Design of Fault Tolerant Control Technique for SRM Drive

Peter Dubravka, Pavol Rafajdus, Pavol Makys,
Adrian Peniak, Valeria Hrabovcova
UNIVERSITY OF ZILINA
Univerzitna 1
Zilina, Slovakia
Tel.: +41 / 513 2270
E-Mail: peter.dubravka@fel.uniza.sk
URL: http://fel.uniza.sk/

Lorand Szabo, Mircea Ruba
TECHNICAL UNIVERSITY OF
CLUJ-NAPOCA
Memorandumului 28
Cluj-Napoca, Romania
Tel.: +40 / 264 401 827
E-Mail: Lorand.Szabo@emd.utcluj.ro
URL: http://ie.utcluj.ro/

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Keywords

«Switch reluctance motor», «Parameter analysis», «Fault operation», «Current hysteresis control» , «Direct instantaneous torque control»

Abstract

This paper deals with the improvement of the switched reluctance motor's fault tolerant control for traction drives. The main purpose is to use a control technique which is able to retain the required speed for various load torques at minimal torque ripple also during one opened phase operation. The paper focuses on the comparative study of the current hysteresis control and direct instantaneous torque control (DITC) techniques.

Introduction

SRM is one of the simplest electrical machines from construction point of view. The torque of SRM is produced by the tendency of rotor to move to a position where the inductance of the excited winding is maximized [1]. It is a double salient electrical machine which has only stator windings and its rotor is passive. Each phase comprises of two or four coils wound on opposite stator poles and connected in series or parallel [2], [3].

In many applications the drive reliability is a very important task from the fault operation point of view. There are several types of faults which could occur during the SRM operation: mechanical, magnetic or electrical faults. This paper is focused on electrical faults of SRM. These could be: short circuit in one coil of a phase (all, or a part of the turns), a whole coil bridged by a short circuit, the whole phase is short circuited, open circuit in one coil of a phase, a short circuit between two different phases, a short circuit from one winding to ground [4], [5].

In [6] electrical faults detection and special fault tolerant design of a 12/14 SRM are studied, where the winding scheme is a six phase duplex type (each phase is doubled). When a fault of one channel is occurred the second channel still contributes to the torque generation. Authors in [7], [8] devote their studies to the analysis of static and dynamic faults in SRM. In [9] a fault-tolerant SRM drive with adaptive fuzzy logic controller providing smooth torque with minimum ripple under normal and faulty conditions is described. Some fault conditions of the SRM are analyzed also in [10]. Phase currents are simulated under the absence of one phase and using the proposed fault tolerant control strategy.

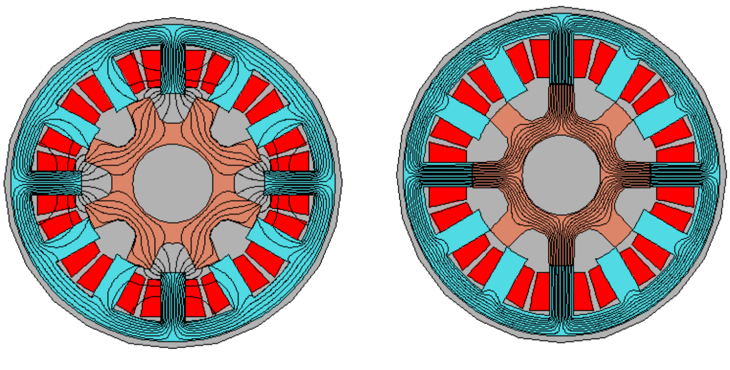
This paper is mainly devoted to a SRM used as drive in electric vehicle. During its faulty state (when one phase is opened) the most important task is to get the car even at a lower speed to the nearest service station where it can be repaired.

The investigated SRM is of 3-phase, 12/8 poles, 540 V, 3000 rpm, 3700 W. For this motor one opened phase is a very serious fault. During this state it is not possible to reach the rated speed and torque without a special design of the motor, which enables higher currents, which leads to higher prices. So, the only possibility during the faulty state is to decrease the speed to maintain the currents in their acceptable limits, and to try to minimize torque ripple.

