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CURRENT AND TORQUE HARMONIC ANALYSIS OF SIX-PHASE INDUCTION MACHINE WITH PWM INVERTER SUPPLY UNDER FAULT CONDITIONS

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Six-phase induction machines have attracted attention due to their high efficiency and enhanced fault tolerance. Compared to conventional three-phase machines, six-phase drives can operate under the open-circuit of one, two, or even three stator phases, while still generating electromagnetic torque and sustaining mechanical load, although torque ripple, harmonic distortion, and some efficiency loss increase. This behaviour is attributed to the interaction between spatial harmonics, which are largely determined by the machine design and winding configuration, and time harmonics, which are related to the supply scheme of the pulse-width modulation inverter.

This article presents a current and torque harmonic analysis of six-phase induction machines with pulse-width modulation inverter supply, based on the interaction of spatial and time harmonics. The study considers both normal operation and fault scenarios, highlighting the effects of harmonic components on torque pulsations, speed fluctuations, and total harmonic distortion.

The interaction of spatial harmonics of the machine's with time harmonics from the voltage source inverter with pulse-width modulation causes pulsations in the electromagnetic

torque. Under normal operation, spatial harmonics dominate the torque and current waveforms. In single-phase open-circuit faults, the second harmonic becomes dominant due to the negative-sequence component of the air-gap magnetic field, while the 6^{th} and 12^{th} torque harmonics are reduced. In three-phase open-circuit faults, the machine operates under reduced load, and the harmonic spectrum shows lower total harmonic distortion compared to normal operation, with spatial harmonics remaining dominant. These findings highlight the importance of harmonic analysis for optimizing control strategies and improving the overall performance and reliability of six-phase drives. The voltage source inverter with pulse-width modulation has negligible influence under these fault conditions, as higher-order harmonics in the current and torque are insignificant.

Keywords: six-phase induction machine, spatial harmonics, pwm voltage source inverter, mathematical modelling, fault conditions.

Introduction

In recent years, extensive research has been devoted to improving the energy efficiency and operational reliability of multiphase electrical machines. Among them, six-phase induction machines (6PIM) have attracted significant attention due to their ability to combine high efficiency with enhanced fault tolerance [1,2].

Analysis of recent research and publications. Problem description

Compared with conventional three-phase machines, six-phase drives exhibit superior performance under abnormal and fault conditions. One of their major advantages lies in their capability to operate under phase disconnection faults, such as the open-circuit of one, two, or even three stator phases, as well as the availability of a dual-channel power supply system with the ability to seamlessly transition from dual-channel to single-channel operation [3,4].

Under such fault scenarios, the machine is still able to generate electromagnetic torque and sustain the operation of the mechanical load, although with certain performance degradation in terms of torque ripple, efficiency, and harmonic distortion. This inherent fault-tolerant capability makes 6PIM a promising solution for safety-critical applications, such as electric vehicles, aerospace systems, and offshore wind energy conversion [5,6].

The increased energy efficiency of 6PIM can be attributed to the reduced presence of higher-order harmonics in the machine's electromagnetic fields. In general, two main categories of harmonics affect machine performance: spatial harmonics and time harmonics [7-9]. Spatial harmonics are primarily introduced by the distribution of stator winding turns within the slots and the resulting non-ideal magnetic field distribution. These harmonics influence the magnetomotive force (MMF) waveform and can increase core losses as well as torque pulsations. On the other hand, time harmonics originate from the supply system, particularly when the stator windings are energized by semiconductor-based power converters, such as six-step voltage source inverters or pulse width modulation (PWM) voltage source inverters [10,11].

Modern 6PIM drives are typically implemented using voltage source inverters with PWM**.** These inverters provide flexible control of phase voltages, enable precise regulation of speed and torque, and allow for the implementation of advanced modulation strategies that reduce harmonic distortion and improve overall drive efficiency [11,12].

Two types of 6PIM are commonly distinguished: asymmetrical machines, in which the two three-phase windings are spatially shifted by 30°, and symmetrical machines, in which the windings are shifted by 60°. The symmetrical 6PIM offers enhanced opportunities from the control perspective, allowing for more uniform distribution of currents, reduced harmonic content, and simplified implementation of advanced control strategies [13-15]. In this study, the focus is on the symmetrical 6PIM, as it provides a convenient basis for harmonic analysis.

While spatial harmonics are largely determined by the machine design and winding configuration, time harmonics are closely related to the inverter topology and the applied modulation strategy. The interaction of these harmonic components directly impacts both current distortion and electromagnetic torque ripple and energy efficiency. Therefore, a comprehensive analysis of spatial and temporal harmonic contributions is essential for accurately predicting machine performance, especially under fault conditions**,** as well as for improving energy efficiency and enhancing the overall reliability of 6PIM drives.

Definition of goals and tasks of the article

The aim of the research presented in this article is to perform a comprehensive harmonic analysis of the impact of both time and spatial harmonics on the electromagnetic behaviour and compatibility of the symmetrical 6PIM fed by the PWM voltage source inverter, particularly under stator fault conditions. The study utilises mathematical modeling techniques to evaluate how harmonic interactions influence key performance indicators such as stator current distortion, torque ripple, and overall machine efficiency.

The scientific contributions of the article are as follows:

- development of the mathematical model of the symmetrical 6PIM, in which the stator windings are supplied by the PWM voltage source inverter, incorporating the effects of spatial harmonics of the MMF. The model enables accurate prediction of electromagnetic behaviour under both normal and fault conditions;
- comprehensive harmonic analysis of the stator currents and electromagnetic torque of the 6PIM under various fault scenarios, including single-phase open-circuit and three-phase faults. This analysis highlights the impact of harmonic components on torque ripple, current distortion, and drive performance;
- evaluation of fault-tolerant capabilities of the symmetrical 6PIM under PWM inverter supply, demonstrating how the machine maintains operation despite phase disconnections, and quantifying the performance degradation due to harmonic interactions.

