Formation of failure matrix and failure-free control algorithm for multi-sectioned Switched-reluctance drive

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Abstract. We review fault-tolerant switched reluctance drive with sectioning of the three-phase stator winding. In the operating process of an electric drive, there will be continuous monitoring of the operating state on the basis of a developed algorithm to analyse drive operability and formation tabulate a failure matrix. The paper introduces a failure-free control algorithm for multi-section switch - reluctance motor with formation the assignment values of amplitude phase currents taking into account the failure matrix. We show that in an emergency such single failure or multiple failure in switched-reluctance drive it is possible to provide reduction of torque fall and pro-gressively stock depletion with providing fault-tolerance of drive system. A method of residual life evaluation is proposed on the basis of calculating the coefficient of operability of the electric drive system that gives possibility to control the endurance of electric drive in real time from operational to completely unusable.

1. Introduction

In electric drives of industrial mechanisms of dangerous manufacturing is necessary to use failure-free control of electric drives with ensuring of fault tolerance. As known, the property of fault tolerance can be only in systems with redundancy, and this property ensured by partitioning the stator windings. The one way of ensuring failure-free control in switched-reluctance electric drive (SRD) in emergency situations like failure one or more phases of electric motors is both using multi-sectioned switched-reluctance motor and formation special algorithms of control. In this case the redundancy is formed by the complex using of both structural redundancy in multi-sectioned electric motor and functional backup, that is based on the possibility of work on remaining operational phases of electric motor after some failures. Required marginal current ensured by marginal load capacity that is giving possibility to work under nominal load when each sections work on the half of their nominal capacity [1].

2. Formation of failure matrix and failure-free control algorithm

The decision of issue ensuring failure-free control involve the real-time monitoring of technical drive status with creating appropriate failure bits in failure matrix in case of open-phase mode of operating with further full or partly operation recovery with using the special algorithm of failure-free control.

Required information and computing margin for realization of technical drive status monitoring and further operation recovery ensured by designed-in information reserve. The multi-sectioned electric motor created on the base of independent m-phase stator windings established on the one common shaft of electric motor. Structure scheme of two-sectioned switched-reluctance drive (m=2) shown on the figure 1.

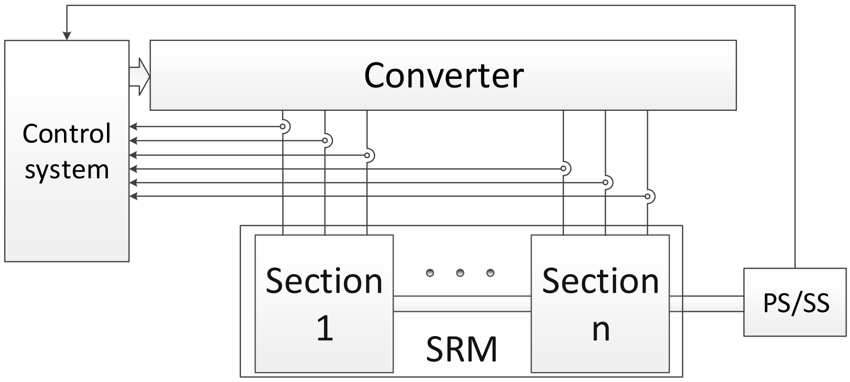

Figure 1. Structure scheme of two-sectioned SRD.

This two-sectioned switched-reluctance drive consist of control system, converter, two-sectioned SRM, position and speed sensor (PS/SS), current sensors each one on the each phase. Operation of this electric drive carry-out on account of the position and speed sensors signals which entered in the control system. In control system, on the base of appropriate current sensors signals of each phases are formed real-time assignment current values for converter. The converter performs switching transistors thereby ensuring feeding phases of each electric motor sections alternately [1, 2].

