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Correction of the operating modes of the induction motor with damage in the stator as part of an electric drive with DTC

***Abstract**. The provision of reliable operation of power electrical systems is one of the basic requirements for most modern industrial applications. Thereby, it is necessary to develop a control strategy that would provide the continuous operation of applications in the event of equipment failures. The paper presents a method of fault-tolerant control of an induction motor as part of an electric drive system with direct torque control in the event of damage in the power circuit of the electric motor stator. The proposed control method is based on the introduction of an additional compensation signal into a closed loop for controlling the motor electromagnetic torque. The results of the research of the presented system confirm the possibility of compensating for the variable components of the electromagnetic torque and power consumption, which is reflected in the reduction of additional vibrations of the motor and a decrease in thermal overloads in the elements of the electromechanical system. The proposed control strategy is simple to implement and does not require the installation of new sensors or changes in the power circuit of a standard direct torque drive system.*

***Streszczenie.** Zapewnienie niezawodnej pracy systemów elektroenergetycznych jest jednym z podstawowych wymagań dla większości nowoczesnych zastosowań przemysłowych. Tym samym konieczne jest opracowanie strategii sterowania, która zapewni ciągłość działania aplikacji w przypadku awarii sprzętu. W artykule przedstawiono sposób bezawaryjnego sterowania silnikiem indukcyjnym w ramach elektrycznego układu napędowego z bezpośrednią regulacją momentu obrotowego w przypadku uszkodzenia obwodu mocy stojana silnika elektrycznego. Zaproponowany sposób sterowania polega na wprowadzeniu do pętli zamkniętej dodatkowego sygnału kompensacyjnego do sterowania momentem elektromagnetycznym silnika. Wyniki badań prezentowanego układu potwierdzają możliwość kompensacji składowych zmiennych momentu elektromagnetycznego i poboru mocy, co przekłada się na zmniejszenie dodatkowych drgań silnika oraz zmniejszenie przeciążeń cieplnych elementów elektromechanicznych system. Zaproponowana strategia sterowania jest prosta w realizacji i nie wymaga instalacji nowych czujników ani zmian w obwodzie zasilania standardowego układu bezpośredniego napędu momentu obrotowego. **(Poprawa trybów pracy silnika indukcyjnego z uszkodzeniem stojana jako element napędu z DTC**)*

Keywords: induction motors; DTC system (direct torque control); fault-tolerant systems.
Słowa kluczowe: silniki indukcyjne, system DTC (bezpośrednie sterowanie momentem), systemy tolerancji uszkodzeń

Introduction

An AC variable-frequency electric drive (ED) with an induction motor (IM) is the basis for the creation of many technical systems of the forward and rotational principle of action. The method of direct control of the stator torque and flux (DTC) is of particular interest among the existing methods of IM control [1]. Its control scheme is very simple. The DTC itself is a hysteresis stator flux and torque control. In this case, the control system directly selects one of six nonzero and two zero discrete voltage vectors of the inverter. Due to this, one can achieve the highest system performance. Using this principle enables the control of the flow and torque without making coordinate transformations. The dependence of the dynamic and energy characteristics of the electric drive on the accuracy of determining the resistive impedance of the IM stator windings is a significant drawback of DTC systems [2].

The authors of papers [3–6] demonstrate that, despite its simplicity and reliability, IM is subject to many failures due to a number of problems, such as overloads, mechanical vibrations and loads, power quality, severe operating conditions or manufacturing defects. Research [7–9] reveals that up to 38 % of IM failures are caused by stator winding failures. It is known that damage to the stator winding begins with a short circuit, including several turns in the coil, and then transforms into a dangerous short circuit between two phases or a phase-to-earth short circuit (IM body).

Since the DTC circuit uses the IM stator resistance to estimate the stator flux, a change in stator resistance due to stator winding faults results in an error in the calculated stator flux position, which can subsequently cause a failure of the entire electric drive system [10]. The termination of the operation of ED systems, due to the occurrence of the above problems, can cause a violation of the safe operation of equipment, as well as significant economic losses in case of accidents at facilities with a non-stop cycle of operation. Based on this, the development and use of fault-tolerant control systems (FTC) for frequency control systems of three-phase IM is of particular interest.