Main matter description

The frequency-controlled electric drive under investigation comprises the symmetrical 6PIM coupled with the six-phase voltage source inverter with PWM. The 6PIM features two three-phase stator windings, spatially offset by 60 electrical degrees, which are energized by the inverter, as shown in Fig. 1. The phase voltages applied to these two three-phase windings are time-shifted by 60 electrical degrees.

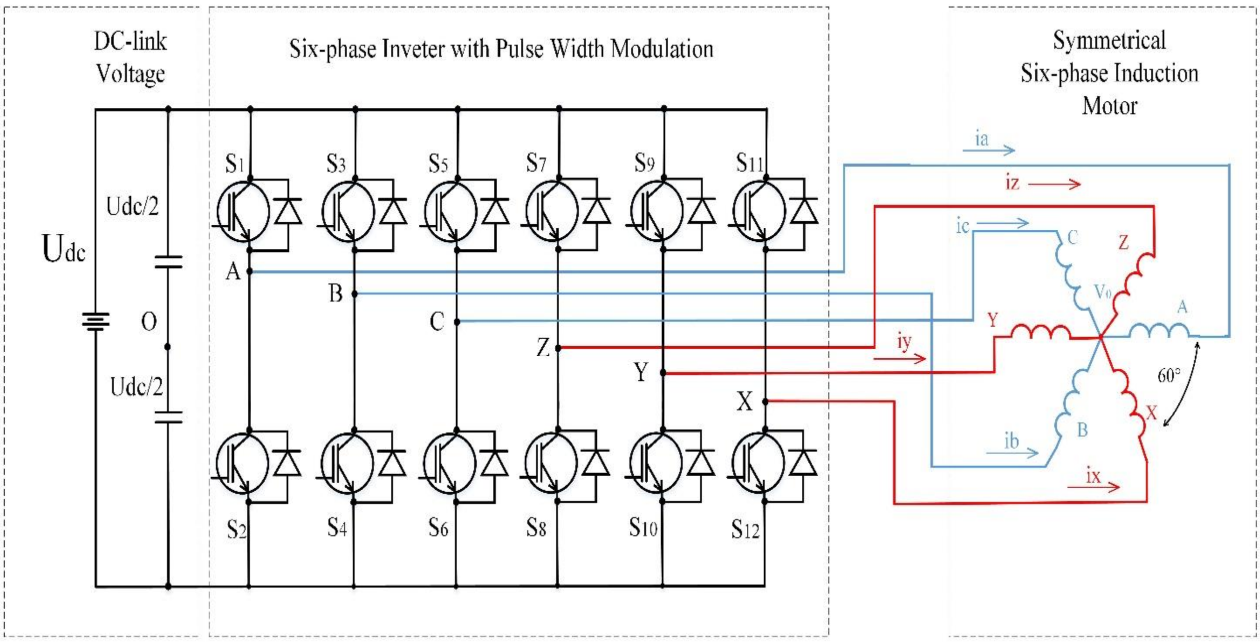

Fig. 1. Symmetrical six-phase motor fed by PWM voltage source inverter.

To analyze the current and electromagnetic torque of the 6PIM in the frequency-controlled electric drive under the single and three-phase failure conditions, the mathematical model of the system was developed using the method of average voltages in the integration step [16].

Methodological Aspects

Mathematical modeling of 6PIM

The electrical part of the 6PIM model is represented in phase coordinates based on the method of average voltages in integration step [15], taking into account the change in flux linkage during the numerical integration step $\Delta\vec{\psi}_{am} = L_{am1}\vec{i}_1 - L_{am0}\vec{i}_0$, by the vector equation:

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

where $\vec{U} = \frac{1}{\Delta t}\int_{t_0}^{t_0+\Delta t}\vec{U}_{am}(t)dt$ is the vector of average voltages in the step of numerical integration, u_{am} is the vector of instantaneous voltage values of the stator windings ABC and XYZ, and the rotor windings abc, $\vec{i}_0$, $\vec{i}_1^{\,T}$ are vectors of currents at the beginning and end of the numerical integration step, $R = \mathrm{diag}(R_A, R_B, R_C, R_X, R_Y, R_Z, R_a, R_b, R_c)$ is the matrix of active resistances. $L_{am0} = L_{am}(\gamma_{R0})$, $L_{am1} = L_{am}(\gamma_{R1})$ 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:

$$\frac{d\vec{\psi}_{am}(\vec{i}, \gamma_R)}{dt} = \frac{\partial\vec{\psi}_{am}(\vec{i}, \gamma_R)}{\partial\vec{i}}\frac{d\vec{i}}{dt} + \frac{\partial\vec{\psi}_{am}(\vec{i}, \gamma_R)}{\partial\gamma_R}\frac{d\gamma_R}{dt} = L_{am}\frac{d\vec{i}}{dt} + \frac{\partial L_{am}}{\partial\gamma_R}\vec{i}p\Omega, \tag{3}$$

where p is the number of pole pairs, Ω is the rotation frequency.

