The Partial Average Power as a Fault Diagnostic Parameter Applied to SRM Drives

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Abstract- **A new fault diagnostic parameter, applied to switched reluctance motor drives, is presented. The proposed parameter is a partial average power based on the power converter supply current and the rotor mechanical position information. At high speed operating conditions phase current is not regulated and the machine closed-loop control only needs to observe one current, which is the power converter supply current, in order to avoid excessive current amplitudes. The adopted control strategy is clearly explained. Several simulation results are presented and discussed considering different operating conditions. The normal operation, a fault occurrence in a power switch and a sudden mechanical load decrease are analysed. The simulation results permit to validate the proposed partial average power as an appropriate parameter for the diagnosis of an open-circuit fault in a power switch.**

I. INTRODUCTION

One of the main features of the switched reluctance motor is its fault tolerance capability. The disconnection of a motor phase, due to a fault occurrence, does not affect other motor phases operation and the machine can keep running, if an appropriated power converter with independent motor phase control is used [1], until a repairing action is possible. This feature promotes the machine to be suited for aircraft applications. However, the interest on switched reluctance motors is relatively recent due to power converter and control devices demands. Nowadays, several electrical machines use a power converter, in order to increase efficiency, especially in variable speed applications, which permits to face SRM drives as a competitive solution.

The switched reluctance motor is of a very simple construction. Both stator and rotor exhibit salient poles and there is no windings or magnets in the rotor. The currents in the rotor are almost nonexistent and they are not responsible for the machine rotation. Thus, Joule heating in the rotor is very small and rotor cooling is not a concern. All these characteristics contribute to its robust feature, being well suited to operate in harsh industrial environments as on mining industry, for example. The salient poles configuration is responsible for magnetic independence between motor phases, since each stator pole lodge only one phase, and permits to control each phase independently. Mutual inductances are commonly neglected. However, the salient poles configuration is also responsible for torque ripple, especially during phase commutation. Torque ripple can be minimized by appropriate adaptations of the magnetic circuit design or by improved control strategies [2]. Some examples can be seen in [3-5]. Usually, the SRM control system is based on the instantaneous phase current or flux regulation in order to guarantee a proper dynamic operation. The supply current of the SRM power converter is, generally, not observed, but on sensor failure situations it can be of extreme importance. At high speed operating conditions the phase currents are not regulated and the control system can operate observing only one current which is the power converter supply current, in order to avoid over-current problems. The analysis of the power converter supply current is then important to develop appropriate fault tolerant control strategies regarding failures or errors on phase current measurements and also fault diagnostic techniques. This paper presents a new diagnostic parameter based on the partial average power using the power converter supply current and rotor mechanical position information.

II. SRM MODEL AND CONTROL STRATEGY

The switched reluctance motor presents a very simple operating principle, similar to the step machine operation. However, define a mathematical model that characterize its electromagnetic behavior is more complicated than it is for other AC or DC machines. This is due to its nonlinear electromagnetic characteristics, dependent on rotor position and magnetic saturation level. Several authors have developed mathematical formulas to describe flux linkage [6][7] or inductances [8] as a function of the respective phase current amplitude and rotor mechanical positions. Other authors use a simple look-up-table [9] to characterize SRM flux linkage behavior. In all cases, the necessary data are achieved by experimental measurements or finite elements analysis.

The SRM model adopted here is based on laboratory test results [10]. Several tests were conducted, preserving the normal operation of the SRM drive, for different load and

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speed levels. Those tests permitted to relate the flux linkage (ψ) with the rotor position and the phase current amplitude. The electromagnetic torque (T), for each phase, was subsequently calculated using the adopted definition of the flux linkage and based on numerical differentiation of the respective coenergy. Mutual inductance and magnetic core losses are neglected.

The SRM drive used was a four phase ($m = 4$) commercially available drive with 8 stator poles ($N_s = 8$) and 6 rotor poles ($N_r = 6$), 1.1 kW, 3500 rpm with a 24 DC voltage supply.

With the purpose of simulation time reduction, two look-up-tables were used to characterize the SRM electromagnetic and electromechanical behaviors: the $\psi(\theta,i)$ look-up-table, where θ represents the mechanical rotor position and i represents the phase current; and the instantaneous torque (T) look-up-table ($T(\theta,i)$).

