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Six-phase symmetrical induction machine under fault states-modelling, simulation and experimental results

Streszczenie. *Artykuł przedstawia podstawowy stan wiedzy z zakresu maszyn wielofazowych oraz sposób modelowania 6-fazowej, symetrycznej maszyny indukcyjnej w wybranych stanach awaryjnych podczas pracy z 2-poziomowym falownikiem napięcia. Całość układu zamodelowano i przeanalizowano w środowisku Matlab/Simulink, a następnie zweryfikowano na stanowisku eksperymentalnym.**(Symetryczna sześcio-fazowa maszyna indukcyjna podczas stanów awaryjnych – modelowanie, symulacja i badania eksperymentalne)***

Abstract*. Paper presents principles of multiphase machines and modelling of symmetrical 6-phase induction machine connected to 2-level 6-phase Voltage Source Inverter during chosen fault states. Presented model was built, analyzed in Matlab/Simulink simulation software and verified on laboratory test bench.*

Słowa kluczowe: maszyny wielofazowe, praca w trybach awaryjnych, wielofazowe systemy wytwarzania energii, praca w przypadku awarii.
Keywords: multiphase machine, fault tolerant, fault modeling, multiphase energy generation systems.

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Introduction

Power electronics has been utilized in many fields of industry for over several decades now, and due to its continuous development many areas have been deeply investigated. One of the earliest field of application for power electronics were an electrical drives, what resulted in a well-known and widely used technology today. It is worth mentioning that modern civilization demands more and more for electric machines in vast range of applications. There are several reasons for this situation among which a searching for an alternative energy sources [1], introducing more efficient solution for automotive [2] and aircraft industry [3], can be listed.

Many of applications in mentioned fields such an off-shore wind turbines, vehicles drives and aircraft generators or aileron actuators, require devices with an ability to uninterruptable work. For remote applications such an off-shore wind energy generation this kind of systems are motivated mainly due to maintenance costs whereas in both: electric vehicles and more electric aircraft safety reason is a number one objective. Additionally, among many other fields where higher reliability is required a ship propulsion, military, or nuclear energy systems could be listed.

Unfortunately, a ubiquitous 3-phase machines suffer from a huge shortcoming in this aspect. Namely, during one phase failure the 3-phase machine is unable to work properly anymore without additional neutral wire and divided DC-link in power electronics converter [4]. Moreover, in order to reinforce reliability issues, some redundant solutions are applied such those described in [5]. However, these solutions are occupied by a necessity of extra space which is needed to install other machine-converter set, and yield higher costs.

All these mentioned factors caused that many researchers focus on multiphase machines and their inherent ability for post-fault operation.

Dealing with fault states is a risky task, thus a proper machine model operating under these conditions is required first. Then, following paper focuses mainly on a basic approach for modelling 6-phase induction machine connected to 2-level Voltage Source Inverter (VSI) performing under chosen fault states such an open-phase. Moreover, other possible scenarios are mentioned. This paper is an important part for analyzing so-called fault-tolerant control strategies.

Multiphase machine

As it was mentioned in previous section, the increased interest in uninterruptable operation of electrical machines can be solved by introducing a multiphase machines. It should be noticed that term 'multiphase' refers to machines with phase number higher than 3. Historically, those devices were used for high power application to decrease current values [6] in one phase by splitting them for a larger number of phases. It was caused by a low rated current values of early semiconductors. The main advantage of multiphase machines over 3-phase counterparts is that after failure of one phase, the machine is still able to generate rotating vector of magnetic flux. Additionally, those machines have other features such as:

- higher power density coefficient (PDC),
- lower electromagnetic torque ripples,
- lower audible noise.

It is worth mentioning that most of typical 3-phase machines such an induction synchronous and asynchronous, permanent magnet or reluctant ones have their multiphase counterparts. Another issue is a phase number and its winding displacement. Most common types are machines with odd number of phases or with number of $N = k{\cdot}3$, where k belongs to *{2,3,4…}* what corresponds to k sets of 3-phase windings. In this latter case, it is important what is an angle γ of two adjacent windings. This results in so-called symmetrical (where γ is constant between each phase) or asymmetrical (where each set of 3-phase winding is shifted by angle γ in respect to the other 3-phase set) machines (Fig 1). Moreover, for machines with winding number being multiple of three can be connected into single or separated k neutral points. More detailed work about multiphase machines in general is published in [7].

