

Article

An Analysis of Asymmetrical and Open-Phase Modes in a Symmetrical Two-Channel Induction Machine with Consideration of Spatial Harmonics

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Abstract: This paper focuses on analyzing asymmetric and open-phase fault modes in symmetrical two-channel six-phase induction machines while considering the spatial harmonics of the electromagnetic field in the air gap. Under sinusoidal power supply, the magnetomotive force exhibits high-order spatial harmonics, which arise due to the winding design. The interaction between these spatial harmonics and the first-time harmonic of the power supply results in the presence of high-order harmonics in the current and electromagnetic torque. The harmonic content of the currents and torque under asymmetric and open-phase operation mode while taking into account spatial harmonics is analyzed. It is shown that in asymmetrical modes, in addition to the 5th, 7th, 11th, and 13th higher harmonics found in symmetrical modes, harmonics in multiples of the 3rd are introduced into the stator winding currents. As for the composition of the electromagnetic torque in asymmetrical modes, all even harmonics are present, in addition to the 6th and 12th harmonics that are characteristic of symmetrical modes. A mathematical model of the six-phase induction machine has been developed using the average voltages within the integration step method. Its adequacy was verified by comparing the simulation results with the experimental results obtained from the developed prototype.

Keywords: induction machine; electrical fault; electromagnetic fields; electromagnetic torque; harmonic analysis



Citation: Kutsyk, A.; Korkosz, M.; Bogusz, P.; Semeniuk, M.; Lozynskyy, A. An Analysis of Asymmetrical and Open-Phase Modes in a Symmetrical Two-Channel Induction Machine with Consideration of Spatial Harmonics. *Energies* **2024**, *17*, 870. <https://doi.org/10.3390/en17040870>

Academic Editor: Claus Leth Bak

Received: 30 November 2023

Revised: 4 February 2024

Accepted: 8 February 2024

Published: 13 February 2024



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1. Introduction

Multi-winding induction machines have a lot of advantages that determine their application in modern electric vehicles. These advantages include higher electromagnetic compatibility and the electromechanical compatibility of the machine with the load compared to conventional three-phase machines [1,2]. In addition, special attention is given to the issue of increased fault tolerance in these machines [3]. This refers to the operation of the machine in the case of fault conditions, such as one or several phases being missing. Under such conditions, the electric machine continues to operate with slightly degraded performance compared to a conventional three-phase machine [4,5]. Reference [6] presents strategies for optimal control in the fault modes in a six-phase induction machine, aiming to improve the electromechanical compatibility of the machine with the load. Reference [7] analyzes the topology of a six-phase asynchronous generator in a wind power system and its fault tolerance capability. Reference [8] proposes a control law for a six-phase induction motor in a positional system in the case of the open-phase fault.

Most works propose the use of six-phase [9] or two-channel induction machines [10], in which the windings are shifted in space by a certain angle.

References [11,12] focus on the fault modes of the two-channel induction machines under sinusoidal supply. However, these and similar publications do not take into consideration the influence of spatial harmonics of the magnetomotive force (MMF) caused by the non-sinusoidal distribution of winding turns in space. Meanwhile, as demonstrated in [13,14], spatial harmonics do affect the current waveform and electromagnetic torque of the machine.

To investigate the spatial harmonics' influence on the electromagnetic torque of the induction machine, field theory-based mathematical models combined with the finite element method (FEM) are commonly used [15,16]. These models make it possible to study the influence of spatial harmonics on static characteristics and to analyze the steady-state operation. However, such models are characterized by low computational performance and are challenging to use for transient analysis [17,18]. At the same time, the synthesis of electric drive control systems requires models with increased computational performance to analyze long transients, especially in multi-machine systems with controlled power supplies. To solve such problems, the above models are not very suitable. In this case, faster circuit-theory-based mathematical models are used, which, however, do not take into consideration the influence of spatial harmonics [19]. Therefore, to analyze the influence of spatial harmonics on both steady-state and transient operation modes of an induction machine, the paper proposes a circuit theory-based mathematical model based on the authors' AVIS method in combination with an analytical description of the magnetizing force, which is formed as a result of the interaction of the spatial harmonics of the winding coils' distribution function with the first-time harmonic of the supply. A feature of the developed mathematical model is the representation of the induction machine in the form of a multipole, which makes it possible to implement various options for connecting windings to power sources. This paper's objective is to analyze the influence of spatial harmonics on the stator current and electromagnetic torque of the six-phase symmetrical induction motor (6PSIM) containing two three-phase windings on the stator, with a spatial displacement of 60 electrical degrees [4,20]. This analysis was carried out for steady-state and transient regimes under asymmetrical modes and open-phase faults using the developed mathematical model and experimental investigations on a prototype of the 6PSIM. It should be noted that in the known studies of emergency modes of multi-channel (multi-winding) induction machines, the influence of spatial harmonics is usually neglected, since their influence is less than the influence of time harmonics caused by the negative sequence field in an asymmetric system. In this paper, the analysis of asymmetrical operating modes and phase failure modes is carried out (taking into consideration spatial harmonics) and quantitatively shows the influence of spatial harmonics on machine's characteristics.

The structure of the paper is as follows. An analytical description of the magnetomotive force of the 6PSIM for the asymmetric operating modes taking into consideration spatial harmonics is included in Section 2. Section 3 presents the calculation scheme for the system with the 6PSIM and the mathematical model of 6PSIM. A special feature of this model is the representation of calculation schemes of the power source and 6PSIM in the form of multipoles, which makes it possible to implement various schemes for connecting windings to the power source. The experimental test bench developed by the authors with the prototype of the 6PSIM is given in Section 4. The experimental and simulation results for the 6PSIM in asymmetrical operation modes and under the open-phase faults are presented in Section 5. The tasks for further research are discussed in Section 6. The conclusions are finally summarized in Section 7.

2. Analytical Description of the MMF for Asymmetric Operating Modes

This section focuses on providing an analytical description of the MMF of the 6PSIM consisting of two three-phase windings, ABC and XYZ, shifted by an angle of 60 electric degrees under the condition of sinusoidal power supply for asymmetric operating modes

in which the amplitudes (effective values) of the phase currents are not identical. Such asymmetry may be due to differences in phase supply voltages or differences in the electromagnetic parameters of the phases (for example, due to inter-turn short circuits in one of the winding phases).

It is well established that the magnetic field in the air gap created by a three-phase winding (ABC) comprises not only the fundamental harmonic but also higher harmonics. With this in mind, the expressions representing the MMF for phases A, B, and C are formulated as follows (expression will be similar for XYZ):

$$F_{ABC} = w_A i_A + w_B i_B + w_C i_C = \sum_i w_i \cos(i\eta) \sum_j I_{Amj} \cos(j\omega t) + \sum_i w_i \cos(i\eta - i\rho) \sum_j I_{Bmj} \cos(j\omega t - j\rho) + \sum_i w_i \cos(i\eta + i\rho) \sum_j I_{Cmj} \cos(j\omega t + j\rho), \quad (1)$$

where w_A, w_B, w_C are the functions of winding coil's distribution $w(\eta)$; w_i is the magnitude of the winding function's spatial harmonics; i_A, i_B, i_C are the stator currents; $I_{Amj}, I_{Bmj}, I_{Cmj}$ are the stator currents magnitudes for j -th harmonics; $i = 2n \pm 1, j = 2n \pm 1, (n = 0, 1, 2, \dots, M)$ are the harmonics' order; η is the spatial angle in electric degrees; and $\rho = 2\pi/3; \omega = 2\pi f, f$ is the frequency of the current.

Because

$$I_{Amj} \cos(j\omega t) [w_3 \cos(3\eta)] + I_{Bmj} \cos(j\omega t - j\rho) [w_3 \cos(3\eta - 3\rho)] + I_{Cmj} \cos(j\omega t + j\rho) [w_3 \cos(3\eta + 3\rho)] = 0, \quad (2)$$

if $I_{Amj} = I_{Bmj} = I_{Cmj}$ in symmetrical mode, there are no harmonics multiples of three in the MMF composition. In this case, the 5th, 7th, 11th, and 13th spatial harmonics are found to have the most significant impact. An analysis of the interaction of these spatial harmonics with time harmonics of the power supply for symmetrical modes is presented in [13], where, in particular, it is noted that the interaction between the first-time-harmonic of the winding supply and the 5th, 7th, 11th, and 13th spatial harmonics of the winding coil's distribution function causes the appearance of the 6th and 12th harmonics in the magnitude of the MMF and electromagnetic torque of the machine. Additionally, 5th, 7th, 11th, and 13th time harmonics appear in the stator currents in the case of a sinusoidal supply.

