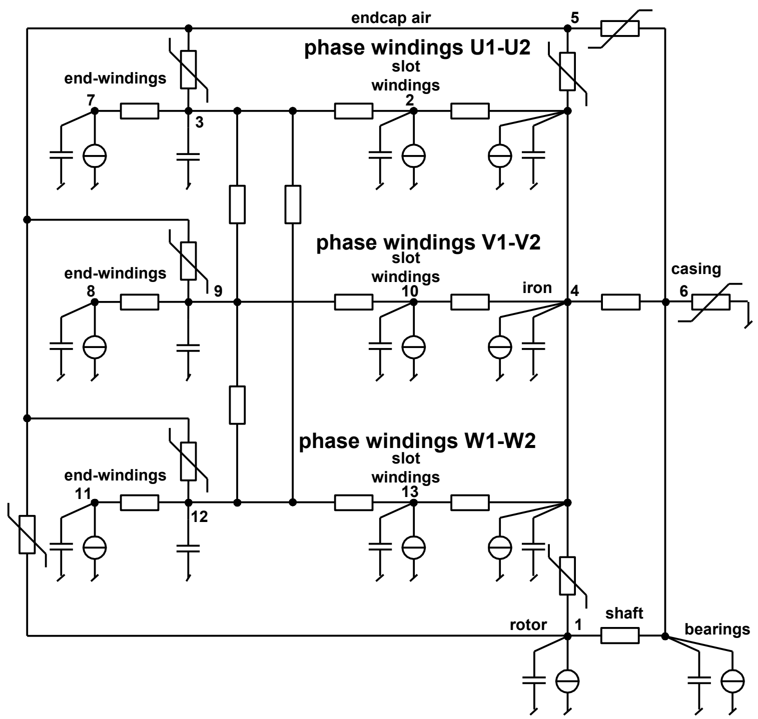

Fig. 1. The applied non-linear thermal network of a totally-enclosed induction cage motor [Gnaciński 2008]

Rys. 2. Nieliniowy cieplny schemat zastępczy silnika indukcyjnego budowy całkowicie zamkniętej [Gnaciński 2008]

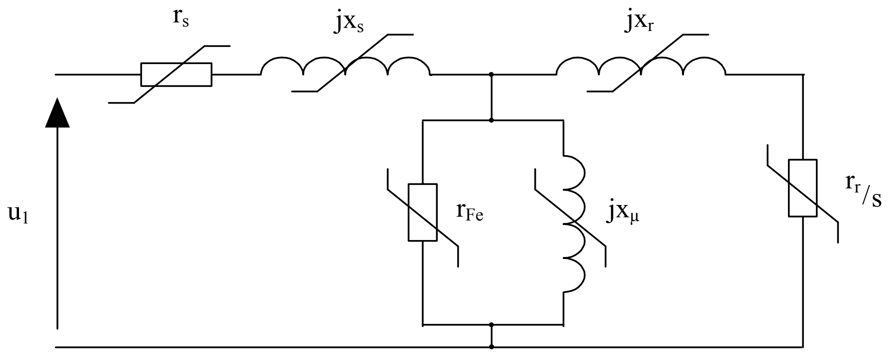

Fig. 2. The equivalent circuit type T of a cage induction motor

Rys. 3. Schemat zastępczy typu T silnika indukcyjnego klatkowego

4. RESULTS OF INVESTIGATIONS

Below there are the results of computer calculations concerning the effect of voltage and frequency deviation on load carrying capacity of an asynchronous motor. During the computations the permissible load power and torque were determined so that to keep windings temperature rise corresponding to the nominal conditions. The calculations were carried out for an induction cage motor Sg 132-S4 type with comparatively weakly saturated magnetic circuit [Gnaciński 2014], which parameters are given in Table 1.

Table 1. Parameters of the investigated cage machine Sg 132-S4 type

Tabela 1. Parametry znamionowe badanego silnika indukcyjnego typu Sg 132-S4

Machine type	Sg 132-S4
Rated power [kW]	5.5
Rated frequency [Hz]	50
Rated voltage [V]	380
Rated current [A]	11.4
Rated rotational speed [rpm]	1445
Non-load current [% I_{rat}]	40

Figure 3 shows permissible load power versus frequency of supply voltage. Its value was changed within the range 95–105% f_{rat}. The numerical computations were performed for supply voltage U = 100% U_{rat} and U = 90% U_{rat}. For nominal value of supply voltage and frequency equal to f = 95% f_{rat} the permissible load is above 98% of the rated power P_{rat}. Further, for voltage frequency f = 105% f_{rat} the permissible load is above 101.6% of the rated power P_{rat}. For undervoltage (U = 90% U_{rat}.) and frequencies f = 95% f_{rat}, f = 105% f_{rat} the permissible load is equal 90.4% P_{rat} and 92.3% P_{rat} respectively. It is worth mentioning that the curves of permissible load for $U = U_{rat}$ and U = 90% U_{rat} are rising (it means that permissible load rises when the voltage frequency is rising) for the motor under investigation as well as for machine with comparatively strongly saturated magnetic circuit considered in [Budziłowicz and Gnaciński 2018].