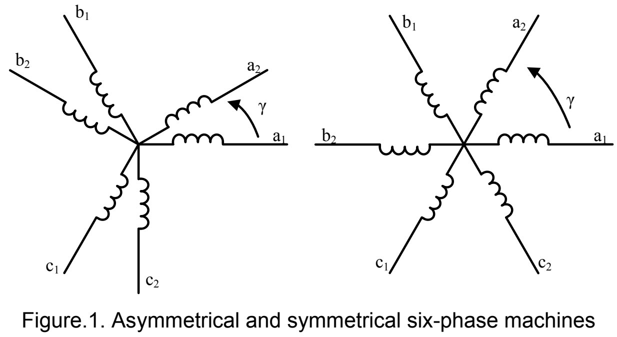

Figure.1. Asymmetrical and symmetrical six-phase machines

In following paper a single neutral point, six-phase symmetrical induction machine under fault condition is modelled, simulated and experimentally verified.

To control this machine a 6-phase, 2-level VSI is connected as presented in Fig. 2. Similarly to 3-phase machines, in this case many different control algorithms can be utilized such as: DTC [8], FOC [9] or a predictive control [10]. However, due to simplicity the simple *U/f = const* method is applied to model and analyze chosen fault states.

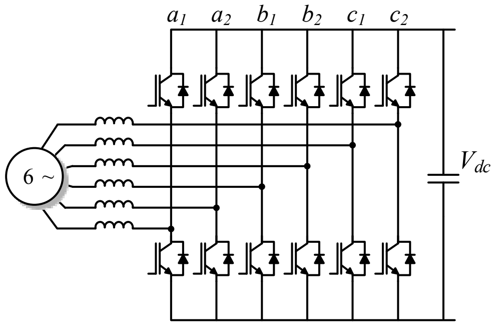

Figure 2. Simulated machine-converter system

It has to be noted that multiphase machines can be utilized even more efficiently with advanced fault-tolerant control methods that can maintain a circular trajectory of stator magnetic flux which and that is described deeply in [11]. However, this is out of scope of this paper.

Machine model

A basic set of electrical equations for modelling induction machine of any phase number is presented in (1):

$$\mathbf{v_s} = \mathbf{R_s} \cdot \mathbf{i_s} + \frac{d}{dt}\left[\mathbf{L_{ss}} \cdot \mathbf{i_s} + \mathbf{L_{sr}} \cdot \mathbf{i_r}\right]$$
$$\mathbf{v_r} = \mathbf{R_r} \cdot \mathbf{i_r} + \frac{d}{dt}\left[\mathbf{L_{rr}} \cdot \mathbf{i_r} + \mathbf{L_{rs}} \cdot \mathbf{i_s}\right] \tag{1}$$

where: v - phase voltages vector (length N), i - phase currents vector (length N) , L – inductances matrix ($N{\times}N$) and s and r subscripts denotes stator and rotor values. Additionally, indices ss and rr describes self-inductance and mutual inductances within stator and rotor respectively whereas indices sr and rs correspond to stator-to-rotor and rotor-to-stator mutual inductances, respectively.

Phases notation in this paper, for six-phase induction machine is following: $a_1,a_2,b_1,b_2,c_1,c_2,$ where indices denotes a typical 3-phase winding with $2\pi/3$ phase shift. This notation is used for all quantities such a voltages, currents and fluxes - denoted as g in (2). Similarly to 3-phase machine it is possible to present machine model by a set of other equations which simplify analysis and application of control algorithms. For this reason a Space Vector Decomposition (SVD) method is applied:

$$\begin{bmatrix} g_\alpha \\ g_\beta \\ g_{x1} \\ g_{y1} \\ g_{x2} \\ g_{y2} \end{bmatrix} = \mathbf{T}_6 \cdot \begin{bmatrix} g_{a1} \\ g_{a2} \\ g_{b1} \\ g_{b2} \\ g_{c1} \\ g_{c2} \end{bmatrix} \tag{2}$$

with proper transformation $\mathbf{T_6}$ (3):

$$\mathbf{T}_6 = \sqrt{\frac{2}{6}} \begin{bmatrix} 1 & \cos\gamma & \cos 2\gamma & \cos 3\gamma & \cos 4\gamma & \cos 5\gamma \\ 0 & \sin\gamma & \sin 2\gamma & \sin 3\gamma & \sin 4\gamma & \sin 5\gamma \\ 1 & \cos 2\gamma & \cos 4\gamma & \cos 6\gamma & \cos 8\gamma & \cos 10\gamma \\ 0 & \sin 2\gamma & \sin 4\gamma & \sin 6\gamma & \sin 8\gamma & \sin 10\gamma \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \end{bmatrix} \tag{3}$$

where: γ denotes the angle between adjacent phases and equals $2\pi/6$ for six-phase symmetrical machine.

