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Post-fault operation of FOC-controlled 5-phase induction machine with hysteresis and PI+SVM current control

Abstract. *The paper presents a post-fault operation of 5-phase induction machine supplied from 2-level, 5-leg power converter. Presented simulation results consider an open-phase fault operation without fault-tolerant control. Thus this work compares torque and speed ripples in this faulted condition for Field Oriented Control (FOC) system with nonlinear hysteresis current controller (HCC) and linear PI + Space Vector Modulator (PI+SVM), respectively.*

Streszczenie*. Artykuł prezentuje pracę 5-fazowej maszyny indukcyjnej w przypadku awarii spowodowanej przerwą w jednej z faz. Przedstawione wyniki symulacyjne dotyczą zachowania się algorytmu sterowania wektorowego zorientowanego względem strumienia wirnika dla dwóch różnych metod regulacji prądu. Pierwsza z nich wykorzystuje metodę histerezową, druga natomiast liniową regulację prądów w wirującym układzie współrzędnych oraz modulator wektorowy SVM. (****Praca w przypadku awarii 5-fazowej maszyny indukcyjnej z wykorzystaniem histerezowych oraz liniowych PI+SVM regulatorów prądu****).*

Słowa kluczowe: maszyny wielofazowe, praca awaryjna, zwiększona niezawodność, sterowanie zorientowane polowo.
Keywords: multiphase machines, post-fault, reliable machines, Field Oriented Control.

Introduction

A constant development in power electronics results in systematically changing trends that consider and highlight a contemporary and near future issues. As it is mentioned in [1] a main goals and directions in power electronics presented in 1974 differ from current problems. It happed mainly due to the fact that previously indicated directions have been deeply investigated and developed during over 40 years existence of this discipline. This situation can be clearly seen in a field of electrical machines, where many different control algorithms and converter topologies appeared relatively quickly and have been developed for long time. This in turn led to saturation in this field and no breakthrough solutions have appeared recently. Nonetheless, it has a positive effect, because the more technology is know the easier is its application in an industrial environment. And this again implies further problems such a maintenance cost and reliability issues that force scientists for further development in these fields.

These mentioned trends can be easily noticed in growing number of works that refer not only to deeper investigations of power components physics research to improve their reliability, but also in fault-tolerant algorithms that allow to operate a devices in post-fault conditions [2]. The reliability issues of power electronics are crucial in a fields such a traction, aircraft and space industry as well as in energy generation systems. The two former disciplines demand for highly reliable devices mainly due to safety reasons and are promising solution for so-called more electric aircraft concept [3]. On the other hand, in case of energy conversion systems, high reliability is required mainly due to lowering maintenance and repair cost. This is especially important for off-shore wind turbines where an important part of these cost can be included in downtimes when a faulted unit is not able to deliver energy to the grid. As it is mentioned in [4] the longest downtimes are result of fault in large volume device such a transformer or a generator.

As it was mentioned before, the growing number of papers devoted for reliability issues, focus mainly on reconfiguration and algorithms improvements. However an another way to increase reliability is a utilization of redundant elements such a inverter branch [5], or whole redundant machine set [6] . Unfortunately, these solutions result in increased device volume and costs what is not always accepted. This is a reason why a multiphase machines (with phase number N>3) are especially promising solution in case of offshore turbines or aircraft onboard generators. They are able to work in so-called open-phase fault without any additional control modification. Moreover, it is possible to start the machine up in this condition what is impossible in case of 3-phase counterpart. However, due to supply asymmetry a torque ripples are generated what have a negative influence on bearings and elements connected to the machine's shaft. Additionally, an increased current amplitudes result in excessive machine heating what can lead to shorten windings' lifetime. That is a reason for developing a fault-tolerant algorithms that are widely described in [7], [8] and [9] just to name a few. It can be easily noted that most of publications in this field address a Hysteresis Current Control (HCC) for fault-tolerant operation [10].

Thanks to applied open-phase fault modelling approach it is possible to observe transient and post-fault steady states, what in turn allows for comparison of different current control methods for Field Oriented Control (FOC) what has not been described in literature to the author's knowledge. This is important from a fault-tolerant algorithm point of view where in practical application a fault detection has to be conducted to choose proper algorithm [2], [11].

