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AN INFLUENCE OF THE TIME AND SPATIAL HARMONICS ON AN ELECTROMAGNETIC TORQUE OF A SYMMETRICAL SIX-PHASE INDUCTION MACHINE WITH A SIX-STEP INVERTER SUPPLY UNDER OPEN PHASE CIRCUIT FAULT

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Six-phase induction machines offer several advantages over traditional three-phase machines, including higher levels of electromechanical compatibility with loads, energy efficiency, and fault tolerance.

This article presents an analysis of the impact of harmonics in the winding distribution function in the stator slots and the harmonics of the machine's supply on its electromechanical compatibility with the load during a single-phase failure.

Using the developed mathematical model, which accounts for spatial harmonics of the six-phase induction machine and time harmonics from the stator windings powered by a six-step voltage source inverter, the interaction of spatial and time harmonics in the phase failure mode and their effects on the electromagnetic torque and copper losses of the machine are analyzed. Specifically, in the normal (healthy) operating mode, the interaction of the first spatial harmonic with the 5^{th}, 7^{th}, 11^{th}, and 13^{th} time harmonics leads to the emergence of the 6^{th} and 12^{th} harmonics in the electromagnetic torque. Similar harmonics appear in the electromagnetic torque when the first time harmonic interacts with the 5^{th}, 7^{th}, 11^{th}, and 13^{th} spatial harmonics.

Under open single-phase fault in the six-phase induction machine, additional harmonics, including the 2^{nd}, 4^{th}, 8^{th}, and 10^{th}, appear in the electromagnetic torque. The second harmonic, caused by the reverse sequence component of the field, has the most significant impact on the electromagnetic torque. Notably, in this mode, the 6^{th} and 12^{th} harmonics in the electromagnetic torque decrease due to the absence of stator current under open phase fault.

Copper losses in the six-phase induction motor, which are caused by time and spatial harmonics, decrease under phase open fault. This is attributed to the absence of higher harmonics from the missing phase and the reduction in the THD for the currents of the healthy phases.

Keywords: symmetrical six phase induction machine, electromechanical compatibility, open-circuit fault, six-step voltage source inverter, mathematical modeling.

Introduction

Improving the energy efficiency of multiphase induction machine depends on minimizing spatial and time harmonics, which determine the harmonic content of the electromagnetic torque and power losses of the machine. Six-phase induction machines (6PIMs) are widely used in the locomotive traction, industrial high-power applications, electric and hybrid-electric vehicles [1].

Analysis of recent researches and publications. Problem description

The 6PIMs and drives provide some important advantages over three-phase motors. These benefits include higher power density, improved efficiency, enhanced reliability and fault tolerance [2–4].

The increased energy efficiency of the 6PIM is due to the reduced content of higher harmonic in machine. There are spatial harmonics which are related to the distribution of winding turns in the stator slots in machine and time harmonics which are associated with the supplying of the stator winding by semiconductor converter (six-step voltage source inverter and PWM voltage source inverter) [5, 6].

The high fault tolerance of the 6PIM lies in machine ability to operate under fault conditions such as failure one or more phases or a short circuit in the voltage source inverter or induction machine circuit. Under these conditions, the 6PIM continues to operate with somewhat degraded performance compared to the three-phase induction machine [7, 8].

Unlike the classical three-phase machine, the 6PIM contains two three-phase windings on the stator. The presence of these windings in the machine results in machine characteristics described above. The impact on the electromagnetic torque of the 6PIM is exerted by harmonics of the stator current: the 5^{th}, 7^{th}, 11^{th} and 13^{th} harmonics. The 5^{th} and 7^{th} harmonics in the stator currents of the 6PIM cause the 6^{th} harmonic in the electromagnetic toque. The 11^{th} and 13^{th} harmonics in the stator currents of the 6PIM cause the 12^{th} harmonic in the electromagnetic toque. To reduce the influence of spatial harmonic of the 6PIM, certain methods of the shifting the three-phase stator windings are used. In particular, the shifting the stator windings by 30 electrical degrees in space allow the 6^{th} harmonic in the electromagnetic toque to be eliminated when windings are supplied with sinusoidal voltage. These 6PIM is called asymmetrical [9, 10].