For ensuring fault-tolerance properties of electric drive, it is necessary to diagnose system in time based on the analysis of the phase currents. For functionality of failure-free algorithm are requires that each m-phase winding of two-sectioned SRM been alternately supplied unipolar current pulse. Separately for each section of m-phase two-sectioned switched-reluctance drive based on the signals from current sensors are formed failure bits: $\overline{a}_{1i}$, $\overline{a}_{2i}$, i=(X_1=A), (X_2=B), (X_3=C),…,(X_m), by analysis of the instantaneous amplitude values of phase currents in the motor sections, where X – phase index. For first section if $|I_{1in\ i}-I_{1i}|\geq\delta$, then system identifies the failure in the i-phase of first section and based on this analysis formed failure bit that is taking on the value either boolean zero or one: a_{1i}=1, $\overline{a}_{1i}$ =0. This giving possibility to formation the failure matrix of electric drive. For the second section similarly if $|I_{2in\ i}-I_{2i}|\geq\delta$, then system identifies the failure in the i-phase of second section: a_{2i}= 1, $\overline{a}_{2i}$ = 0. Where: $I_{1in\ i}$ - given values of instantaneous amplitudes of the phase currents formed for the i-phase of the first section; $I_{2in\ i}$ - given values of instantaneous amplitudes of the phase currents formed for the i-phase of the second section; δ – admissible error of current controller; I_{1i} – current feedback value from current sensor of i-phase of first section; I_{2i} - current feedback value from current sensor of i-phase of second section [1]. Based on failure bits is formed failure matrix of electric drive.

Failure matrix and the matrix of phase currents of two-sectioned switched-reluctance motor in normal operating mode has the form:

$$\alpha_{ni}=\begin{bmatrix} a & 0 & 0\\ 0 & b & 0\\ 0 & 0 & c\\ d & 0 & 0\\ 0 & e & 0\\ 0 & 0 & f\end{bmatrix}=\begin{bmatrix} 1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\\ 1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{bmatrix};\quad I_{ni}=\begin{vmatrix} I_{1A}\cdot\alpha & 0 & 0\\ 0 & I_{1B}\cdot\beta & 0\\ 0 & 0 & I_{1C}\cdot c\\ I_{2A}\cdot d & 0 & 0\\ 0 & I_{2B}\cdot e & 0\\ 0 & 0 & I_{2C}\cdot f\end{vmatrix};$$

Where α_{ni} – matrix of failure bits; *a,b,c* – failure bits for phases of first sections of SRM, *d,e,f* - failure bits for phases of second sections of SRM. I_{ni} - i-phase current of n-section of SRD.
Based on the design features of the SRD and considering that taking into account the assumptions take torque on the motor shaft equal to the electromagnetic torque.

$$M_{ni}=\frac{\Delta M_{ni}}{\Delta\theta_r}=\frac{\partial L_{ni}(i_{ni},\theta_r)}{\partial\theta_r}\cdot\frac{{i_{ni}}^2}{2} \qquad (1)$$

Where: M_{ni} –torque formed by i-phase of n-section of SRD.

θ_r - rotation angle of the motor shaft.

L_{ni} - inductance i-phase of n-section of SRD. [3]

Then the matrix of torques formed by phases of the motor in two-sectioned switched-reluctance drive in normal operating mode has the form:

$$M_{ni} = \begin{bmatrix} M_{1A}(i_{1A}\cdot\alpha,\theta_r) & 0 & 0 \\ 0 & M_{1B}(i_{1B}\cdot\beta,\theta_r) & 0 \\ 0 & 0 & M_{1C}(i_{1C}\cdot c,\theta_r) \\ M_{2A}(i_{2A}\cdot d,\theta_r) & 0 & 0 \\ 0 & M_{2B}(i_{2B}\cdot e,\theta_r) & 0 \\ 0 & 0 & M_{2C}(i_{2C}\cdot f,\theta_r) \end{bmatrix};$$

The SRM torque is represents the sum of torques formed by phases of the motor, considering that the phases are independent and are not associated electric and magnetic interactions [3].

