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Sensorless vector-control system with the correction of stator windings asymmetry in induction motor

Abstract. *Estimation of induction motor stator windings asymmetry influence on power and dynamic characteristics of sensorless vector control systems is performed. A system of vector control in a three-phase coordinate system is developed. This system makes it possible to compensate for induction motor windings asymmetry by correction of flux linkage assignment.*

Streszczenie. *Analizowano wpływ asymetrii uzwojeń twornika silnika indukcyjnego na właściwości dynamiczne przy sterowaniu bezczujnikowym. Badano układ silnika trójfazowego. Przedstawiono metody korekcji wpływu asymetrii uzwojeń. (**Bezczujnikowe wektorowe sterowanie silnikiem indukcyjnym z korekcją asymetrii uzwojeń**)*

Key words: asymmetry, stator windings, power characteristics, vector control system.
Słowa kluczowe: silnik indukcyjny, sterowanie bezczujnikowe, asymetria uzwojeń

Introduction

Sensorless induction motor (IM) vector control systems (VCS) are widely spread in industry.

Long-term performance of IM results in occurrence of various damages. As diagnostics results show [1], at present, a great number of IM with unsymmetrical stator windings are used.

According to statistic data, more than half IM failures occur due to stator windings damages [2, 3]. The main reason for this consists in damages of conductor and slot insulation which can be caused by both violation of motor production or repair methods and abuse. It results in short circuits: winding short circuits, interfacial ones and ironwork faults [4, 5]. As, due to the crisis, industrial enterprises reduce the amount of repair work, when some sections of stator winding of high- and medium-power motors fail, these sections are not removed out of the slots, but are excluded from the circuit and the sections ends are connected passing over the faulty ones [3]. As a result, the stator winding becomes asymmetric and henceforth the motor operates with this winding.

Consequences of operation of IM with unsymmetrical stator windings can be rather considerable for both the motor and the working mechanism. Therefore, the aim of the research is estimation of operating conditions and correction of power indices of systems of sensorless vector control of electric drive with an asymmetric induction motor.

Theory

Research of dynamic and power conditions of operation of sensorless VCS with unsymmetrical IM was made using mathematical models. IM was described by differential equations in a three-phase coordinate system and VCS was created in an orthogonal coordinate system with orientation to the vector of rotor flux linkage [6]. As indirect methods of determining rotor flux linkage were considered following [7,8]:

– *observer No.1* – on the basis of equations of stator circuit in a fixed coordinate system;

– *observer No. 2* – on the basis of equations of rotor circuit in a rotating coordinate system;

– *observer No. 3* – on the basis of equation for the case when the real axis of the rotating coordinate system is oriented to the rotor flux linkage vector.

VCS research using indirect methods for determination of motor rotation speed was carried out for observers of two types [9, 10]:

– *observer No. 1* - is based on the calculation of supply voltage frequency in a fixed coordinate system and calculation of rotor EMF in the rotating coordinate system with orientation to stator flux linkage vector.

– *observer No 2* - is based on the calculation of supply voltage frequency and rotor EMF frequency according to the projections of voltage and current space vectors on the axis connected with the stator fixed coordinate system.

Research of sensorless VCS power operating conditions was carried out for control system structures based on a combination of the described observers. Mathematic modeling of these systems was performed for IM 4A100L2У3: $P_n=5.5$ kW; $n_n=2820$ rev/min; $\cos\varphi=0.91$; $\eta=0.875$; $R_s=0.728$ Ohm; $R_r=0.437$ Ohm; $L_s=0.00209$ H; $L_r=0.004249$ H; $L_\mu=0.147$ H.

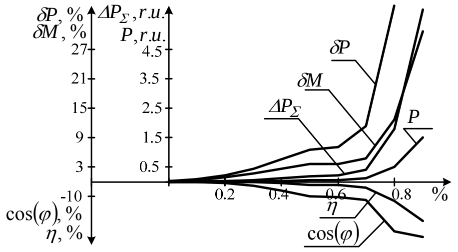
Analyzed sensorless VCS power parameter dependences on the IM stator windings asymmetry level are shown in Figs. 1-2. As a winding asymmetry level we imply the following ratio:

$$\varepsilon=\left(1-R_d/R_h\right)100\%,$$

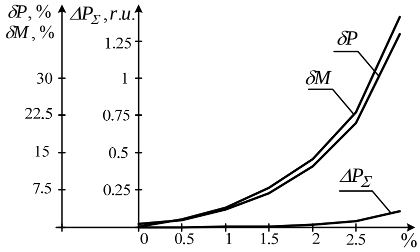
where R_d is the percentage of active resistance in damaged phase; R_h is the active resistance of a healthy phase.

