STARTUP AND FAULT TOLERANCE OF THE SRM DRIVE WITH THREE-PHASE BRIDGE INVERTER AND STAR CONNECTION OF THE PHASES WINDINGS.

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***Abstract*— The switched reluctance motor can be driven by a three phase bridge inverter. In this case, the machine should have three phases and their windings should be connected in star or delta. When the phase windings are connected in star, the star's center it should be connected to the center point of the inverter DC bus capacitors. This connection demands the use of voltage equalization mechanisms of the capacitors. The voltage balance of the DC bus capacitors is obtained with the change of the phase current direction of the machine along the operation. This strategy doesn't prevent that in the startup one of the DC bus capacitors is totally unloaded.The short circuit of one of the capacitors for a relay during the startup solves the problem of discharge of the capacitor, it allows to operate SRM in very low speed, but it imposes an equivalent performance of an R-Dump inverter, where the discharge resistance of the energy of the turned off phase is the own coil resistance of the phase. In this paper, a SRM startup technique will be presented to work with a three phase bridge inverter and machine windings connected in star, without startup relay. The technique bases on allows two phases to conduct at the same time during startup. A comparison of the system proposed with the Split and Asymmetric Half Bridge inverters will also be presented, analyzing the fault tolerance in the inverter. Experimental results demonstrate the validity of the proposed technique.**

***Keywords*— Switched Reluctance Motor, three phase bridge inverter, star connection, delta connection, fault tolerance, PIC.**

I. INTRODUCTION

The Switched Reluctance Motor (SRM) can be driven by a three phase bridge inverter. For this inverter the machine windings can be connected in delta or star. In the connection delta it is necessary to connect diodes in series with the phase windings for to ensure unipolar currents [1][2][3]. The main problem when using this connection is the increase of the tail current time when the phase is turned off. The change of the diodes for thyristor eliminates the problem of increase of the tail current time and the three phase bridge inverter performance is very close at the performance of the asymmetric half bridge inverter [4]. The use of the three phase bridge inverter to drive SRM with their phases connected in delta doesn't present tolerance the fault in the power switches, as it happens with the asymmetric half bridge inverter.

In the other connection the machines phases are connected in star, the point common of connection must be linked to the central point of the DC bus capacitors. That connection demands the use from some procedure that maintains the capacitors voltage balanced [5]. The method of change the current polarity in the SRM phases during the operation allows to maintain the capacitors voltage balanced, however, when the SRM is put in operation the superior capacitor or the inferior capacitor of the DC bus can be unloaded totally. To avoid this effect is necessary to use startup procedures, as the use of a relay that maintains one of the DC bus capacitors in short circuit during the startup. In spite of efficient, the method can commit the operation in very low speeds. To avoid the use of the relay in low speeds and in the startup of the machine, can be used the technique where two machine phases are energized at the same time [6]. The appropriate choice of the instants of application of the currents with opposed signals at the machine phases maintains the voltage of the DC bus capacitors balanced without interfering in the torque generation. In this paper will be presented the technique of energizing two phases of the machine simultaneously with currents of opposite polarities and also as the system can operate with fault in more than two power switches without loss performance and without loss balance voltage of the DC bus capacitors.

II. SRM MODEL

The expression for the voltage and the mechanical equations of the SRM model are given for:

$$v_k = r_k i_k + \frac{d\lambda_k(\theta, i)}{dt} \tag{1}$$
$$\frac{d\omega}{dt} = \frac{C_e - C_l}{J} \tag{2}$$
$$\frac{d\theta}{dt} = \omega \tag{3}$$

where:
v_k voltage in the kth phase of the machine;
r_k coil resistance of the kth phase of the machine;
i_k current in the kth phase of the machine;
ω mechanical angular speed;
C_e electromagnetic torque generated;
C_l load torque;

J é rotor inertia;
$\lambda_k(\theta, i)$ kth phase flux linkage, give for:

$$\lambda_k(\theta, i) = \sum_{n=1}^{q} L_{kn}(\theta, i_n)\, i_n \tag{4}$$

where q represent the number of machine phases.