In order to take advantage of the magnetic independences in the SRM, an asymmetric bridge converter is used (Fig. 1). Each phase can be separately controlled and easily removed in a faulty situation. The power converter presents, per phase, two controlled power switches which permits to apply three voltage levels to each phase winding.

Fig. 2 presents the block diagram of the proposed SRM drive system control. It is assumed that the SRM drive only operates at high speed. Unlike what happens at low speed, at high speed operating conditions the phase currents cannot be regulated due to a higher value of the back electromotive force as compared to the supply voltage. Thus, the phase current information is not a need and the acquisition of the power converter supply current (I_s) will be enough for over-current prevention. Control parameters, defined by the commutation scheduler, are the ignition angle (θ_i) and the commutation angle (θ_c). A positive voltage is applied to the winding phase between θ_i and θ_c. This is achieved by turning on the two associated power switches. After the commutation angle both power switches are turned off. The voltage controller is responsible for providing the appropriate switching signal to the various power switches using rotor mechanical position and switching angles information. During the time interval when a phase is conducting there is always an electrical connection between the winding phase and the supply. The contribution of the phase current for I_s magnitude is easily established.

At high speed operating conditions the phase current amplitude does not increase in all the rotor mechanical position range between θ_i and θ_c, but only till the respective stator pole starts overlapping with a rotor pole. Phase current maximum amplitude is then dependent on θ_i and rotor mechanical speed (ω) and impose the amount of the respective phase electromagnetic torque contribution. The commutation scheduler (Fig. 3) uses a PI controller to establish the ignition angle. If the reference speed (ω_{ref}) is higher than the rotor mechanical speed it means that each phase must produce a higher electromagnetic torque and θ_i must be advanced to permit higher phase current amplitudes. If ω_{ref} is lower than ω, the ignition angle is progressively delayed. The commutation angle is calculated from ignition angle and rotor mechanical speed information using a look-up-table, $\theta_c(\theta_i,\omega)$. The recorded values are previously obtained by the phase current simulation under constant rotor mechanical speed operating conditions. Several tests were conducted to fully define the commutation angle look-up-table, considering several ignition angles and rotor mechanical speed values arrangements. The main objective is to keep the motor phase conducting during the larger time interval that permits to avoid a relevant negative electromagnetic torque contribution.

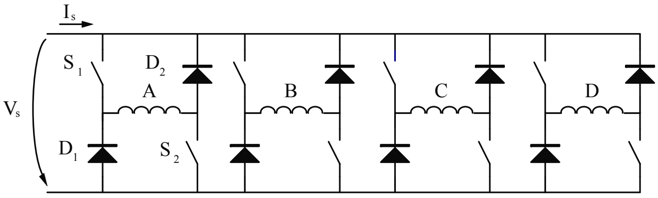

Fig. 1. Power converter for a four phase SRM drive.

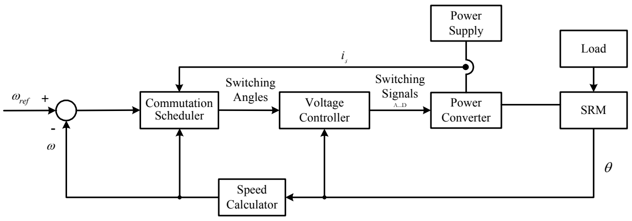

Fig. 2. Block diagram of the SRM drive system.

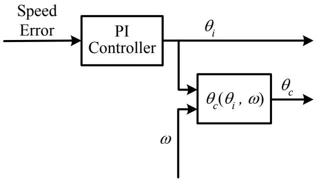

Fig. 3. Block diagram of the commutation scheduler.

III. THE PROPOSED PARTIAL AVERAGE POWER APPROACH

In a balanced SRM the several motor phases present identical electromagnetic and electromechanical characteristics and in steady state conditions phase currents exhibit similar waveforms. The phase displacement between two successive phase currents is dependent on the number of motor phases and the number of rotor poles, being 360º/(m*Nr). In a steady state operating condition, control actions are repeated in every 360º/m rotor mechanical position interval. This means that the phase current period is the time interval necessary to cover 360/m rotor mechanical degrees. However, due to the identical electromagnetic and electromechanical characteristics of the several phases, the power converter supply current exhibits a time period smaller than the phase current period, under normal operating conditions. If a failure affects a motor phase behavior, I_s is automatically affected and its period will be extended, being equal to the phase current period. Besides the normal or faulty operating conditions, the SRM average power can be easily calculated if I_s amplitude is observed, during a time interval that corresponds to 360º/m, being 60º for the adopted SRM. The average power (P_{avg}) is calculated by the integrative equation:

$$P_{avg} = \frac{1}{t_y - t_x} \int_{t_x}^{t_y} I_s(t) V_s dt \qquad (1)$$

where t_x is the time where the rotor mechanical position presents an arbitrary value of θ_x degree and t_y is the time where the rotor mechanical position is θ_x+60º. It is assumed that the supply voltage (V_s) presents a constant value.