In the case of asymmetric operating modes, equality (2) is not satisfied, resulting in the influence of harmonics in multiples of three on the MMF, currents, and electromagnetic torque. Thus, in addition to the aforementioned harmonics for the symmetrical mode [13], harmonics caused by the interaction of the k -th odd spatial harmonics in multiples of three ($k = 3, 9, 15, \dots$) with the first-time harmonic of the power supply will appear in the composition of the magnetizing force (for the first ABC channel):

$$F_{ABC1k} = \frac{I_{mA1} w_k}{2} [\cos(k\eta - \omega t) + \cos(k\eta + \omega t)] + \frac{I_{mB1} w_k}{2} [\cos(k\eta - \omega t + \rho) + \cos(k\eta + \omega t - \rho)] + \frac{I_{mC1} w_k}{2} [\cos(k\eta - \omega t - \rho) + \cos(k\eta + \omega t + \rho)], \quad (3)$$

and for the second XYZ channel:

$$F_{XYZ1k} = \frac{I_{mX1} w_k}{2} [\cos(k\eta - \omega t + \beta_{1k}) + \cos(k\eta + \omega t + \beta_{2k})] + \frac{I_{mY1} w_k}{2} [\cos(k\eta - \omega t + \beta_{1k} + \rho) + \cos(k\eta + \omega t + \beta_{2k} - \rho)] + \frac{I_{mZ1} w_k}{2} [\cos(k\eta - \omega t + \beta_{1k} - \rho) + \cos(k\eta + \omega t + \beta_{2k} + \rho)], \quad (4)$$

where F_{ABC1k}, F_{XYZ1k} are the components of the MMF caused by the interaction of the k -th multiples-of-three spatial harmonics with the first-time harmonic of the power supply; $\beta_{1k} = \frac{(k-1)\pi}{3}, \beta_{2k} = \frac{(k+1)\pi}{3}, k = 3, 9, 15, 21, \dots$

The additional component of the total MMF caused by the asymmetry will be equal to

$$F_{\text{asym}} = \sum_{k=3,9,15} (F_{\text{ABC1k}} + F_{\text{XYZ1k}}) \quad (5)$$

and will contain the 3rd, 9th, and 15th harmonics (higher harmonics can be neglected).

The magnitude of the MMF of the symmetrical 6PSIM is determined by substitution $\eta = \omega t$ in (3) and (4), according to the following expressions:

$$\begin{aligned} F_{\text{ABC1km}} = & \frac{I_{m\Delta 1} w_k}{2} [\cos((k-1)\omega t) + \cos((k+1)\omega t)] + \\ & + \frac{I_{mB1} w_k}{2} [\cos((k-1)\omega t + \rho) + \cos((k+1)\omega t - \rho)] + \\ & + \frac{I_{mC1} w_k}{2} [\cos((k-1)\omega t - \rho) + \cos((k+1)\omega t + \rho)]. \end{aligned} \quad (6)$$

$$\begin{aligned} F_{\text{XYZ1km}} = & \frac{I_{mX1} w_k}{2} [\cos((k-1)\omega t + \beta_{1k}) + \cos((k+1)\omega t + \beta_{2k})] + \\ & + \frac{I_{mY1} w_k}{2} [\cos((k-1)\omega t + \beta_{1k} + \rho) + \cos((k+1)\omega t + \beta_{2k} - \rho)] + \\ & + \frac{I_{mZ1} w_k}{2} [\cos((k-1)\omega t + \beta_{1k} - \rho) + \cos((k+1)\omega t + \beta_{2k} + \rho)]. \end{aligned} \quad (7)$$

$$F_{\text{masym}} = \sum_{k=3,9,15} (F_{\text{ABC1km}} + F_{\text{XYZ1km}}) \quad (8)$$

The additional content of the 3rd and higher odd multiples-of-three harmonics in the instantaneous values of the MMF (Equations (3) and (4)) results in the emergence of these harmonics in the electromotive forces and in the winding currents of the induction machine. Consequently, the influence of spatial harmonics in asymmetric modes leads to a greater distortion of currents compared to symmetric operation.

The amplitude of the magnetizing force, in this case, is pulsating and contains (in addition to the 6th, and 12th harmonics) all even harmonics (Equations (6)–(8)). Among them, the 2nd, 4th, 8th, and 10th harmonics have a notable influence. The electromagnetic torque of an induction motor will have a similar harmonic composition. The harmonic composition of currents and the electromagnetic torque of an induction motor are extensively analyzed in Section 5.

3. Mathematical Model of the 6PSIM

The mathematical model of the 6PSIM was developed by the authors using the average voltages in integration step (AVIS) method, which is described in detail in [21]. The AVIS method has the advantages of high computational efficiency and numerical stability, making it possible to create fast-response mathematical models that can operate in real-time mode and interact with physical objects using hardware-in-the-loop technology. For instance, such models have been developed for electrical drives with three-phase induction motors [22,23] and multi-phase induction machines [13]. Moreover, the AVIS method has been used to create models of a power generation system with a synchronous generator [24] and electrical systems with parallel calculations [25]. These examples demonstrate the adequacy and efficiency of the AVIS method for modeling electromagnetic and electromechanical processes in electromechanical systems. The mathematical model created using the AVIS method can be used in estimators and observers as an element of the control system due to its increased performance and numerical stability.

The mathematical model of the 6PSIM is represented in phase coordinates (Figures 1 and 2) as a multipole. Representing the 6PSIM model in the form of a multipole structure allows for the investigation of the various options for winding connections and expands capabilities for analyzing fault modes. Three-phase stator windings of the 6PSIM are placed with the phase displacement of $\alpha = 60$ electric degrees between stator sets (sA, sB, sC) and (sX, sY, sZ).

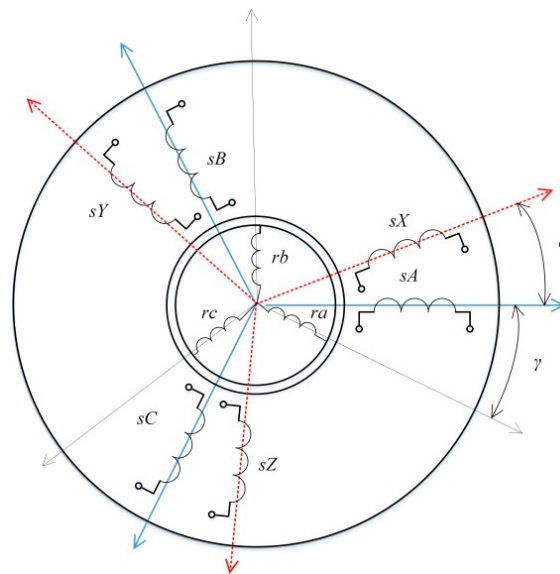


Figure 1. The winding scheme of the 6PSIM mathematical model.

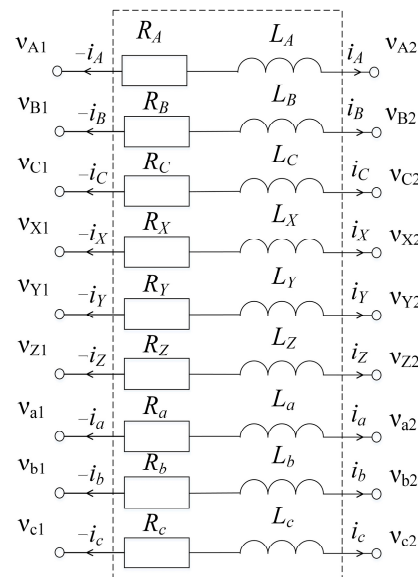


Figure 2. The calculation scheme of the 6PSIM mathematical model as a multipole.

The mathematical model of a three-phase asynchronous machine in the form of a 12-pole machine, developed using the second-order AVIS method, is described in [26]. This model is created by employing the universal equation of the AVIS method for an electrical branch containing resistance R and inductance L [21]:

$$U - u_{R0} - u_{C0} - \sum_{k=1}^{m-1} \left(\frac{R \Delta t^k}{(k+1)!} \cdot \frac{m-k}{m+1} \right) \frac{d^k i_0}{dt^k} + \left(\frac{R}{m+1} \right) (i_0 - i_1) + \frac{1}{\Delta t} (\Psi_0 - \Psi_1) = 0, \quad (9)$$

where i_0, i_1 are the branch current values at the beginning and the end of the integration step; m is the order of the polynomial that describes the current curve in the integration step (order of the method); $U = \frac{1}{\Delta t} \int_{t_0}^{t_0+\Delta t} u dt$ is the average of the integration step values of the branch voltage; u_{R0} is the voltage on the resistance at the beginning of the integration step; ψ_0, ψ_1 are the flux linkages at the beginning and the end of the integration step; and Δt is the integration step value.