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 of the 6PIM is as follows:

$$\frac{d\gamma_R}{dt} = p\Omega. \tag{5}$$

The angular velocity of the 6PIM is given by:

$$\frac{d\Omega}{dt} = \frac{T_e - T_L}{J}. \tag{6}$$

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

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

$$T_e = \frac{p}{2}\left[\psi_A(i_B - i_C) + \psi_B(i_C - i_A) + \psi_C(i_A - i_B) + \psi_X(i_Y - i_Z) + \psi_Y(i_Z - i_X) + \psi_Z(i_X - i_Y)\right], \tag{7}$$

where $i_A, i_B, i_C, i_X, i_Y, i_Z$ are stator winding currents, $\psi_A, \psi_B, \psi_C, \psi_X, \psi_Y, \psi_Z$ are flux linkages of the 6PIM.

The consideration of spatial harmonics in the 6PIM model is achieved by introducing time harmonics into the magnetizing inductance, as described in [8].

Validation of 6PIM model

The adequacy of the 6PIM model was verified by comparing the results of mathematical modeling and experiment. The comparison confirmed the adequacy of the six-phase machine model and is presented in [8]. The study was conducted for sinusoidal supply of the stator windings, with current distortion caused by the influence of spatial harmonics.

A comparison of the results obtained from the 6PIM mathematical model and the laboratory sample was performed for load application, as well as single-phase and three-phase faults.

Mathematical modeling of PWM inverter

The modulation strategy of PWM inverter is given in Fig.2. The switching frequency corresponds to the frequency of the carrier signal, and its amplitude is determined by the DC-link voltage. As illustrated in Figure 2, when the phase reference voltage Urefk exceeds the positive carrier U1, the phase is connected to the positive DC-link (Uk0=Udc/2). In other case, the phase is connected to the neutral point of the DC-link(Uk0=0). Where k is phase indicator (k = A, B, C, X, Y, Z). Uk0 is the voltage between phase and the fictive mid-point of the DC-link.

Pole voltages are related to phase voltages by:

$$\begin{bmatrix} U_{an} \\ U_{bn} \\ U_{cn} \\ U_{xn} \\ U_{yn} \\ U_{zn} \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} & 0 & 0 & 0 \\ -\frac{1}{3} & \frac{2}{3} & -\frac{1}{3} & 0 & 0 & 0 \\ -\frac{1}{3} & -\frac{1}{3} & \frac{2}{3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ 0 & 0 & 0 & -\frac{1}{3} & \frac{2}{3} & -\frac{1}{3} \\ 0 & 0 & 0 & -\frac{1}{3} & -\frac{1}{3} & \frac{2}{3} \end{bmatrix} \cdot \begin{bmatrix} U_{ao} \\ U_{bo} \\ U_{co} \\ U_{xo} \\ U_{yo} \\ U_{zo} \end{bmatrix}. \quad (8)$$

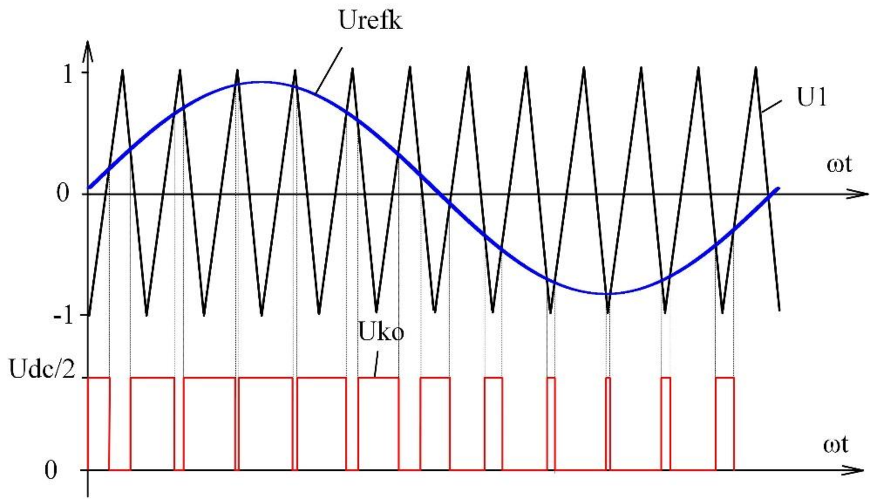

Fig. 2. The modulation strategy of PWM inverter

Investigation methodology

For a comparative analysis of the stator currents and the electromagnetic torque of 6PIM under different operating conditions, the following investigations were conducted:

- 50% load step – the experiment was performed at half the nominal load to evaluate the harmonic content of the stator currents and torque pulsations under normal operation conditions.
- single-phase open-circuit fault at 50% load – simulation of a fault condition with phase A open to study the changes in currents of the remaining phases and its effect on the electromagnetic torque.
- single-channel power supply at 50% load – simulation of a critical fault with phases A, B, and C open to assess the drive behaviour under severe supply disruption.

In each operating mode, the harmonic spectrum of the stator currents and the electromagnetic torque was analyzed, and the total harmonic distortion (THD) was calculated to evaluate the impact of fault conditions on the machine's performance.

Results

The 6PIM considered in this study has a rated power of 1.5 kW, rated voltage of 400 V, rated current of 1.43 A, rated speed of 2812 rpm, and rated torque of 5.04 Nm. Its electrical parameters include a stator leakage inductance $L_{\sigma 1}$ = 0.06 H, rotor leakage inductance referred to the stator , $L'_{\sigma 2}$ = 0.01 H, magnetizing inductance L_m= 1.3 H, stator resistance R_1 = 8.0 Ω, and rotor resistance referred to the stator, R'_2 = 4.0 Ω. The machine's moment of inertia is J = 0.015 kg·m^2. The 6PIM is supplied by a voltage source inverter employing pulse-width modulation at a switching frequency of 1 kHz.