Estimation of power operating conditions of the considered electric drives (ED) with VCS was made on the basis of such indices (table 1): $1.2\Delta P_{Cu1}$ – motor overload; $1.5P$ – converter overload; $5..10\Delta P_{Cu1}$ – quickly increasing thermal overloads; $\delta M<10\%$ – admissible level of electromagnetic moment variable component; $\delta M>20\%$ – inadmissible level of electromagnetic moment variable component. In figures 1-2 and table 1 we imply the following explanation: ΔP_{Cu1} – stator copper losses, r.u.; ΔP_Σ – total losses, r.u.; P – power consumption, r.u.; η – efficiency, %; $\cos(\varphi)$ – power coefficient, %; δM – variable component of electromagnetic moment, %; δP – variable component of instantaneous power, %. Mentioned criteria are reduced to counterparts in nominal symmetrical operation mode of IM. Boundary values of IM windings asymmetry level, according to the presented indices, are shown in table 1. It also contains the asymmetry level at which sensorless VCS fails.

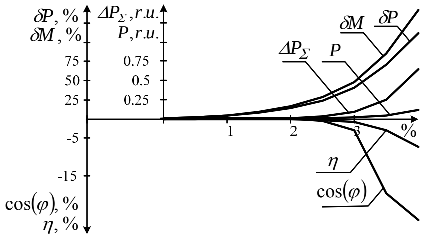
The mathematical research demonstrated that the use of VCS with indirect methods for determination of rotor flux linkage and motor rotation speed for IM with stator windings asymmetry results in considerable deterioration of power and dynamic characteristics or even in complete failure of ED system. The research results also showed that, in spite of considerable deterioration of power characteristics of the considered systems, direct indices of the quality of transition processes concerning IM rotation speed and electromagnetic moment remain practically unchanged.



a) observer No.1

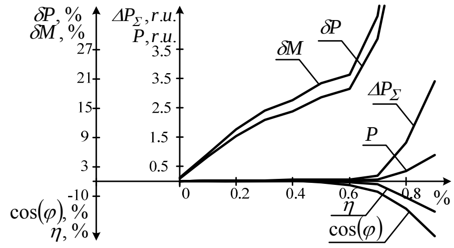


в) observer No.2

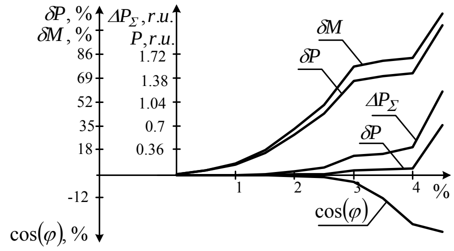


c) observer No.3

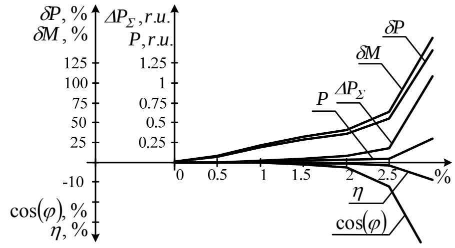
Fig. 1 – Deviations of power parameters of sensorless VCS with speed observer No. 1 and flux linkage observers



a) observer No.1



b) observer No.2



c) observer No.3

Fig. 2 - – Deviations of power parameters of sensorless VCS with speed observer No. 2 and flux linkage observers

Table 1 – Estimation of operating conditions of ED with sensorless VCS

VCS		Estimation criteria					
Speed observers	Flux linkage observers	$1.2\Delta P_{Cu1}$	$1.5P$	$5..10\Delta P_{Cu1}$	$\delta M<10\%$	$\delta M>20\%$	System failure
		Asymmetry level					
Observer No. 1	Observer No. 1	0.42	0.8	0.81	0.75	0.84	> 0.86
	Observer No.2	2.75	–	–	2.05	2.65	> 2.85
	Observer No. 3	2.95	–	–	1.55	2.15	> 3.8
Observer No. 2	Observer No. 1	0.65	0.83	0.845	0.185	0.5	> 0.95
	Observer No2.	2.55	4.35	–	1.12	1.55	> 4.5
	Observer No. 3	2.05	–	–	0.55	0.95	> 3.2