Investigated system

Almost every 3-phase machine has its multiphase counterpart [12]. Moreover, an increased number of phases allows for different winding configuration for instance a symmetrical or asymmetrical with connected or separated neutral points [7]. Additionally, the higher phase number offers more phase-to-phase configuration such ones presented in [13]. However, in following paper a simple star-connected, 5-phase induction machine (IM) supplied from 2-level, 5-leg inverter is investigated as presented in Figure 1 where a natural phase reference frame is denoted as consecutive letters a, b, c, d, e, respectively. Additionally, the phase 'a' has a possibility to break the current what is depicted customarily with a switch S1.

It has to be mentioned that mathematical equations for this kind of machine are rather well-known and are deeply investigated in [12], thus modelling of such a device is out of scope of this paper. However, it must be mentioned that approach presented in [12] utilizes a decoupling, power invariant transformation matrix T_5 (described in the next section) that allows to simplify 5-phase machine to its 3-phase counterpart where torque production can be considered in α-β complex plane only.

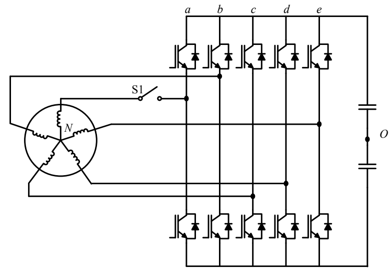


Fig.1. Investigated multiphase converter-machine set

This allows for applying a typical, well-known control strategies in a very similar manner as for 3-phase machines. Unfortunately, 5-phase machine has another complex planes where losses are mapped and this has to be considered in case of modulation what will be developed further in this work. Finally, mentioned open-phase fault modelling method bases on calculation of back-EMF in faulted phase and was originally presented [14].

FOC scheme for 5-phase IM

The Field Oriented Control bases on addressing the AC machine as its DC-counterpart where an independent control of flux and torque is possible. In case of induction machine it is done by synchronization with e.g. rotor flux and further considering the machine in rotating d'-q reference frame. This method is known as Indirect Rotor Flux Oriented Control, however further in this paper the FOC name is utilized customarily. Then it can be assumed that d' current component adjusts the flux, whereas the q component – is proportional to the torque. This approach allows for sudden, torque step response for AC induction machine. The practical application of FOC requires a current control such a e.g. Hysteresis Current Control (HCC) or PI+ Space Vector Modulator (PI+SVM) [15].

A) Hysteresis Current Control

Hysteresis current controllers are often addressed as a simplest solution for fault-tolerant algorithms of multiphase machines [10]. Thus, the scheme presented in Figure 2 shows FOC control algorithm with the HCC. The torque reference value is the output of speed controller, and d'-as a current corresponding to flux production is set as a constant value. It has to be explained that flux producing component has the prime suffix to differentiate it against phase d. The reference $i_{d'}$-i_q values are further transformed by rotational transformation matrix R(θ), and then after inverse transformation of T_5^{-1} a signals are defined in natural reference frame where HCC compares reference current values with measured ones.

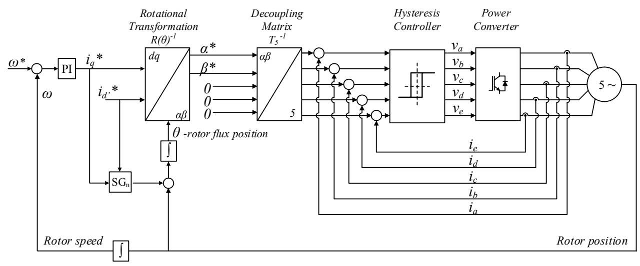


Fig.2. FOC scheme with HCC

Hysteresis controllers guarantee simplicity and high dynamic of the overall system. Unfortunately, variable switching frequency depends strongly on the load parameters and varies with the ac side converter voltage. Also, the operation is somewhat rough caused by the limit cycle; thus protection of the converter is difficult.