Whenever operating conditions are changed, due to load variations or failure occurrence, for example, the average power will be modified. However, this parameter cannot detect power flow variations during the conducting time interval of the various motor phases, which can be indicative of a fault occurrence. For that purpose, a partial average power approach has been developed. Its integral time corresponds to 15º which is also the power converter supply current period when normal and steady state operating conditions are considered. Several different 15 degrees intervals are used to obtain power flow variations detailed information. In the present work the reference rotor mechanical position (0º) corresponds to phase A unaligned position which is also phase C aligned position. The partial average power is calculated using the generic equation:

$$P_{\theta_y avg} = \frac{1}{t_{\theta_y} - t_{\theta_y - 15^\circ}} \int_{t_{\theta_y - 15^\circ}}^{t_{\theta_y}} I_s(t).V_s dt \qquad (2)$$

The previous equation define the partial average power at time t_{θ_y} ($P_{\theta_y avg}$), where the rotor mechanical position is θ_y. The lower integral limit $t_{\theta_y - 15^\circ}$ corresponds to the instant where the rotor mechanical position is $\theta_y - 15^\circ$.

It is considered several different lower integral times, which correspond to 0º or to any other mechanical position that is a multiple of 3º. This means that only four different integrative equations are used at a time. Whenever an integral calculation is concluded its value is transmitted to the partial average power signal (P_{15avg}) as well as the respective time information. The partial average power is then a discrete signal and its sampling time is not constant but corresponds to 3º. In order to better understand the previous calculation a particular example is presented:

$$P_{24^\circ} = \frac{1}{t_{24^\circ} - t_{9^\circ}} \int_{t_{9^\circ}}^{t_{24^\circ}} I_s(t).V_s dt \qquad (3)$$

The partial average power when the rotor mechanical position is 24º ($P_{24º}$) is obtained by the integration of the instantaneous power ($I_s(t)V_s$) during the previous time interval that corresponds to 15º. At the upper integral time, $t_{24º}$, the rotor mechanical position is 24º and at the lower integral time, $t_{9º}$, the rotor mechanical position is 9º.

IV. SIMULATION RESULTS

SRM dynamic simulations, presented in the next sections, consider a 5 Nm load and a 1500 rpm reference speed.

A. Normal Operating Conditions

Fig. 4 and Fig. 5 present simulated phase currents and power converter supply current, respectively. All phase currents present similar waveforms due to the identical electromagnetic behavior of all motor phases. It is clear that power converter supply current period is four times smaller than the phase current period. I_s presents a maximum amplitude higher than the phase current amplitude due to the simultaneous magnetization of two motor phases. The demagnetization of the various phases promote I_s negative amplitudes. Fig. 6 exhibits the partial average power. It can be seen that under normal and steady state operating conditions the partial average power presents a constant value. This amplitude equals the SRM average power amplitude, because power flow is repeated in every 15º. Fig. 7 presents a polar chart of the partial average power. In order to relate each axis with an aligned position and an unaligned position the angle adopted, for the polar chart representation, is six times the rotor mechanical position. Thus, the positive real axes corresponds to phase A unaligned position and the positive imaginary axes corresponds to phase B unaligned position. The relation between the polar chart angle and the

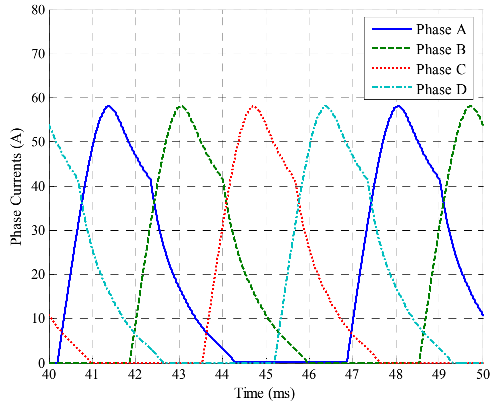

Fig. 4. Simulated phase currents under normal operating conditions.