Recently, a large number of research groups have been developing and implementing the FTC in industrial applications [11–13]. The main function of such control systems is to maintain the operability of the system in the event of various kinds of malfunctions. Based on this, an algorithm for detecting various types of damage in the early stages of their manifestation should function in the FTC systems. It will allow modifying the control law to solve the problem of extending the efficiency of electric drives till there is a possibility of their replacement or repair of the drive electric motor [14]. Thus, the rational use of the FTC system includes industrial applications that must maintain operability despite the deterioration in dynamic performance and energy efficiency [15].

The purpose of this paper is to develop an FTC system based on an ED system with DTC in case of damage in the stator power circuits in the early stages of their development to prevent unexpected stoppages of industrial processes.

Theoretical theses

A large number of FTC methods and systems are known today [16]. So, in [17] it was proposed to use the variable component of the electromagnetic torque to compensate for the vibrations of the damaged IM torque, in the classical direct vector control (FOC) system. The received signal is fed to the input of the regulator of the torque-generating component of the stator current in the speed control channel. Using this approach enables the reduction of the variable component of the motor electromagnetic torque to an acceptable level.

The presence in the systems of direct torque control of the control circuit of the IM electromagnetic torque makes it possible to modify the specified method. Then the calculated value of the variable component of the electromagnetic moment $\widetilde{T}_e$ enters the input of the relay torque regulator in the angular speed control channel. Accordingly, the signal for setting the electromagnetic torque will be defined as:

(1) $$T'_{e(ref)} = T_{e(ref)} - \tilde{T}_e \, .$$

The value of the variable component of the IM electromagnetic torque is extracted from the torque signal based on equation:

(2) $$\tilde{T}_e(t) = T_e(t) - \frac{1}{T}\int_0^T T_e(t)dt,$$

where $T_e(t)$, T_{er} – is IM electromagnetic torque and its rated value, respectively; T – is the signal period of the variable component of electromagnetic torque.

In DTC systems the electromagnetic moment is determined by indirect calculation methods based on readily available variables.Then, the electromagnetic torque can be calculated from the measured components of the stator voltage and current as follows:

(3) $$T_e = \frac{3}{2} z_p \left(\Psi_{s\alpha} I_{s\beta} - \Psi_{s\beta} I_{s\alpha}\right)$$

where z_p – the number of pairs of poles; $I_{s\alpha}, I_{s\beta}$ – the projections of the stator current vector on the axis of the fixed coordinate system; $\Psi_{s\alpha}, \Psi_{s\beta}$ – the projections of the stator flux linkage vector on the axis of the fixed coordinate system, which are calculated as follows:

(4) $$\Psi_{s\alpha} = \int \left(U_{s\alpha} - I_{s\alpha} R_s\right)dt; \; \Psi_{s\beta} = \int \left(U_{s\beta} - I_{s\beta} R_s\right)dt,$$

where $U_{s\alpha}, U_{s\beta}$ – the projections of the stator voltage vector on the axis of the fixed coordinate system; R_s – resistance of stator windings.

The functional diagram of the proposed system of fault-tolerant control of an induction motor as part of an electric drive system with DTC in the event of damage in the power circuit of the electric motor stator is shown in Fig. 1.

Research method

The FTC system was researched on mathematical models. A classical structure was chosen as a model of a frequency converter (FC), which includes: a three-phase uncontrolled rectifier, an LC filter in the DC link and a three-phase autonomous voltage inverter. To solve the problem of modeling IM, a model in a three-phase coordinate system was used, in which the asymmetry coefficient ε_w is applied to simulate damage in the stator phase windings [18]. The research was carried out for the 4A112M4U3 series IM, the parameters of which are presented in Table 1. VS-15ETH06PBF diodes were taken as the power switches of the uncontrolled rectifier, IRG4PC50UD transistors – for the autonomous voltage inverter; their parameters are given in Table 2.