As it can be noticed, the SVD (2) produces another set of 6 differential equations for both rotor and stator expressions. However, now they creates 3 sets of orthogonal complex planes α-β, x_1-y_1, x_2-y_2. Often, the third complex plane is named zero sequence part. Even if it can be difficult to interpret these planes it simply says that vectors placed on each do not affect each other. Nevertheless, an advantage of (2) is that during balanced conditions, components corresponding for electromagnetic torque generation are mapped only in a α-β complex plane – exactly in the same manner as in case of 3-phase machine. That is why this matrix (3) is also known as decoupling matrix. Rest of equations correspond to losses. It is worth mentioning that transformation (3) is power-invariant matrix what in this case simplifies inverse matrix $\mathbf{T_6}$ as:

$$\mathbf{T}_6^{-1} = \mathbf{T}_6^{T} \tag{4}$$

Executing (2), (3) for both sides of equations (1) it has to pointed out that there are separate complex planes for stator and rotor frames. Customarily it is denoted with an apostrophe sign, however in this paper it is omitted and all equations in (5) refer to stator rotating reference frame.

$$\begin{aligned}
v_{s\alpha} &= R_s i_{s\alpha} + \left(L_{ls} + L_m\right)\frac{di_{s\alpha}}{dt} + L_m \frac{d}{dt}\left(i_{r\alpha}\cos\theta_r - i_{r\beta}\sin\theta_r\right) \\
v_{s\beta} &= R_s i_{s\beta} + \left(L_{ls} + L_m\right)\frac{di_{s\beta}}{dt} + L_m \frac{d}{dt}\left(i_{r\alpha}\sin\theta_r + i_{r\beta}\cos\theta_r\right) \\
v_{sx1} &= R_s i_{sx1} + L_{ls}\frac{di_{sx1}}{dt} \\
v_{sy1} &= R_s i_{sy1} + L_{ls}\frac{di_{sy1}}{dt} \\
v_{sx2} &= R_s i_{sx2} + L_{ls}\frac{di_{sx2}}{dt} \\
v_{sy2} &= R_s i_{sy2} + L_{ls}\frac{di_{sy2}}{dt} \\
0 &= R_s i_{r\alpha} + \left(L_{lr} + L_m\right)\frac{di_{r\alpha}}{dt} + L_m \frac{d}{dt}\left(i_{s\alpha}\cos\theta_r - i_{s\beta}\sin\theta_r\right) \\
0 &= R_s i_{r\beta} + \left(L_{lr} + L_m\right)\frac{di_{r\beta}}{dt} + L_m \frac{d}{dt}\left(i_{s\alpha}\sin\theta_r + i_{s\beta}\cos\theta_r\right) \\
0 &= R_s i_{rx1} + L_{lr}\frac{di_{rx1}}{dt} \\
0 &= R_s i_{ry1} + L_{lr}\frac{di_{ry1}}{dt} \\
0 &= R_s i_{rx2} + L_{lr}\frac{di_{rx2}}{dt} \\
0 &= R_s i_{ry2} + L_{lr}\frac{di_{sy2}}{dt}
\end{aligned} \tag{5}$$

where: L_{ls} – stator leakage inductance, L_{lr} – rotor leakage inductance, L_m – per-phase equivalent circuit magnetizing inductance, θ_r – rotor electrical position.

To complete machine equations two additional equations are required. Namely, production of electromagnetic torque:

$$T_e = PL_m\left[\cos\theta_r\left(i_{r\alpha}i_{s\beta}-i_{r\beta}i_{s\alpha}\right)-\cos\theta_r\left(i_{r\alpha}i_{s\alpha}-i_{r\beta}i_{s\beta}\right)\right] \tag{6}$$

where: P – is a poles pair number

and a mechanical equation:

$$T_e - T_L = J\frac{d\omega_{rm}}{dt}+h\omega_{rm} \tag{7}$$

where: T_L – is a load torque, J – inertia of rotating mass, h- friction coefficient, ω_{rm} – rotor mechanical speed.
Equations (5)-(7) can be implemented in Matlab/Simulink package in block form. However, to be able to utilize SimPowerSystem power electronics components such the `‘Universal Briege’` converter it is necessary to connect this machine model via simple interface consisted of `‘Current Control Sources’` that are controlled by machine phase currents.