Similar to [26], the vector equation for the stator and rotor windings of 6PSIM as a multipole is written as follows:

$$\begin{aligned} & \frac{1}{\Delta t} \int_{t_0}^{t_0+\Delta t} \vec{v}_1 dt - \frac{1}{\Delta t} \int_{t_0}^{t_0+\Delta t} \vec{v}_2 dt - \mathbf{R}_{6PIM} \vec{i}_{6PIM0} + \frac{\mathbf{R}_{6PIM}}{3} \vec{i}_{6PIM0} - \\ & - \frac{\mathbf{R}_{6PIM}}{6} \Delta t \frac{d\vec{i}_{6PIM0}}{dt} - \frac{\mathbf{R}_{6PIM}}{3} \vec{i}_{6PIM1} - \frac{1}{\Delta t} (\vec{\psi}_{6PIM1} - \vec{\psi}_{6PIM0}) = 0, \end{aligned} \quad (10)$$

where $\vec{v}_1 = (v_{A1}, v_{B1}, v_{C1}, v_{X1}, v_{Y1}, v_{Z1}, v_{a1}, v_{b1}, v_{c1})^T$, $\vec{v}_2 = (v_{A2}, v_{B2}, v_{C2}, v_{X2}, v_{Y2}, v_{Z2}, v_{a2}, v_{b2}, v_{c2})^T$ are the vectors of the external poles' potentials; $\vec{i}_{6PIM0} = (i_{A0}, i_{B0}, i_{C0}, i_{X0}, i_{Y0}, i_{Z0}, i_{a0}, i_{b0}, i_{c0})^T$, $\vec{i}_{6PIM1} = (i_{A1}, i_{B1}, i_{C1}, i_{X1}, i_{Y1}, i_{Z1}, i_{a1}, i_{b1}, i_{c1})^T$ are the vectors of stator and rotor currents at the beginning and the end of the integration step; $\mathbf{R}_{6PIM} = \text{diag}(R_A, R_B, R_C, R_X, R_Y, R_Z, R_a, R_b, R_c)$ is the matrix of stator and rotor winding resistance; and $\vec{\Psi}_{6PIM0} = (\psi_{A0}, \psi_{B0}, \psi_{C0}, \psi_{X0}, \psi_{Y0}, \psi_{Z0}, \psi_{a0}, \psi_{b0}, \psi_{c0})^T$, $\vec{\Psi}_{6PIM1} = (\psi_{A1}, \psi_{B1}, \psi_{C1}, \psi_{X1}, \psi_{Y1}, \psi_{Z1}, \psi_{a1}, \psi_{b1}, \psi_{c1})^T$ are the vectors of stator and rotor winding flux linkages at the beginning and end of the integration step.

The vectors of stator and rotor winding flux linkages at the beginning and end of the integration step are written as follows:

$$\vec{\psi}_{6PIM0} = \mathbf{L}_{6PIM0} \vec{i}_{6PIM0}, \quad \vec{\psi}_{6PIM1} = \mathbf{L}_{6PIM1} \vec{i}_{6PIM1}, \quad (11)$$

where $\mathbf{L}_{6PIM0}$, $\mathbf{L}_{6PIM1}$ are the vectors of inductances at the beginning and end of the integration step.

The values of inductances $\mathbf{L}_{6PIM0}$, $\mathbf{L}_{6PIM1}$ depend on the rotor's angular position, γ , and phase displacement, α , between the stator set of 6PSIM three-phase windings. The rotor's angular position γ is changed in the integration step and determined according to the following equation:

$$\frac{d\gamma}{dt} = p\omega, \quad (12)$$

where ω is the angular rotation speed of the rotor, and p is the number of pole pairs.

The equation for the 6PSIM model as a multipole is as follows:

$$\vec{i}_{IM} + \mathbf{G}_{IM} \frac{1}{\Delta t} \int_{t_0}^{t_0+\Delta t} \vec{v}_{IM} dt + \vec{C}_{IM} = 0, \quad (13)$$

where $\vec{i}_{IM} = \begin{bmatrix} -\vec{i}_{6PIM1} \\ \vec{i}_{6PIM1} \end{bmatrix}$ is the vector of the external branch's currents; $\vec{v}_{6PIM} = \begin{bmatrix} \vec{v}_1 \\ \vec{v}_2 \end{bmatrix}$ is the vector of the poles' potentials; and the matrices of coefficients are $\mathbf{G}_{IM} = \begin{bmatrix} \mathbf{R}_{IM}^{-1} & -\mathbf{R}_{IM}^{-1} \\ -\mathbf{R}_{IM}^{-1} & \mathbf{R}_{IM}^{-1} \end{bmatrix}$,

$$\mathbf{R}_{IM} = \frac{\mathbf{R}_{6PIM}}{3} + \frac{\mathbf{L}_{6PIM1}}{\Delta t}, \quad \vec{C}_{IM} = \begin{bmatrix} -\mathbf{R}_{IM}^{-1} \left(\left(\frac{2\mathbf{R}_{6PIM}}{3} - \frac{\mathbf{L}_{6PIM0}}{\Delta t} \right) \vec{i}_{6PIM0} + \frac{\mathbf{R}_{6PIM}\Delta t}{6} \frac{d\vec{i}_{6PIM0}}{dt} \right) \\ \mathbf{R}_{IM}^{-1} \left(\left(\frac{2\mathbf{R}_{6PIM}}{3} - \frac{\mathbf{L}_{6PIM0}}{\Delta t} \right) \vec{i}_{6PIM0} + \frac{\mathbf{R}_{6PIM}\Delta t}{6} \frac{d\vec{i}_{6PIM0}}{dt} \right) \end{bmatrix}.$$

The equation for the rotation speed is written as follows:

$$\frac{d\omega}{dt} = \frac{T_e - T_L}{J}, \quad (14)$$

where T_e is the electromagnetic torque of 6PSIM; T_L is the load torque; and J is the inertia.

The electromagnetic torque is determined from the equation based on the currents of the stator and rotor windings in the $\alpha\beta$ reference frame:

$$T_e = \frac{3}{2} p L_m (i_{r\beta} i_{s\alpha} - i_{r\alpha} i_{s\beta}), \quad (15)$$

where the stator and rotor winding currents in the $\alpha\beta$ reference frame, $i_{s\alpha}$, $i_{s\beta}$, $i_{r\alpha}$, $i_{r\beta}$, are determined from the known coordinate transformation equations, taking into account the angles between the windings.

The matrix of 6PSIM's inductances is written as follows:

$$\mathbf{L}_{6PIM}(\gamma) = \begin{bmatrix} \mathbf{L}_{s1s1} & \mathbf{L}_{s1s2} & \mathbf{L}_{s1r} \\ \mathbf{L}_{s1s2}^T & \mathbf{L}_{s2s2} & \mathbf{L}_{s2r} \\ \mathbf{L}_{s1r}^T & \mathbf{L}_{s2r}^T & \mathbf{L}_{rr} \end{bmatrix}, \quad (16)$$

where the matrix of self and mutual inductances for stator (indexes s1 and s2) and rotor windings (index r) are as follows:

$$\mathbf{L}_{s1s1} = \mathbf{L}_{s2s2} = \begin{bmatrix} 2L_m/3 + L_{\sigma1} & -L_m/3 & -L_m/3 \\ -L_m/3 & 2L_m/3 + L_{\sigma1} & -L_m/3 \\ -L_m/3 & -L_m/3 & 2L_m/3 + L_{\sigma1} \end{bmatrix}, \quad (17)$$

$$\mathbf{L}_{rr} = \begin{bmatrix} 2L_m/3 + L_{\sigma2} & -L_m/3 & -L_m/3 \\ -L_m/3 & 2L_m/3 + L_{\sigma2} & -L_m/3 \\ -L_m/3 & -L_m/3 & 2L_m/3 + L_{\sigma2} \end{bmatrix}$$

The matrix of mutual inductances between the stator windings is as follows:

$$\mathbf{L}_{s1s2} = \frac{2}{3} \begin{bmatrix} L_m \cos(\alpha) & L_m \cos(\alpha + \rho) & L_m \cos(\alpha - \rho) \\ L_m \cos(\alpha - \rho) & L_m \cos(\alpha) & L_m \cos(\alpha + \rho) \\ L_m \cos(\alpha + \rho) & L_m \cos(\alpha - \rho) & L_m \cos(\alpha) \end{bmatrix}, \quad (18)$$

The matrix of mutual inductances between the stator and rotor windings is as follows:

$$\mathbf{L}_{s2r} = \frac{2}{3} \begin{bmatrix} L_m \cos(\gamma - \alpha) & L_m \cos(\gamma - \alpha + \rho) & L_m \cos(\gamma - \alpha - \rho) \\ L_m \cos(\gamma - \alpha - \rho) & L_m \cos(\gamma - \alpha) & L_m \cos(\gamma - \alpha + \rho) \\ L_m \cos(\gamma - \alpha + \rho) & L_m \cos(\gamma - \alpha - \rho) & L_m \cos(\gamma - \alpha) \end{bmatrix}, \quad (19)$$

$$\mathbf{L}_{s1r} = \frac{2}{3} \begin{bmatrix} L_m \cos(\gamma) & L_m \cos(\gamma + \rho) & L_m \cos(\gamma - \rho) \\ L_m \cos(\gamma - \rho) & L_m \cos(\gamma) & L_m \cos(\gamma + \rho) \\ L_m \cos(\gamma + \rho) & L_m \cos(\gamma - \rho) & L_m \cos(\gamma) \end{bmatrix}.$$

To take into account the spatial harmonics that cause the pulsation of the magnetizing force amplitude, as proposed in [13], we introduce harmonic components into the magnetizing inductance:

$$L_m = L_{m0} + \sum_d L_{md} \cos(d\omega t) d = 2, 4, 6, 8, 10, 12, \quad (20)$$

where L_{m0} is the magnitude of the zero harmonic, and L_{md} is the magnitude of the even harmonic presenting in the composition of the magnetizing force module (described in Section 2).