50% Load Step of 6PIM

To perform harmonic analysis of the stator currents and the electromagnetic torque of 6PIM under normal and fault conditions, the operation of the electric drive under load is considered. In this case, in addition to the fundamental (first) harmonic, the current waveforms contain harmonics of the 5th, 7th, 11th, 13th, and 19th orders. The presence of the 5th, 7th, 11th, and 13th harmonics in the stator current is caused by the non-sinusoidal distribution of the magnetic field in the machine's air gap. The 19th harmonic of the current is insignificant (0.35%) and is associated with the supply from the PWM voltage inverter (Fig. 3).

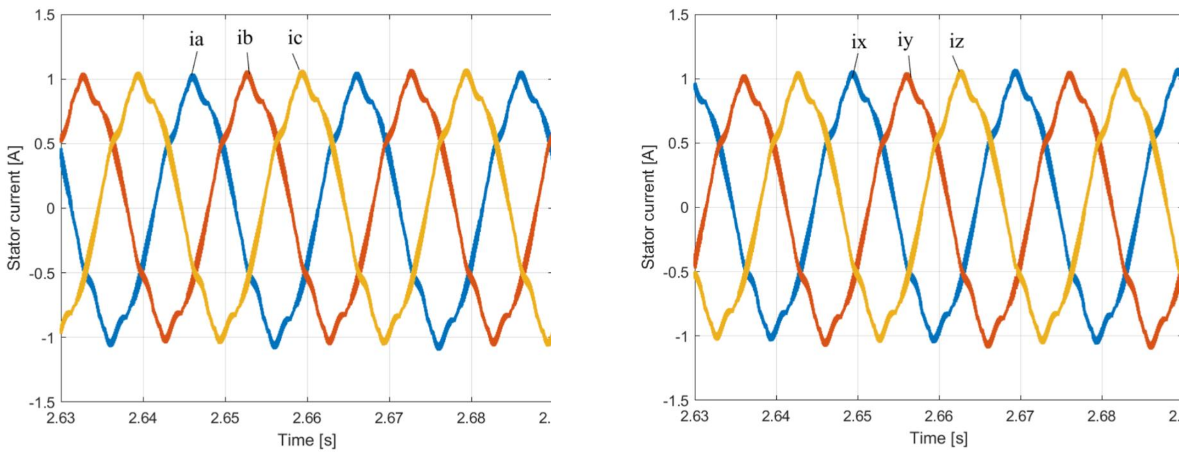

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Fig. 3. Stator currents of A,B,C phases (a) and X,Y,Z phases (b) of the symmetrical 6PIM for the 50% load

The THD of the stator current at 50% load is 6.22% (Fig. 4).

The presence of the aforementioned harmonics in the machine's stator currents causes pulsations in the electromagnetic torque and angular speed of the machine (Fig. 4). Specifically, the interaction of the fundamental harmonic with the 5th and 7th harmonics in the currents leads to the appearance of the 6th harmonic in the electromagnetic torque. The interaction of the fundamental with the 11th and 13th harmonics results in the 12th harmonic of the torque. Additionally, the interaction of the fundamental with the 19th harmonic in the currents causes the emergence of the 18th harmonic in the electromagnetic torque (Fig. 5).

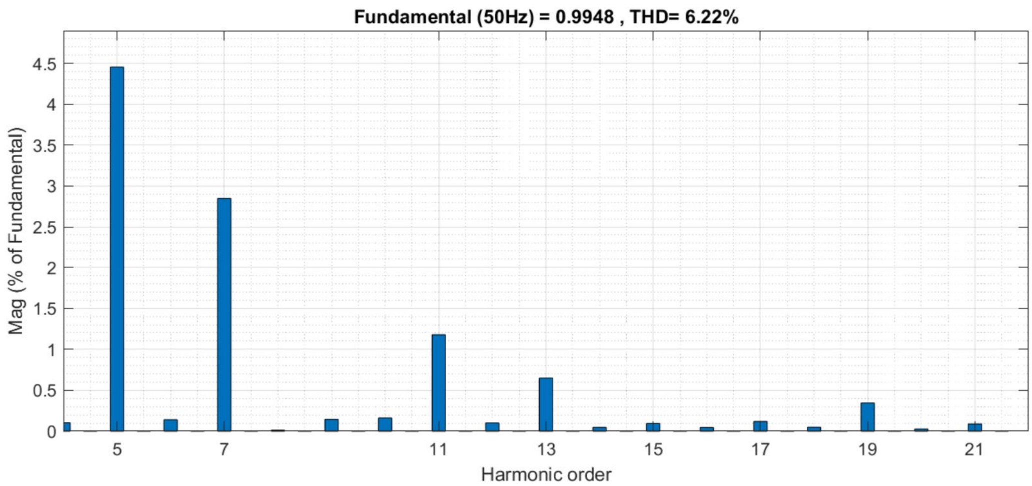

Fig. 4. Harmonic spectrum of the current of the symmetrical 6PIM for the 50% load