Therefore:

$$M_{SRM} = \sum_{j=1}^{m} M_{nj}\left(i_{nj},\theta_r\right) \qquad (2)$$

For two-sectioned SRD in normal operating mode the torque of motor will be determined by the following expression:

$$M_{\partial в} = M_{nX_1} + M_{nX_2} + \ldots + M_{nX_m} =$$
$$M_{1A}(i_{1A}\cdot\alpha,\theta_r) + M_{1B}(i_{1B}\cdot\beta,\theta_r) + M_{1C}(i_{1C}\cdot c,\theta_r) + M_{2A}(i_{2A}\cdot d,\theta_r) + M_{2B}(i_{2B}\cdot e,\theta_r) + M_{2C}(i_{2C}\cdot f,\theta_r)$$

Consider the example when loss of phase A in first section of SRM. Timing chart of formation failure bit based on analysis of amplitude values of phase current in phase A first section of SRM shown on the figure 2. For this used the simulation model of SRD that discussed in detail in [4].

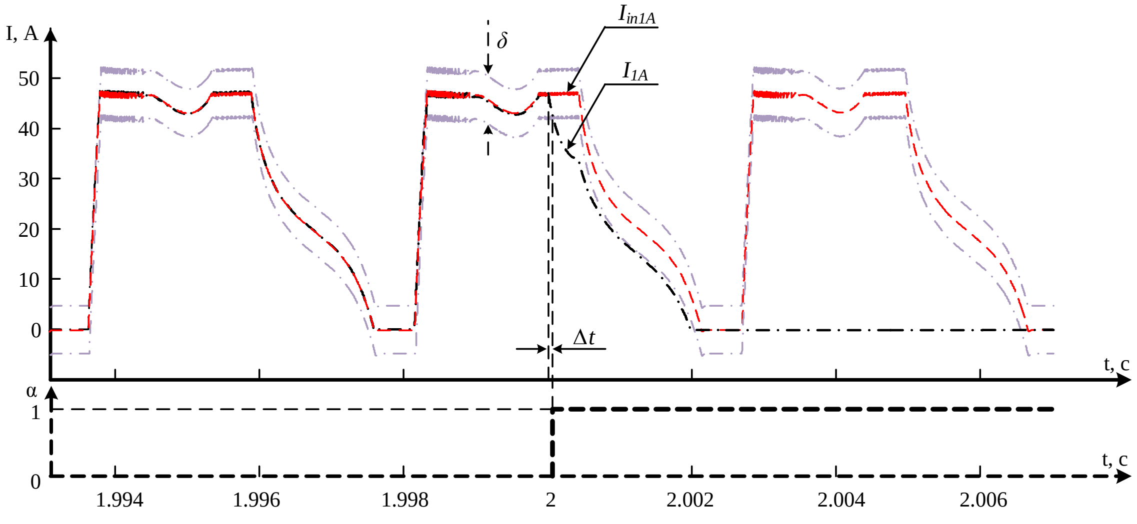

Figure 2. Timing chart of formation failure bit based on analysis of amplitude values of phase current in phase A first section of SRM. I – current, A; α – boolean signal characterizing the operation of phase (failure bit).

Where: δ – admissible error of current controller (10% zone of deviations), I_{in1A} - given value of instantaneous amplitude of the phase current formed for the A-phase of the first section, I_{1A} - current feedback value from current sensor of A-phase of first section, α - boolean signal characterizing the operation of phase (failure bit), Δt - the time interval from the start tripping motor phase to the end of the analysis the phase current and formation the failure bit. In this case, the failure matrix, matrix of phase currents matrix of torques formed by phases of the motor in two-sectioned switched-reluctance drive with loss of phase A in the first section has the form:

$$\alpha_{ni}=\begin{bmatrix} a & 0 & 0\\ 0 & b & 0\\ 0 & 0 & c\\ d & 0 & 0\\ 0 & e & 0\\ 0 & 0 & f\end{bmatrix}=\begin{bmatrix} 0 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\\ 1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{bmatrix};\ I_{ni}=\begin{bmatrix} 0 & 0 & 0\\ 0 & I_{1B}\cdot\beta & 0\\ 0 & 0 & I_{1C}\cdot c\\ I_{2A}\cdot d & 0 & 0\\ 0 & I_{2B}\cdot e & 0\\ 0 & 0 & I_{2C}\cdot f\end{bmatrix};\ M_{ni}=\begin{bmatrix} 0 & 0 & 0\\ 0 & M_{1B}\left(i_{1B}\cdot\beta,\theta_r\right) & 0\\ 0 & 0 & M_{1C}\left(i_{1C}\cdot c,\theta_r\right)\\ M_{2A}\left(i_{2A}\cdot d,\theta_r\right) & 0 & 0\\ 0 & M_{2B}\left(i_{2B}\cdot e,\theta_r\right) & 0\\ 0 & 0 & M_{2C}\left(i_{2C}\cdot f,\theta_r\right)\end{bmatrix};$$