B) Linear PI+SVM control

The PI+SVM method instead, offers fixed switching frequency but in cost of an additional transformations and complexity of the modulator for 5-phase machine. Within this approach all measured currents have to be transformed into a rotating d-q reference frame. In this frame the reference signal $i^*_{d'}$ is set as a constant value and is compared with measured current. Then the calculated error is further delivered to Proportional Integral (PI) controller. The same approach is used for i_q where its reference value is generated by the speed controller output, and further is compared with measured i_q value that is obtained in the same manner as i_d measured signal. Finally, both values transformed by inverse transformation $R(\theta)^{-1}$ are applied as a reference voltage vector in α-β reference frame into Space Vector Modulator which generates proper gate signals. A scheme of FOC with PI+SVM is shown in Fig. 3.

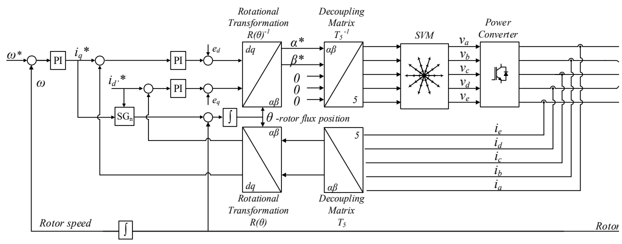


Fig.3. FOC scheme with PI+SVM current control

The SVM bases on the approach where all states of converter legs can be represent as a vectors where state '1' correspond to upper switch closed and '0' – to upper switch open (transistors in a single leg are control with negation) respectively. For a multiphase machines it is a common practice to convert those 5-digit binary number into its decimal representation for simplicity. As it was mentioned earlier, the analysis of multiphase machines utilizes decoupling transformation T_5 (1) that introduces additional complex planes in addition to α-β plane; thus it has to be considered in converter states analysis as well. This is also described deeply in [16].

$$T_5 = \sqrt{\frac{2}{5}} \begin{bmatrix} 1 & \cos(\gamma) & \cos(2\gamma) & \cos(3\gamma) & \cos(4\gamma) \\ 0 & \sin(\gamma) & \sin(2\gamma) & \sin(3\gamma) & \sin(4\gamma) \\ 1 & \cos(2\gamma) & \cos(4\gamma) & \cos(6\gamma) & \cos(8\gamma) \\ 0 & \sin(2\gamma) & \sin(4\gamma) & \sin(6\gamma) & \sin(8\gamma) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \tag{1}$$

where: $\gamma=2\pi/5$ and denotes angle between two consecutive phases.

As a result two sets of vectors are obtained what is shown in Figure 4. It must be stated that there is another complex plane x_0-y_0 according to T_5 transformation. However, as far as vectors in this plane lay on a straight line they do not affect modulation technique and it can be omitted for further considerations.

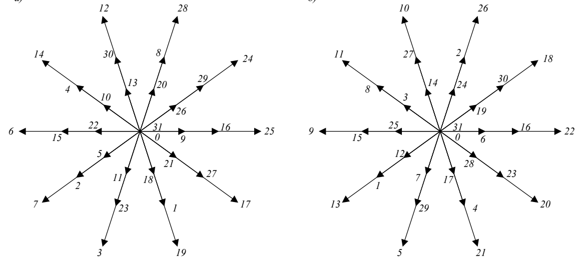


Fig.4. Representation of complex vector planes a) α-β and b) x_1-y_1 of 5-phase 2-level inverter.