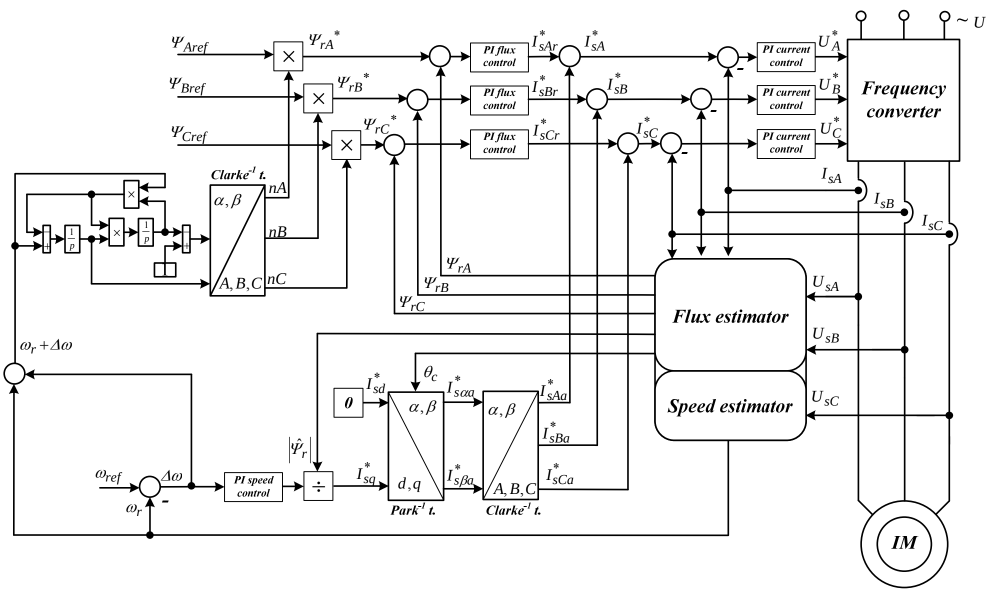


Fig.3 Block diagram of sensorless VCS with separate regulation of phases flux linkages

Thus, VCSs based on orthogonal models prevent one from achieving efficient operation of ED when IM windings are unsymmetrical. To provide the possibility of compensation for IM stator windings asymmetry a sensorless VCS with separate control of phases flux linkages was created (Fig. 3).

In the presented system the circuit of motor speed control is made in a synchronously rotating coordinate system *d, q*. Division of the initial signal of speed regulator by rotor flux linkage module makes it possible to get stator current active component (I_{sq}^*) assignment signal whose value is transformed into three-phase system ($I_{sAa}^*, I_{sBa}^*, I_{sCa}^*$) by means of coordinate converters. Flux linkage control circuit is made in a fixed coordinate system, and control is made separately for each phase and signals of flux linkage ($\Psi_{rA}^*, \Psi_{rB}^*, \Psi_{rC}^*$) assignment are presented in a three-phase coordinate system. Output signals of flux linkage regulators present signals of stator phases currents reactive components ($I_{sAr}^*, I_{sBr}^*, I_{sCr}^*$). The sum of current active and reactive components shows the signals of assignment of stator complete currents ($I_{sA}^*, I_{sB}^*, I_{sC}^*$). Signals of current control output present the signals of IM phase voltages (U_A^*, U_B^*, U_C^*) assignment.

As flux linkage regulation in the presented system of separate control is performed separately at each phase of the motor, it is proposed to use an observer in a three-phase coordinate system ($\Psi_{rA}, \Psi_{rB}, \Psi_{rC}$) to calculate rotor flux linkage.

When separate vector control system with asymmetric IM operates, due to formation of voltage at the stator in the function of flux, speed and current of the motor, this voltage becomes considerably asymmetric, which increases currents asymmetry (Fig. 4).Motor flux linkage remains symmetric in this case.

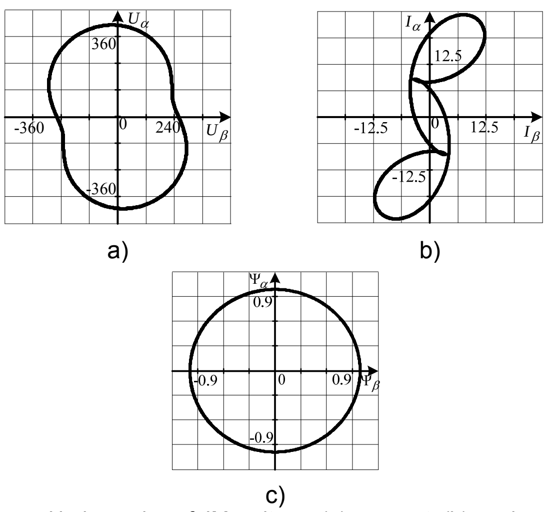


Fig. 4 Hodographs of IM voltage (a), current (b) and rotor flux linkage (c) in the system of separate vector control with asymmetric stator windings (windings asymmetry coefficient is 10%) without windings asymmetry compensation

Separate control of power transfer reactive channel allows changing reactive (magnetizing) currents components in IM stator separate phases. When flux linkage assignment signal is changed in one phase of control system, current magnetizing component and, consequently, voltage of the corresponding motor phase change. An asymmetric system of supply voltages is formed. Accordingly, it influences the processes of power transformation in the IM itself.

The performed research of separate regulation system demonstrated that IM stator windings asymmetry influence on power and dynamic characteristics of ED systems with VCS can be compensated for by correction of flux linkage assignment signal in the motor asymmetric phase.

