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doi:10.15199/48.2019.01.36

The review of methods and systems of the fault-tolerant control of variable-frequency electric drives

Abstract. *An express analysis of the methods and systems of fault-tolerant control of induction motors of variable-frequency electric drives is presented. Classification features are suggested to evaluate the possibility of using existing fault-tolerant control methods in modern variable-frequency electric drives, taking into account the capabilities of control systems. As one of the promising directions, the usage of modern p-q and cross-vector instantaneous power theories and its modifications are allocated for solving inseparable connected tasks of damages diagnostics and compensation of their influence on the operation modes of the frequency-controlled electric drive.*

Streszczenie. *W artykule przedstawiono analizę metod i systemów sterowania. Zasugerowano właściwości klasyfikacyjne do oceny możliwości wykorzystania istniejących metod sterowania w nowoczesnych napędach elektrycznych o zmiennej częstotliwości, biorąc pod uwagę ich operatywność. Jeden z obiecujących kierunków, a mianowicie użycie nowoczesnych teorii mocy oraz ich modyfikacje s ą przydzielone do rozwiązywania nierozdzielnie związanych zadań diagnozowania uszkodzeń i kompensacji ich wpływu na stany działania zmienno-częstotliwościowych napędów elektrycznych.* ***(Przegląd metod I systemów odpornego na uszkodzenia sterowania zmienno-częstotliwościowymi napędami elektrycznym)***

Key words: *variable-frequency electric drives, induction motors, fault-tolerant control, diagnostics*
Słowa kluczowe: *zmienno-częstotliwościowy napęd elektryczny, silniki indukcyjne, sterowanie bezawaryjne, diagnostyka*

Introduction

Correct functioning of variable-frequency electric drives (VFD) with induction motors (IM) depends on the reliable operation of IM, a three-phase autonomous voltage invertor (AVI), and a control system (CS).

IM malfunctions include failures of:
- one or several phases of the stator;
- electrical asymmetry;
- magnetic asymmetry;
- mechanical breaks, etc.

AVI malfunctions include:
- the failure of a separate semiconductor switch;
- the failure of one or two invertor arms;
- the malfunction or failure of the control driver, etc.

CS malfunctions include:
- the break of angular rotation frequency sensor;
- the break of the current sensors;
- the breaks at the formation of the control signals, etc.

The share of IM malfunction is the biggest in the whole scope of VFD failures. When IM operates with insignificant defects or with the breaks at the early stages of their development the system maintains its operability. In this case the quality of control deteriorates; the indices of the energy efficiency of the process of the electromechanical energy conversion decreases, the losses increase essentially and variable components of the electromagnetic torque and consumed active power appear.

In such cases fault-tolerant control systems (FTC) are of great interest. They usually consist of two parts: the system of diagnostics and fault revelation and the system of the formation of special control impacts for their compensation.

The scope of FTC systems is determined by the elements for which it is important to maintain an operational state in case of damage, despite the reduction in power, speed and energy efficiency:
- electric transport drive;
- electric drive of critically important technological objects;
- electric drive of fire pumps, pumping stations of public water supply and water disposal;
- electric drive of ventilation systems.

Problem statement

With the given significant number of developed fault tolerant induction motors control methods, it is necessary to classify and analyze the applicability of these methods in modern variable-frequency electric drives.

Material and results of the research

Generally, one can divide FTC into two types: passive and active ones. The systems which switch the main mode of control to the reserve one at the identification of a certain break are an example of passive FTC. So, when we use the vector control with a velocity sensor as the main mode, there is a transfer to the mode of a non-sensor vector or a scalar control.

Unlike the passive FTC, the active ones can response to the failures of VFD components due to the alteration of the control impacts and the whole system may retain its stability and the acceptable productivity. At first those systems reveal and localize the failure then change the control law to achieve the required result. In such cases they compensate the malfunction consequences by the choice of a preliminarily calculated or a newly-synthesized control law.

Up to now, a large number of methods for the formation of control and compensating influences are used for FTC IM.

The analysis of published sources allows creating a classification of the most common methods used for FTC IM in the VFD.

- Depending on the character of the interaction with the object of control.
- Depending on the type of the frequency control.
- According to the character of VFD elements breakage.
- Methods differ depending on the chosen coordinate system.
- There are different methods depending on the chosen parameter with correctable or compensated components.
- Depending on the methods of obtaining the initial information and the breakage diagnostics.
- Depending on the methods of the calculation and formation of the correcting impacts.

Depending on the character of the interaction with the object of control, they are:
- active [1-5, 8-12, 14-20, 25-40],
- passive [6, 13, 21-24].