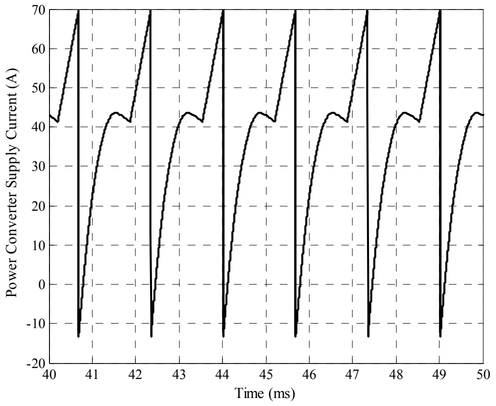

Fig. 5. Simulated power converter supply current under normal operating conditions.

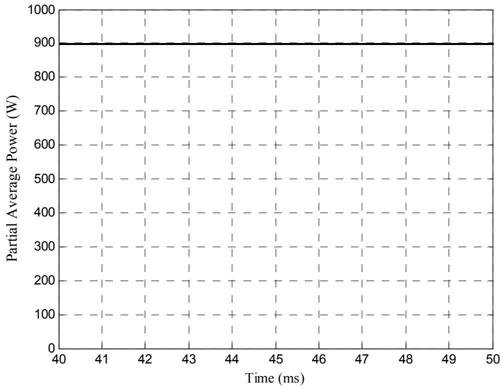

Fig. 6. Simulated partial average power results under normal operating conditions.

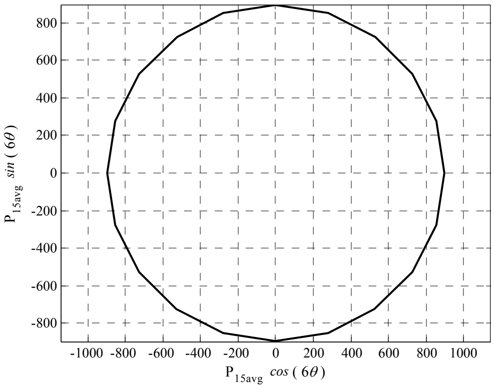

Fig. 7. Simulated partial average power polar chart results under normal operating conditions.

rotor mechanical position permits also to represent in the 360º of the polar chart a complete SRM cycle. The polar chart amplitude is the partial average power amplitude. At normal and steady state operating conditions the polar chart is a perfect circle which radius is the partial average amplitude.

B. Open-Circuit Fault in a Converter Power Switch

An open-circuit fault occurrence, in one of the converter power switches of phase A, was simulated at 55 ms. At high speed operating conditions, using the adopted power converter, an open-circuit fault in any of the two power switches, associated to the same motor phase, would cause the same disturbance and electric and mechanical parameters would present the same behavior. When the open-circuit fault occurs, phase A current (Fig. 8) presents a more pronounced decrease than at normal operating conditions and considering equal rotor mechanical position. The open-circuit fault occurs when phase current amplitude has already been decreased. If the fault occurs in an earlier instant, when phase current exhibits increasing amplitudes, the open-circuit fault would invert the phase current amplitude slope. After the fault occurrence and after the following fully phase A demagnetization, phase A magnetization is no more possible, unless a power converter reconfiguration takes place, and phase A current is permanently zero as well as its electromagnetic torque contribution. When the fault occurs, phase A contributes with a smaller electromagnetic torque due to a smaller current amplitude and rotor mechanical speed decrease immediately. The control loop reacts advancing the ignition angle in order to increase phase current amplitude and permits that healthy phases compensate the absence of phase A. The reference speed (Fig. 9) is reestablished but the speed ripple is clearly higher, as compared to normal operating conditions. The motor speed decreases during every time interval where phase A should be conducting and contributing with positive electromagnetic torque. The partial average power (Fig. 10) does not present an immediate decrease since it is a discrete function. However, the fault occurrence effect is quickly noticed. During any time interval where phase A should be magnetized the partial average power amplitude decreases because the energy flow from the supply source to the machine obviously decreases. This time interval corresponds to the angle interval between phase A ignition angle and phase A commutation angle which are, at the new steady state -3.5º and 17.5º respectively. This can be observed in Fig. 11. However, the decrease does not occur precisely at the aforementioned angle interval due to the discrete feature of the partial average power. After 17.5º, where phase A should start to be demagnetized and should returned the energy stored in its magnetic field to the source, the partial average