It can be noted that plotted vectors divide each plane into 10 sectors and have three different lengths (small, medium and large) and the angle between consequent vectors is $\gamma=2\pi/5$. Moreover, vectors located in the plane x_1-y_1 and corresponding vectors in α-β plane have different orientation except the zero vectors. For instance vector 24 (b11000) is the largest one in the α-β plane whereas the same vector in x_1-y_1 appears to be the shortest one with different angle. As it was mentioned, the zero vectors (decimal: 0 binary: 00000, and decimal: 31 binary: 11111) are placed in the same positions in both planes.
Many works such a [17] stress that if a typical SVM method for 2-level, 3-phase converter is adapted for 5-phase case, the higher third harmonics distortion is generated. It is mainly caused by averaged voltage vector in x_1-y_1 complex plane of non-zero value. This in turn is caused by different orientation of particular vectors in orthogonal complex planes: α-β and x_1-y_1, respectively. Due to this issue another approaches were proposed in [16],[18] where four different vectors are utilized instead of two large ones. Chosen large and medium (l, and m indices) vectors of two adjacent axes (a and b, respectively) are used in α-β plane and are presented in Figure 5a. Vectors v_{al} and v_{am} correspond to large and medium length vector on a-axis, respectively. Utilizing this set of four converter vectors it is possible to generate rotating reference vector v* in α-β plane keeping corresponding average voltage vector 0 in x_1-y_1 plane at the same time. This is shown clearly in Figure 5b where, additional different vector mapping in complex planes can be noticed. As an example it can be described in large vector v_{al} in α-β plane has its counterpart in x_1-y_1 plane as a short vector with negative real part.

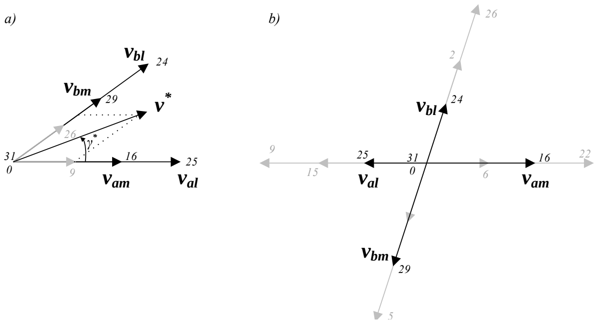


Fig.5. The SVM method with utilization of 4 active and 2 zero vectors for 5-leg, 2-level inverter where a) presents reference voltage vector v* and active vectors in α-β plane, b) corresponding vectors in x_1-y_1 complex plane, respectively.

As far as a particular vectors length and angles are known in both planes for given sector, it is possible to solve a set of equations such in [16] what allows for proper modulation without additional losses. Proper vector times can be described with following dependencies:

(2)
$$T_{am}=\sin\left(\frac{\pi}{5}\right)\cdot M\cdot T_s\cdot\sin\left(\frac{\pi}{5}-\gamma^*\right)\quad T_{bm}=\sin\left(\frac{\pi}{5}\right)\cdot M\cdot T_s\cdot\sin\left(\gamma^*\right)$$
$$T_{al}=\sin\left(\frac{2\pi}{5}\right)\cdot M\cdot T_s\cdot\sin\left(\frac{\pi}{5}-\gamma^*\right)\quad T_{bl}=\sin\left(\frac{2\pi}{5}\right)\cdot M\cdot T_s\cdot\sin\left(\gamma^*\right)$$
$$T_{31}=T_0=\frac{\left(T_s-T_{am}-T_{al}-T_{bm}-T_{bl}\right)}{2}$$

Where T_s – sampling period, M-modulation index, T_{31} and T_0 – zero vectors, γ^*-reference voltage vector angle in particular sector.

Figure 6a presents particular vector times for the first sector as discussed earlier. Figure 6b presents the whole period of output duty cycle for given phase for modulation index of M=1.06.

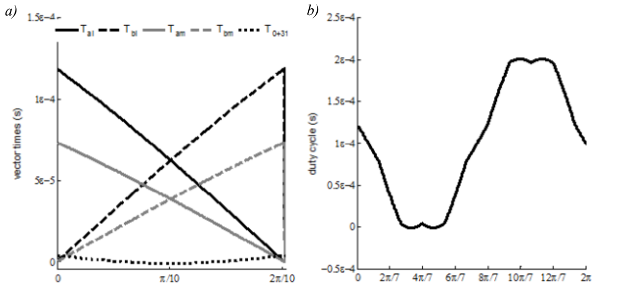


Fig. 6. The SVM method with utilization of 4 active and 2 zero vectors for 5-leg, 2-level inverter where a) particular vectors times for the first sector, b) duty cycle value for one of inverter transistors during one period, respectively.