Fault states analysis

Figure 2 presents a simulated machine-converter system. It is rather obvious that a higher number of switches and phases increases a probability that any of this part can be broken. Following fault states can be considered as the simplest ones:

- switch fault *(A)*
- machine phase fault *(B)*

A) Due to the fact that any typical power electronic switch consist of IGBT transistor with anti-parallel diode different cases should be considered. Both fault such short-circuit and open-switch can happen for both upper and lower transistor in converter's branch. Nonetheless, anti-parallel diode is still able to conduct current and block voltage in case of open-switch failure. This faults result in high current values in faulted phase. Some work about changed modulation with switches disconnected by additional fuses was conducted in [12]. However, this failure type can be easily modelled by setting gate signal to 0 or 1 for all time for chosen switch and thus it is beyond of the scope of this work.

B) Second fault state is more complex from the modeling as well as a performance point of view. Namely, phase lost can be result of disconnection of phase cable or failure of whole inverter's leg. This influences significantly the machine's phase currents, and in turn, on trajectory of a rotating vector of stator magnetic flux. This flux is presented in Figure 3.

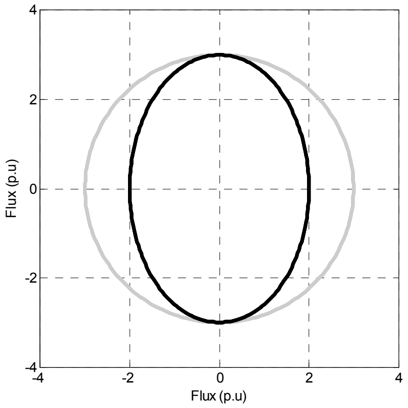

Figure 3. Trajectory of rotating stator magnetic flux vector

Gray color depicts the magnetic vector trajectory during healthy, whereas the black color – failure case. This is only simplified hodograph based on setting one ideal current source to 0. However, in simulation and real test bench cases, the six phase system becomes unbalanced and magnitude in remaining phases differs from each other. It can be briefly mentioned that one of the main goals of fault-tolerant control methods is to keep circular trajectory with reduced phase number.

There are several methods to simulate an open-phase fault for multiphase machine in Matlab/Simulink. Due to the fact that model described by (5-7) is the voltage based representation, setting voltage in the phase input terminal to 0 would result in short-circuiting this terminal. Therefore, other approaches can be considered. One of solutions bases on putting very large resistor values in series into chosen phase. Similar behavior can be obtained by using `‘break’` element from SimPowerSystem library. Unfortunately, latter method does not allow to choose any time moment to apply fault because `‘break’` switch, turns itself off only in case of current zero-crossing condition. The other approach, presented in this paper, bases on calculating back-EMF induced in faulted phase and feeding it back into input voltage terminal. This can be obtained using dependencies in equations obtained by multiplying phase current and voltages by transformation (2) with zeroing current in faulted phase [13]. For an example the a_1 phase is taken as a faulty one. Following equations can be presented for back-EMF calculation. After multiplying equations (2) and (3) with faulty a_1 phase it can be noticed that variables $g_{s\alpha}$, g_{sx1}, g_{x2} and g_{sy2} will be affected. Moreover, following dependencies can be derived:

$$\begin{aligned} g_{s\alpha}-g_{sx1} &= \sqrt{\frac{2}{6}}\left(g_{sa2}-2g_{sb2}+g_{sc2}\right) \\ g_{s\alpha}+g_{sx1} &= \sqrt{\frac{2}{6}}\left(2g_{sa1}-g_{sb1}+g_{sc1}\right) \end{aligned} \tag{8}$$

It is known that in case of fault the broken phase current equals to 0 and substituting it into the second equation of (8). It can be seen that

$$i_{s\alpha}+i_{sx1} = -\sqrt{\frac{2}{6}}\left(i_{sb1}+i_{sc1}\right) \tag{9}$$