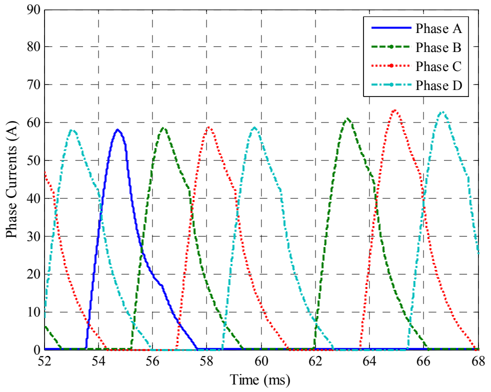

Fig. 8. Simulated phase currents under the occurrence of an open-circuit fault in a phase A power switch at 55ms.

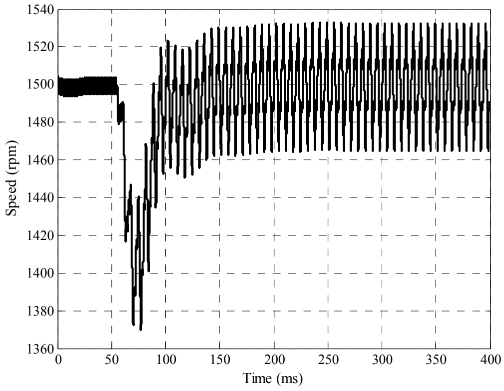

Fig. 9. Simulated rotor mechanical speed under the occurrence of an open-circuit fault in a phase A power switch at 55ms.

power increases. It can be concluded that the minimum partial average power amplitude occurs at the time where the rotor mechanical position is near the commutation angle. The absence of phase A causes negative partial average power amplitudes. This means that during some 15 rotor mechanical degree intervals the machine present a generative behavior. If the machine is used as a motor and all phases are conducting, only a severe delay of the ignition angle could produce, under normal operating conditions, a negative partial average power. Thus, if the ignition angle has been advanced, preserved or smoothly delayed and a negative partial average power amplitude is achieved it means that one motor phase is disconnected. The rotor mechanical positions where this occurs depends on which motor phase is affected by the fault occurrence. It was previously explained that the minimum partial average power is achieved at the commutation angle of the faulty motor phase, consequently to identify the faulty phase, four rotor mechanical position intervals are defined in each SRM control cycle (60º). Each one of this rotor mechanical position interval cover 15º and is defined around a phase commutation angle. The negative partial average power occurs inside the rotor mechanical position interval related to the respective faulty phase. Considering the commutation angle of 17.5º, the rotor mechanical position interval to identify phase A, as the faulty phase, starts at 10º and ends at 25º, which are θ_c-7.5º and θ_c+7.5º, respectively. The rotor mechanical position interval to identify phase B is defined between 25º and 40º. The same analysis can be made for phase C and D. It must be remembered that 0º corresponds to the phase A unaligned position. Thus, if the commutation angle is 17.5º, the commutating conduction mode of phase A, B, C and D occurs at 17.5º, 32.5º (17.5+15), 47.5º and 2.5º respectively.

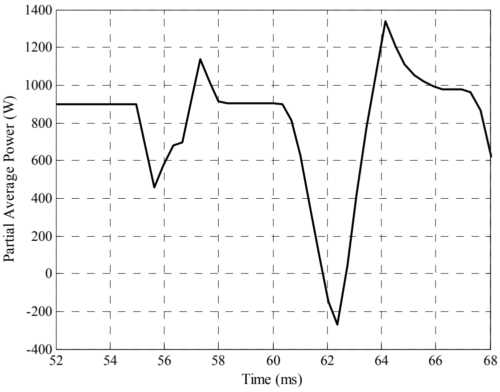

Fig. 10. Simulated partial average power results under the occurrence of an open-circuit fault in a phase A power switch at 55ms.