Comparative investigation

This section presents comparison of a post-fault operation for two different current control methods applied for FOC control algorithm. The parameters of the simulated model are listed in Table 1.

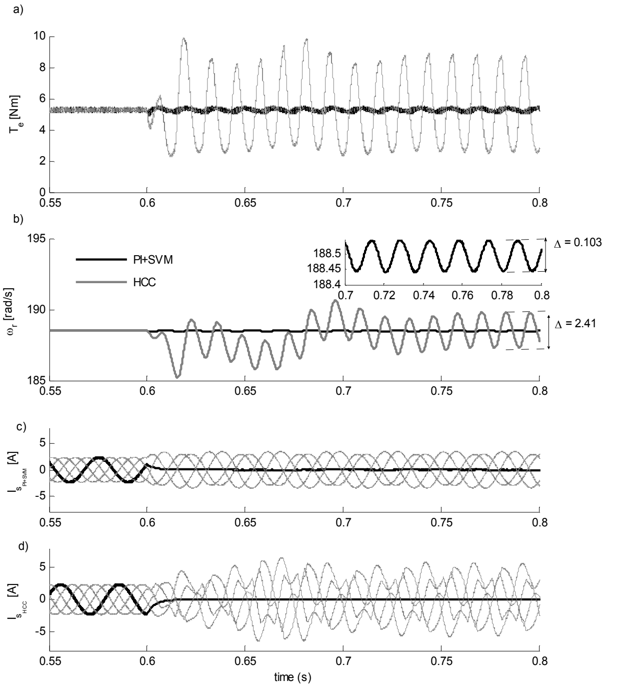
Table 1. 5-phase IM model parameters

Parameter	Symbol	Value
Rated power	P_r	2,65 kW
DC-link voltage	V_{dc}	600 V
Stator leakage inductance	L_{ls}	41 mH
Rotor leakage inductance	L_{lr}	41 mH
Magnetizing inductance	L_m	420 mH
Stator resistance	R_s	10 Ω
Rotor resistance	R_r	10 Ω
Rotor inertia	J	0.01
Friction coefficient	C	0.0029
Pole pairs	P	2

Simulation results presented in this section were obtained using MATLAB/Simulink software, where *SimPowerSystem* library was used for power electronic components. Moreover, both modulation techniques were simulated with specified sampling times given in Table 2. Simulation code execution were adjusted to real test bench conditions, however all presented PI controllers operated in continuous mode.

Figure 7 shows a post-fault operation of 5-phase IM, where a chosen operating point is defined by reference electrical rotor speed set to 188.49 rad/s (it corresponds to 30Hz stator currents frequency for 2 pole pair machine), and load torque equal to 25% of the rated value. The first waveform from the top shows electromagnetic torque for both compared current control strategies. It can be seen that HCC (denoted as gray color) has significantly higher ripples after fault occurrence in t_f=0.65 s. Unfortunately, due to switching nature of power electronic converter, it is difficult to compare both generated torques in reasonable manner. This is why the speed waveforms are presented below, where inertia of the rotor acts like a low-pass filter. It can be noticed that speed ripples for SVM (black color) are significantly lower than ones caused by HCC (gray color). This difference is so significant that the inset window with enlarged speed ripples amplitude was introduced for the SVM case. Additionally, stator current waveforms were presented for PI+SVM (I_{SVM}) and HCC (I_{HCC}) methods, respectively. In both waveforms the faulted 'a' phase current is shown in black color.

Moreover, it can be noted that after the fault, in both cases, the remaining currents are deformed in amplitude and phase shift. Worth mentioning is a fact, that in case of HCC for different load torque values, the system produces ripples which amplitudes are proportional to a load torque. Furthermore, there is a critical value of load torque when the control algorithm losses synchronization. A comparison data, and simulation parameters are summed up in Table 2. The currents, and speed controller parameters were designed using a simplified procedures of approach presented in [19].



Rys.7. Comparison of post-fault operation of HCC and PI+SVM current control methods, respectively. From top: electromagnetic torque, electrical rotor speed, stator currents (PI+SVM), stator currents (HCC).