The static characteristics of the SRM taken into study were investigated by means of FEM. These are used for dynamic simulation of hysteresis current control of the health and fault SRM. The results of simulation are validated by measurements. In the next step the simulation of DITC with modifications due the converter peak currents limitations was done and the results were compared with those obtained by means of hysteresis current control. This analysis is applied in low power SRM (3700 W) and in the future it will be used for high power SRM for electrical vehicles.

The SRM static characteristics analysis

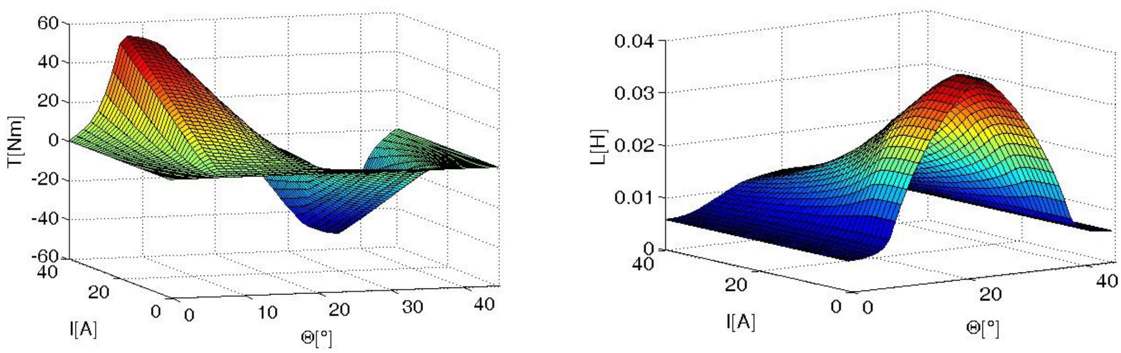
The static characteristics of the phase inductance and electromagnetic torque versus the phase current and rotor angular position were investigated by means of FEM. The SRM model with distribution of flux lines can be seen in the Fig. 1 for aligned and unaligned rotor positions. The SRM model was created in Opera2D software. The precision of the result depends on the mesh size and the accuracy of the input parameters.



a) b)

Fig. 1: Flux lines distribution a) unaligned rotor position, b) aligned rotor position

The calculation was carried out for each individual rotor position and current under static condition. The rotor position Θ was moved from unaligned Θ_u (0 mechanical degrees) to aligned position Θ_a (22.5 mechanical degrees) with a step of 1°. In each rotor position the current was changed within the range of 0 to 40 A. The values for generating mode (22.5÷45 mechanical degrees) are mirrored. The obtained static characteristics, required by the dynamic simulations, are given in Fig. 2.



a) b)

Fig. 2: Static parameters obtained from FEM model of SRM, a) torque versus rotor position and current, b) phase inductance versus rotor position and current

Dynamic model of SRM

Dynamic model of the SRM was created on the base of the next equations and by using a mathematical model, which enabled the calculation of the phase current, speed, voltage, rotor position and dynamic torque.

The electromagnetic torque of SRM is derived from:

$$T_e = \frac{\partial \int_0^i \Psi di}{\partial \Theta} \tag{1}$$

The mathematical model of SRM consists of the following equations, if:

leakage inductances between phases are neglected,
iron losses are neglected,
phase inductance depends on phase current and rotor position.

The voltage equation of one SRM phase is given as:

$$v = Ri + \frac{d\psi}{dt} \tag{2}$$

where R is phase resistance, i the phase current and ψ the flux linkage. This last depends on both the phase current and rotor position ($\psi = f\,(i,\ \Theta)$). Then:

$$\frac{d\psi}{dt} = \frac{\partial \psi}{\partial i}\frac{di}{dt} + \frac{\partial \psi}{\partial \Theta}\frac{d\Theta}{dt} \tag{3}$$

The phase current is calculated from combination of (2) and (3) as:

$$\frac{di}{dt} = \frac{v - \left(R + \frac{dL\,(i,\Theta)}{d\Theta}\omega \right) i}{L\,(i,\Theta)} \tag{4}$$

The real angular speed is calculated from equation:

$$\frac{d\omega}{dt} = \frac{1}{J}\left(\sum_{j=1}^{m} T_j(\Theta, i) - T_{load} \right) \tag{5}$$

where J is the moment of inertia and T_{load} the load torque.