Motor asymmetric flux linkage is formed under the condition of IM asymmetry compensation due to the change of asymmetric phase flux linkage (Fig. 5). Compensation of the moment variable component and, in its turn, of consumed power, occurs due to formation of asymmetric flux linkage at asymmetric currents.

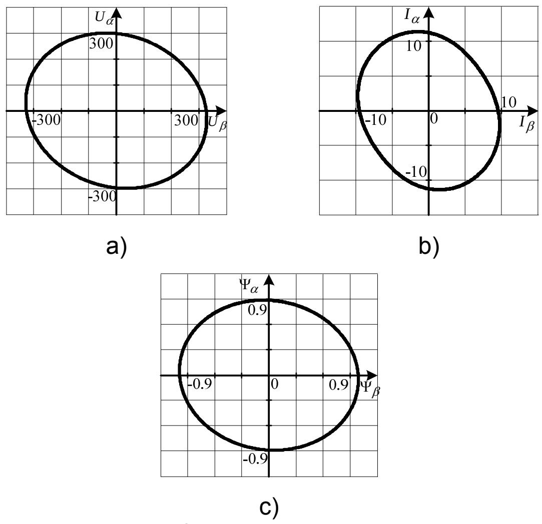


Fig. 5 Hodographs of IM voltage (a), current (b) and rotor flux linkage (c) in the system of separate vector control with asymmetric stator windings (windings asymmetry coefficient is 10%) with windings asymmetry compensation by decrease of asymmetric phase flux linkage by 10%

Graphs of speed and moment transition processes in IM with asymmetry of one winding of the stator phase and subsequent compensation by decrease of flux linkage of the corresponding phase are shown in Fig. 6.

It should be also pointed out that, compared with orthogonal control systems, analyzed above, the presented control system does not fail even at considerable levels of IM windings asymmetry.

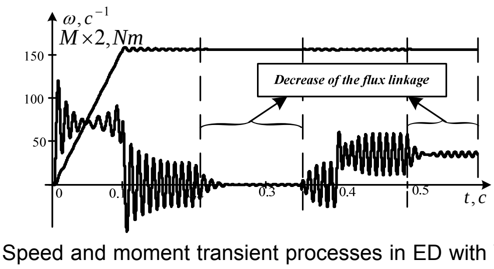
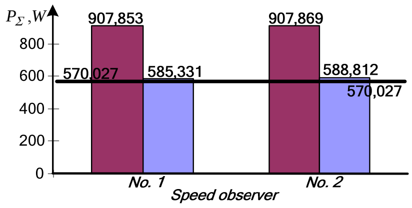
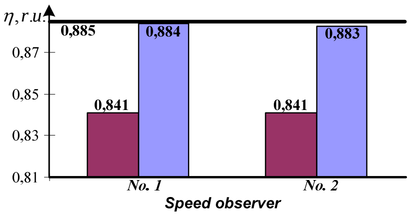


Fig. 6 Speed and moment transient processes in ED with VCS and IM stator winding asymmetry with and without compensation

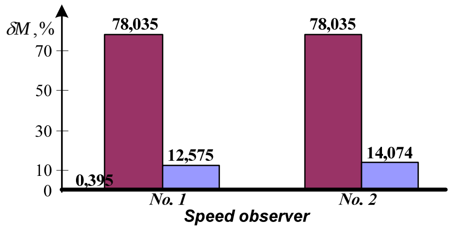
Research results [11] showed that, when motor asymmetric phase flux linkage assignment signal decreases proportionally to the value of active resistances asymmetry in phases, power characteristics of ED system with VCS approach the values of corresponding criteria in systems with symmetric IM. So, Fig. 7 contains comparison of power characteristics of sensorless VCS with two considered speed observers at 5% asymmetry of motor windings and at decrease of flux linkage assignment signal in asymmetric phase by 5%.



a) overall loss, W



b) efficiency, r.u.



c) electromagnetic moment variable component, %

Fig.7 Comparison of power characteristics of sensorless ED with VCS:

– with symmetric IM;

– without compensation;

– with compensation.

Conclusions

A sensorless system of electric drive vector control by means of dividing the channels of flux linkage and current active component control separately for each phase of induction motor has been improved. Unlike the conventional control systems, it provides the possibility to carry out the adjustment of phases flux linkage regulators in accordance with electromagnetic parameters of the equivalent circuit and to correct the operation conditions of electric drive with an unsymmetrical motor by changing the signals of assignment of stator phases flux linkage.

A method for correction of electric drive operating conditions has been proposed. This method makes it possible to improve power indices at vector control in the presence of induction motor stator winding asymmetry due to decrease of flux linkage in an asymmetric phase proportionally to asymmetry of active resistances in phases.

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