Table 1. IM parameters

Parameter	Value	Parameter	Value
P_r (kW)	5.5	R_s (Ω)	1.036
p	2	R_r (Ω)	0.787
n_r (rev/min)	1445	$L_{s\sigma}$ (mH)	4.75
cosφ	0.85	$L_{r\sigma}$ (mH)	7.94
η (%)	85.5	L_μ (H)	0.171

Table 2. The parameters of FC semiconductor switches

Rectifier diodes		Inverter transistors	
Parameter	Value	Parameter	Value
$I_{F(AV)}$ (A)	15	I_C (A)	27
V_F (V)	1.3	$V_{CE(on)}$ (V)	1.65

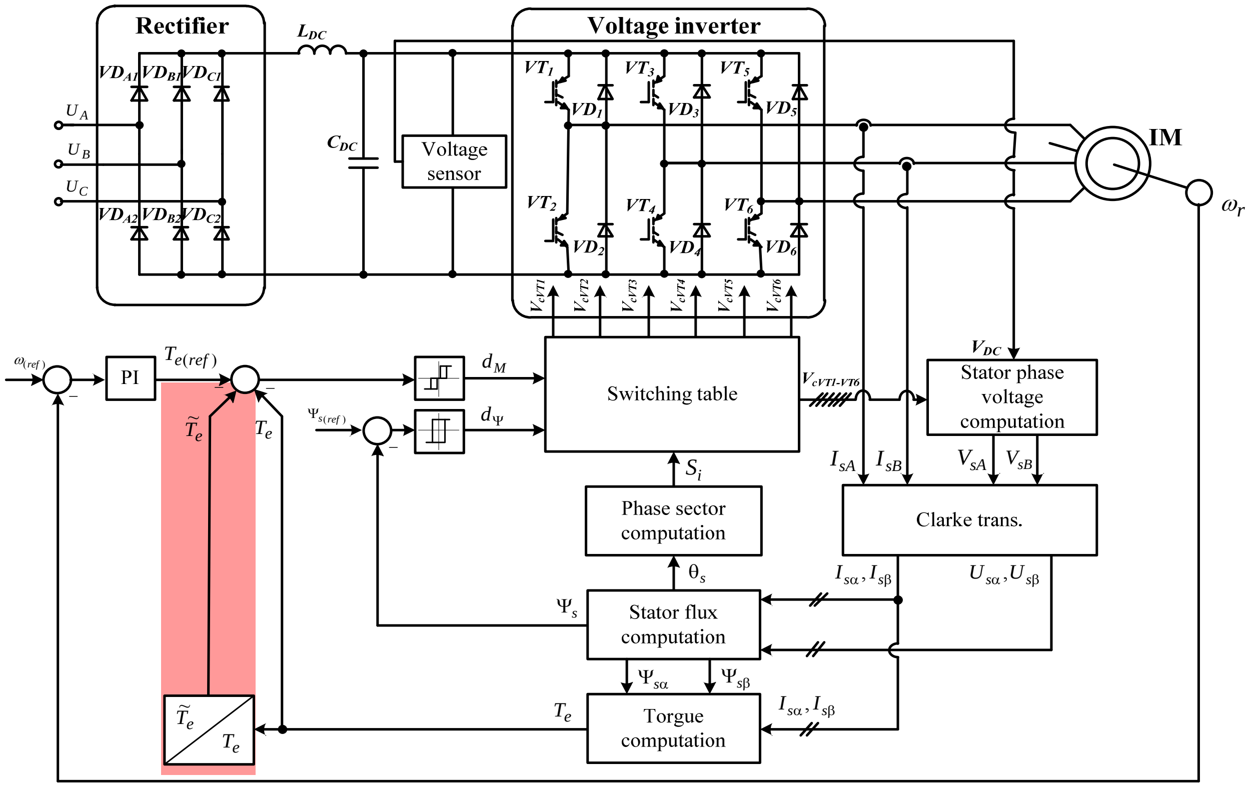


Fig. 1. A functional diagram of the DTC system with the function of compensation for the variable component of the electromagnetic torque of the IM

To assess the modes of the operation of the presented FTC, the following parameters were selected in the paper:

– $\tilde{p}_e / P_r$, $\tilde{p}_{fc} / P_r$ – relative values of the variable components of the consumed active power and active power at the output of the FC.