The equation (5) represents in a simplified way the torque generated by SRM considering the hypothesis that there is no saturation.

$$C_e = \frac{1}{2} i_k^2 \frac{dL_k(\theta)}{\partial\theta} \tag{5}$$

Based on the equation (5) the following observations can be made [7]:

1) The torque is proportional to the square of the current (machine can operate with unipolar currents). The possibility of the current to be unipolar, it allows the use of inverter with just a key for leg, since the same satisfies the other demands of the drive system;
2) The SRM requires a controllable inverter for its operation and cannot be operated directly from a three-phase line supply;
3) Because the current only needs to be unidirectional for all quadrants of operation, all inverters for this machine have a switch in series with a machine phase winding. With this configuration, there is a significant delay time in the rise of the current which allows the protection circuits to be activated to isolate the faults.

III. Star connection

The Figure 1 shown the star connection of the SRM windings. The SRM is driven by a three phase bridge inverter. It is clearly observed the connection of the star center of the phase windings at the capacitor center point.

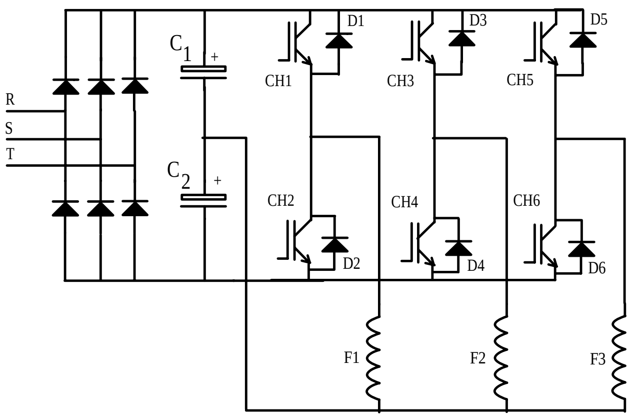

Fig. 1. Structure with three phase inverter and SRM with star connection of the phase windings.

In this configuration, the current in an energized phase of the machine is controlled for just one of the power switches of the inverter leg that is connected to the machine phase. Also, only one capacitor, C1 or C2, contributes to the energized phase. The figure 2 shown the current flow for the phase 1 of the machine during the energized phase and when the phase is turned off. When CH1 is turned on, current flows through CH1 and phase F1. C1 is being discharged

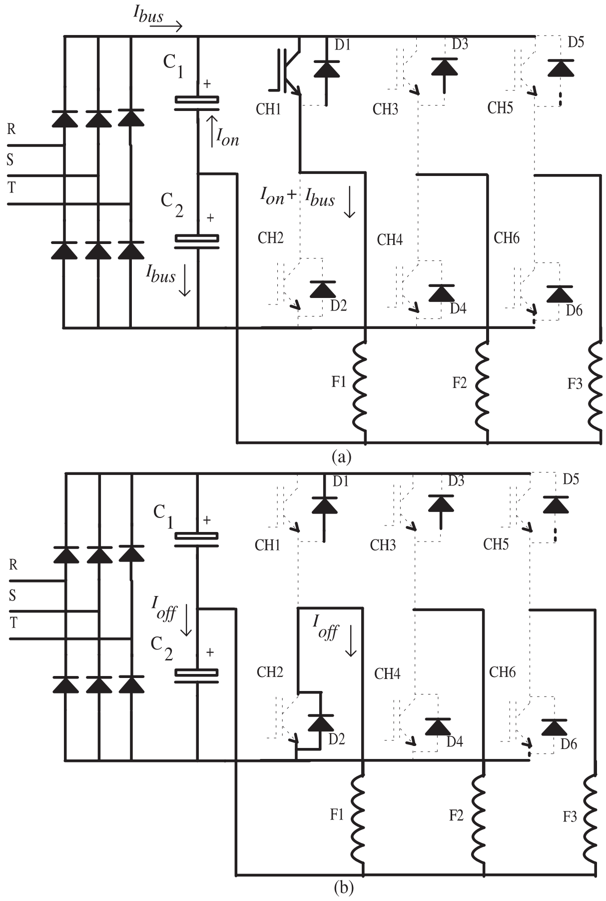

Fig. 2. (a) Energized cycle: CH1 turn on and capacitor C1 feeding phase F1, (b) phase turned off: CH1 turn off , D2 active and capacitor C2 receiving load current of the phase F1

and C2 is being charged, as shown the currents I_{on} and I_{bus}, respectively, in the Figure 2(a). When CH1 is turned off, the current I_{off} in phase F1 goes through D2 and C2, hence, C2 is charged again and Vc2 increases further, as shown in the Figure 2(b).