Figure 4 presents curves of permissible torque versus frequency of supply voltage. For nominal voltage value $U = U_{rat}$ and frequency equal to f = 95% f_{rat}, the permissible torque is above 102.7% of the rated torque T_{rat}, while for frequency f = 105% f_{rat} and the same voltage the permissible torque is equal 96,9 T_{rat}. For voltage U = 90% U_{rat} and frequencies f = 95% f_{rat} and f = 105% f_{rat} the permissible torque is above 95.6% T_{rat} and 88.5% T_{rat} respectively. When we compare curves of permissible torque for the motor under investigation and the machine considered [Budziłowicz and Gnaciński 2018] (with a comparatively strongly saturated magnetic circuit), it can be seen that for the motor with comparatively weakly saturated magnetic circuit the curve is falling. It means that the permissible torque is falling when the frequency is rising. But in the case of motor with comparatively strongly saturated magnetic circuit the curve presented [Budziłowicz and Gnaciński 2018] is rising.

In the next figures (Fig. 5–6) curves the permissible load power and torque versus value of supply voltage are presented. The calculations are performed for two voltage frequencies - $f = f_{rat}$ and f = 105% f_{rat}. In the Figure 4 the permissible load for supply voltage and nominal frequency $f = f_{rat}$ is shown. For U = 90% U_{rat} the permissible load is above 91.6% P_{rat}, whereas for U = 106% U_{rat} the permissible load is equal 103.7% P_{rat}.

Figure 6 shows the permissible torque for frequencies $f = f_{rat}$ and f = 105% f_{rat}. For the lowered supply voltage value – U = 90% U_{rat} and frequency equal the fundamental one, the permissible torque is above 92.2% T_{rat}. For U = 106% U_{rat} and frequency $f = f_{rat}$ the admissible torque is above 103.4% T_{rat}. Furthmore for the frequency f = 106 f_{rat} and U = 90% U_{rat} the permissible torque is above 88.5% T_{rat}, but for the same frequency ($f = f_{rat}$) and U = 106% U_{rat} the calculated permissible torque is above 100.7 T_{rat}. For the motor with comparatively weakly saturated magnetic circuit the permissible load and torque rise when the frequency is rising in both investigating cases (for $f = f_{rat}$ and f = 106% f_{rat}). For comparison, analogous characteristics presented [Budziłowicz and Gnaciński 2018] for the machine with comparatively strongly saturated magnetic circuit are nearly constant or falling. To sum up, the major torque drop for investigated induction motor occurs for undervoltage and an increase in frequency. The major load power drop appears for frequency decrease undervoltage. Nevertheless for U = 90% U_{rat} the difference in load power between f = 95% f_{rat} and f = 105% f_{rat} is only 2%. In the case of induction machine working with comparatively strong magnetic circuit is quite different [Budziłowicz and Gnaciński 2018]. It means that major torque and power load drop occurs when there is frequency decrease and overvoltage. The differencies are caused by properties of magnetic circuit.

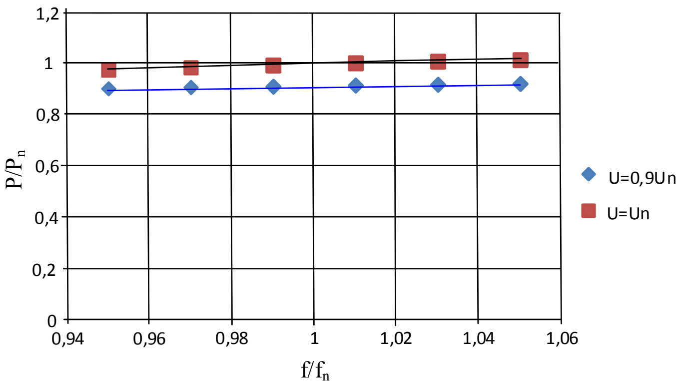

Fig. 3. Permissible load power versus frequency of supply voltage

Rys. 3. Charakterystyka dopuszczalnego obciążenia mocą w funkcji częstotliwości napięcia zasilającego