The symmetrical 6PIM provides the shifting the stator windings by 60 electrical degrees. The symmetrical 6PIM provides improved opportunities based on the point of view for control forming. [11–14]. The presented scientific research considers the symmetrical 6PIM.

To ensure improved energy efficiency performance of the 6PIM, it is important to analyze the influence of spatial and time harmonics on electromagnetic torque and power losses. Therefore, conducting such an analysis using mathematical modeling methods and physical experiments is a relevant scientific task.

Definition of goals and tasks of article

The aim of the research presented in the article is to analyze the impact of time and spatial harmonics on the electromagnetic compatibility of the symmetrical 6PIM under condition of a sing-phase fault, using mathematical modeling methods.

The scientific contribution of the article includes:

- development of the mathematical model for the 6PIM with stator winding supplied by a six-phase inverter, taking into account the spatial harmonics of the winding distribution function in the stator slot;

- conducting harmonic analysis of the influence of spatial and time harmonics on electromagnetic torque of the 6PIM under open phase circuit fault;
- analyzing the impact of stator and rotor current harmonics in the 6PIM on copper power losses.

Main matter description

A frequency-controlled electric drive consists of the symmetrical 6PIM and a six-phase voltage inverter. The two three-phase stator windings of the 6PIM, spatially shifted by 60 electrical degrees, are powered by the six-phase voltage inverter. The supply voltages for the three-phase stator windings of the six-phase motor are time-shifted by 60 electrical degrees (Fig. 1). The input of the voltage inverter is connected to the DC voltage source (V_{dc}).

To analyze the impact of spatial and time harmonics on the electromagnetic torque of the 6PIM in the frequency-controlled electric drive under the single phase failure condition, a mathematical model of the system was developed using the method of average voltages in the step of numerical integration [15].

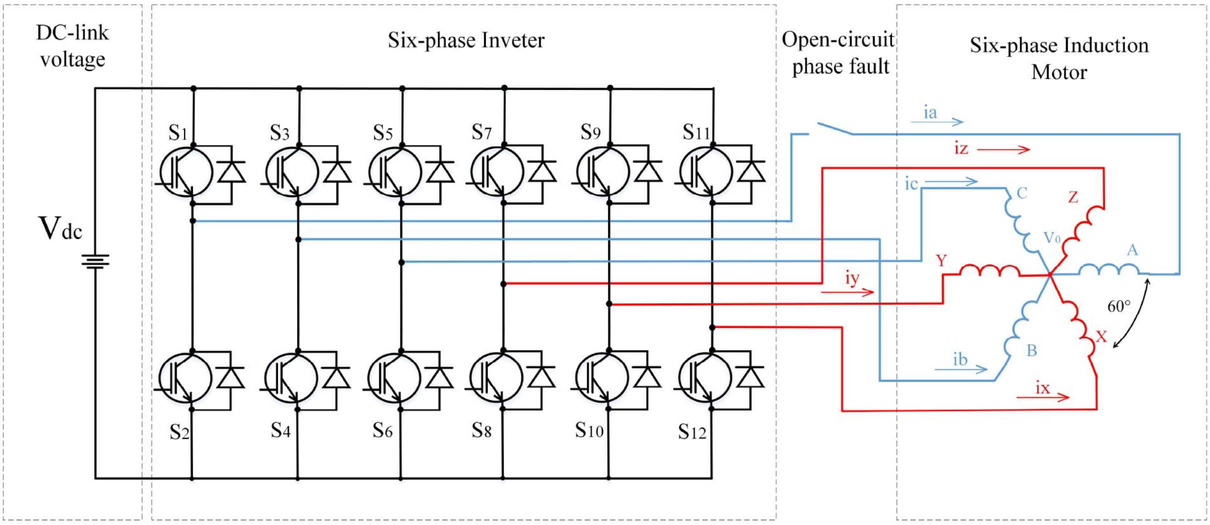


Fig. 1. Six-phase drive topology

Mathematical modeling of the 6PIM and model validation

According to the method of average voltages in integration step [15], the vector equation for the stator and rotor windings of the 6PIM, taking into account the increment of flux linkage at the step of numerical integration $\Delta\vec{\Psi}_{am} = L_{am1}\vec{i}_1 - L_{am0}\vec{i}_0$, is as follows:

$$\vec{U} - \mathbf{R}\vec{i}_0 + \left(\frac{\mathbf{R}}{3} + \frac{\mathbf{L}_{am0}}{\Delta t}\right)\vec{i}_0 - \frac{\mathbf{R}\Delta t}{6}\frac{d\vec{i}_0}{dt} - \left(\frac{\mathbf{R}}{3} + \frac{\mathbf{L}_{am1}}{\Delta t}\right)\vec{i}_1 = 0, \tag{1}$$

where $U = \frac{1}{\Delta t}\int_{t_0}^{t_0+\Delta t} u_{am}(t)dt$ is the vector of average voltages in the step of numerical integration, $u_{am} = (u_A, u_B, u_C, u_X, u_Y, u_Z, u_a, u_b, u_c)^T = (u_A, u_B, u_C, u_X, u_Y, u_Z, 0,0,0)^T$ is the vector of instantaneous voltage values of the stator windings ABC and XYZ, and the rotor windings abc, $\vec{i}_0 = (i_{A0}, i_{B0}, i_{C0}, i_{X0}, i_{Y0}, i_{Z0}, i_{a0}, i_{b0}, i_{c0})^T$, $\vec{i}_1 = (i_{A1}, i_{B1}, i_{C1}, i_{X1}, i_{Y1}, i_{Z1}, i_{a1}, i_{b1}, i_{c1})^T$ are vectors of currents at the beginning and end of the numerical integration step, $\mathbf{R} = \mathrm{diag}(R_A, R_B, R_C, R_X, R_Y, R_Z, R_a, R_b, R_c)$ is the matrix of active resistances. $\mathbf{L}_{am0} = \mathbf{L}_{am}(\gamma_{R0})$,

$\mathbf{L}_{am0} = \mathbf{L}_{am}(\gamma_{R1})$ are matrix inductance at the beginning and end of the numerical integration step, γ_{R0}, γ_{R1} are the rotor angular positions at the beginning and end of the numerical integration step.

To determine the currents of the 6PIM according to the second-order average voltage method, information about the current derivatives is required, which are determined by the following expression:

$$\vec{U} = \mathbf{R}\vec{i} + \frac{d\vec{\psi}_{am}(\vec{i}, \gamma_R)}{dt}, \tag{2}$$

Considering that the flux linkage in expression (2) is a function of currents and the rotor angular position, the flux linkage derivatives are determined as follows:

$$\frac{d\vec{\psi}_{am}(\vec{i}, \gamma_R)}{dt} = \frac{\partial\vec{\psi}_{am}(\vec{i}, \gamma_R)}{\partial\vec{i}}\frac{d\vec{i}}{dt} + \frac{\partial\vec{\psi}_{am}(\vec{i}, \gamma_R)}{\partial\gamma_R}\frac{d\gamma_R}{dt} = \mathbf{L}_{am}\frac{d\vec{i}}{dt} + \frac{\partial\mathbf{L}_{am}}{\partial\gamma_R}\vec{i}p\Omega = \vec{E}_{TR} + \vec{E}_{ROT}, \tag{3}$$

where p is the number of pole pairs, Ω is the rotation frequency, $\vec{E}_{TR}, \vec{E}_{ROT}$ are the transformation electromotive force (EMF) and rotation electromotive force (components of the stator windings' EMF).

According to expressions (2) and (3), the current derivatives are determined by the following formula:

$$\frac{d\vec{i}}{dt} = \left(\vec{U} - \mathbf{R}\vec{i} - \frac{\partial\mathbf{L}_{am}}{\partial\gamma_R}\vec{i}p\Omega\right)\mathbf{L}_{am}^{-1}, \tag{4}$$

The expressions for the rotor angular position and angular velocity of the 6PIM are as follows:

$$\frac{d\gamma_R}{dt} = p\Omega,$$
$$\frac{d\Omega}{dt} = \frac{T_e - T_L}{J}. \tag{5}$$

where T_L is static load torque, T_e is electromagnetic qorque of the 6PIM, J is the moment of inertia.