To guarantee that the voltage of the capacitors is balanced it is used an algorithm that defines the current flow in each phase being energized. The algorithm uses the information of the voltage in each capacitor to define the direction of the current. In the Figure 3 the curves of phase current and voltage of the DC bus capacitors are shown, with the machine operand the a speed of 112RPM. It can be observed in the current the polarity inversion and in the capacitors the balance of the voltages.

IV. Startup operation

The torque generated by a SRM is proportional to the square of the phase current (5). Thus, the machine can be driven with currents of any polarity. In the star connection the three phase bridge inverter can energize the phases of SRM with positive current or negative current. The direction of the current depends on the group of used elements (power switch, capacitor and free wheel diode, for example, CH1, C1 and D2). The commutation technique of the current polarity, defined by the equalization algorithm [5], it is guarantees the machine operation in steady-state. However, in the startup, when a phase is energized by a long time, the capacitor used to energize the phase can be unloaded totally, as shown in figure 4.

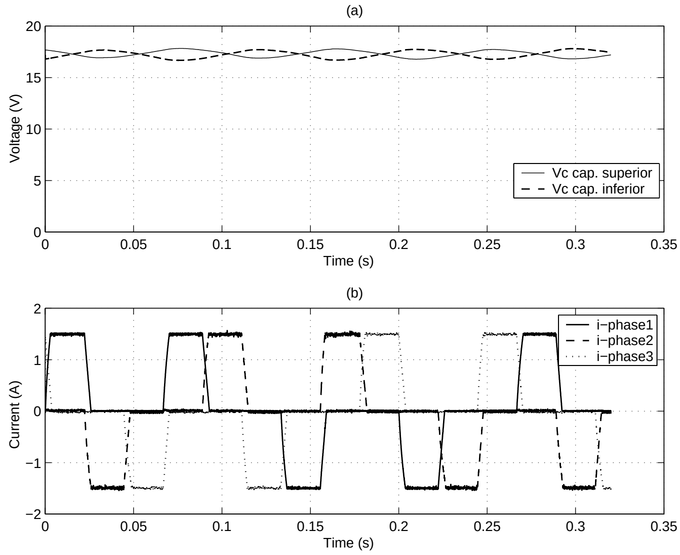

Fig. 3. Experimental result - Operation without load, speed of 112 RPM: (a) voltage in the DC bus capacitors and (b) current in the machine phases.

If the startup current is high, or the mechanic load connected to the axis of the SRM present high startup torque, or a combination of those factors, then it could be necessary to use capacitors with high μF values. To avoid to use great capacitors it is possible short circuit one of the DC bus capacitors using a relay. In this configuration the three phase bridge inverter behaves as the R-Dump inverter, where the energy stored in the phase being turned off would be dissipated in the own resistance of the coil [5].

In general, the coil resistance of the SRM phase winding is very low, like this, the time constant of the current fall tends to be high when the relay is active. The long time of the current fall can provoke the generation of negative torque, committing the performance of the SRM drive system. As the relay is active just in the instant in that SRM startup and when the SRM operates in low speed (below of 1 rad/s), these