The SRM is controlled on the base of rotor position Θ, therefore it is as following:

$$\Theta = \int \omega dt \tag{6}$$

Hysteresis current control of SRM with PI speed regulator

This type of control belongs among the simplest types of SRM control techniques, but it has some disadvantages related with torque ripple. The only way how to decrease ripple is to use convenient combination of turn on and off angles for different speed and load. Moreover the result may not have been as it is desired.

Dynamic simulation

In order to simulate SRM transients and also faulty state the block diagram of hysteresis current control with PI speed controller was created (Fig. 3).

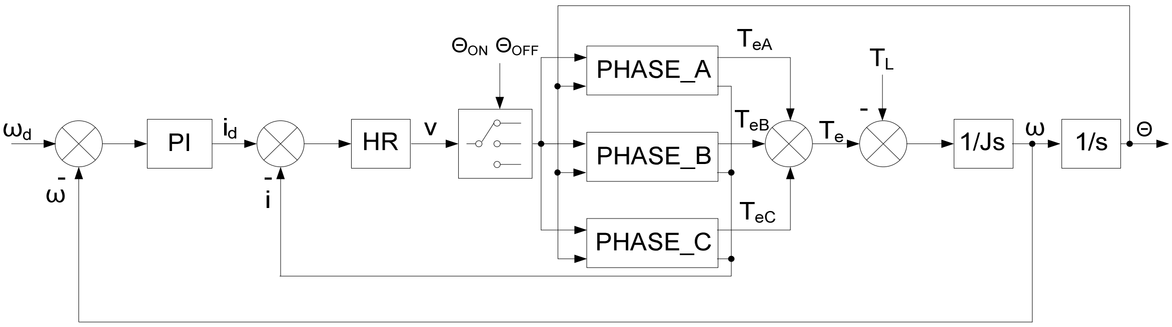


Fig. 3: The block diagram of hysteresis current control with PI speed controller.

The waveforms of current, electromagnetic torque and speed are shown in the Fig. 4. Demanded speed was set to 500 rpm and parameters from 2D FEM was used. The load torque 12 Nm was connected in time 0.2 s and phase *B* fallout (it means, phase B was opened) occurred in time 0.3s. During normal operation the minimal torque ripple was reached with turn on and off angles 0° and 21°. When the faulty state occurred the turn off angle of the phase A before opened phase *B* had to be changed to 19° because of producing negative torque, which was originally covered by phase *B*. For higher speeds the turn off angle have to be less than 19°. The constants of the speed PI regulator were set by trial and error method. As it can be seen the torque and speed ripple is very significant for this kind of control.