Similar dependency can be addressed for $v_{s\alpha}$ voltage:

$$v_{s\alpha} = \sqrt{\frac{2}{6}}\left(v_{sa2}-2v_{sb2}+v_{sc2}\right)+v_{sx1} \tag{10}$$

Then, knowing (9) and the voltage can be calculated knowing basic equation of (1) v_{sx1} can be calculated:

$$v_{sx1} = -R_s\sqrt{\frac{2}{6}}\left(i_{sb1}-2i_{sc1}+i_{s\alpha}\right)-L_{ls}\frac{d}{dt}\left[\sqrt{\frac{2}{6}}\left(i_{sb1}+i_{sc1}\right)+i_{s\alpha}\right] \tag{11}$$

Finally, it can be written that:

$$\begin{aligned} v_{sa1} = \sqrt{\frac{6}{2}}v_{s\alpha} &- \left[v_{sa2}\cos\gamma+v_{sb1}\cos 2\gamma+v_{sb2}\cos 3\gamma\right. \\ &\left.+v_{sc1}\cos 4\gamma+v_{sc2}\cos 5\gamma\right] \end{aligned} \tag{12}$$

It can be noted that back-EMF (12) can be calculated using mainly phase voltages of remained phases. However in practical model application and utilization of power interface of SimPowerSystem it is convenient to apply following equation in *α-β* reference frame.

Simulation results

As it was mentioned earlier, simulation model was built in Matlab/Simulink environment. Additionally, SimPowerSystem library was involved for modelling power electronic devices. Following assumptions were made:

- machine core saturation and core losses are neglected
- machine electrical parameters are time and temperature independent
- converter ideal switches

Parameters of simulated system are based on parameters of 2.5kW 6-phase machine that was obtained by rewinding a 3-phase induction motor. This approach can result in slightly worse performance than in case of dedicated 6-phase machine design. Mentioned parameters are presented in Table I.

In following simulations an operating point with 40% of rated torque is used during testing fault states. Simulation results for the a_1 open-phase failure are shown in Figure 4. As it was assumed, after fault at time t_f = 0.5s phase current reaches zero. Moreover, torque ripples can be observed, what has negative influence for machine performance and can shorten life of the machine's bearings.

Tabela 1. Model parameters

Parameter	Symbol	Value
Motor rated power	P	2.65kW
Stator leakage inductance	L_{ls}	41 [mH]
Rotor leakage inductance	L_{lr}	41 [mH]
Magnetizing inductance	L_m	410 [mH]
Stator resistance	R_s	10 [Ω]
Rotor resistance	R_r	10 [Ω]
Rotor intertia	J	0.03 [kg*m2]
Friction coefficient	k	0.0015
Pole pairs	P	2
Phase angle	γ	2π/6
DC-link voltage	V_{dc}	660 [V]
Control strategy	-	U/f = const
Modulation technique	-	Sine-PWM
Switching frequency	f_{sw}	5 [kHz]
Reference frequency	f	50 [Hz]

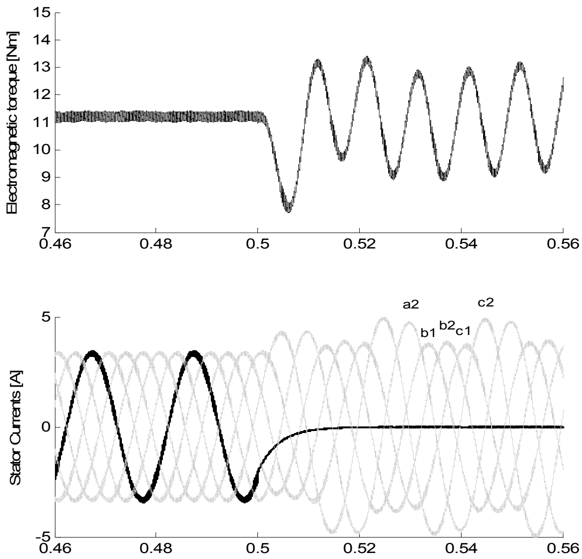

Figure 4. Phase a_1 (black) open-phase fault. Waveforms from top: electromagnetic torque, stator currents

Additionally, magnitudes of currents in remained phases increase, what can be dangerous if their rated values are exceeded. Worth noting is a fact that due to presented currents, machine heats in a non-uniform manner what can drastically shorten life time of windings insulation.