Depending on the type of the frequency control, they are:

- scalar [6, 9, 12, 13, 16, 21, 31-35];
- vector [1-5, 7, 8, 10, 11, 14, 17-21, 25, 27, 28, 30, 31, 36-40];
- direct torque control [26, 29].

According to the character of VFD elements breakage:

- the stator phase break [1-14, 23-24, 27-30, 32-40];
- the asymmetry of the stator winding resistances [23-29, 31-40];
- the rotor eccentricity [32-35];
- the occurrence of the points of contact with high resistance [16-20];
- the broken rotor bars or the alteration of the rotor resistance [21, 22];
- the failure of the elements of the energy power convertor [21-23].

Methods differ depending on the chosen coordinate system:

- a three-phase UVW [6, 9, 12, 13, 32-35, 38-40];
- a fixed coordinate system αβ [1-5, 11];
- a rotating coordinate system *d-q* [1-5, 7, 8, 10, 11, 14, 17-20, 27, 28, 31, 36-37].

There are different methods depending on the chosen parameter with correctable or compensated components:

- the electromagnetic torque [1-5, 9, 11, 12, 29, 30, 37];
- the electrical power at the input [32-36];
- the stator currents [6, 13, 16-20, 27, 28, 30, 36-40].

Depending on the methods of obtaining the initial information and the breakage diagnostics:

- the use of the viewer based on the IM bilinear model with breakage [31];
- the revelation of the rotor eccentricity using a wavelet-analysis [24];
- the use of the rotor flux viewer based on the "backstepping" method [28];
- the use of the neural network to identify the degree of the stator windings asymmetry [29];
- the identification of IM breaks by the analysis of the harmonics of the current or the consumed power [32-35];
- the identification of breaks by the values of the parameter variable components [7, 8, 10, 14];
- the calculation of the rotor resistance with the use of the expended Kalman filter [5];
- the calculation of the electromagnetic torque via the direct measurement of the field in the gap and the phase currents or via the measurement of the phase currents and voltages [6, 13, 16-20, 36].

Depending on the methods of the calculation and formation of the correcting impacts:

- the displacement of current of working phases vectors on an angle π/3 [6, 13];
- introduction of additional harmonics of voltage for elimination of the second and higher harmonics of torque pulsations [9, 12];
- the use of the additional controlling circuits with classical PI-controller [17-20];
- the introduction of a variable component into the controlling circuit of the torque-creating component of the current [27-31, 37];
- the use of the theory of instantaneous powers: the modified method of *p-q* power theory [36], the cross-vector power theory [32-35];
- the separate correction of the flux linkage by three phases [38-40];
- the use of the coordinate transformations additional block with a mathematical apparatus based on the determined positions of the current vector [7, 8, 10, 14];
- the use of the genetic algorithm for the adjustment of the coefficients of the controller of the angular rotation frequency [1-5, 11];
- the switch between the control algorithm from the more difficult to the easier one [21-24].

Conducted analysis indicated a numerous existing methods used to control IM with damages, which, more-less ensure its operability and allow one adjust operation modes of motor as a part of variable frequency electric drive.

Nowadays in practice only passive methods are intensively used, which allows only switching between control algorithms from more complex to more simple in case of different damages occurrence. They are widely used for cases of damage occurrence in informative part of controlled electric drive: failure or malfunction in current sensors or angular rotational frequency sensors.

Operation of variable frequency electric drive with damaged IM is characterized by non-uniform current and heat load of windings and power switches of inverter. However, in most part of reviewed papers these questions remains not solved.

Most part of analyzed methods allows one compensate influence of single damage type. Use of these methods for cases of simultaneous occurrence of several damage types either impossible, or is not investigated yet. Number of methods is based on the use of cumbersome mathematic calculations, which does not allow using them even using modern signal processors under strict requirements to processing speed.

The use of modern p-q and cross-vector instantaneous power theories [32, 41-43] makes it possible to increase the efficiency of the control system through operations with the same set of variables for solving inseparable connected tasks of IM damages diagnostics [44-47] and FTC [33-37]. So, the proposed scalar and vector control systems [33-37] allow to effectively compensate the influence of the IM stator windings asymmetry on the electric drive characteristics.

Conclusions

The use of the classification proposed by the authors makes it possible to choose the most rational methods and ways for the fault-tolerant control of the induction motors as parts of variable-frequency electric drives taking into account the hard- and software possibilities of the modern control systems.

As one of promising ways it is possible to single out the use of modern *p-q* and cross-vector instantaneous power theories and their modifications to solve indissoluble connected tasks of motor damage diagnostics and compensation of their influence on operation modes of variable frequency electric drive.

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