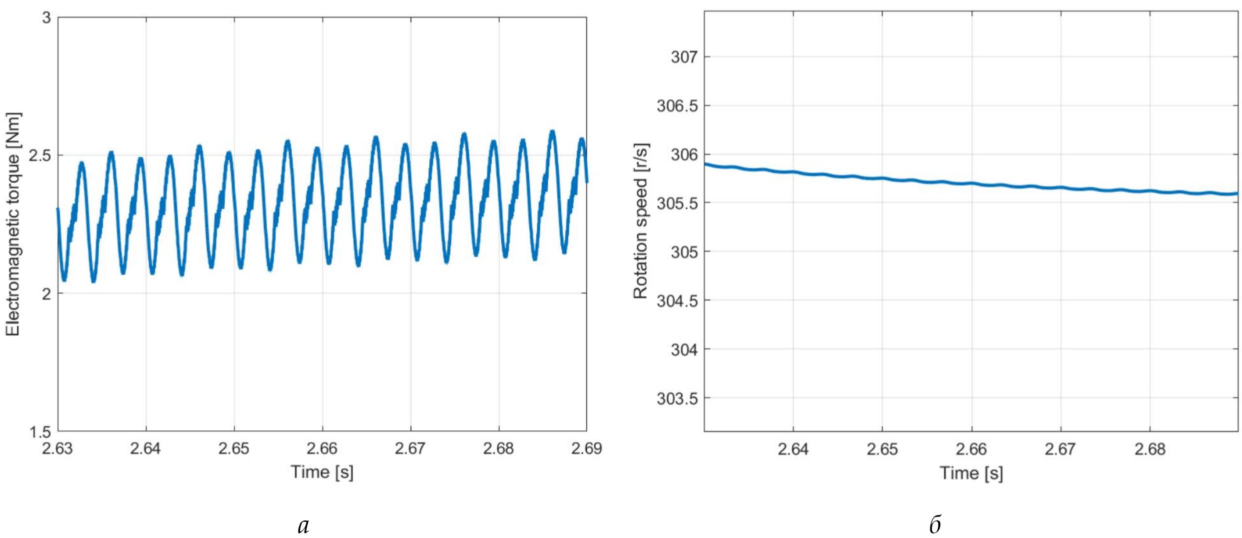

Fig. 5. Electromechanical torque (a) and rotational speed (b) of the symmetrical 6PIM for the 50% load

THD of the machine's electromagnetic torque at 50% load is 8.216% (Fig. 6).

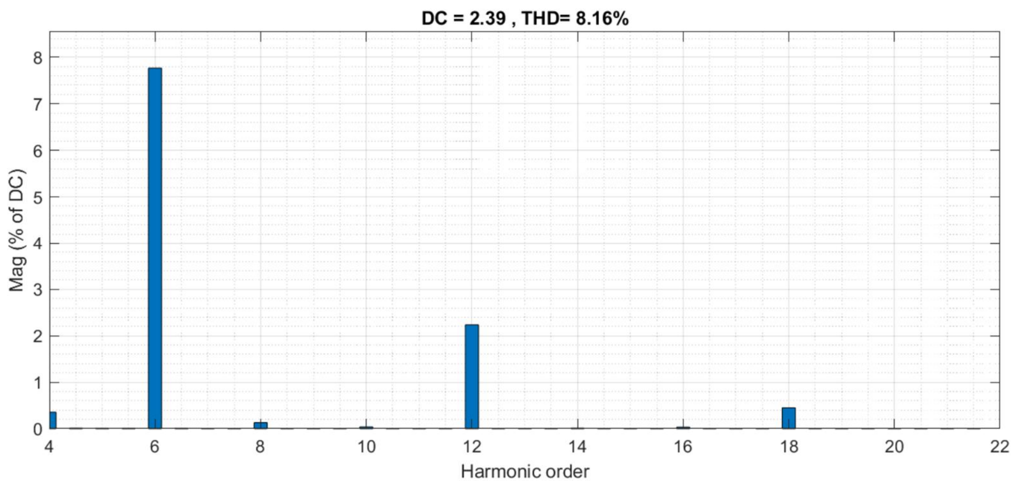

Fig. 6. Harmonic spectrum of the torque of the symmetrical 6PIM for the 50% load

Phase A Open-Circuit Fault of 6PIM

In the event of the phase A open-circuit fault, the stator currents in the remaining phases increase (Fig. 7) to maintain the required electromagnetic torque. The presence of the 5th, 7th, 11th, and 13th harmonics in the stator currents is due to the non-sinusoidal distribution of the magnetic field in the machine's air gap. The 11th harmonic of the current is negligible (0.18%) and is associated with the supply from PWM voltage inverter (Fig. 8).

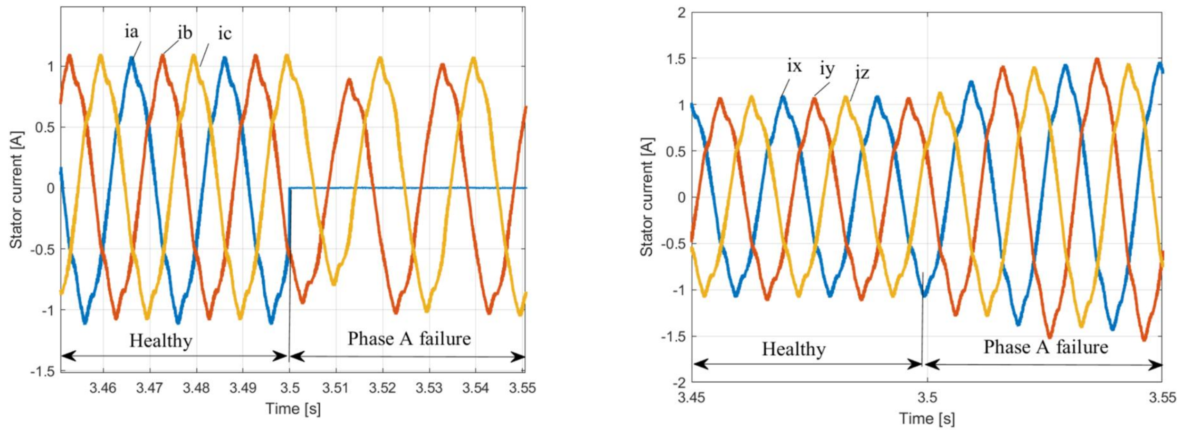

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Fig. 7. Stator currents of A,B,C phases (a) and X,Y,Z phases (b) of the symmetrical 6PIM for the 50% load and open-phase fault