The calculation scheme for the electromechanical system with the 6PSIM is shown in Figure 3. It consists of an 18-pole structure representing the 6PSIM model and six-pole models for the PN1 and PN2 power sources. The three-phase voltages of the PN1 and PN2 power source are phase-shifted by an electrical angle of 60 electrical degrees. Constructing the models in the form of multipole structures allows for the implementation of different supply schemes. Figure 3 illustrates a scheme with an isolated neutral for the power sources PN1 and PN2.

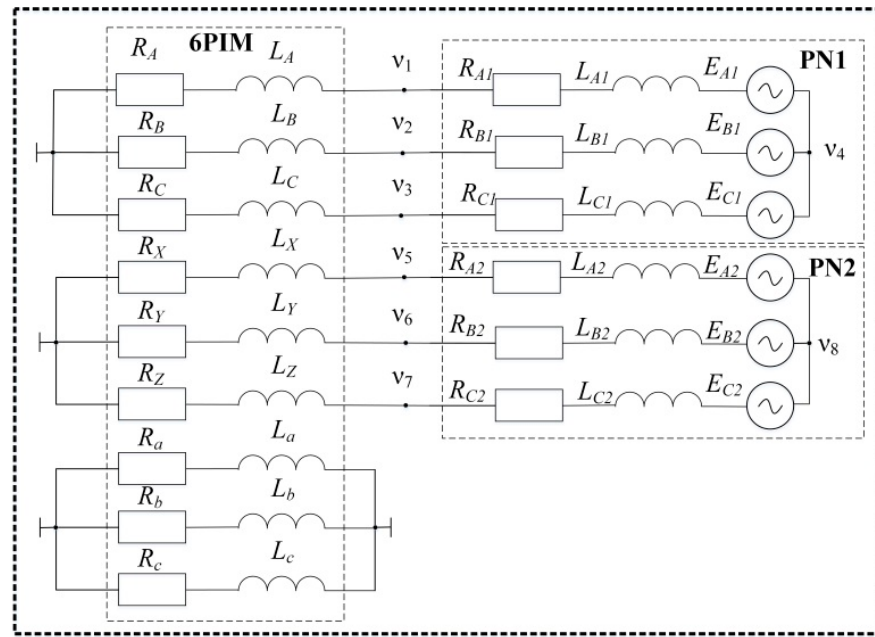


Figure 3. The calculation scheme for the system with the 6PSIM.

The vector equation for the power source model as a multipole (according to AVIS method) is as follows:

$$\vec{i}_{PN} + \mathbf{G}_{PN} \frac{1}{\Delta t} \int_{t_0}^{t_0 + \Delta t} \vec{v}_{PN} dt + \vec{C}_{PN} = 0, \quad (21)$$

where $\vec{i}_{PN}$ is the vector of the external branch's currents of the power source; $\vec{v}_{PN}$ is the vector of the poles' potentials, and the coefficients' matrices are $\mathbf{G}_{PN} = \begin{bmatrix} \mathbf{R}_{PN}^{-1} & -\mathbf{R}_{PN}^{-1} \\ -\mathbf{R}_{PN}^{-1} & \mathbf{R}_{PN}^{-1} \end{bmatrix}$,

$$\mathbf{R}_{PN} = \frac{\mathbf{R}_{3P}}{3} + \frac{\mathbf{L}_{3P}}{\Delta t}, \quad \vec{C}_{PM} = \begin{bmatrix} -\mathbf{R}_{PN}^{-1} \left(\left(\frac{2\mathbf{R}_{3P}}{3} - \frac{\mathbf{L}_{3P}}{\Delta t} \right) \vec{i}_{PN0} + \frac{\mathbf{R}_{3P}\Delta t}{6} \frac{d\vec{i}_{PN0}}{dt} \right) \\ \mathbf{R}_{PN}^{-1} \left(\left(\frac{2\mathbf{R}_{3P}}{3} - \frac{\mathbf{L}_{3P}}{\Delta t} \right) \vec{i}_{PN0} + \frac{\mathbf{R}_{3P}\Delta t}{6} \frac{d\vec{i}_{PN0}}{dt} \right) \end{bmatrix}; \quad \mathbf{R}_{3P} = \text{diag}$$

($\mathbf{R}_{PA}, \mathbf{R}_{PB}, \mathbf{R}_{PC}$) is the matrix of power source resistance; and $\mathbf{L}_{3P}$ is the matrix of power source inductances.

The algorithm of mathematical modeling, which involves determining the potentials of independent system nodes ($v_1 \dots v_8$) based on the coefficients of the equations for element multipoles in the form (13), (21) and determining the currents based on the potentials of the system nodes, is described in [21,26].

4. Experimental Test Bench

The authors designed the prototype of the 6PSIM with the following parameters: a nominal power of 1.5 kW, voltage 400 V and a synchronous speed of 3000 rpm. Additionally, for the experimental study using the asymmetrical and fault mode of the 6PSIM, the authors developed an experimental test bench (Figure 4). The test bench includes the 6PSIM; power transformers PT1 and PT2, which supply the 6PSIM stator windings; and a permanent magnet synchronous generator with an electrical DC load (Figure 5). The three-phase voltages of the PT1 and PT2 secondary windings are shifted by 60 electrical degrees. The winding scheme of the 6PSIM is given in Figure 6.

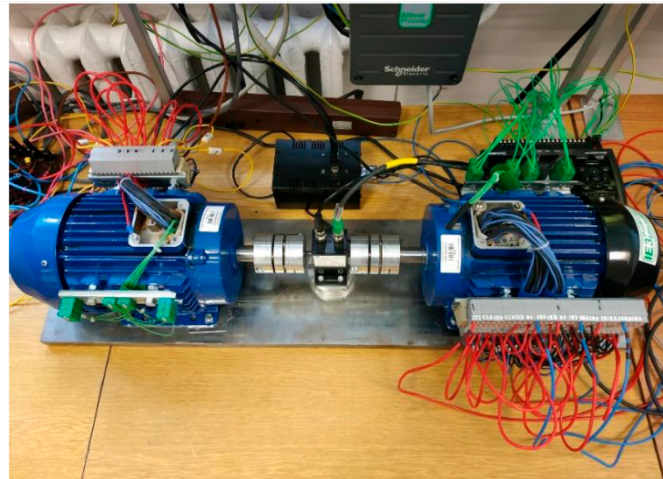


Figure 4. The experimental test bench with the 6PSIM.

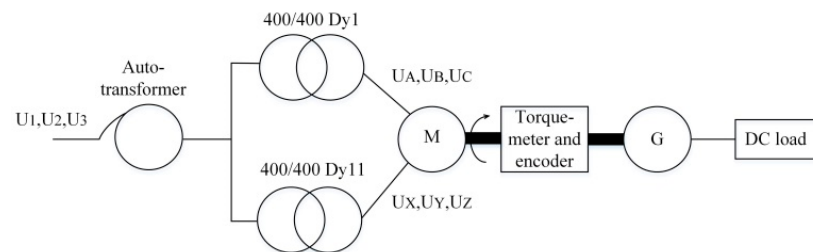


Figure 5. The block diagram of the experimental test bench with the 6PSIM.