The electromagnetic torque of the 6PIM is determined by the following expression:

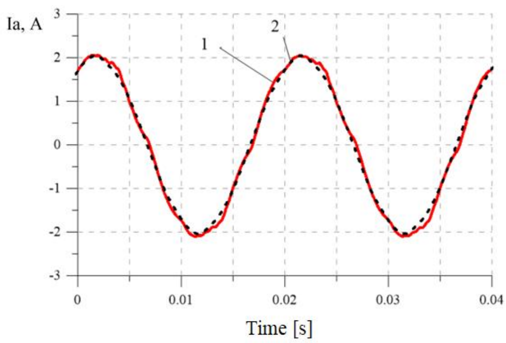
$$T_e = \frac{3}{2}pL_m\left(i_{r\beta}i_{s\alpha} - i_{r\alpha}i_{s\beta}\right), \tag{6}$$

where $i_{s\alpha}, i_{s\beta}, i_{r\alpha}, i_{r\beta}$ are the stator winding currents in the *αβ* coordinate system.

A detailed description of the 6PIM mathematical model with consideration of spatial harmonics is given in [5].

The adequacy of the 6PIM model was verified by comparing the results of mathematical modeling and experiment using the developed in Rzeszow University of Technology experimental sample (Fig. 2, a). The study was conducted for sinusoidal supply of the stator windings, with current distortion caused by the influence of spatial harmonics.

a



b

Fig. 2. The experimental sample (a) and stator current (b) of the symmetrical 6PIM: experimental results (curve 1) and results of mathematical modeling (curve 2)

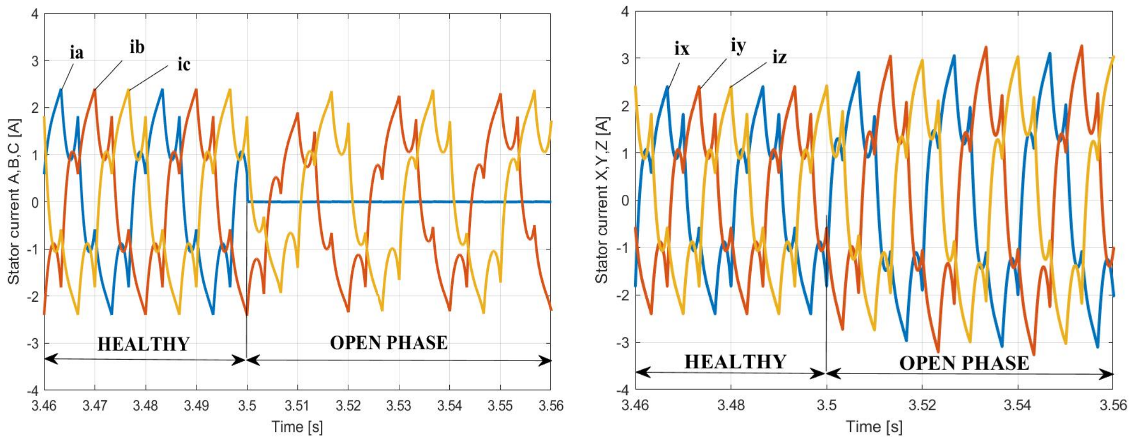
A comparison of the results of a physical experiment and mathematical modeling of 6PIM shows their high convergence (Fig. 2, b) and is given in [5].

According to approach [5], spatial harmonics of the 6PIM are considered by introducing harmonic components into the magnetizing inductance.

Research results

The research of the frequency-regulated induction electric drive with 6PIM in the mode of one-phase open fault was carried out for the nominal load torque (Fig. 3 – Fig. 4). Passport data of the 6PIM: P_N = 1.5 kW, U_N = 400 V, I_N = 1.43 A, n = 2812 rpm, T_N = 5.04 Nm, $L_{\sigma 1}$ = 0.06 H, $L'_{\sigma 2}$ = 0.01 H, L_m= 1.3 H, R_1 = 8.0 Ohm, R'_2 = 4.0 Ohm та J = 0.015 kg·m^2.