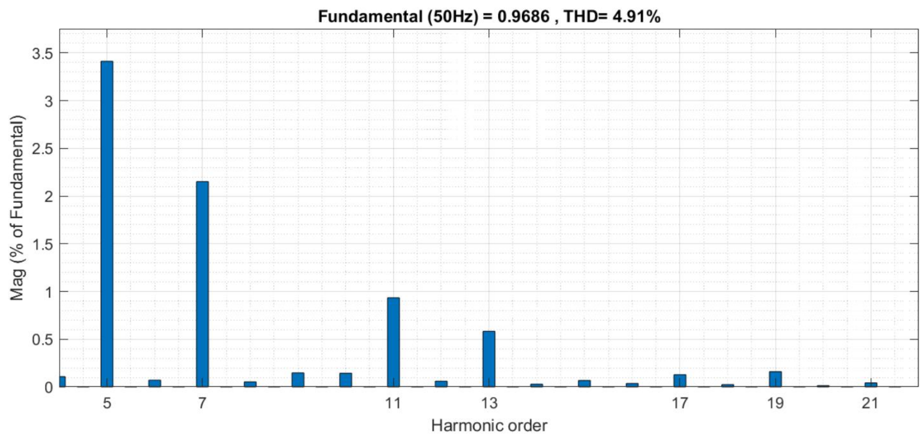

Fig. 8. Harmonic spectrum of the current of the symmetrical 6PIM for the 50% load and open-phase fault

The presence of the aforementioned harmonics in the machine's stator currents causes pulsations of the electromagnetic torque and the machine's angular speed (Fig. 9). It should be noted that, in addition to the harmonics observed in normal operation (specifically the 6th, 12th, and 18th), the 2nd harmonic also appears, caused by the negative-sequence component of the magnetic field. This harmonic is dominant and determines the THD of the electromagnetic torque at the level of 14.39% (Fig. 10).

Single-channel power supply at 50% load in 6PIM

In the event of an open-circuit fault of phases A, B, and C, the stator currents in the remaining phases increase (Fig. 11) to maintain the required electromagnetic torque. The presence of the 5th, 7th, 11th, and 13th harmonics in the stator currents is due to the non-sinusoidal distribution of the magnetic field in the machine's air gap. The 19th harmonic of the current is negligible (0.18%) and is associated with the supply from PWM voltage inverter (Fig. 12).

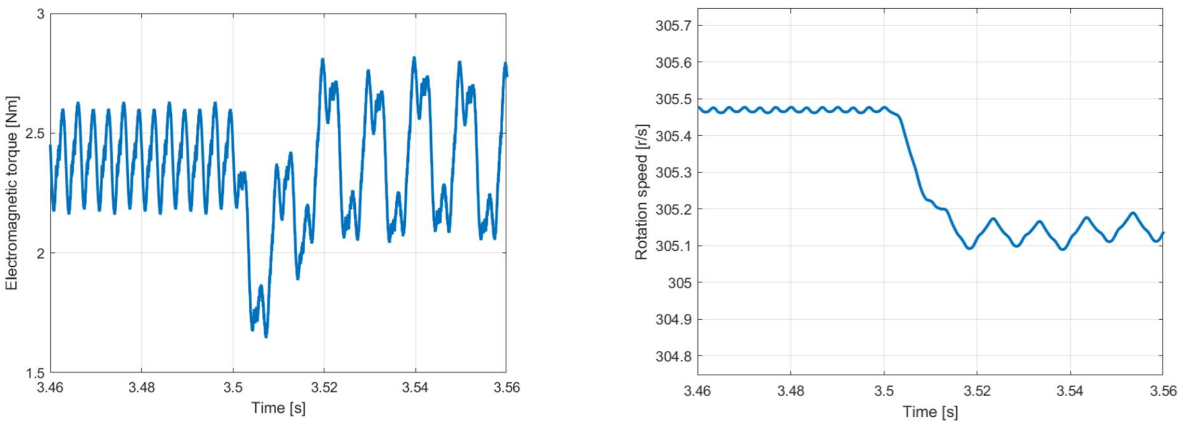

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Fig. 9. Electromechanical torque (a) and rotational speed (b) of the symmetrical 6PIM for the 50% load

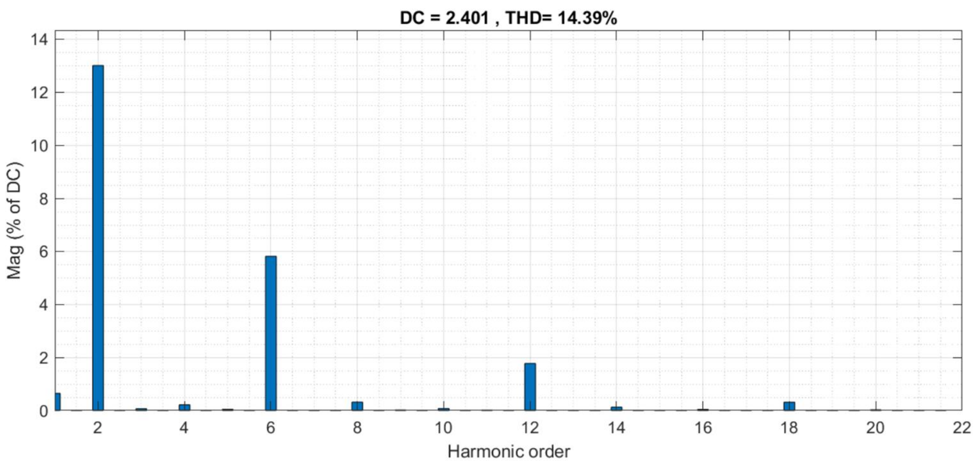

Fig. 10. Harmonic spectrum of the torque of the symmetrical 6PIM for the 50% load and open-phase fault