– $\tilde{T}_e / T_{er}$ – relative value of the variable component of the electromagnetic moment;

– ΔP_{Cu1} – losses in copper of the IM stator in each phase separately;

– ΔP_{rec} – losses in uncontrolled rectifier diodes;

– ΔP_{VT} – losses in transistors of an autonomous voltage inverter.

When calculating the active power, the mathematical apparatus of the p-q theory of power was used [19–20]. During analyzing variable components from instantaneous power and torque signals, harmonics above the fifth were excluded.

Research results

Research of the operating modes of the proposed FTC system was carried out on mathematical models for the following levels of damage to the stator windings:

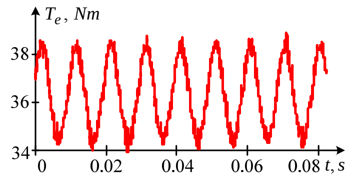
– mode 1 (ε_{wA} = 0.95) – phase A asymmetry of 5 %;

– mode 2 (ε_{wA} = 0.9) – phase A asymmetry of 10 %;

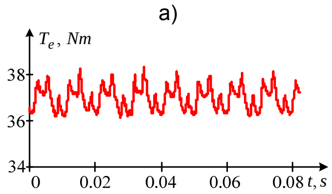
– mode 3 (ε_{wA} = 0.95, ε_{wC} = 0.97) – phase A asymmetry of 5 %, and phase C asymmetry of 3 %;

– mode 4 (ε_{wA} = 0.9, ε_{wC} = 0.93) – phase A asymmetry of 10 %, phase C asymmetry of 7 %.

So, the signals of the electromagnetic moment of the researched IM with damaged stator windings in the classical and proposed FTC system are shown in Fig. 2. The results are shown for the 2nd mode of operation (ε_{wA} = 0.9).



a)



b)

Fig. 2. The electromagnetic moment of the damaged IM in the classical (a) DTC system and the proposed (b) FTC system

Thus, the use of the proposed control system makes it possible to reduce the variable component of the electromagnetic torque. The root-mean-square values of the variable components of the IM torque for the indicated cases of damage to the stator windings are shown in Fig. 3 where the following designations of the researched parameters are adopted:

■ – without FTC; ■ – using FTC.

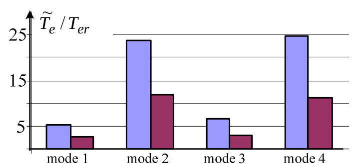
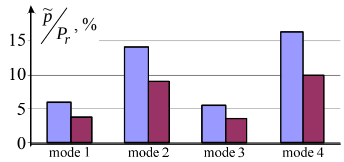


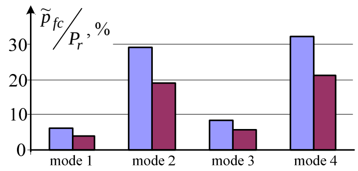
Fig. 3. Relative values of IM electromagnetic torque variable components

Thus, the use of the proposed FTC system enables one to reduce the variable component of the electromagnetic torque by 50 % for cases of damage in one and two phases of the motor. The use of the proposed FTC system also makes it possible to reduce the variable components of the power consumption, the root-mean-square values of which are shown in Fig. 4.

The results of the research revealed that the use of the proposed method of fault-tolerant control allows reduction of the variable component of active power consumed from the network by an average of 37 %, and the variable component of the power consumed from the inverter by 34 % in case of damage both in one and two phases of IM.



a)



b)

Fig. 4. Variable components of active power consumed from the network (a) and from the FC (b)

In [17], it is shown that with a decrease in the variable component of the consumed active power, a decrease in energy losses in individual elements of the electric drive is also observed. So the redistribution of losses in copper of the stator windings of the damaged IM (2nd mode of operation) in the classical DTC system and the proposed FTC system are shown in Fig. 5.