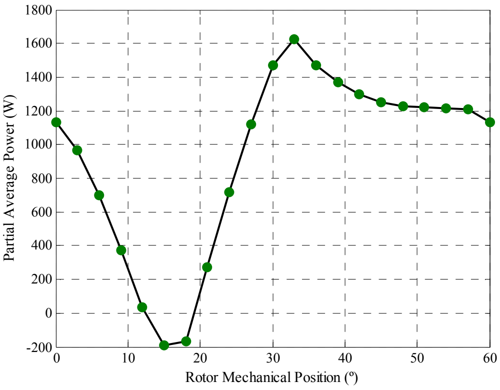

Fig. 11. Simulated partial average power results, at steady state, after the occurrence of an open-circuit fault in a phase A power switch.

Fig. 12 exhibits the partial average power polar chart. In the upper haft-plane the waveform comes near the origin of the coordinates and returns back to higher amplitudes. The half-plane, where this effect occurs, permits to detect which motor phase is disconnected since each motor phase conducts mostly between its unaligned and aligned position.

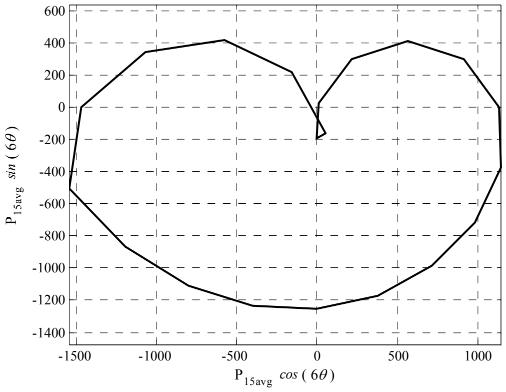

Fig. 12 Simulated partial average power polar chart result, at steady state, after the occurrence of an open-circuit fault in a phase A power switch.

C. *Normal Operating Conditions Considering a Sudden Mechanical Load Decrease*

The following simulating results consider the sudden decrease of torque load from 5 Nm to 2.5 Nm at 50ms. When the mechanical load decreases the speed increases because an excessive electromagnetic torque is being produced. A negative speed error occurs causing a progressive increase of the ignition angle in order to reduce the time interval where a motor phase is being conducting. Consequently its electromagnetic torque contribution is decreased. The decrease of the partial average power (Fig. 13) occurs as the sudden load variation occurs but it is not so pronounced than it is under the absence of one motor phase. The partial average power amplitude is never negative. Only a more drastic sudden load decrease would eventually cause negative partial average power amplitudes. When the reference speed is reestablished the partial average power presents a constant amplitude, which is obviously smaller than the amplitude at the previous steady state. The partial average power polar chart (Fig. 14) permits to relate the amplitude variation with rotor position. It can be concluded that, in a simplest analysis, the amplitude decreases progressively independently of the rotor mechanical position. At the new steady state the polar chart is, once more, a perfect circle with a smaller radius as compare to the initial steady state condition.

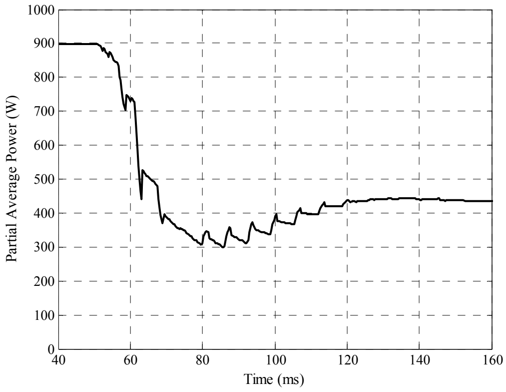

Fig. 13. Simulated partial average power results under a sudden mechanical load decrease at 50ms.

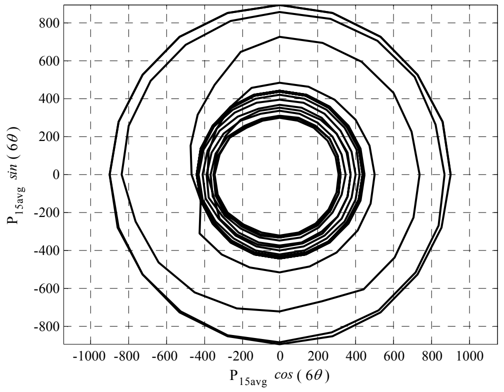

Fig. 14. Simulated partial average power polar chart results under a sudden mechanical load decrease at 50ms.

V. CONCLUSIONS

A control algorithm, based on the power converter supply current and rotor mechanical position information for SRM drives, is presented. Since, only one current is observed, a single pulse strategy is adopted for the phase current control. The presented control algorithm is than more indicated for high speed operating applications.