Motor torque with loss of phase A in the first section has the form:

$$M_{SRM}=M_{nX_1}+M_{nX_2}+...+M_{nX_m}=$$
$$0+M_{1B}\left(i_{1B}\cdot\beta,\theta_r\right)+M_{1C}\left(i_{1C}\cdot c,\theta_r\right)+M_{2A}\left(i_{2A}\cdot d,\theta_r\right)+M_{2B}\left(i_{2B}\cdot e,\theta_r\right)+M_{2C}\left(i_{2C}\cdot f,\theta_r\right)$$

With losses of other phases and sections the failure matrix will changes according to the current state of SRD. Two-sectioned switched-reluctance drive has 64 operating and emergency states. Therefore, the control system of electric drive already contains in a controller memory all operating and emergency states of SRD, that giving possibility during the diagnostic of electric drive system determine the current number of state from table and start the failure-free algorithm for this state of SRD system. Moreover, it helps to assess the current level of SRD redundancy and coefficient of operability of the electric drive system. Principle of operation of failure-free algorithm based on formation of value assignment of amplitude currents values of sections in accordance with the data obtained after monitoring of SRD system.

The two-sectioned SRD failure-free control algorithm has the form:

$$\begin{aligned}
I_{1A}&=I_{\omega}\cdot a\cdot(1+d)\cdot\frac{2}{4^{d}}\cdot\left[1+sign(\varphi(\theta_e,I)-\varphi(t))\right];\\
I_{1B}&=I_{\omega}\cdot b\cdot(1+e)\cdot\frac{2}{4^{e}}\cdot\left[1+sign(\varphi(\theta_e,I)-\varphi(t))\right];\\
I_{1c}&=I_{\omega}\cdot c\cdot(1+f)\cdot\frac{2}{4^{f}}\cdot\left[1+sign(\varphi(\theta_e,I)-\varphi(t))\right];\\
I_{2A}&=I_{\omega}\cdot d\cdot(1+a)\cdot\frac{2}{4^{a}}\cdot\left[1+sign(\varphi(\theta_e,I)-\varphi(t))\right];\\
I_{2B}&=I_{\omega}\cdot e\cdot(1+b)\cdot\frac{2}{4^{b}}\cdot\left[1+sign(\varphi(\theta_e,I)-\varphi(t))\right];\\
I_{2C}&=I_{\omega}\cdot f\cdot(1+c)\cdot\frac{2}{4^{c}}\cdot\left[1+sign(\varphi(\theta_e,I)-\varphi(t))\right],
\end{aligned}\qquad(3)$$

Where: I_{ni} – amplitude values of formed phase currents; $\theta_e=N_r\theta_r$ - electrical angle of rotor, rad; N_r - the number of rotor poles, θ_r - mechanical angle of rotation, $\phi(\theta_e,I)$ - assignment angle value, $\phi(t)$ - the instantaneous value of angle from the position sensor.

