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Decrease of the thermal overloads of a variable-frequency electric drive at damages in the electric circuit of an induction motor stator

Abstract. *The paper deals with a method of fault-tolerant control of an induction motor at damages in the stator power electrical circuit. The method bases on the decrease of the damaged phase flux linkage, which enables the reduction of the level of the consumed power variable component. The research concerned the cases of the stator winding damages at the early stage of their development. At such damages, the induction motor can operate for a long time in the asymmetric mode without protection actuation but with essential thermal overload of particular phases. The results of the research of the proposed system of fault-tolerant control confirmed the possibility of the decrease of the thermal overloads of the induction motor windings and frequency convertor semiconductor switches, which will allow the increase of their life span.*

Streszczenie. *W artykule przedstawiono metodę kontroli odporności na uszkodzenia silnika indukcyjnego przy uszkodzeniach w obwodzie elektrycznym stojana. Metoda opiera się na zmniejszeniu uszkodzonego połączenia fazowego, co umożliwia obniżenie poziomu zużytej zmiennej składowej mocy. Badania dotyczyły uszkodzeń uzwojenia stojana na wczesnym etapie ich rozwoju. Przy takich uszkodzeniach silnik indukcyjny może działać przez długi czas w trybie asymetrycznym bez włączenia zabezpieczeń ale z istotnym przeciążeniem termicznym poszczególnych faz. Wyniki badań proponowanego systemu odpornego na uszkodzenia potwierdziły możliwość zmniejszenia przeciążeń termicznych uzwojeń silnika indukcyjnego i półprzewodnikowych łączników przemienników częstotliwości, co pozwoli na zwiększenie ich żywotności.(**Zmniejszenie przeciążeń termicznych napędów zmienno-częstotliwościowego napędu elektrycznego przy uszkodzeniu obwodu elektrycznego w stojanie silnika indukcyjnego**)*

Key words: induction motors; frequency control; fault-tolerant systems
Słowa kluczowe: silniki indukcyjne; kontrola częstotliwości; systemy odporne na uszkodzenia.

Introduction

Damages in the stator power electric circuits stand out of the main causes of induction motors (IM) failure. Therefore, according to the research [1], the cause of 25% - 40% of IM failures consists in turn-to-turn shorting resulting from the stator winding insulation damages. The occurrence of turn-to-turn shorting in the windings of IM of alternating current variable-frequency electric drives (ED) results in local overheat of particular semiconductor switches of frequency convertors (FC). A break of the whole winding or a parallel section of IM phase winding is a logical development of the turn-to-turn shorting. For IM with the number of parallel winding paths exceeding four a break of one path results in the asymmetry of the stator winding three-phase system and usually ends in the motor emergency outage. ED operation with asymmetric windings of the stator phases may also result in thermal overloads of particular FC switches and IM phases [2].

Timely detection and elimination of IM damages at the early stages of their development may increase the life span of the technological equipment and reduce the financial losses caused by unpredictable disconnection of the equipment resulting from technological faults or IM failure. Thus, fault-tolerant control systems (FTC) are of special interest as they are able to detect various types of damages at the initial stage and operatively adapt the control law in such a way that ED functionality remains for a long time till there is a possibility of IM repair or change [3].

There are two groups of the conventional methods of fault-tolerant control of IM with damages in the stator power electric circuit.

The first group includes methods only allowing the detection of occurring damages and the termination of ED operation at their further development [4, 5]. This group may also include software redundancy methods based on the switch between the control algorithms from complex to simpler ones [6, 7]. The use of the fault-tolerant control systems from the first group makes it possible to maintain the functionality of ED with insignificant damages in the IM power circuit. In this case, the problem of compensation for the stator damages influence on the ED system characteristics and FC operation mode is not under consideration at all.

The second group of methods enables not only the detection of the damages, but also the alteration of the IM control algorithm for the provision of the required dynamic characteristics of ED system. Such methods ground on both the complication of control systems due to the increase of the closed regulation circuits [8, 9], and on the introduction of additional compensation signals into the existing regulating circuits [10, 11]. The second group of methods provides the functionality to some extend and allows partial correction of the operation modes of IM as a part of a variable-frequency ED. One of the most effective methods for estimation of energy conversion processes in an electromechanical complex with the use of instantaneous power method was described in [12]. However, the problems of ED power characteristics correction and the problems of IM damages influence on FC operation modes remain unsolved.