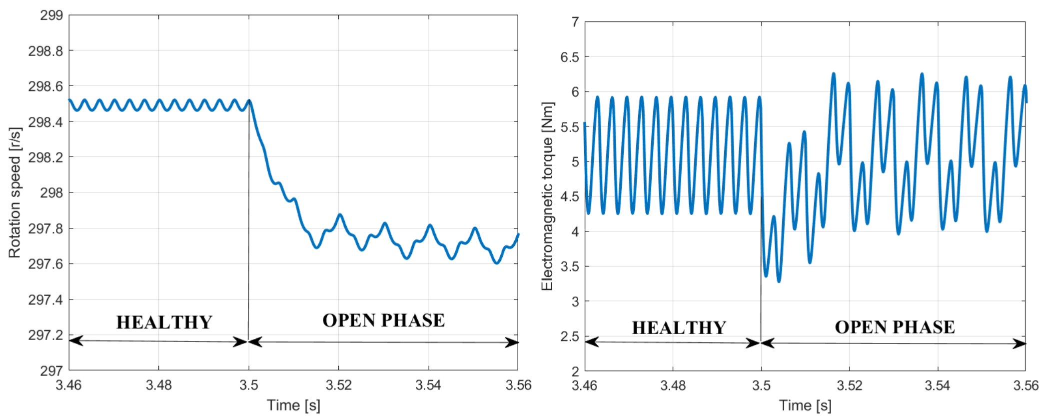
The fault operating mode, which involves the open fault of one of the machine's phases under nominal load, is of significant interest. Phase A is disconnected for 3.5 seconds (Fig. 3a). In this mode, the effective values of the XYZ stator winding currents increase (Fig. 3b) to ensure the required value of the machine's electromagnetic torque (Fig. 4b). The 2nd and 4th harmonics appear in the electromagnetic torque due to the one phase fault circuit.



а б

Fig. 3. Stator currents of A,B,C phases (a) and X,Y,Z phases (b) of the symmetrical 6PIM for the nominal load under open phase fault

The rotational speed of 6PIM under the open phase fault practically does not change (the decrease is 0.26 %). The amplitude of the rotational speed oscillations triples compared to the healthy mode (Fig. 4a).



a b

Fig. 4. Rotation speed (a) and electromagnetic torque (b) of the symmetrical 6PIM for the nominal load under open phase fault

Harmonic analysis of the electromagnetic torque of the 6PIM demonstrates the presence of the 6th harmonic with amplitude of 16.91 % and the 12th harmonic with amplitude of 3.24 % in the machine's nominal operating mode. Under phase open fault mode, additional 2nd, 4th, 8th, and 10th harmonics appear in the electromagnetic torque. In this case, the 2nd harmonic has a significant impact on the electromagnetic torque, with amplitude of 12.75 %. It is also noted that in this mode, the amplitude of the 6th harmonic (13.07 %) and the 12th harmonic (2.9 %) decreases, which is due to the absence of one phase, and consequently, the reduced influence of higher current harmonics of this phase on the electromagnetic torque (Fig. 5).

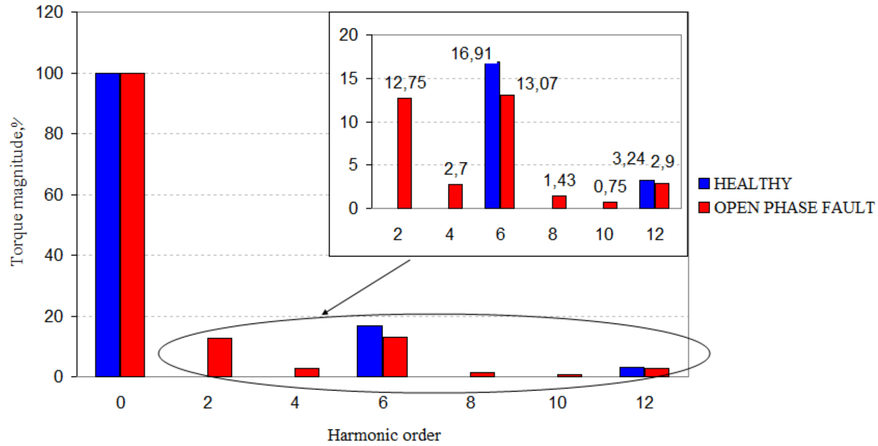


Fig. 5. Harmonic analysis for the electromagnetic torque of the symmetrical 6PIM under healthy and open phase fault for the nominal load

It should be noted that the machine's time and spatial harmonics cause the appearance of the 5th and 7th, as well as the 11th and 13th harmonics in the machine's currents under normal (healthy) operating conditions. These harmonics affect the power losses in the stator and rotor windings. Copper losses in the stator and rotor windings for the symmetrical operating mode, taking into account first and higher harmonics, are determined according to expressions (7) and (8).