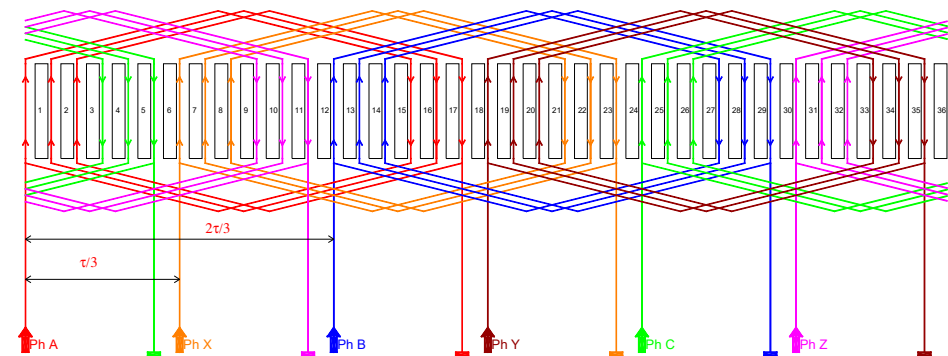


Figure 6. The winding scheme of the symmetrical 6PSIM.

5. Research Results

The objective of the research was to determine the influence of spatial harmonics on the currents and electromagnetic torque of a 6PSIM in asymmetric mode and in the open-phase mode under sinusoidal power supply. The research was carried out by computer simulation using the developed mathematical model, as well as by physical experiment on the developed experimental test bench (it should be noted that it was impossible to investigate the shape of the electromagnetic torque via a physical experiment) The results of the simulation and physical experiment were compared to evaluate the adequacy of the developed model.

The model uses the following parameters of the 6PSIM replacement scheme (corresponding to the parameters of the designed prototype): leakage inductances of the stator and rotor windings (rotor circuit parameters are referred to as the stator) $L_{\sigma 1} = 0.06$ H and $L'_{\sigma 2} = 0.05$ H, magnetization inductance $L_{m0} = 0.75$ H, and resistances of the stator and rotor windings $R_1 = 8.0$ Ohm and $R'_2 = 6.0$ Ohm.

5.1. Asymmetric Mode

Figure 7 shows the stator currents of the 6PSIM in the asymmetrical mode, in which the amplitudes of the phase currents are not identical. The harmonic composition of the currents for this mode is given in Table 1 (harmonics with a content of less than 0.3% are omitted). Due to the sinusoidal nature of the supply voltage, current distortion occurs as a result of the influence of spatial harmonics. The presence of the third and ninth harmonics is a characteristic feature of the asymmetric operation mode. The simulation results closely resemble the qualitative composition of the currents obtained experimentally. The discrepancies can be attributed to the challenges in accurately identifying the actual winding parameters.

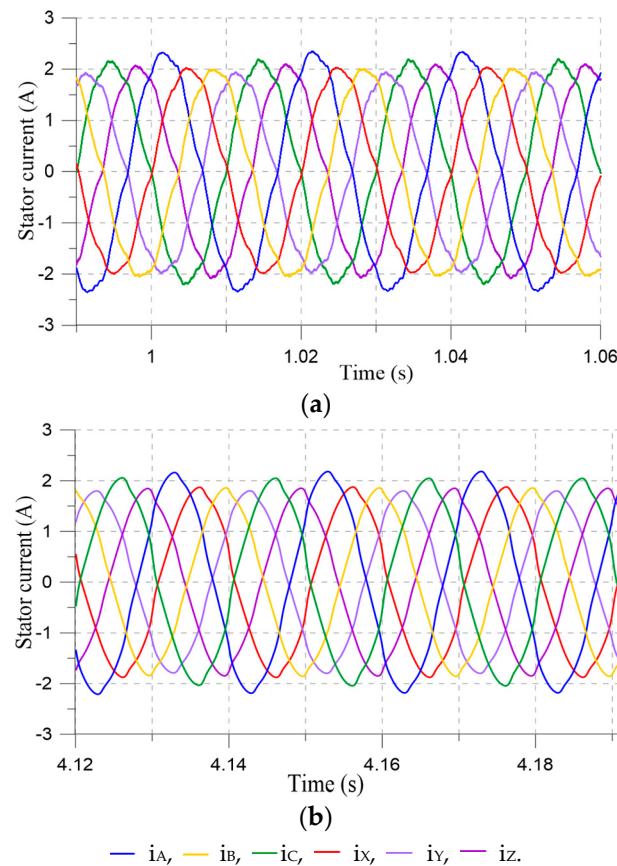


Figure 7. The stator current of the 6PSIM in asymmetric mode for nominal load: experimental results (a) and simulation results (b).

Table 1. Harmonic spectrum of the stator current for the nominal load of the 6PSIM in asymmetric mode.

Harmonic Frequency, Hz	Harmonic Order	Stator Current Harmonic Magnitude, %		
		Experimental Results	Simulation Results	
			without Spatial Harmonics	with Spatial Harmonics
50	1	100	100	100
150	3	0.81	0.05	1.73
250	5	2.70	0.03	1.81
350	7	3.17	0.02	1.38
450	9	0.39	0.01	0.31
550	11	0.48	0.01	0.58
650	13	0.74	0.01	0.47

Figures 8 and 9 show the results of calculating the electromagnetic torque of 6PSIM for an asymmetric operation mode with and without taking into consideration the influence of spatial harmonics and for different loads. The harmonic composition of the electromagnetic torque is shown in Table 2 (harmonics with a content of less than 0.3% are omitted).

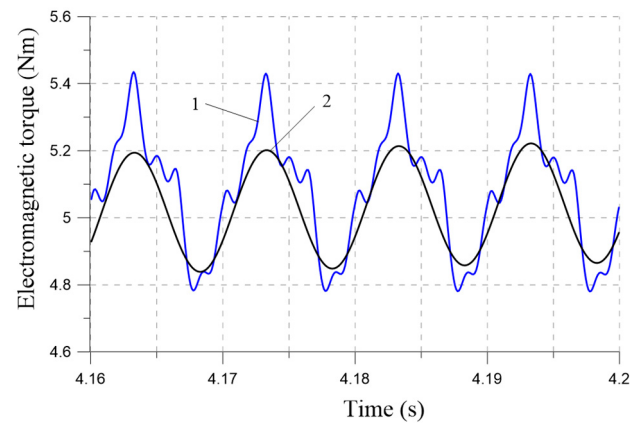


Figure 8. The electromagnetic torque of the 6PSIM in asymmetric mode for the nominal load (simulation results): 1—taking into account spatial harmonics, 2—without taking into account spatial harmonics.

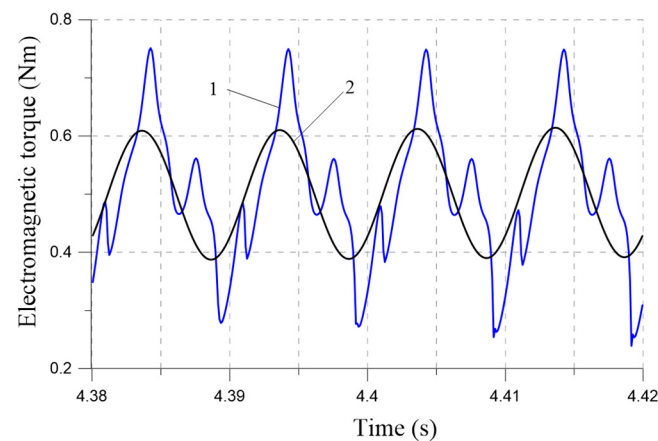


Figure 9. The electromagnetic torque of the 6PSIM in asymmetric mode for a 10% load (simulation results): 1—taking into account spatial harmonics, 2—without taking into account spatial harmonics.

Table 2. Harmonic spectrum of electromagnetic torque of the 6PSIM in asymmetric mode.

Harmonic Frequency, Hz	Harmonic Order	Harmonic Magnitude of the Electromagnetic Torque, %			
		Simulation without Spatial Harmonics		Simulation with Spatial Harmonics	
		Nominal Load	10% Load	Nominal Load	10% Load
0	DC	100	100	100	100
100	2	3.53	22.17	4.6	27.6
200	4	0.03	0.08	0.49	9.18
300	6	0.02	0.02	1.38	12.64
400	8	0.01	0.02	0.35	3.25
500	10	0.01	0.02	0.15	3.7
600	12	0.01	0.01	0.85	4.25

The presented results enable the estimation of the influence of spatial harmonics on the shape of the electromagnetic torque. The shape of the electromagnetic torque is primarily determined by the second harmonic, which arises from the presence of the negative sequence field component in the asymmetric mode. However, the spatial harmonics, particularly the third harmonic, have a significant impact on the torque shape. It is worth noting the increase in the instantaneous values of the electromagnetic torque due to the influence of spatial harmonics in the asymmetric mode, as illustrated in Figures 8 and 9.

Table 3 presents the calculated total harmonic distortion (THD) values for the stator currents and electromagnetic torque of the 6PSIM across various load values. The results indicate that a decrease in load results in an increase in the presence of higher harmonics and a deterioration in the shape of currents and torque.