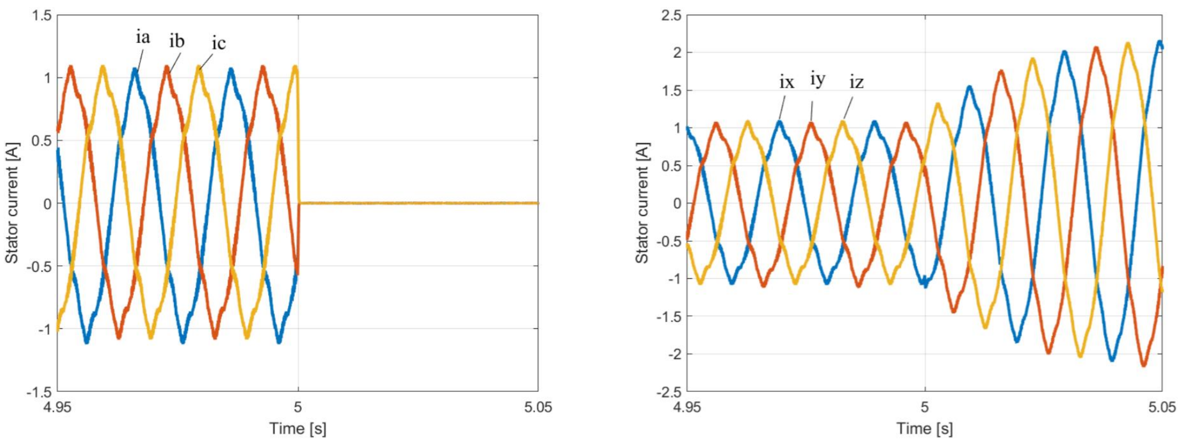

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Fig. 11. Stator currents of A,B,C phases (a) and X,Y,Z phases (b) of the symmetrical 6PIM for the 50% load and three open-phase fault

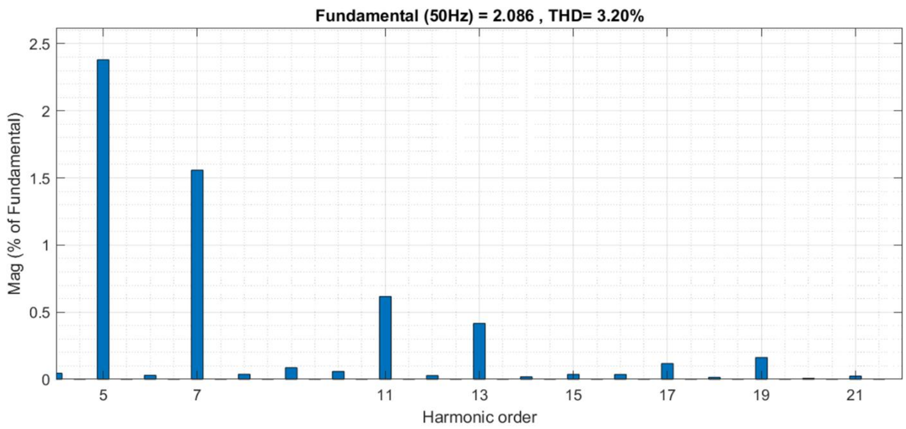

Fig. 12. Harmonic spectrum of the current of the symmetrical 6PIM for the 50% load and three-phase fault

The presence of the aforementioned harmonics in the stator currents causes pulsations of the electromagnetic torque and the machine's angular speed (Fig. 13). It should be noted that the amplitude of the torque pulsations in this mode is reduced compared to normal operation. Consequently, the THD of the electromagnetic torque decreases to 14.39% (Fig. 14).

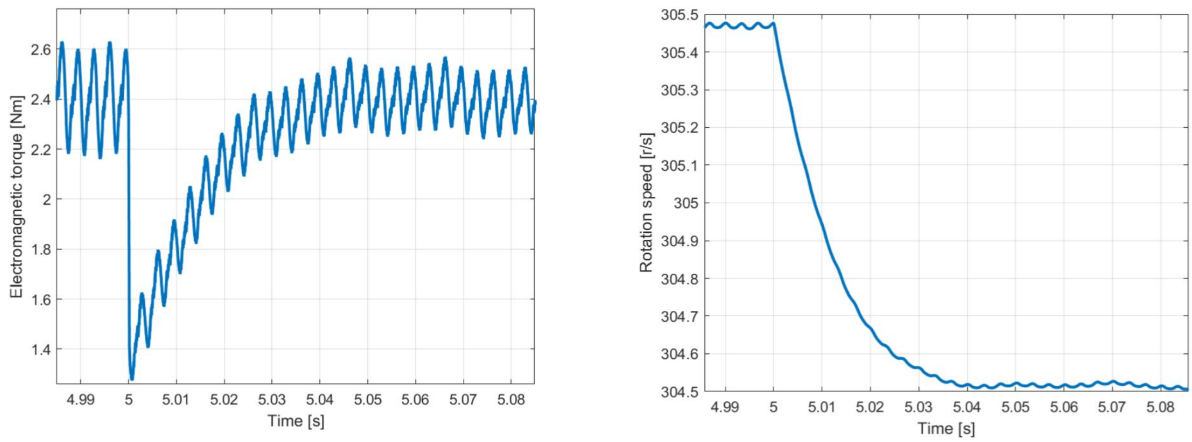

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Fig. 13. Electromechanical torque (a) and rotational speed (b) of the symmetrical 6PIM for the 50% load and three-phase fault