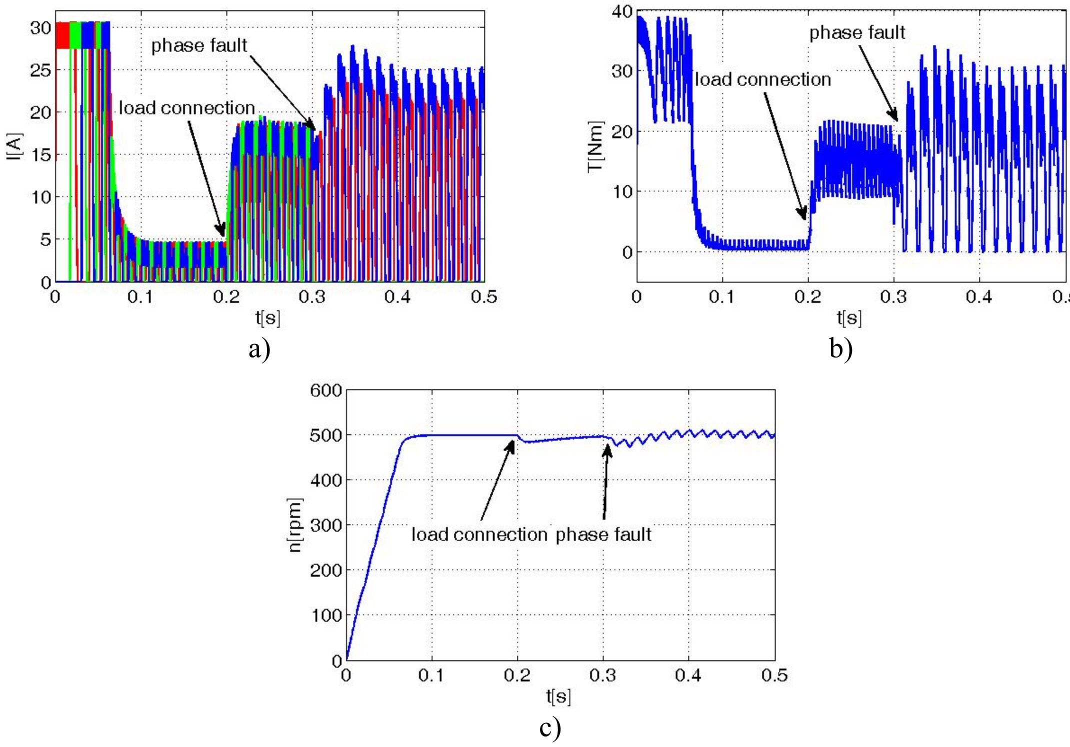


Fig. 4: SRM simulated waveforms for hysteresis current control: a) currents, b) torque, c) speed.

Experimental results

To verify the simulated dynamic results experimental tests were carried out. The SRM converter contains control board equipped with Digital Signal Controller from Freescale.

The measured waveforms of the currents, torque and speed of the healthy motor are depicted in the Fig. 5. Firstly, the startup of the motor to the speed 500 rpm was realized and at 5.4 s the load of 12 Nm was connected.

The same conditions were created for the case when one phase is opened. In the Fig. 6 is shown the reaction of the currents, torque and speed, for this case after the load was connected at 62.4 s.

To remove the noise, the speed was filtered by exponential first order filter.