Results of power utilization during pre- and post-fault cases are considered in Figure 5. A mechanical power is referred to the power supplied from DC-link circuit. Presented waveform were obtained due to utilization of moving average filter which allows to remove switching noise as well as power ripples.

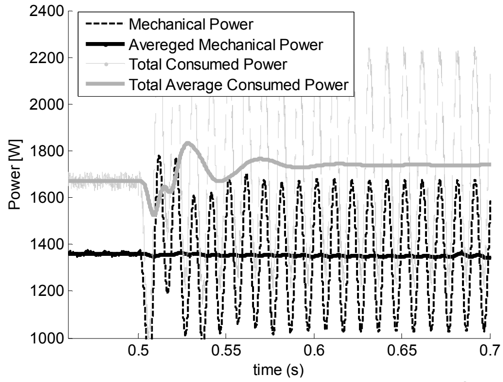

Figure 5. Mechanical and total consumed power waveform in pre- and post- fault performance with half rated load torque

As it can be noticed the increase of consumed DC-link power occurs due to fault presence. This increase is about 2% for particular operation point and this method can be method utilized for examination of the post-fault characteristics.

Figure 6 shows a trajectory of the stator rotating magnetic flux vector in both healthy and failure cases for the operating point presented in Figure 4. As it was mentioned in previous section post-fault trajectory slightly differs from it simplified counterpart in Figure 3.

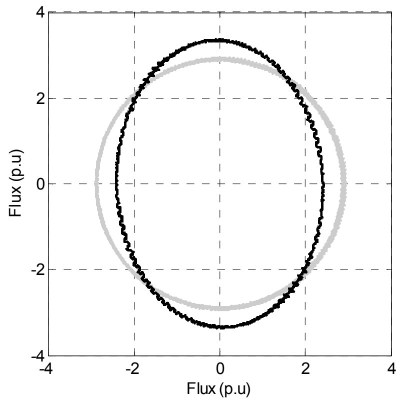

Figure 6. Stator magnetic flux vector trajectories for healthy (gray) and faulty (black) conditions

Experimental results

The a_1 open-phase fault was verified on a 2.5kW six-phase symmetrical, single neutral induction machine coupled to 3-phase 5.5kW induction machine test bench shown in Figure 7. Six-phase machine was connected to two typical 3-phase converters in parallel to the same DC-link. For simple open-loop control method a converter transistor gates were controlled be TMS28335 DSP.

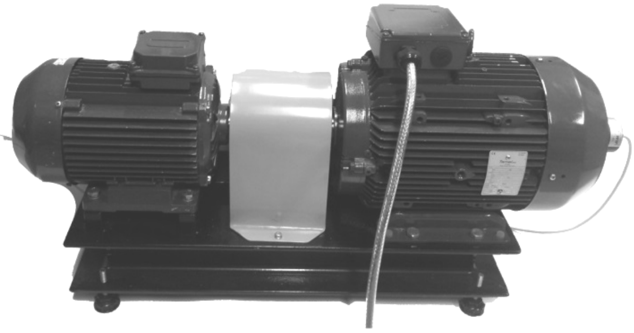
Figure 7. Laboratory multiphase machine test-bench

Due to safety reason the multiphase machine was supplied with lowered DC-link voltage and frequency decreased proportionally to 25 Hz. Switching frequency was set to 5kHz. Figure 8a shows sampled phase currents after fault occurrence. Presented signals are available in TMS28335 DSP processor memory through AD converters. Figure 8b and 8c present waveforms measured with two 4-channel Tektronix oscilloscopes. A significant current distortion that can be observed is resulted by rewound six-phase stator winding distribution where different phases share the same slots. This can be clearly noticed when faulted a_1 reduces distortions in phase b_2. Nonetheless, it can be noticed that amplitudes of remaining currents in post-fault condition were simulated properly what was the main goal of presented paper. Simulation results differs slightly in currents amplitudes mainly due to real machine parameters that should be measured carefully. The latter issue is also crucial for more advanced control strategies such i.e Field Oriented Control. Worth noting is a fact that precise parameters measurement obtained by typical locked-rotor and no-load tests of chosen induction machine requires properly contracted symmetrical six-phase transformer.

a)