$$P_{cus} = P_{cus}^{1} + P_{cus}^{thd} = 6R_s I_{s1}^2 + 6R_s \sum_{n=2}^{\infty} I_{sn}^2 = 6R_s I_{s1}^2 + 6R_s I_{s1}^2 THD_{si}^2, \quad (7)$$

$$P_{cur} = P_{cur}^{1} + P_{cur}^{thd} = 3R_r I_{r1}^2 + 3R_r \sum_{n=2}^{\infty} I_{rn}^2 = 3R_r I_{r1}^2 + 3R_r I_{r1}^2 THD_{ri}^2, \quad (8)$$

where P_{cus} is copper losses of the stator winding taking into account first and higher harmonics, P_{cus}^{1} is copper losses of the stator winding taking into account first harmonic, P_{cus}^{thd} is copper losses of the stator winding taking into account higher harmonics, R_s is stator winding resistance, I_{s1} is first harmonic of the stator current, THD_{si} is total harmonic distortion of the stator current, P_{cur} is copper losses of the rotor winding taking into account first and higher harmonics, P_{cur}^{1} is copper losses of the rotor winding taking into account first harmonic, P_{cur}^{thd} is copper losses of the rotor winding taking into account higher harmonics, THD_{ri} is total harmonic distortion of the rotor current,

Since the open phase fault mode is an asymmetrical operating condition for the machine, the copper losses caused by higher harmonics will be determined according to expressions (9) and (10).

$$P_{cus}^{hh} = R_s I_{sa1}^2 THD_{sai}^2 + R_s I_{sb1}^2 THD_{sbi}^2 + R_s I_{sc1}^2 THD_{sci}^2 + R_s I_{sx1}^2 THD_{sxi}^2 + R_s I_{sy1}^2 THD_{syi}^2 + R_s I_{sz1}^2 THD_{szi}^2, \quad (9)$$

$$P_{cur}^{hh} = R_r I_{ra1}^2 THD_{rai}^2 + R_r I_{rb1}^2 THD_{rbi}^2 + R_r I_{rc1}^2 THD_{rci}^2. \quad (10)$$

Copper losses in the stator windings of the 6PIM amount to 41.87 W under nominal conditions, with losses due to higher harmonics accounting for 8.95 %. In the case of the open phase fault, copper losses in the stator windings of the 6PIM increase to 53.47 W, while losses due to higher harmonics decrease to 5.67 %. This is attributed to the absence of current in phase A and the reduction in the THD for the stator currents X, Y, and Z, which increase in this mode (Fig. 6).

Copper losses due to higher harmonics in the rotor windings of the 6PIM decrease during the phase A failure, amounting to 8.85 % compared to the nominal (healthy) condition (9.28 %).

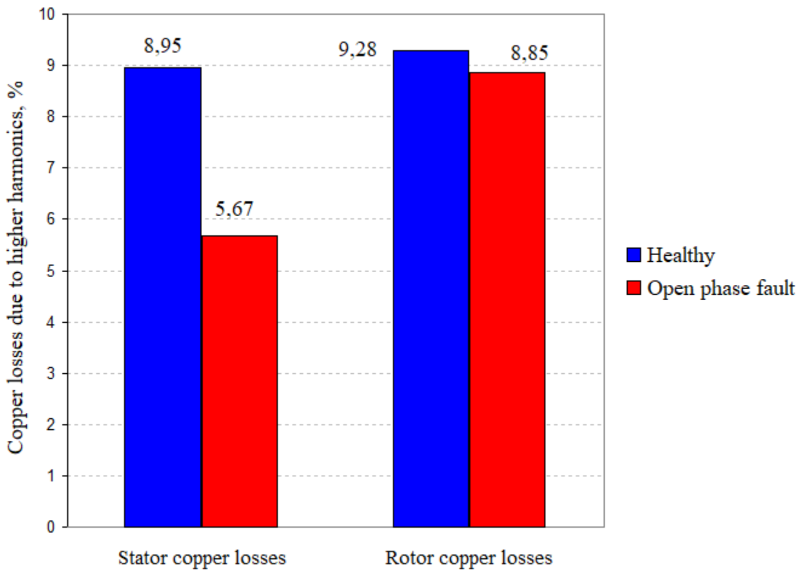


Fig. 6. Stator and rotor copper losses due to high harmonics of the 6PIM under healthy mode and open phase fault

Conclusion

Analysis using the developed mathematical model of the symmetrical 6PIM powered by a six-step voltage source inverter indicates that spatial harmonics of the winding distribution function and time harmonics of the stator winding supply have the impact on the electromechanical compatibility of the 6PIM with the load, both under healthy and fault conditions, such as phase failure.