Table 3. THD of the stator current and the electromagnetic torque of the 6PSIM in asymmetric mode.

THD, %					
Experimental Results	Simulation Results				
	Stator Current		Electromagnetic Torque		
	Stator Current	Without Spatial Harmonics	With Spatial Harmonics	Without Spatial Harmonics	With Spatial Harmonics
	for 10% load				
7.05	0.54	6.28	22.18	32.62	
for nominal load					
4.58	0.32	3.99	3.54	4.91	

The developed mathematical model possesses the distinctive feature of accounting for the influence of spatial harmonics in transient calculations. This sets it apart from models based on the finite element method (FEM), which, while offering higher modeling accuracy through field calculations, are often too computationally intensive and unsuitable for transient studies, particularly in complex systems. Figures 10 and 11 depict the transient process of the electromagnetic torque and the changes in angular speed in the case of load reduction.

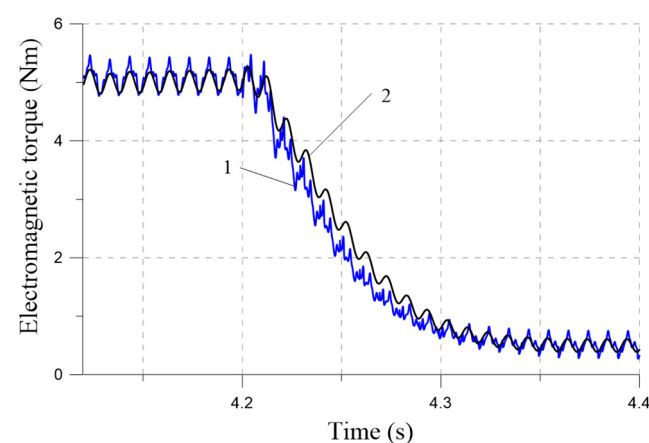


Figure 10. The electromagnetic torque of the 6PSIM in transient asymmetric mode with changing loads (simulation results): 1—taking into consideration spatial harmonics, 2—without taking into consideration spatial harmonics.

5.2. Open-Phase Mode

Figures 12–16 present the research results for the steady-state and transient open-phase failure mode (when phase A is missing) in one power supply channel of a two-

channel 6PSIM. This is an emergency mode (although the advantage of multi-channel electric machines is that they can operate for a certain time in such modes with certain deterioration of characteristics). The schematic diagram of the two-channel 6PSIM is shown in Figure 3. An important characteristic of the utilized two-channel 6PSIM power supply scheme with galvanically separated channels is the alteration in the phase shift of the operating phase currents when one phase is lost (Figure 11). The comparison between the simulation and experimental results confirms the suitability of the developed model for analyzing transients caused by phase breaks. Figure 13 demonstrates that the calculated shape of the 6PSIM stator current closely resembles the actual current obtained from the experimental prototype.

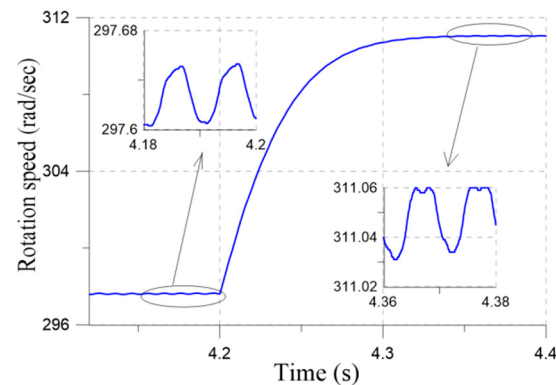


Figure 11. The rotation speed of the 6PSIM in transient asymmetric mode with changing loads (simulation results).

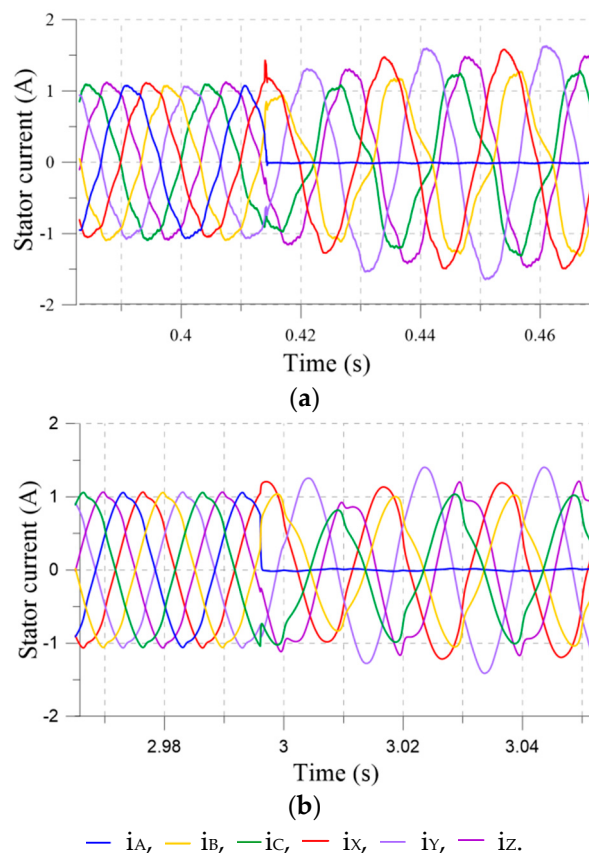


Figure 12. The stator current of the 6PSIM in the open-phase fault mode (when phase A is missing) under pre-fault and fault circumstances: experimental results (a) and simulation results (b).

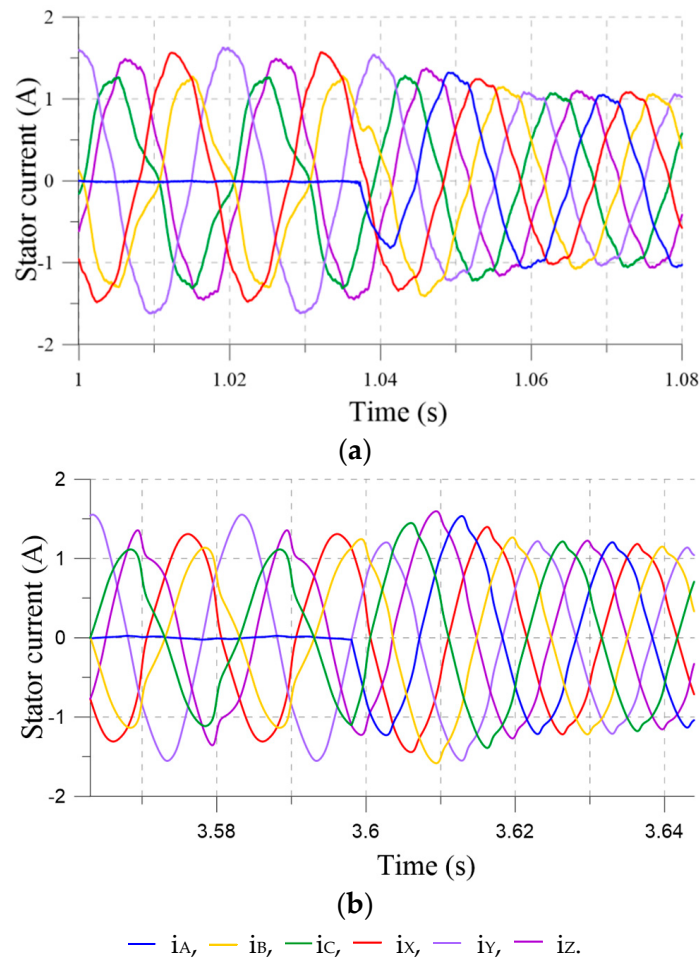


Figure 13. The stator current of the 6PSIM in the open-phase fault mode (when phase A is missing) under fault and post-fault circumstances: experimental results (a) and simulation results (b).

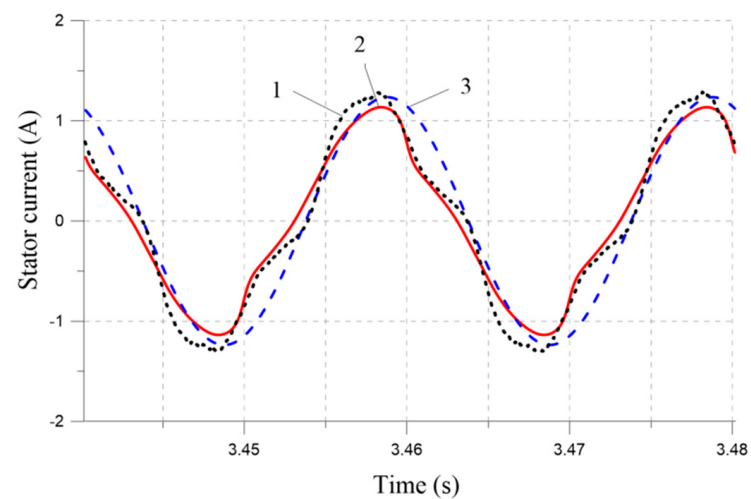


Figure 14. The stator current of the 6PSIM in the open-phase fault mode (when phase A is missing): experimental results (1); simulation results taking into account spatial harmonics (2) and without taking into account spatial harmonics (3).