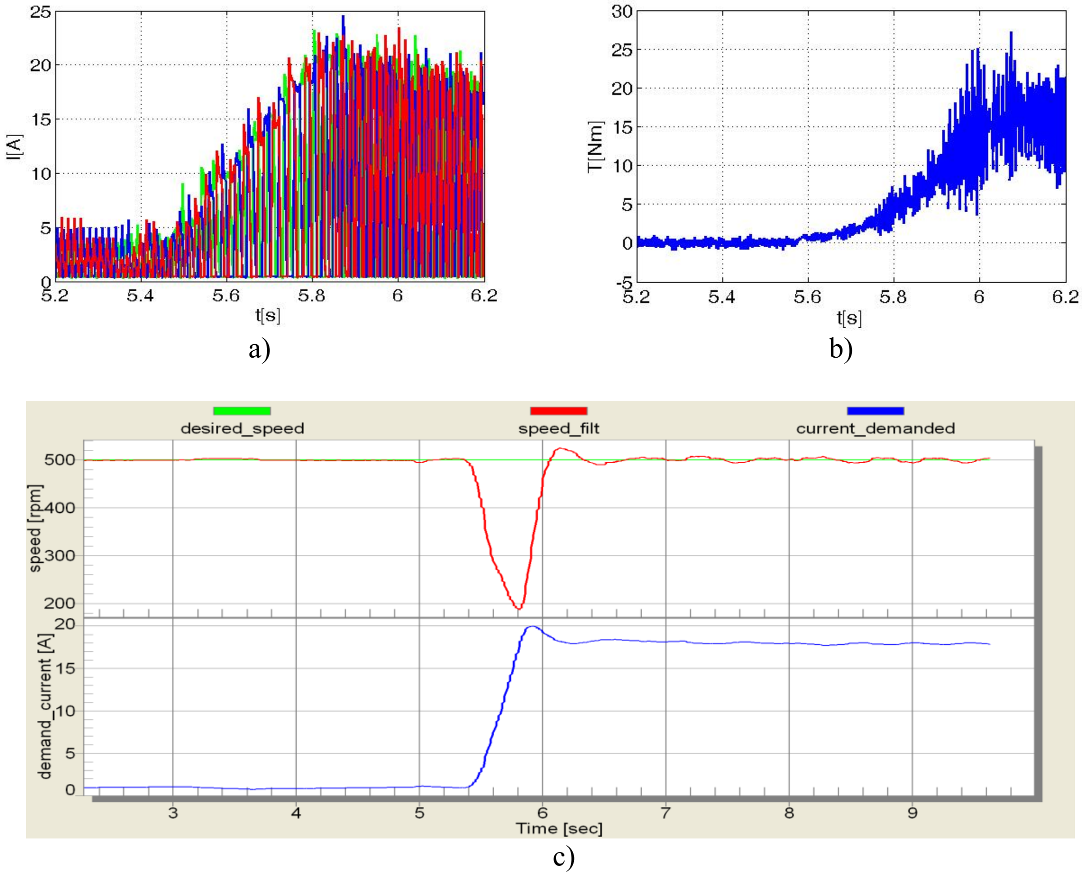


Fig. 5: Measured waveforms of the healthy SRM: a) currents, b) torque, c) speed.

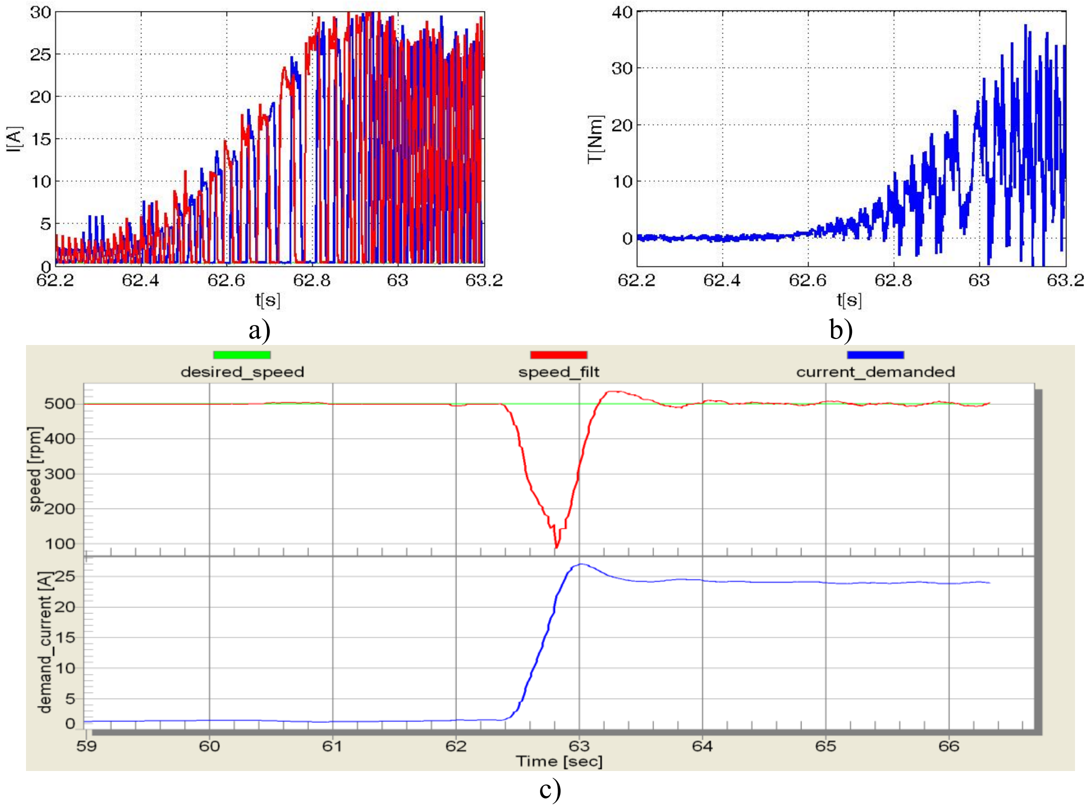


Fig. 6: Measured waveforms of the faulty SRM: a) currents, b) torque, c) speed.