Table 2. Controller parameters and post-fault operation comparison.

	Parameters		Sampling	$\Delta\omega_e$
HCC	H=0.01		80kHz	1,28%
PI+SVM	Speed controller		5kHz	0,055%
	PI	Kp= 0.8232 Ki= 95.1326		
	Current controllers			
	PI	Kp_d= 0.1864 Ki_d= 74.1326 Kp_q= 0.1864 Ki_q= 74.1326		

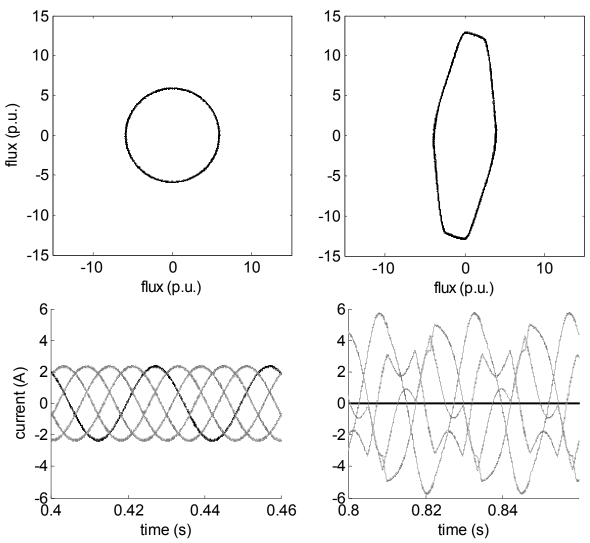


Fig.8. Stator flux hodographs and currents waveforms for healthy and post-fault condition for HCC.

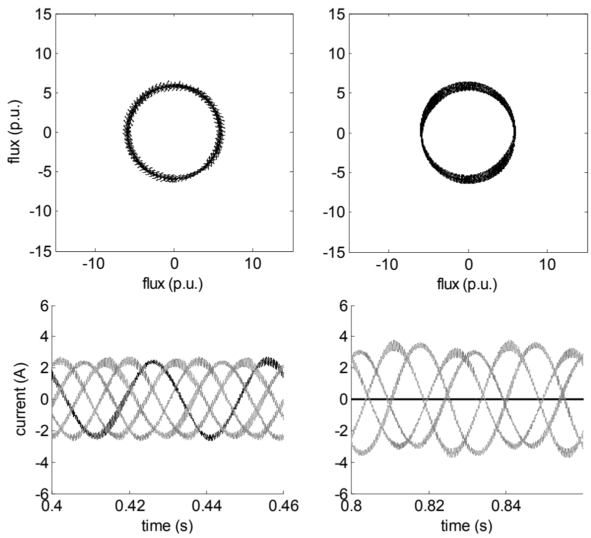


Fig.9. Stator flux hodographs and currents waveforms for healthy and post-fault condition for PI+SVM.

Figure 8 and Figure 9 present stator currents and stator flux hodographs for healthy and post-fault condition for HCC and PI+SVM, respectively. The increase in currents amplitudes is particularly noticeable for HCC method. Due to the fact that presented hodographs were calculated on a basis of phase currents it resulted in ripples content that are greatly higher for 5kHz SVM method.

Conclusion

The paper addresses the problem of open-phase, post-fault operation for two different current control methods in Field Oriented Control (FOC) scheme of 5-phase induction machine connected to 2-level converter. This condition is important due to practical reasons where in real application certain amount of time is required for proper diagnosis and thus an adequate fault-tolerant algorithm application. As it was presented in simulation results, the PI+SVM control with modulation technique is definitely advantageous over the Hysteresis Current Control due to lower torque ripples and lower stator current amplitudes during the post-fault operation. These different results may be explained by utilization of transformed current values for the control in case of PI+SVM, with only α, β component matter. Moreover, only these two values are utilized for space vector modulation as well. On the other hand, in case of the HCC method all information contained in deformed currents is utilized for control what, with its non-linear character, results finally in losing control. However, this hypothesis should be studied further for deeper explanation.

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