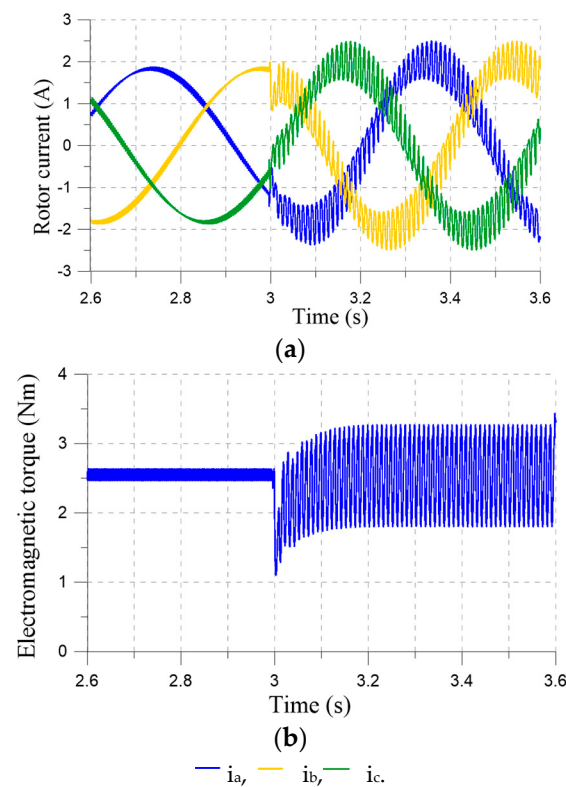


Figure 15. Simulation results of the rotor currents (a) and electromagnetic torque in a transient state (b).

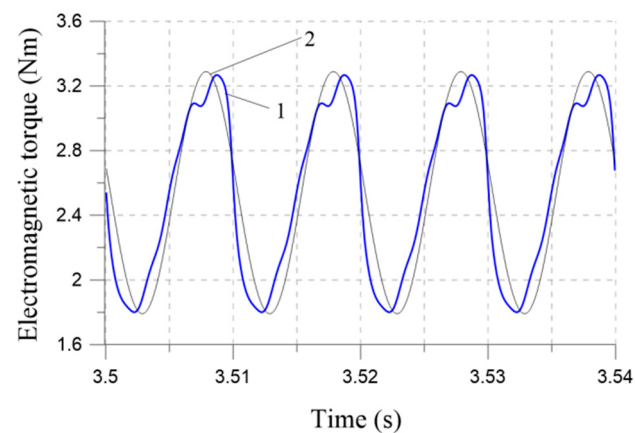


Figure 16. The electromagnetic torque of the 6PSIM in the open-phase fault (when phase A is missing) mode, taking into account spatial harmonics (blue curve 1) and without taking into account spatial harmonics (black curve 2).

In the steady-state symmetrical mode (before the phase break), the 6PSIM currents and electromagnetic torque are also distorted due to the influence of spatial harmonics and contain higher harmonics that are characteristic of the symmetrical operation mode. Specifically, the stator currents exhibit the 5th, 7th, 11th, and 13th harmonics, while the rotor currents and electromagnetic torque exhibit the 6th and 12th harmonics. Notably, the higher harmonics of the electromagnetic torque are also present in the rotor currents. As is evident from Figures 12 and 15, Tables 4–6, when an open phase occurs in one power supply channel, the distortions in the stator and rotor winding currents as well as the electromagnetic torque of the 6PSIM (which is asymmetrically driven) significantly increase. Additionally, harmonics of the asymmetric operation mode emerge in their composition. Specifically, these are the 3rd and 9th harmonics in the stator currents, and the 4th, 8th, and 10th harmonics in the electromagnetic torque.

Table 4. Harmonic spectrum of the stator current of the 6PSIM for open-fault mode (when phase A is missing) and 50% load.

Harmonic Frequency, Hz	Harmonic Order	Stator Current Harmonic Magnitude, %		
		Experimental Results	Simulation Results	
			Without Spatial Harmonics	With Spatial Harmonics
50	1	100	100	100
150	3	15.12	0.0	9.56
250	5	6.85	0.0	5.24
350	7	2.33	0.0	2.52
450	9	0.47	0.0	1.48
550	11	0.66	0.0	1.11
650	13	0.57	0.0	0.69

Table 5. THD of the stator current and the electromagnetic torque of the 6PSIM for open-fault mode (when phase A is missing) and 50% load.

THD, %				
Experimental Results	Simulation Results			
	Stator Current		Electromagnetic Torque	
	Without Spatial Harmonics	With Spatial Harmonics	Without Spatial Harmonics	With Spatial Harmonics
16.96	0	13.38	29.475	29.49

Table 6. Harmonic spectrum of electromagnetic torque of the 6PSIM for 50% load and open-fault mode (when phase A is missing).

Harmonic Frequency, Hz	Harmonic Order	Harmonic Magnitude of the Electromagnetic Torque, %	
		Simulation without Spatial Harmonics	Simulation with Spatial Harmonics
0	DC	100	100
100	2	29.47	28.47
200	4	0	6.21
300	6	0	4.21
400	8	0	2.26
500	10	0	1.28
600	12	0	0.8

The impact of spatial harmonics on the shape of the 6PSIM electromagnetic torque in the open-phase mode is illustrated by the simulation results shown in Figure 16. The predominant harmonic in the rotor currents and electromagnetic torque is the second harmonic, which arises from the presence of a negative sequence field component in the asymmetric mode and is unrelated to spatial harmonics. While spatial harmonics introduce an additional distortion to the torque shape, their influence is not as significant compared to the distortions resulting from considerable asymmetry in the power supply channel, as indicated in Table 6.

6. Discussion

The presented results explain the influence of spatial harmonics on the currents and electromagnetic torque of a symmetrical two-channel induction machine in normal and emergency modes. It is worth noting that the influence of spatial harmonics depends on the

magnitude of the asymmetry. Under the circumstances of significant asymmetry (for example, in open-phase mode), the spatial harmonics' influence on the electromagnetic torque is insignificant compared to the influence of time harmonics caused by the asymmetry. The consequences of such influence in terms of increased losses, deterioration of operational properties and characteristics of the induction drive, and control system improvement will be the subject of further research.

7. Conclusions

Spatial harmonics in the distribution of winding turns in the spatial domain of a six-phase induction machine cause the emergence of higher-order time harmonics in the composition of MMF, currents, and electromagnetic torque under sinusoidal power supply. In asymmetrical operating modes, in addition to the 5th, 7th, 11th, and 13th higher harmonics found in symmetrical modes, harmonics in multiples of three are introduced into the stator winding currents, with the 3rd and 9th harmonics exerting the greatest influence. As for the composition of the electromagnetic torque in asymmetrical operating modes, all even harmonics are present, in addition to the 6th and 12th harmonics that are characteristic of symmetrical modes.

The second harmonic, caused by the negative sequence field component, has the most significant influence on rotor currents and electromagnetic torque in asymmetric modes. Nonetheless, the presence of spatial harmonics notably enhances the instantaneous values (pulses) of the electromagnetic torque in asymmetric modes, with an increase of up to 25% observed in the no-load mode. This effect is especially noticeable at low loads and low rotational speeds.

In a two-channel (two-winding) induction machine, an asymmetry in one channel results in higher-order current harmonics caused by spatial harmonics in all windings, leading to increased power losses. The distortion factor (THD) depends on the magnitude of the asymmetry and reaches its maximum values in the event of a open-phase failure. Therefore, when analyzing the energy efficiency of electric drives utilizing highly tolerant multichannel induction machines capable of operating in a long-term mode with a damaged power supply, it is essential to consider the influence of spatial harmonics resulting from the spatial distribution of winding turns and the time harmonics they generate.

The mathematical model of a two-channel six-phase induction machine, developed using the AVIS method, enables the consideration of spatial harmonics in transient and steady-state calculations while exhibiting high computational efficiency compared FEM-based models. This model is appropriate for developing control methods and improving existing control systems while taking into account the influence of spatial harmonics. The adequacy of the developed model was verified by comparing the modeling results with the results of physical experiments.