In the normal operation mode, consider the example of the algorithm operation (3) an example on the phase A:

$$I_{1A} = I_{\omega} \cdot 1 \cdot (1+1) \cdot \frac{2}{4^1} \cdot \left[1 + sign(\varphi(\theta_e, I) - \varphi(t))\right] = I_{\omega} \cdot \left[1 + sign(\varphi(\theta_e, I) - \varphi(t))\right];$$

$$I_{2A} = I_{\omega} \cdot 1 \cdot (1+1) \cdot \frac{2}{4^1} \cdot \left[1 + sign(\varphi(\theta_e, I) - \varphi(t))\right] = I_{\omega} \cdot \left[1 + sign(\varphi(\theta_e, I) - \varphi(t))\right];$$

In emergency mode in SRD based on the diagnostic of system are formed zero boolean failure bits for appropriate phase in sections of electric drive. As example consider situation when loses phase A in first section. Then a_{1A}=0, this phase A is blocked and further value assignment of amplitude current for this phase is not formed, simultaneously for same named phase of second section further value assignment of amplitude current is formed doubled. Thus based on (1 and 2) the resulting motor torque and motor speed maintained at the same level. It is possible on condition that multi-sectioned motor has margin in load capacity under nominal load.

When the phase A loses in firs section of SRM, value assignment of amplitude current for this phase according to the failure-free algorithm (3) take the form:

$$I_{1A} = I_{\omega} \cdot 0 \cdot (1+1) \cdot \frac{2}{4^1} \cdot \left[1 + sign(\varphi(\theta_e, I) - \varphi(t))\right] = 0;$$

$$I_{2A} = I_{\omega} \cdot 1 \cdot (1+0) \cdot \frac{2}{4^0} \cdot \left[1 + sign(\varphi(\theta_e, I) - \varphi(t))\right] = 2 \cdot I_{\omega} \cdot \left[1 + sign(\varphi(\theta_e, I) - \varphi(t))\right];$$

Based on the proposed failure-free algorithm is provided control with single and multiple failures in SRD without loses in torque and speed. And is possible to calculate the coefficient of operability of the electric drive system, that gives possibility to assess the residual service life of SRD up to full incapacitation. From equation (2) implies that the output motor torque will vary directly with the number remaining operation phases. For normal operating state: $M_{SRM} = M_{\mathrm{SRM.nominal}}$, for state with losing one phase in one section $M_{SRM} = (1 - \frac{1}{6}) \cdot M_{SRM.nominal}$.

If we take redundancy (s) for number remain operation phases, and take index of operability (p) that is show in relative units the current level of (residual) torque m-phases motor relative to the initial nominal value, it is possible to calculate the coefficient of operability SRD system:

$$k = \frac{(s \cdot p)}{m}. \qquad (4)$$

Below examples of some emergency states of SRD in table 1.

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Table 1. Examples of some emergency states of switched-reluctance drive.

Failure	№	a	b	c	d	e	f	Redundancy, S	Index of operability, p		Coefficient of operability, k=(s*p)/m	
									With algorithm	Without algorithm	With algorithm	Without algorithm
Without failures (Normal operation state)	1	1	1	1	1	1	1	6	1	1	1	1
Loses of phase A in first section	2	0	1	1	1	1	1	5	1	0,833	0,833	0,694
Loses of phases A and B in first section	5	0	0	1	1	1	1	4	1	0,66	0,667	0,44
Full failure of first section	8	0	0	0	1	1	1	3	1	0,5	0,5	0,25
Full failure of first section and loses of phase A in second section	58	0	0	0	0	1	1	2	0,66	0,33	0,22	0,11
Full failure of first section and loses of phases A and B in second section	61	0	0	0	0	0	1	1	0,3	0,167	0,05	0,028
Full failure of SRD (electric drive is unworkable)	64	0	0	0	0	0	0	0	0	0	0	0

The coefficient of operability of switched-reluctance drive system gives possibility to assess the current state of electric drive and calculate residual service life of SRD up to full incapacitation after one or more failures.

3. Conclusions:

1. Developed the continuously monitoring algorithm of switched-reluctance drive on the base of analysis of the instantaneous values of the phase currents with formation the appropriate failure bits tabulated in failure matrix.
2. Developed the failure-free control algorithm for three-phase two-sectioned switched - reluctance drive that is giving the possibility to provide fault-tolerance property at the single failure or multiple failures in switched-reluctance drive with progressively stock depletion of electric drive.
3. A method of residual life evaluation is proposed on the base of calculating the coefficient of operability of the electric drive system that gives possibility to control the endurance of electric drive in real time from operational to completely unusable.

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