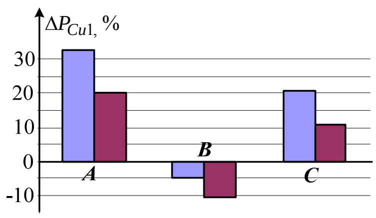
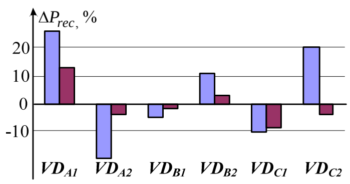
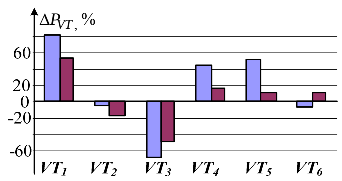


Fig. 5. Deviation of losses in stator windings without using the FTC system and when using it

The redistribution of losses in the semiconductor switches of FC when working with a damaged IM (2nd mode of operation) in the classical DTC system and the proposed FTC system are shown in Fig. 6.



a)



b)

Fig. 6. The deviation of losses in rectifier diodes (a), transistors of an autonomous inverter (b) from their rated values without using the FTC system and when using it

Based on the analysis of energy processes in the considered system, it can be judged that the use of the proposed control method makes it possible:

– to reduce the deviation of losses in copper in the most loaded phase by 40 % in case of damage both in one and two phases;

– to reduce losses in power diodes of an uncontrolled rectifier by 50 % in case of damage in one phase, and by 42% in case of damage in two phases of the motor;

– to reduce losses in transistors of an autonomous voltage inverter by 35 % in case of damage in both one and two phases.

Conclusions

The induction motor FTC system has been developed based on an ED with a DTC with the function of compensating for the variable component of the electromagnetic torque. The proposed method of fault-tolerant control of IM makes it possible to reduce the variable component of the electromagnetic torque of the motor to an acceptable level, while there is a slight decrease in the variable components of the consumed power and losses in the power section of the variable-frequency electric drive.

The proposed control system is easy to implement and does not require the installation of new sensors or changes in the power circuit of a standard electric drive system with direct torque control.

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REFERENCES

[1] L. Dube and E. Bayoumi, "Robust DTC Against Parameter Variation for Three Phase Induction Motor Drive Systems," 2020 International Conference on Electrical, Communication, and Computer Engineering (ICECCE), 2020, pp. 1-6, doi: 10.1109/ICECCE49384.2020.9179205.

[2] S. S. Kale and R. C. Pawaskar, "Analysis of Torque and Flux Ripple Factor for DTC and SVM - DTC of Induction Motor Drive," 2018 International Conference On Advances in Communication and Computing Technology (ICACCT), 2018, pp. 45-49, doi: 10.1109/ICACCT.2018.8529651.

[3] Siwei Cheng, Pinjia Zhang and T.G. Habetler, “An Impedance Identification Approach to Sensitive Detection and Location of Stator Turn-to-Turn Faults in a Closed-Loop Multiple-Motor Drive,” *IEEE Transactions on Industrial Electronics*, vol. 58, no. 5, pp. 1545–1554, May 2011.

[4] V. Prus, A. Nikitina, M. Zagirnyak, D. Miljavec, “Research of rnergy processes in circuits containing iron in saturation condition”, Przeglad Elektrotechniczny, vol. 87, no. 3, pp. 149-152, 2011.

[5] M. V. Zagirnyak, V. V. Prus, A. V. Nikitina, “Grounds for efficiency and prospect of the use of instantaneous power components in electric systems diagnostics”, Przeglad Elektrotechniczny, vol. 82, no. 12, pp. 123-125, 2006.

[6] M. Zagirnyak, A. Kalinov, V. Melnykov and P. Stakhiv, "Fault-tolerant control of an induction motor with broken stator electric circuit," 2016 Electric Power Networks (EPNet), 2016, pp. 1-6, doi: 10.1109/EPNET.2016.7999372.

[7] M. Zagirnyak, D. Mamchur, A. Kalinov, “Comparison of induction motor diagnostic methods based on spectra analysis of current and instantaneous power signals”, Przeglad Elektrotechniczny, vol. 88, no. 12 B, pp. 221-224, 2012.