Specifically, in the normal (healthy) operating mode, the interaction of the 1st spatial harmonic with the 5th, 7th, 11th and 13th time harmonics leads to the emergence of the 6th and 12th harmonics in the electromagnetic torque. Similar harmonics in the electromagnetic torque are observed when the 1st time harmonic interacts with the 5th, 7th, 11th and 13th spatial harmonics.

In the event of the open phase fault in the 6PIM, in addition to the aforementioned harmonics, the electromagnetic torque also exhibits 2nd, 4th, 8th, and 10th harmonics. The second harmonic, resulting from the reverse sequence component of the field, has the most significant effect on the electromagnetic torque. It is noteworthy that in this mode, the 6th and 12th harmonics in the electromagnetic torque decrease due to the absence of higher harmonics associated with the failed phase.

Copper losses in the 6PIM depend on both time and spatial harmonics and constitute 9 % of the total copper losses in the normal operating mode. During the one phase failure, the losses due to higher harmonics decrease, attributed to the absence of current in this phase and the reduction in the THD for the stator currents of the healthy phases, whose effective values increase in this mode.

Direction of further research

In further research, it is planned to analyze the influence of spatial and time harmonics on the electromagnetic torque of the six-phase induction motor in the case of different power supply methods for the two three-phase stator windings (with common and separate neutrals) under single-phase and two-phase open-circuit faults. This will allow for the development of recommendations regarding the electromagnetic and electromechanical compatibility of the six-phase motor in fault conditions with various power supply configurations.

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ВПЛИВ ЧАСОВИХ ТА ПРОСТОРОВИХ ГАРМОНІК НА ЕЛЕКТРОМАГНІТНИЙ МОМЕНТ СИМЕТРИЧНОЇ ШЕСТИФАЗНОЇ АСИНХРОННОЇ МАШИНИ З ЖИВЛЕННЯМ ВІД ШЕСТИТАКТНОГО ІНВЕРТОРА НАПРУГИ ЗА ВІДСУТНОСТІ ФАЗИ

Шестифазні асинхронні машини мають цілу низку переваг, порівняно з класичними трифазними машинами, зокрема високі показники електромеханічної сумісності з навантаженням, енергоефективності та відмовостійкості.

Наведено аналіз впливу гармонік функції розподілу витків обмотки машини в пазах статора та гармонік живлення машини на електромеханічну сумісність машини з навантаженням у режимі обриву однієї фази.

За допомогою розробленої математичної моделі, яка враховує просторові гармоніки шестифазної асинхронної машини та часові гармоніки живлення обмоток статора машини від шеститактного інвертора напруги, проаналізовано взаємодією просторових та часових гармонік в режимі обриву фази та їх вплив на електромагнітний момент та втрати в міді машини. Зокрема, у нормальному (здоровому) режимі взаємодія першої просторової гармоніки з 5-ою та 7-ою, 11-ою та 13-ою часовими гармоніками призводять до появи 6-ої та 12-ої гармоніки в електромагнітному моменті. Аналогічні гармоніки в електромагнітному моменті з'являються при взаємодії першої часової гармоніки з 5-ою та 7-ою, 11-ою та 13-ою просторовими гармоніками.

У випадку обриву однієї фази шестифазної машини додатково в електромагнітному моменті з'являються також 2 та 4, та 8 та 10. Друга гармоніка, викликана складовою поля зворотної послідовності, має найбільш значний вплив на електромагнітний момент. Зазначимо, що в цьому режимі 6 та 12 гармоніки в електромагнітному моменті зменшуються у зв'язку з відсутністю струму статора під час обриву цієї фази.

Втрати в міді шестифазного двигуна, спричинені часовими та просторовими гармоніками машини у режимі обриву фази, зменшуються, що зумовлено відсутністю вмісту вищих гармонік струму відсутньої фази та зменшенням коефіцієнта вища гармонік для струмів здорових фаз.

Ключові слова: симетрична шестифазна асинхронна машина, електромеханічна сумісність, обрив фази, шеститактний інвертор напруги, математичне моделювання.