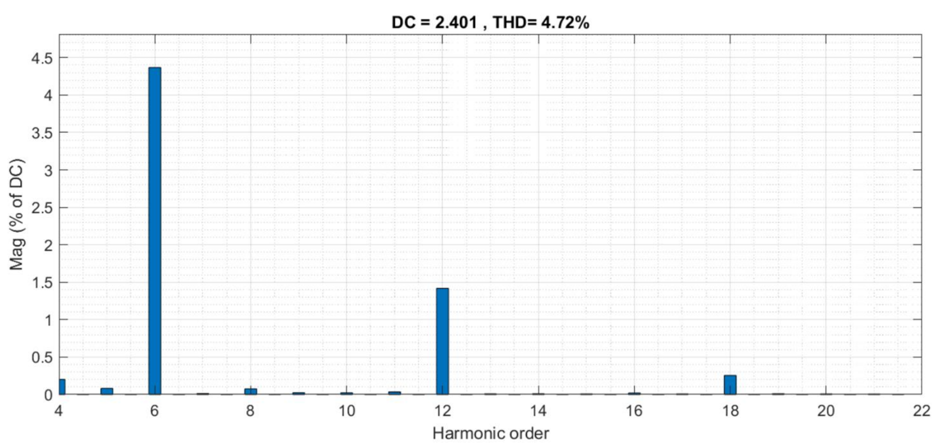

Fig. 14. Harmonic spectrum of the torque of the symmetrical 6PIM for the 50% load and three-phase fault

Conclusion

The interaction between the spatial harmonics of the MMF and the time harmonics generated by PWM voltage inverters causes pulsations of the electromagnetic torque. Harmonic analysis of current and torque indicates that, under normal operating conditions when powered by the PWM inverter, the dominant components are the spatial harmonics.

In fault conditions, particularly when the single-phase open-circuit fault occurs, the second harmonic of the electromagnetic torque becomes dominant due to the negative-sequence component of the air-gap magnetic field. In this scenario, the 6^{th} and 12^{th} torque harmonics, which originate from spatial harmonics, are reduced compared to normal operation due to the absence of current in one phase.

In the case of the single-channel power supply of the 6PIM, the harmonic spectrum of both current and torque shows lower THD than in normal operation. However, in this operating mode, the machine can only operate under reduced load, and the dominant influence remains with the spatial harmonics.

In these operating conditions, the PWM inverter has a negligible influence on the current waveform, as the amplitude of the 19^{th} current harmonic is negligible, and the corresponding 18^{th} torque harmonic is insignificant.

Direction of further research

Future research will focus on a detailed investigation of the effects of various control strategies on reducing the harmonic content of currents and the electromagnetic torque in 6PIM. Special attention will be given to evaluating the effectiveness of these strategies not only under normal operating conditions but also during single-phase and multi-phase fault scenarios. The outcomes of these studies are expected to facilitate the development of optimal control methods that minimize torque and speed pulsations while improving the overall performance and reliability of the electric drive.

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ГАРМОНІЧНИЙ АНАЛІЗ СТРУМУ ТА ЕЛЕКТРОМАГНІТНОГО МОМЕНТУ ШЕСТИФАЗНОЇ АСИНХРОННОЇ МАШИНИ З ЖИВЛЕННЯМ ВІД ІНВЕРТОРА З ШІМ В АВАРІЙНИХ РЕЖИМАХ

Шестифазні асинхронні машини маю значну увагу завдяки високій ефективності та підвищеній стійкості до відмов. Порівняно з традиційними трифазними машинами, шестифазні приводи можуть працювати при обриві однієї, двох або навіть трьох фаз статора, продовжуючи створювати електромагнітний момент і підтримувати механічне навантаження, хоча при цьому зростають пульсації моменту, гармонійні спотворення та спостерігається певне зниження ефективності. Така поведінка пояснюється взаємодією просторових гармонік, які визначаються

переважно конструкцією машини та конфігурацією обмоток, з часовими гармоніками, пов'язаними зі схемою живлення від інвертора з широтно-імпульсною модуляцією.

У статті проведено аналіз гармонік струму та електромагнітного моменту шестифазних асинхронних машин з живленням від інвертора з широтно-імпульсною модуляцією, базуючись на взаємодії просторових і часових гармонік. Дослідження охоплює як нормальний режим роботи, так і аварійні сценарії, висвітлюючи вплив гармонійних складових на пульсації електромагнітного моменту, коливання швидкості та загальний коефіцієнт гармонічних спотворень.

Взаємодія просторових гармонік машини з часовими гармоніками від інвертора напруги з широтно-імпульсною модуляцією викликає пульсації електромагнітного моменту. У нормальному режимі домінують просторові гармоніки у кривих струму та моменту. При однофазному обриві фази домінує друга гармоніка через компоненту магнітного поля з зворотної послідовності, тоді як 6-та та 12-та гармоніки моменту зменшуються. У разі трифазного обриву фаз машина працює при зниженому навантаженні, а гармонійний спектр показує менший коефіцієнт гармонічних спотворень порівняно з нормальним режимом, при цьому просторові гармоніки залишаються домінуючими. Ці результати підкреслюють важливість аналізу гармонік для оптимізації стратегій керування та підвищення загальної продуктивності та надійності шестифазних приводів. Інвертор напруги з широтно-імпульсною модуляцією має незначний вплив у цих аварійних умовах, оскільки гармоніки високих порядків у струмі та моменті є несуттєвими.

Ключові слова: симетрична шестифазна асинхронна машина, просторові гармоніки, інвертор напруги з ШІМ, математичне моделювання, аварійні режими.