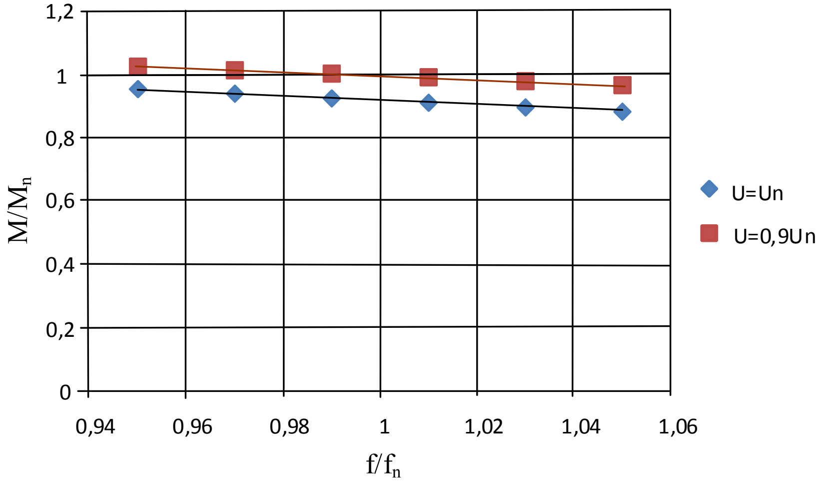

Fig. 4. Permissible load torque versus frequency of supply voltage

Rys. 4. Charakterystyka dopuszczalnego obciążenia momentem w funkcji częstotliwości napięcia zasilającego

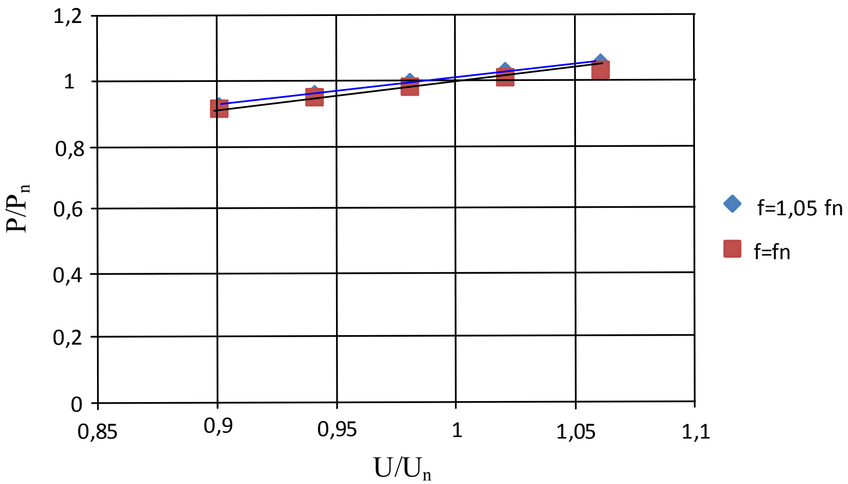

Fig. 5. Permissible load power versus supply voltage

Rys. 5. Charakterystyka dopuszczalnego obciążenia mocą w funkcji napięcia zasilającego

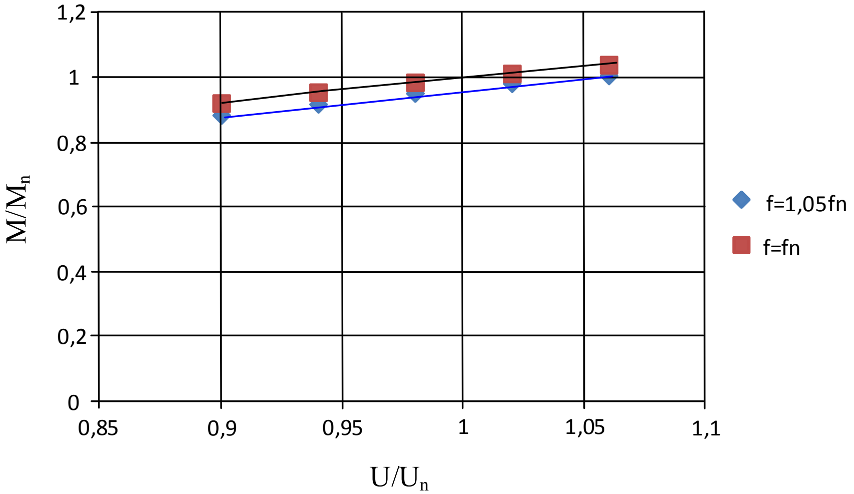

Fig. 6. Permissible load torque versus supply voltage

Rys. 6. Charakterystyka dopuszczalnego obciążenia momentem w funkcji napięcia zasilającego

4. CONCLUSIONS

This paper presents the effect of frequency or voltage deviation on induction cage motor with comparatively weakly saturated magnetic circuit. An effective method of protection of an induction motor against overheating is derating. For investigated machine a maximum decrease in the permissible torque occurs for $U = 90\% \ U_{rat}$ and $f = 105\% f_{rat}$. The maximum loss of permissible load power is for $U = 90\% \ U_{rat}$ and $f = 95\% f_{rat}$. In this case the permissible power load is above 2% less than for the case of the smallest torque ($U = 90\% \ U_{rat}$ and $f = 105\% f_{rat}$). On the contrary, for an induction cage motor with comparatively strongly saturated magnetic circuit [Budziłowicz and Gnaciński 2018] the maximum loss of permissible load and torque appears for overvoltage combined with decrease in frequency.

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