A new fault diagnostic technique, applied to switched reluctance motor, is presented. The proposed partial average power permits to detect an open-circuit fault in a converter power switch and the affected phase identification can also be established.

Under normal operating and steady state conditions the partial average power presents constant amplitudes. If an open-circuit fault occurs in a converter power switch, the partial average power presents almost immediately a decrease. After the fault occurrence, the partial average power exhibits decreasing amplitudes whenever the faulty phase should be conducting and contributing with a positive electromagnetic torque. Under the absence of one motor phase, the partial average power presents negative amplitudes during every rotor mechanical position near the commutation angle of the faulty motor phase. Negative partial average power amplitude can only be observed, under normal operating conditions, if a severe delay of the ignition angle occurs. This delay can be caused by a sudden and drastic decrease of the mechanical load. In order to differentiate the reason that causes negative partial average power amplitudes, the evolution of the ignition angle adopted for consecutive motor phases must be considered. Thus, if the ignition angle has been advanced, preserved or smoothly delayed and a negative partial average power amplitude is achieved it means that one motor phase is disconnected. The rotor mechanical position, where the negative value occurs, permits to identify the faulty motor phase.

Since switched reluctance motor drives can keep running even after the disconnection of one motor phase, a fast open-circuit fault detection technique is not a need. If an open-circuit fault occurs, the afore-mentioned condition, for fault detection, will be sooner or later achieved.

The proposed fault detection technique, for an open-circuit fault in a converter power switch, is of an extreme importance if a power converter reconfiguration can be adopted in order to enhance the SRM performance.

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REFERENCES

[1] C. M. Stephens, “Fault Detection and Management Systems for Fault-Tolerant Switched Reluctance Motor Drive”, *IEEE Trans. Ind. Applicat.*, vol. 27, no. 6, pp. 1098-1102, November/December 1991.

[2] R. B. Inderka and R. W. A. A. De Donker, “DITC – Direct Instantaneous Torque Control of Switched Reluctance Drives”, *IEEE Trans. Ind. Applicat.*, vol. 39, no. 4, pp. 1046-1051, July/August 2003.

[3] J. Choi, T. H. Kim, K. Jang and J. Lee, “Geometric and Electrical Optimization Design of SR Motor Based on Progressive Quadratic Response Surface Method”, *IEEE Trans.on Magnetics,* vol. 39, no. 5, pp. 3241-3243, September 2003.

[4] J. M. Stephenson, A. Hughes and R. Mann, “Torque Ripple Minimisation in a Switched Reluctance Motor by Optimum Harmonic Current Injection”, *IEE Proc. Electr. Power Appl.*, vol. 148, no. 4, pp.322-328, July 2001.

[5] Z. Lin, D. S. Reay, B. W. Williams and X. He, “Torque Ripple Reduction in Switched Reluctance Motor Drives Using B-Spline Neural Networks”, *IEEE Trans. Ind. Applicat.*, vol. 42, no. 6, pp. 1445-1453, November/December 2006.

[6] M. Ilic'-Spong, R. Marino, S. M. Peresada and D. G. Taylor, “Feedback Linearizing Control of Switched Reluctance Motors”, *IEEE Trans. Automat. Contr.,* vol. 32, no 5, pp. 371-379, May 1987.

[7] T. J. E. Miller and M. McGilp, “Nonlinear Theory of the Switched Reluctance Motor for Rapid Computer-Aided Design”, *IEE Proceedings*, vol. 137, Pt. B, no. 6, pp. 337-347, November 1990.

[8] G. Singh and B. C.: Kuo, “Modeling and Simulation of Variable-Reluctance Step Motors with Application to a High-Performance Printer System”, *IEEE Trans. Ind. Applicat.*, vol. 11, no. 4, pp. 373-383, July/August 1975.

[9] J. M Stephenson and J. Corda, “Computation of Torque and Current in Doubly Salient Reluctance Motors from Nonlinear Magnetisation Data”, *IEE Proceedings*, vol. 126, Pt. B, no. 5, pp. 393-396, May 1979.

[10] N. S. Gameiro and A. J. M. Cardoso, “Analysis of SRM Drives Behaviour Under the Occurrence of Power Converter Faults”, in *Proc. IEEE Int. Symp. Industrial Electronics (ISIE),* Rio de Janeiro, Brasil, vol. 2, pp. 821-825, 9-11 June, 2003.