Author Contributions: Conceptualization, A.K., M.K. and M.S.; Data curation, M.S. and A.L.; Formal analysis, P.B.; Funding acquisition, M.K.; Investigation, M.S.; Methodology, M.S.; Project administration, P.B.; Resources, M.K.; Software, M.S.; Supervision, M.K.; Validation, M.K., P.B. and A.L.; Writing—original draft, M.S.; Writing—review and editing, A.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was financed in part by the statutory funds (UPB) of the Department of Electrodynamics and Electrical Machine Systems, Rzeszow University of Technology, and in part by the Minister of Education and Science of the Republic of Poland within the 'Regional Initiative of Excellence' program for the years 2019–2023. Project number 027/RID/2018/19, amount granted: 11,999,900 PLN.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors would like to thank Marek Nowak for his help in carrying out the laboratory tests.

Conflicts of Interest: The authors declare no conflicts of interest.

References

- Levi, E. Multiphase Electric Machines for Variable-Speed Applications. *IEEE Trans. Ind. Electron.* **2008**, *55*, 1893–1909. [\[CrossRef\]](#)
- Bojoi, R.; Farina, F.; Profumo, F.; Tenconi, A. Dual-Three Phase Induction Machine Drives Control—A Survey. *IEEE Trans. Ind. Appl.* **2006**, *126*, 420–429. [\[CrossRef\]](#)
- Alberti, L.; Bianchi, N. Experimental Tests of Dual Three-Phase Induction Motor Under Faulty Operating Condition. *IEEE Trans. Ind. Electron.* **2012**, *59*, 2041–2048. [\[CrossRef\]](#)
- Munim, W.N.W.A.; Duran, M.J.; Che, H.S.; Bermúdez, M.; González-Prieto, I.; Rahim, N.A. A Unified Analysis of the Fault Tolerance Capability in Six-Phase Induction Motor Drives. *IEEE Trans. Power Electron.* **2017**, *32*, 7824–7836. [\[CrossRef\]](#)
- Che, H.S.; Duran, M.; Levi, E.; Jones, M.; Hew, W.P.; Rahim, N.A. Post-fault operation of an asymmetrical six-phase induction machine with single and two isolated neutral points. In Proceedings of the 2013 IEEE Energy Conversion Congress and Exposition, Denver, CO, USA, 15–19 September 2013; pp. 1131–1138. [\[CrossRef\]](#)
- Duran, M.J.; Gonzalez Prieto, I.; Bermudez, M.; Barrero, F.; Guzman, H.; Arahal, M.R. Optimal Fault-Tolerant Control of Six-Phase Induction Motor Drives with Parallel Converters. *IEEE Trans. Ind. Electron.* **2016**, *63*, 629–640. [\[CrossRef\]](#)
- Gonzalez, I.; Duran, M.J.; Che, H.S.; Levi, E.; Barrero, F. Fault-tolerant control of six-phase induction generators in wind energy conversion systems with series-parallel machine-side converters. In Proceedings of the IECON 2013—39th Annual Conference of the IEEE Industrial Electronics Society, Vienna, Austria, 10–13 November 2013; pp. 5276–5281. [\[CrossRef\]](#)
- Betin, F.; Capolino, G.-A. Shaft Positioning for Six-Phase Induction Machines with Open Phases Using Variable Structure Control. *IEEE Trans. Ind. Electron.* **2012**, *59*, 2612–2620. [\[CrossRef\]](#)
- Diab, M.S.; Elserougi, A.; Abdel-khalik, A.S.; Massoud, A.M.; Ahmed, S. A reduced switch-count SEPIC-based inverter for asymmetrical dual three-phase induction machines. In Proceedings of the IECON 2015—41st Annual Conference of the IEEE Industrial Electronics Society, Yokohama, Japan, 9–12 November 2015; pp. 000990–000995. [\[CrossRef\]](#)
- Abdel-Khalik, A.S.; Hamdy, R.A.; Massoud, A.M.; Ahmed, S. Postfault Control of Scalar (V/f) Controlled Asymmetrical Six-Phase Induction Machines. *IEEE Access* **2018**, *6*, 59211–59220. [\[CrossRef\]](#)
- Shamsi-Nejad, M.-A.; Nahid-Mobarakeh, B.; Pierfederici, S.; Meibody-Tabar, F. Fault Tolerant and Minimum Loss Control of Double-Star Synchronous Machines Under Open Phase Conditions. *IEEE Trans. Ind. Electron.* **2008**, *55*, 1956–1965. [\[CrossRef\]](#)
- Alcharea, R.; Nahidmobarakeh, B.; Baghli, L.; Betin, F.; Capolino, G.A. Decoupling Modeling and Control of Six-Phase Induction Machines Under Open Phase Fault Conditions. In Proceedings of the IECON 2006—32nd Annual Conference on IEEE Industrial Electronics, Paris, France, 6–10 November 2006; pp. 5101–5106. [\[CrossRef\]](#)
- Kutsyk, A.; Korkosz, M.; Semeniuk, M.; Nowak, M. An Influence of Spatial Harmonics on an Electromagnetic Torque of a Symmetrical Six-Phase Induction Machine. *Energies* **2023**, *16*, 3813. [\[CrossRef\]](#)
- Kindl, V.; Cermak, R.; Ferkova, Z.; Skala, B. Review of Time and Space Harmonics in Multi-Phase Induction Machine. *Energies* **2020**, *13*, 496. [\[CrossRef\]](#)
- Mezani, S.; Laporte, B.; Takorabet, N. Complex finite element computation of induction motors with consideration of space harmonics. In Proceedings of the IEEE International Electric Machines and Drives Conference, 2003. IEMDC'03, Madison, WI, USA, 1–4 June 2003; Volume 1, pp. 264–268. [\[CrossRef\]](#)
- Oliveira, F.T.; Donsion, M.P. A finite element model of an induction motor considering rotor skew and harmonics. *Renew. Energy Power Qual. J.* **2017**, *15*, 119–122. [\[CrossRef\]](#)
- Carbonieri, M.; Bianchi Nand Alberti, L. Induction Motor Mapping Using Rotor Field-Oriented Analysis Technique. In Proceedings of the 2019 IEEE Energy Conversion Congress and Exposition (ECCE), Baltimore, MD, USA, 29 September–3 October 2019; pp. 2321–2328. [\[CrossRef\]](#)
- Leonardo, L.D.; Popescu, M.; Tursini, M.; Parasiliti Fand Carbonieri, M. Transient Modeling of Induction Motors considering Space Harmonics. In Proceedings of the 2020 International Conference on Electrical Machines (ICEM), Gothenburg, Sweden, 23–26 August 2020; pp. 2553–2559. [\[CrossRef\]](#)
- Gogolyuk, P.F.; Hoholyuk, O.P.; Kutsyk, T.A. Universal mathematical model of asynchronous machine as an element microgrid in smart grid. *Math. Model. Comput.* **2021**, *8*, 444–453. [\[CrossRef\]](#)
- González-Prieto, A. On the Advantages of Symmetrical Over Asymmetrical Multiphase AC Drives with Even Phase Number Using Direct Controllers. *IEEE Trans. Ind. Electron.* **2022**, *69*, 7639–7650. [\[CrossRef\]](#)
- Plakhtyna, O.; Kutsyk, A.; Semeniuk, M. Real-Time Models of Electromechanical Power Systems, Based on the Method of Average Voltages in Integration Step and Their Computer Application. *Energies* **2020**, *13*, 2263. [\[CrossRef\]](#)
- Kuznyetsov, O. Mathematical model of a three-phase induction machine in a natural abc reference frame utilizing the method of numerical integration of average voltages at the integration step and its application to the analysis of electromechanical systems. *Math. Probl. Eng.* **2019**, *2019*, 4581769. [\[CrossRef\]](#)
- Kłosowski, Z.; Fajfer, M.; Ludwikowski, Z. Reduction of the Electromagnetic Torque Oscillation during the Direct on Line (DOL) Starting of a 6 kV Motor by Means of a Controlled Vacuum Circuit-Breaker. *Energies* **2022**, *15*, 4246. [\[CrossRef\]](#)
- Plakhtyna, O.; Kutsyk, A.; Semeniuk, M. An analysis of fault modes in an electrical power-generation system on a real-time simulator with a real automatic excitation controller of a synchronous generator. *Electrotech. Rev.* **2019**, *86*, 104–109.

25. Cieřlik, S. Mathematical Modeling of the Dynamics of Linear Electrical Systems with Parallel Calculations. *Energies* **2021**, *14*, 2930. [[CrossRef](#)]
26. Kutsyk, A.; Lozynskyy, A.; Vantsevitch, V.; Plakhtyna, O.; Demkiv, L. A Real-Time Model of Locomotion Module DTC Drive for Hardware-in-the-Loop Implementation. *Przegląd Elektrotechniczny* **2021**, *97*, 60–65. [[CrossRef](#)]

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