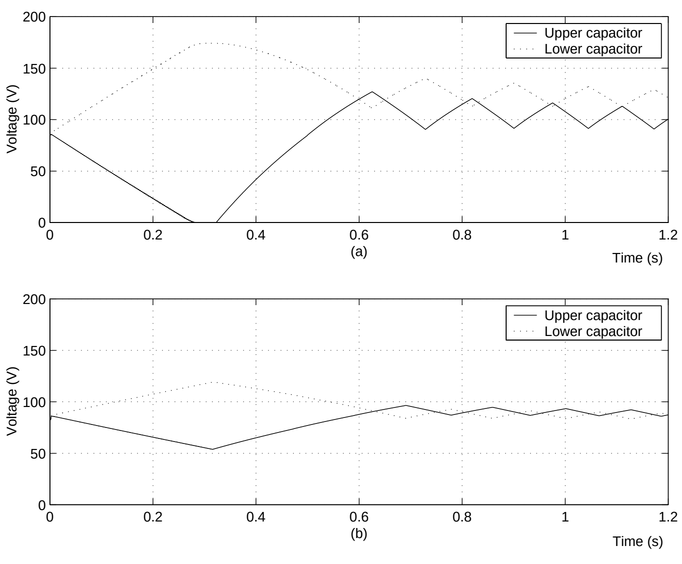

Fig. 4. Simulation results: Capacitor voltage with (a) C1 = C2 = 3.300μF and (b) C1=C2=10.000μF

would be the affected operation conditions for the effect of prolongation of the current fall time.

In the Figure 6 the current curves are presented in three different instants from operation using the relay together with the three phase bridge inverter. In the initial instant, Figure 6(a), the relay is active and short-circuit one of the DC bus capacitors of the inverter. In the following instant, Figure 6(b), the relay is already turned off but the voltage of the capacitors are not still balanced (see Figure 5(a)) and in steady-state, Figure 6(c), when the voltages are already balanced. The decrease of the current fall time can be observed going of the Figure 6(a) for the Figure 6(c).

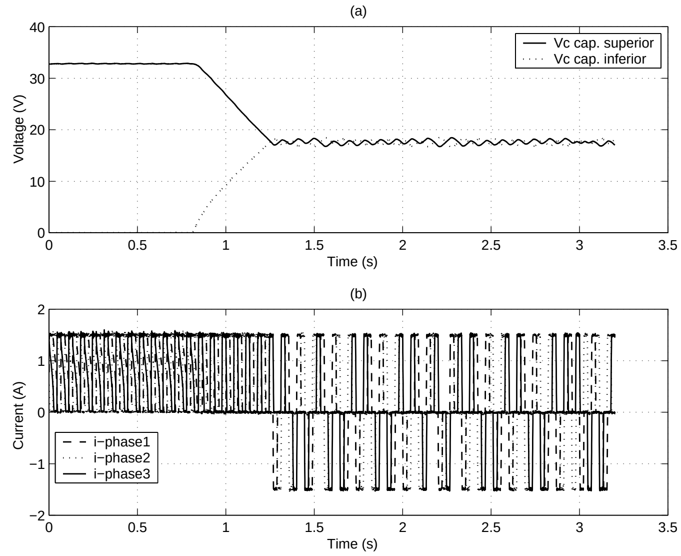

Fig. 5. Experimental results - Motor without load: (a) DC bus capacitor voltages and (b) current in the machine phases

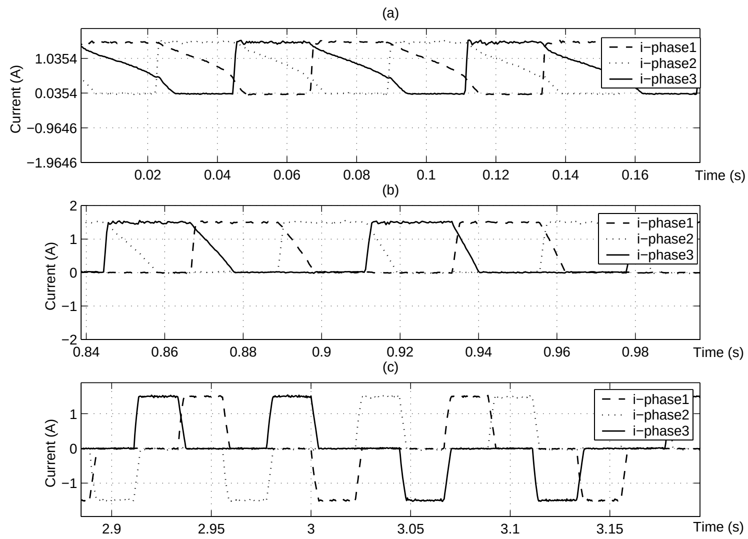

Fig. 6. Experimental results - Phase currents: (a)Capacitor in short-circuit, (b)Capacitor being loaded and (c) voltage of the capacitors balanced