To solve the presented problem the authors of paper [13] proposed a fault-tolerant system of vector control with separate regulation of the contours of flux linkage and the current active component for every IM phase, which enables the correction of the ED operation modes by means of alteration of the signals of assigning the phases flux linkages. The purpose of this paper consists in the research of the method for decrease of the thermal overload of the variable-frequency electric drive at the damages in the power electric circuit of the IM stator.

Methodology of Research

We researched the operation modes of the fault-tolerant systems of IM control using mathematical models. A three-phase uncontrolled rectifier, a LC-filter in a direct current link and a three-phase autonomous inverter of voltage (AIV) represented a FC model. IM was represented by a model in a three-phase coordinate system wherein the damage in the stator phase windings was taken into account by means of asymmetry coefficient ε_w [14]. We performed the research for 4A112M4U3: P_r = 5.5 kW; n_r = 1445 rev/min; $cos\varphi$ = 0.85;

η = 85.5%. We used diodes VS-15ETH06PBF as power switches of the uncontrolled rectifier, and transistors IRG4PC50UD as an autonomous inverter of voltage (AIV). During modeling, the frequency of modulation of AIV transistors was equal to 8 kHz.

We performed the analysis of the operation of the presented system of the fault-tolerant vector control based on the following parameters: the relative values of the variable components of the consumed active power ($\tilde{p}_e / P_r$) and active power ($\tilde{p}_{fc} / P_r$) at FC output, electromagnetic torque ($\tilde{T}_e / T_{er}$), IM stator copper losses (ΔP_{Cu1}) in every separate phase, losses (ΔP_{rec}) in the diodes of the uncontrolled rectifier, losses (ΔP_{VT}) in AIV transistors. During the analysis of the variable components, we excluded the harmonics higher than the fifth one from the instantaneous signals of power and torque.

We calculated the copper losses in the IM stator phase in the following way:

(1) $$\Delta P_{Cu1} = \frac{1}{T}\int_0^T i_{sA,\,sB,\,sC}(t)^2\, r_{A,\,B,\,C},$$

where $i_{sA,\ sB,\ sC}(t)$ – the instantaneous signals of IM phases current; $r_{A,\,B,\,C}$ – the resistive impedance of the corresponding stator phases; T – the period of the analyzed signal.

We calculated the losses in the FC semiconductor switches in the following way:

(2) $$\Delta P_{SS} = \frac{1}{T}\int_0^T i_{ss}(t)^2\, r_{ss},$$

where $i_{ss}(t)$ – the instantaneous values of current passing across the semiconductor switch; r_{ss} – the resistance of the semiconductor switch in an open state.

We calculated the redistribution of the copper losses in IM phases and FC power elements in the deviations from the basic values represented by the losses in the corresponding elements of the variable-frequency ED in the operation with a symmetrical IM. We calculated the relative values of the losses in the power part of the variable-frequency ED based on expression:

(3) $$\Delta P = \frac{\Delta P(\varepsilon) - \Delta P_r}{\Delta P_r} \cdot 100\,\%,$$

where $\Delta P(\varepsilon)$ – the losses in the ED elements for the current value of the windings asymmetry; ΔP_r – the losses in the corresponding ED elements with a symmetrical IM.

The research of the operation modes of the IM fault-tolerant control system

The research of the developed FTC (Fig.1) with separate regulation of the motor phases [15] revealed that to compensate for the electromagnetic torque variable component the value of the flux linkage of the asymmetric phase is to be decreased proportionally to the asymmetry of the motor phase resistive impedance. In this case, the variable component of the consumed active power also insignificantly decreases. It results in the reduction of the thermal overload of both separate phases of the motor and the FC semiconductor switches.

To solve the problem of the decrease of the thermal overload of the variable-frequency electric drive at damages in the power electric circuit of the induction motor stator we must decrease the flux linkage of the IM damaged phase by the value:

(4) $$\varepsilon_\Psi = \varepsilon_w + \left(1 - \frac{\varepsilon_w^2}{\Psi_{(ref\ \max)}}\right),$$

where: ε_w – the coefficient of the asymmetry of the number of turns in the motor phase [15]; ε_Ψ –the coefficient of the correction of the flux linkage in the damaged phase; $\Psi_{(ref\,\max)}$ – the maximum assigning of the flux linkage.