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DITC of SRM with current restriction and PI speed regulator

The DITC is a closed loop instantaneous torque control technique employing a simple hysteresis controller equipped with two hysteresis bands (an interior and an exterior one) in order to maintain the torque at its reference value within the imposed tolerances.

For estimating the torque the static torque characteristics versus rotor position and current are required. The values of these characteristics are stored in a 2D look-up table, which was obtained via FEM. Knowing at each time step the actual current and the rotor position the torque of the SRM can be found by a simple looking in the table.

In single-phase conduction, hysteresis controller regulates torque within interior band. During phase commutation, torque of two adjacent phases is controlled indirectly by controlling the total torque within exterior band. The implemented switching strategy is shown in Table I., where *x* means that phase is not employed to create the torque. *S* can obtain values as follows: 1 ($+U_{dc}$), 0 (0 V) and -1 ($-U_{dc}$). More details are explained in [11], [12]. It is very important to remark that DITC needs higher switching frequencies.

Table I: Switching strategy of three adjacent phases for DITC

Ph n-1 Enable	Ph n Enable	Ph n+1 Enable	Ph n-1 S	Ph n S	Ph n+1 S
0	0	0	x	x	x
1	0	0	1|0	x	x
1	1	0	1|0|-1	1|0	x
0	1	0	-1|x	1|0	x
0	1	1	x	1|0|-1	1|0
0	0	1	x	-1|x	1|0

A disadvantage of DITC is that it can be effectively performed as long as the maximum instantaneous back EMF is equal or less than the dc-bus voltage [11]. The next one is that phase currents are not controlled and it can reach high values, mainly during faulty states when currents in healthy phases are increased to maintain the desired torque. In this case the restriction of current to the value of converter peak current (I_{max}=30 A) has to be done by creating the current control as follows: when the measured phase current reaches the value higher than 29.5 A, the control strategy is switched to hysteresis current control with hysteresis band ±0.5 A. After the decreasing of measured phase current under 29 A the control strategy is changed back to the classical DITC. This intervention can cause decreasing of the torque which can be compensated by accommodation of turn on and off angles for lower speed range. But as it was mentioned above when the faulty state occur the main task is to get the electric vehicle to the nearest service even if the speed is reduced. The block diagram of DITC with current restriction and PI speed regulator is given in the Fig. 7.

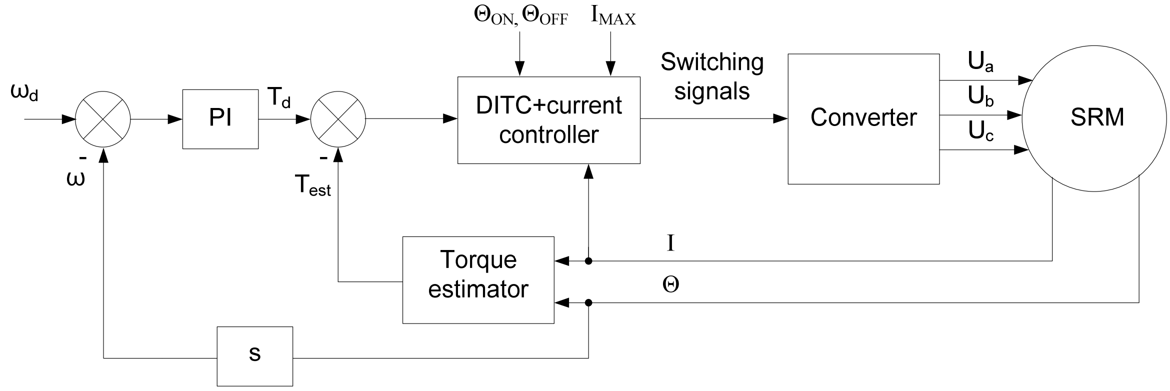

Fig. 7: The block diagram of DITC with current restriction and PI speed controller.

The simulation results of currents, torque and speed can be seen in the Fig. 8. The imposed speed was again 500 rpm. The value of inner and outer torque hysteresis band was set to 0.5 and 1 Nm. The load torque of 12 Nm was imposed at 0.15 s, and phase *B* fallout occurred at 0.3 s. Turn on and off angles were computed for normal and for the faulty operation. Calculation was carried out on the base of different angles combinations used in the model of SRM with DITC. Condition of minimal torque ripple and angle step of 0.1 mechanical degrees were applied.