The use of the relay with the three phase inverter to drive the SRM in the startup or in low speeds it can be substituted by the technique of simultaneous current in two or more machine phases. In a three phase SRM it is possible to apply current simultaneously in two phases without committing the torque generation. A phase generates torque to move the axis of the machine and the other phase allows to balance the voltage of the DC bus capacitors. In the figure 7 and 8 the current and voltage curves, respectively, are presented, using the equalization algorithm and the simultaneous current conduction technique in two phases with the machine in steady-state.

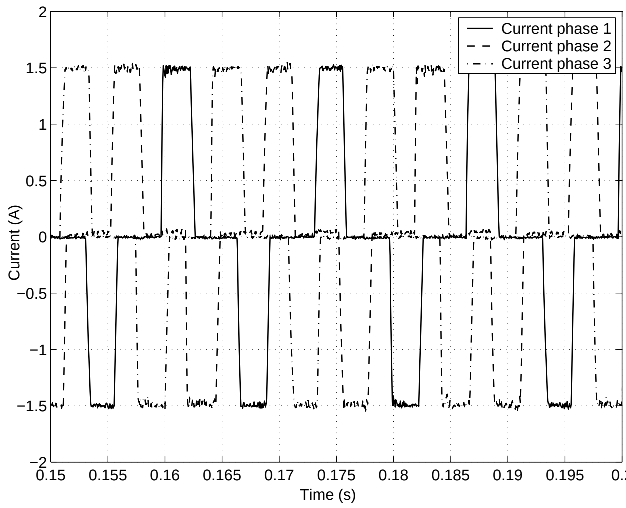

Fig. 7. Experimental results: Currents of the SRM with two phases simultaneos conduction.

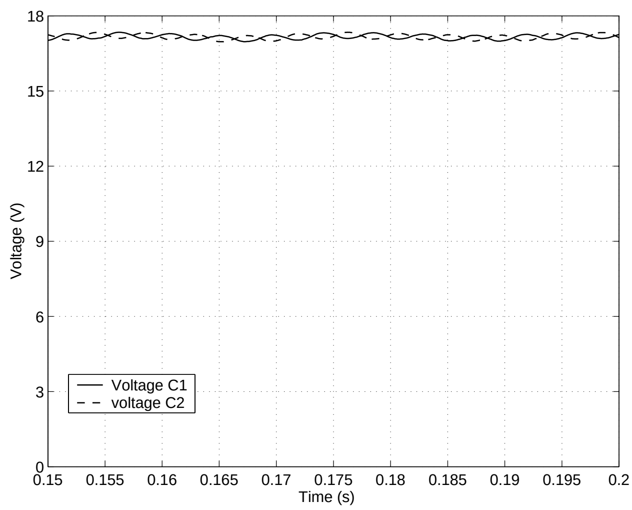

Fig. 8. Experimental results: Inverter bus capacitor voltages using equalization algorithm.

The voltage balance of the DC bus capacitors using the technique of applying current simultaneously in two phase of the SRM, it is eliminates the use of the relay and the limitations of the system, when the machine operates with variable duty cycle and/or in low speed. The technique of energizing two phases simultaneously makes use of the fact that in SRM, with three or more phases, there is always a phase that is in the area where the torque generated is minimum or null ($\frac{dL}{d\theta} \approx 0$), while another phase is in the area where $\frac{dL}{d\theta}$ it is larger than 0, as show the curves in Figure 9 (approximate curves $L(\theta)$ and $\frac{dL(\theta)}{d\theta}$ of the three phase SRM used in the experiments). The simultaneous application of currents of same value and polarities inverted in two machine phases maintain the capacitor voltage balanced.