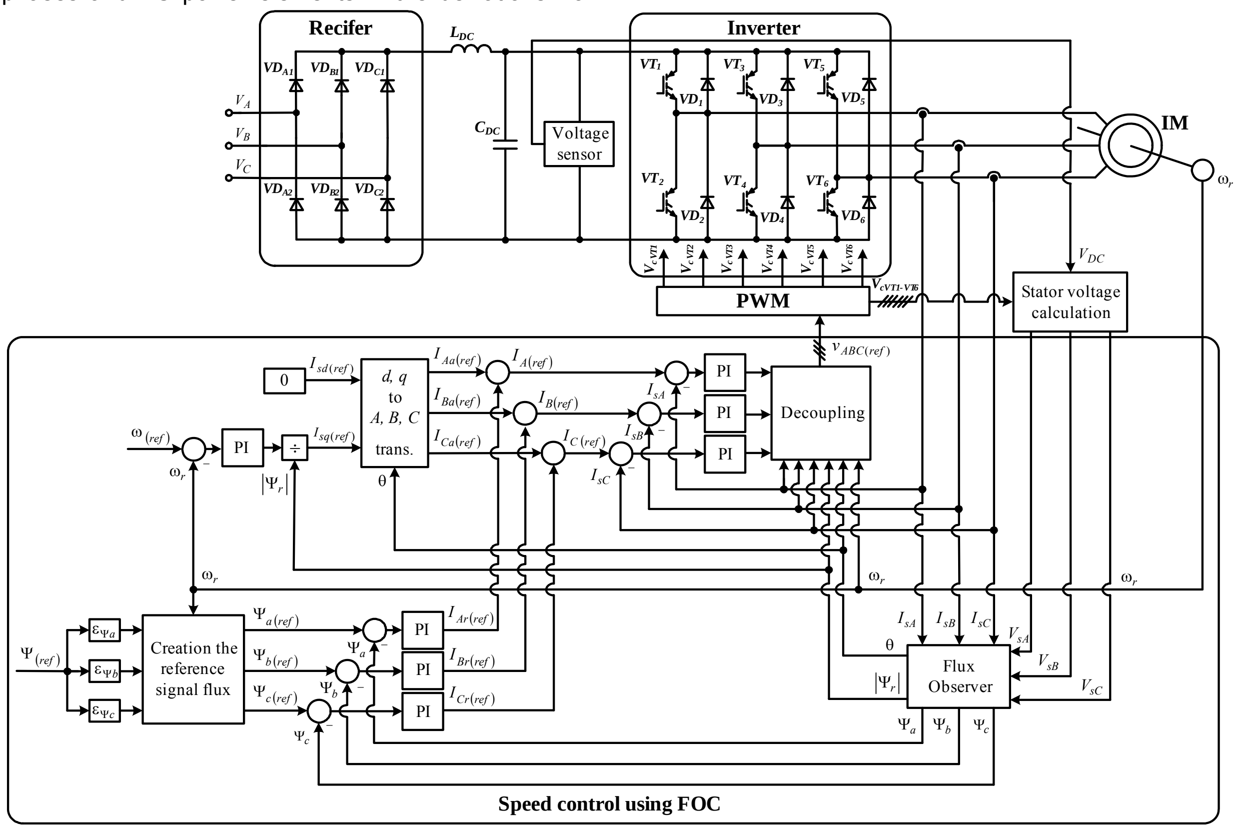
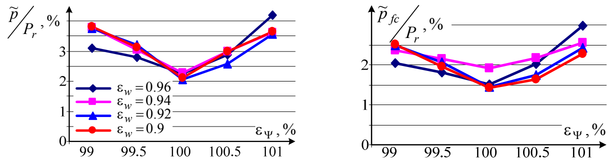


Fig. 1. FTC circuit with separate regulation of the motor phases

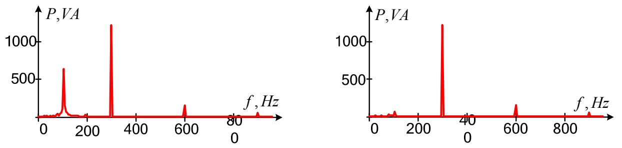


a) b)