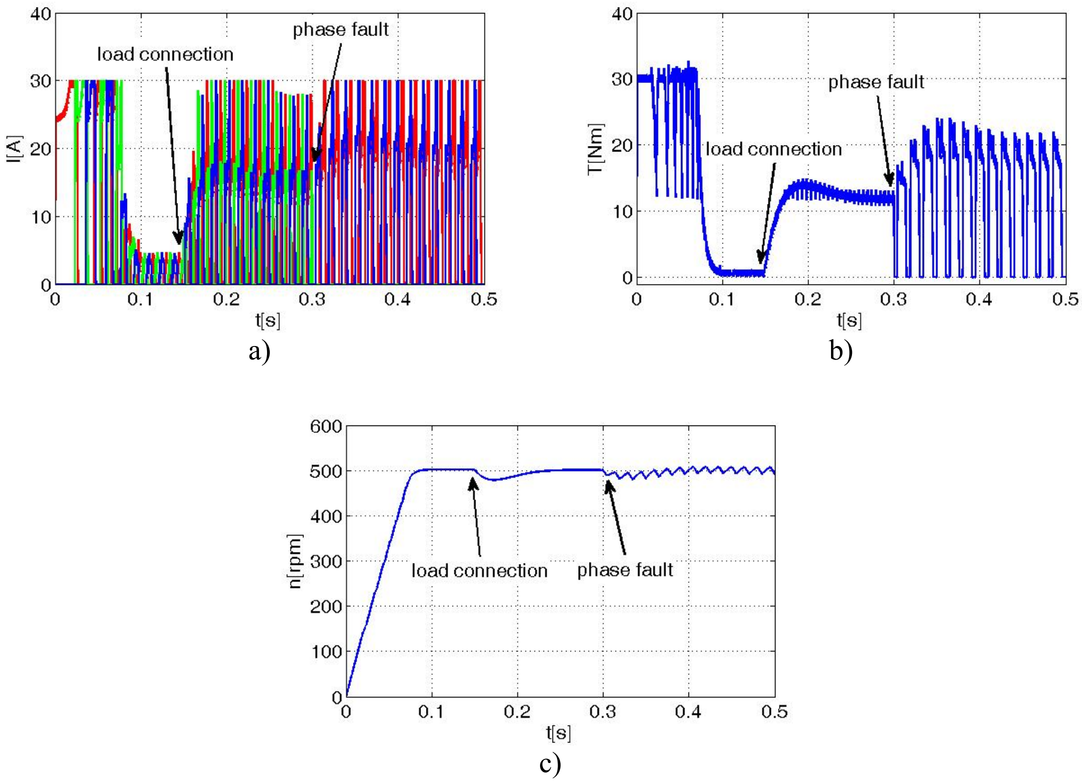

Fig. 8: SRM waveforms for DITC: a) currents, b) torque, c) speed.

Comparison of hysteresis current control and DITC with current limitation

The comparison of these two techniques was carried out on the base of torque ripple which is very important pointer for the drive of electric vehicle. The torque ripple in steady states is calculated according:

$$\Delta T = \frac{T_{MAX} - T_{MIN}}{T_{AV}} \tag{7}$$

where T_{MAX} is the maximum value of torque, T_{MIN} is the minimum value of torque and T_{AV} is the average value of torque calculated from:

$$T_{AV} = \frac{1}{T}\int_0^T T dt \tag{8}$$

The results are depicted in Fig. 9. As it can be seen for DITC the decrease of ripple is significant mainly during normal operation but also for the faulty state.