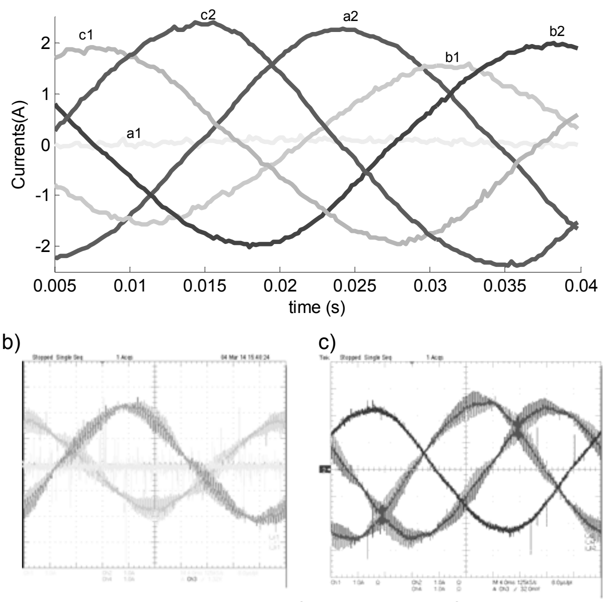

Figure 8 Experimental results of open-phase a_1 fault a) sampled TMS28335 signals, b) a_1,b_1,c_1 c) a_2,b_2,c_2 currents, respectively

Conclusion

Presented paper describes modelling of the symmetrical, six-phase induction machine under open-phase failure case. Both simulation and experimental results for both healthy and faulty conditions are shown. Negative impact of phase lost were explained and briefly analyzed. As it can be noticed a proper design of real machine is extremely crucial due to particular phases coupling. Presented paper presents a basic consideration for further work connected to fault-tolerant control algorithms.

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LITERATURA

[1] Mekri F., Benelghali S., Benbouzid M., Charpentier J. , A fault-tolerant multiphase permanent magnet generator for marine current turbine applications., , (2011) , nr. ,2079-2084.

[2] Riveros J., Bogado B., Prieto J., Barrero F., Toral S. et al. , Multiphase machines in propulsion drives of electric vehicles., , (2010), nr. T5-201-T5-206.

[3] Roboam X., Sareni B., Andrade A. , More Electricity in the Air: Toward Optimized Electrical Networks Embedded in More-Electrical Aircraft. , Industrial Electronics Magazine, IEEE , (6). (2012), nr. 4,6-17.

[4] Liu T.-H.,Fu J.-R.,Lipo T. , A strategy for improving reliability of field-oriented controlled induction motor drives. , Industry Applications, IEEE Transactions on, (29). (1993) , nr. 5,910-918

[5] Burzanowska H., Sario P., Stulz C., Joerg P. , Redundant Drive with Direct Torque Control (DTC) and dual-star synchronous machine, simulations and verification., , (2007), nr. ,1-10

[6] Ward E., Harer H. , Preliminary investigation of an invertor-fed 5-phase induction motor. , Electrical Engineers, Proceedings of the Institution of, (116). (1969), nr. 6, 980-984.

[7] Levi E.,Bojoi R., Profumo F., Toliyat H., Williamson S., Multiphase induction motor drives - a technology status review., Electric Power Applications, IET, (1). (2007), nr. 4, 489-516.

[8] Xu H., Toliyat H., Petersen L., Five-phase induction motor drives with DSP-based control system., Power Electronics, IEEE Transactions on , (17). (2002), nr. 4, 524-533

[9] Hu H., Yang J., Rotor field oriented control strategy of multiphase induction motor.(2011) , nr. , 108-112

[10] Lim C. S., Levi E., Jones M., Rahim N., Hew W. , FCS-MPC-Based Current Control of a Five-Phase Induction Motor and its Comparison with PI-PWM Control. , Industrial Electronics, IEEE Transactions on , (61). (2014), nr. 1, 149-163.

[11] Bianchi N., Bolognani S., Pre M., Impact of Stator Winding of a Five-Phase Permanent-Magnet Motor on Postfault Operations., Industrial Electronics, IEEE Transactions on , (55). (2008), nr. 5, 1978-1987

[12] Richardeau F., Baudesson P., Meynard T. , Failures-tolerance and remedial strategies of a PWM multicell inverter. , Power Electronics, IEEE Transactions on , (17). (2002), nr. 6, 905-912

[13] Karugaba S. F., “Dynamics and Control Of A Five Phase Induction Machine”, the Faculty of the Graduate School Tennessee Technological University, December 2008 M.Sc. thesis

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