Fig. 2. The variable components of the power consumed from the network (a), from FC (b) the active power at the variation of the assigned value of the flux linkage

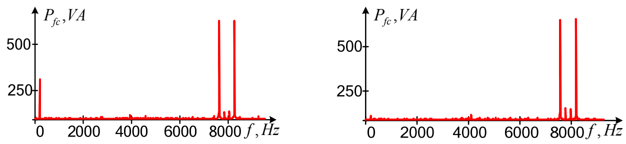
The paper contains the research of the damaged IM operation modes at different ratios of flux linkage in phases (Fig. 2). The research of the indices of the variable components of the consumed power (Fig. 2) is presented for the cases of asymmetry of the number of turns in the motor phase A, equal to 4 % ($\varepsilon_w = 0.96$), 6 % ($\varepsilon_w = 0.94$), 8 % ($\varepsilon_w = 0.92$) and 10 % ($\varepsilon_w = 0.9$).

The results of the research reveal that at the decrease of the flux linkage in an asymmetrical phase, according to expression (4), one can see the reduction of the variable components of active powers consumed from the network and from FC to the admissible level. Therefore, Fig. 3 shows the harmonic components of the active power consumed from the network without the constant component, and Fig. 4 shows the harmonic components of the power at FC output without the constant component. The signals represent the case of asymmetry in phase A equal to 10%.



a) b)

Fig. 3.The harmonic composition of the active power consumed from the network before compensation (a) and (b) after compensation

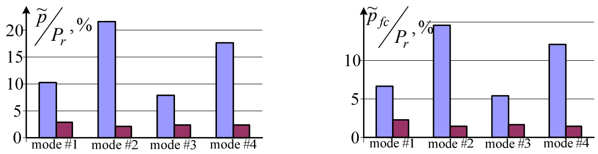


a) b)

Fig. 4. The harmonic composition of the power at FC output before compensation (a) and (b) after compensation

In addition, in the mode of flux linkage reduction, according to expression (4), we can see the minimal exceed of losses of the most overloaded phase of the IM stator.

We carried out the further research of the operation of the proposed system of fault-tolerant control for the following cases: asymmetry in phase *A* is 5 % ($\varepsilon_{wA} = 0.95$) (mode #1); asymmetry in phase *A* is 10 % ($\varepsilon_{wA} = 0.9$) (mode #2); asymmetry in phase *A* is 5 %, in phase *C* – 3 % ($\varepsilon_{wA} = 0.95$, $\varepsilon_{wC} = 0.97$) (mode #3); asymmetry in phase *A* is 10 %, in phase *C* – 7 % ($\varepsilon_{wA} = 0.9$, $\varepsilon_{wC} = 0.93$) (mode #4). Fig. 5 shows the comparison of the root-mean-square (RMS) values of the variable components of the active power consumed from the network and the power at the FC output for the mentioned cases of asymmetry of IM stator windings. The figures contain the following designations of the researched parameters: ▭ – before compensation; ■ – after compensation.



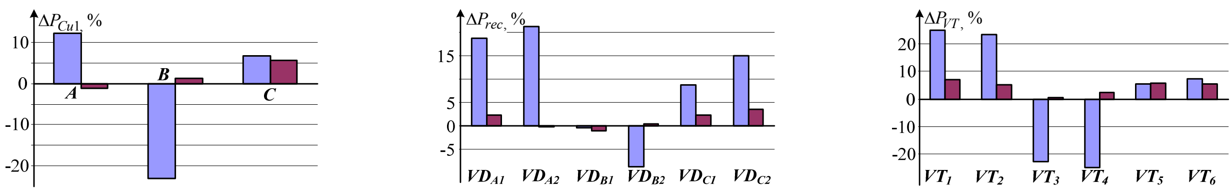
a) b)

Fig. 5. The variable components of the active power consumed from the network (a) and from FC (b)

The results of the research of the operation modes of the presented system of the fault-tolerant control revealed that the variable component of the active power consumed from the network decreases, on average, by 80 %, and the variable component of power at FC output – by 78% for the cases of asymmetry both in one and two IM phases.