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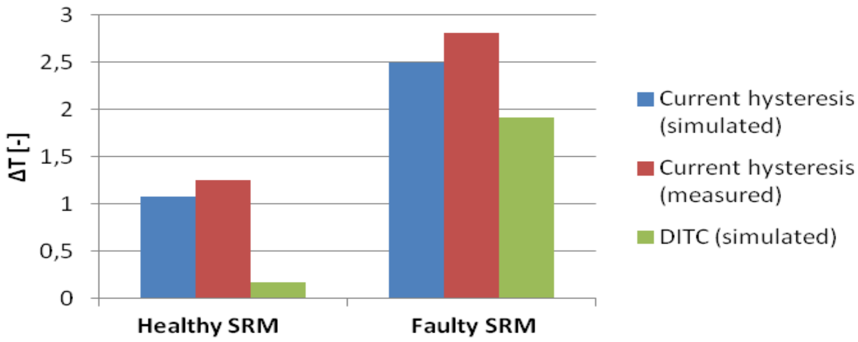

Fig. 9: Comparison of current hysteresis control and DITC on the base of torque ripple

Conclusion

In this paper two control techniques for the 3-phase SRM during normal and faulty operation (one opened phase) are presented. The first method is the current hysteresis control with PI speed regulator, which was simulated and validated by measurements. The next one is the DITC, also with PI speed regulator. Disadvantage of DITC is that currents are not controlled, hence they can damage motor or inverter, mainly during fault operation. Therefore, current limitation was proposed. Restriction of current mean decreasing of the torque in some regions but it can be compensated by accommodation of turn on and off angle for certain speed range which is acceptable for the SRM drive used in electric vehicle. The angles for the speed 500 rpm was computed for the healthy and faulty state. The simulated results of DITC are compared with current hysteresis control on the base of torque ripple.

The future work will be devoted to the computation of angles for wider speed range during normal and faulty operation. Results will be also verified by measurements.

References

[1] Miller, T. J. E.: "*Switched Reluctance Motors and their Cont*rol", Magna Physics, 1992.

[2] Miller, T. J. E.: "*Electronic Control of Switched Reluctance Machines*", Oxford (U.K.): Newnes, 2001.

[3] Pyrhonen, J., Jokinen, T., Hrabovcova, V.: "*Design of Rotating Electrical Machines*", John Wiley & Sons, 2008.

[4] Schinnerl, B., Gerling, D.: "*Analysis of Winding Failure of Switched Reluctance Motors*", Proc. of the IEEE Intern. Electric Machines and Drives Conference (IEMDC '2009), Miami, pp. 738-743.

[5] Terec, R., Bentia, I., Ruba, M., Szabo, L., Rafajdus, P: "*Effects of Winding Faults on the Switched Reluctance Machine's Working Performances*", 3rd IEEE International Symposium on Logistics and Industrial Informatics (LINDI '2011), Budapest, Hungary.

[6] Szabo, L., Ruba, M.: "*On Fault Tolerance Increase of Switched Reluctance Machines*", EUROCON 2009, pp. 18-23.

[7] Suying Zhou ; Rong Qi: *Performance analysis and simulation of switched reluctance motor control system in case of typical faults*, 2011 International Conference on Transportation, Mechanical, and Electrical Engineering (TMEE), pp. 911-914.

[8] Kacenka, V., Rafajdus, P., Makys, P., Vavrus, V., Szabo, L.: "*Static and Dynamic Fault Analysis of Switched Reluctance Motor*", 9th International Conference ELEKTRO 2012, Rajecke Teplice, Slovakia.

[9] Mir, S., Islam, M.S., Sebastian, T., Husain, I.: "*Fault-Tolerant Switched Reluctance Motor Drive Using Adaptive Fuzzy Logic Controller*", IEEE Transactions on Power Electronics, March 2004.

[10] Gameiro, N.S. ; Cardoso, A.J.M.: *Fault tolerant control strategy of SRM drives*, International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM 2008'), pp. 301-306.

[11] Inderka, Robert B; de Donker, R.W.A.A: *DITC-Direct Instantaneous Torque Control of Switched Reluctance Drives*, IEEE Transactions on Industry Applications, vol. 39, no. 4, July-August 2003, pp. 1046-1051.

[12] Szabo, L., Ruba, M., Fodorean, D., Rafajdus, P., Dubravka P.: *Direct Instantaneous Torque Controlled Modular Switched Reluctance Motor Designed for Automotive Applications,* 10th International Conference ELEKTRO 2014, Rajecke Teplice, Slovakia, 2014, pp. 239-244.