[8] S. A. Ethni, S. M. Gadoue and B. Zahawi, "Inter-turn short circuit stator fault identification for induction machines using computational intelligence algorithms," 2015 IEEE International Conference on Industrial Technology (ICIT), 2015, pp. 757-762, doi: 10.1109/ICIT.2015.7125189.

[9] M. Zagirnyak, D. Mamchur, A. Kalinov, “Induction motor diagnostic system based on spectra analysis of current and instantaneous power signals”, IEEE SOUTHEASTCON 2014, 2014, doi: 10.1109/secon.2014.6950721

[10] S. S. Refaat, H. Abu-Rub and A. Iqbal, "ANN-based system for inter-turn stator winding fault tolerant DTC for induction motor drives," 2015 17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe), 2015, pp. 1-7, doi: 10.1109/EPE.2015.7309182.

[11] M. Jannati, A. Monadi and N. R. N. Idris, "Fault-tolerant control of 3-phase IM drive (speed-sensor fault and open-phase fault)," 2015 IEEE Conference on Energy Conversion (CENCON), 2015, pp. 384-389, doi: 10.1109/CENCON.2015.7409574.

[12] N. Boumalha, R. Hachelef, D. Kouchih, M. Tadjine and M. S. Boucherit, "Diagnostic and fault tolerant control by adaptive observer of doubly-fed induction generators with inter-turn rotor and stator fault based wind turbine," 2017 5th International Conference on Electrical Engineering - Boumerdes (ICEE-B), 2017, pp. 1-6, doi: 10.1109/ICEE-B.2017.8192052.

[13] T. Roubache, S. Chaouch and M. S. N. Said, "Backstepping fault tolerant control for induction motor," 2014 International Symposium on Power Electronics, Electrical Drives, Automation and Motion, 2014, pp. 472-477, doi: 10.1109/SPEEDAM.2014.6871905.

[14] Y. Saadi, R. Sehab, A. Chaibet, M. Boukhnifer and D. Diallo, "An Automatic Fault Detection and Localization Strategy for Switched Reluctance Machine Open-Circuit Fault in EVs Applications," 2019 International Conference on Control, Automation and Diagnosis (ICCAD), 2019, pp. 1-6, doi: 10.1109/ICCAD46983.2019.9037933.

[15] V. Kovalchuk, T. Korenkova, The Assessment of the Efficiency of a Pumping Plant with a Variable-Frequency Electric Drive at the Change of the Hydraulic System Parameters, Proceedings of the International Conference on Modern Electrical and Energy Systems, MEES 2019, Kremenchuk, Ukraine, 2019, pp. 134-137. ISBN:978-1-7281-2570-1. doi: 10.1109/MEES.2019.8896618.

[16] M. Zagirnyak, V. Melnykov and A. Kalinov, “The review of methods and systems of the fault-tolerant control of variable-frequency electric drives,” Przeglad Elektrotechniczny, vol. 95, no. 1. pp. 141-144, 2019.

[17] M. Zagirnyak, A. Kalinov and V. Melnykov, "Variable-frequency electric drive with a function of compensation for induction motor asymmetry," 2017 IEEE First Ukraine Conference on Electrical and Computer Engineering (UKRCON), 2017, pp. 338-344, doi: 10.1109/UKRCON.2017.8100505.

[18] M. Zagirnyak, A. Kalinov, V. Melnykov, I. Kochurov, “Correction of the operating modes of an induction motor with asymmetrical stator windings at vector control”, 2015 International Conference on Electrical Drives and Power Electronics (EDPE), pp. 259-265, 2015, doi: 10.1109/edpe.2015.7325303

[19] H. Akagi, E. H. Watanabe and M. Aredes, “Instantaneous power theory and applications to power conditioning,” Wiley-interscience a john wiley & sons, inc. Publication, Mohamed E. El, Hawary, ISBN 978-0-470-10761-4, 2007.

[20] M. Zagirnyak, M. Maliakova, A. Kalinov, “Compensation of higher current harmonics at harmonic distortions of mains supply voltage”, 2015 16th International Conference on Computational Problems of Electrical Engineering (CPEE), 2015, pp. 245-248, doi: 10.1109/CPEE.2015.7333388.

[21]