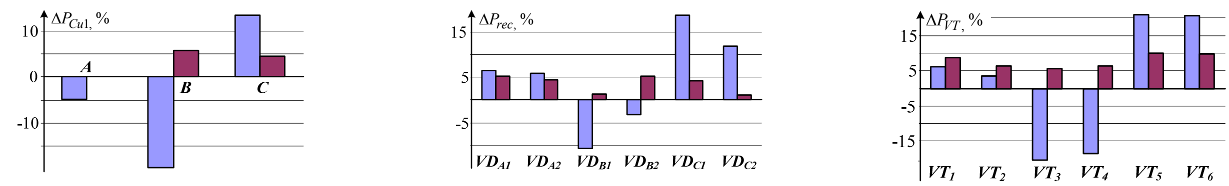
Figs. 6, 7 show the redistribution of the stator copper losses in IM phases for mode #2 ($\varepsilon_{wA} = 0.9$) and mode #4 ($\varepsilon_{wA} = 0.9$, $\varepsilon_{wC} = 0.93$) before and after compensation, respectively.

The use of the presented system of the fault-tolerant control with the developed method enables the reduction of the thermal overload of particular phases of the motor and semiconductor switches of the frequency convertor. The presented method makes it possible, by the decrease of the flux linkage of the damaged phase, to reduce the variable component of the power consumed by asymmetric induction motor, the losses in the stator copper of the most loaded phase, on average, by 56%, the losses in the power diodes of the input rectifier of the most loaded phase, on average, by 73%, the losses in the transistor switches, on average, by 66%.



a) b) c)

Fig. 6. The deviation of the losses in the stator windings (a), the input rectifier diodes (b), the autonomous inverter transistors (c) from their rated values before and after compensation for mode #2 ($\varepsilon_{wA} = 0.9$)



a) b) c)

Fig. 7. The deviation of the losses in the stator windings (a), the input rectifier diodes (b), the autonomous inverter transistors (c) from their rated value before and after compensation for mode #4 ($\varepsilon_{wA} = 0.9$, $\varepsilon_{wC} = 0.93$)

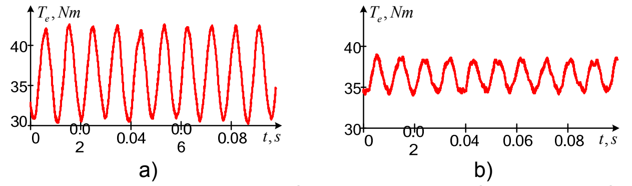


Fig. 8.Electromagnetic torque of asymmetric IM before (a) and after (b) compensation

The performed research reveals that in the mode of compensation for the variable component of the consumed power one can also observe compensation for the variable component of the IM electromagnetic torque. Therefore, Fig. 8 shows the signals of the electromagnetic torque of the researched IM in the presented system of fault-tolerant control. The signals concern the case of asymmetry of the number of turns in phase A equal to 10 % (ε_{wA} = 0.9).

Fig. 9 shows the comparison of the RMS values of the variable components of IM electromagnetic torque for the mentioned cases of asymmetry of IM stator windings.

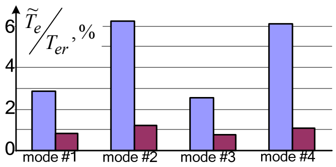


Fig. 9. The variable components of IM electromagnetic torque

Thus, the use of the presented system of fault-tolerant control makes it possible to reduce the variable component of the electromagnetic torque, on average, by 65 % for the cases of asymmetry both in one and two motor phases.

Conclusion

We have developed a method for the correction of the operation modes of induction motors with damages in the stator power electric circuit. According to this method, the decrease of the flux linkage of the damaged phase enables the reduction of the thermal overload of particular phases of the motor and the frequency converter semiconductor switches. It will allow the increase of their life span.

We have demonstrated that the use of the presented system of fault-tolerant control with the developed method makes it possible to decrease the variable component of the active power consumed from the network, on average, by 80 %, and the variable component of the power at FC output – by 78 %. In this case, the thermal overloads of particular phases decrease, on average, by 56 %, of the input bridge rectifier diodes – by 73 %, of the autonomous voltage inverter – by 66 %. It increases the life span of the insulation of the induction motor stator windings and the frequency converter.

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