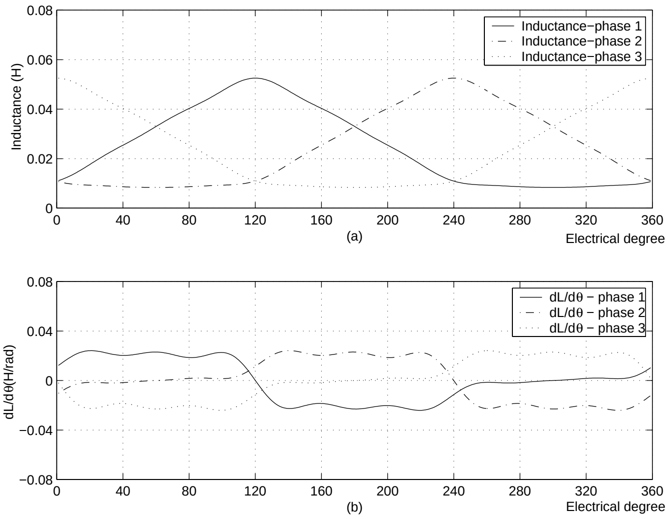

Fig. 9. Curves of the experimental motor: (a) Inductance curve and (b) $\frac{dL}{d\theta}$ curve.

In general the mutual coupling effect among the phases of a SRM is neglected, however, the mutual-flux can reach values of up to 10% of the phase self-flux, generating torque disturbances [8]. When two adjacent phases are energized simultaneously the equations for those phases are written as:

$$v_x = r_x i_x + \frac{d\lambda_x}{dt} \tag{6}$$

$$v_y = r_y i_y + \frac{d\lambda_y}{dt} \tag{7}$$

where

$$\lambda_x = \lambda_x(i_x, i_y\theta) = L_x(i_x,\theta)i_x + M_{xy}(i_x, i_y\theta)i_y \tag{8}$$

$$\lambda_y = \lambda_y(i_x, i_y\theta) = L_y(i_y,\theta)i_y + M_{xy}(i_x, i_y\theta)i_x \tag{9}$$

where M_{xy} represents the mutual inductance among the phases x and y. As the magnetic path of the mutual-flux presents a high resulting airgap, the variation of the mutual-flux value in function of the current is negligible, therefore, the same can be considered function just of the rotor angular position. Substituting the expressions 8 and 9, in the expressions 6 and 7, respectively, and considering that the mutual inductance does not depend on the current, 6 and 7 can be written as:

$$\begin{aligned} v_x &= r_x i_x + \left(L_x + \frac{\partial L_x}{\partial i_x} i_x\right)\frac{di_x}{dt} + \omega\frac{\partial L_x}{\partial\theta} i_x \\ &\quad + \omega\frac{\partial M_{xy}}{\partial\theta} i_y + M_{xy}\frac{di_y}{dt} \end{aligned} \tag{10}$$

$$\begin{aligned} v_y &= r_y i_y + \left(L_y + \frac{\partial L_y}{\partial i_y} i_y\right)\frac{di_y}{dt} + \omega\frac{\partial L_y}{\partial\theta} i_y \\ &\quad + \omega\frac{\partial M_{xy}}{\partial\theta} i_x + M_{xy}\frac{di_x}{dt} \end{aligned} \tag{11}$$

The terms $\omega\frac{\partial M_{xy}}{\partial\theta} i_y + M_{xy}\frac{di_y}{dt}$ e $\omega\frac{\partial M_{xy}}{\partial\theta} i_x + M_{xy}\frac{di_x}{dt}$ are additional disturbances that can demand a larger effort of the current controller in closed loop in an drive system.

V. Fault tolerance

The drive system of the SRM using the three phase bridge inverter and phase windings connected in star reaches an performance equivalent to the obtained with the asymmetric half bridge inverter. When the comparison is made with the Split inverter, it can also be observed an equivalent performance and the fact that with the three phase bridge inverter no there is restriction of the machine to possess an even number of phases, as it happens with the Split Inverter.

The configuration using the three phase bridge inverter allows to operate the machine, without loss performance, same if there is the loss of two power switches in complemental positions of adjacent legs of the inverter, as shown in the Figure 10. In this case it was considered that there was the loss of the command sign of the power switches CH3 and CH6. If the same fault had happened in an asymmetric half bridge inverter or Split inverter, the respective phases would be inoperative.

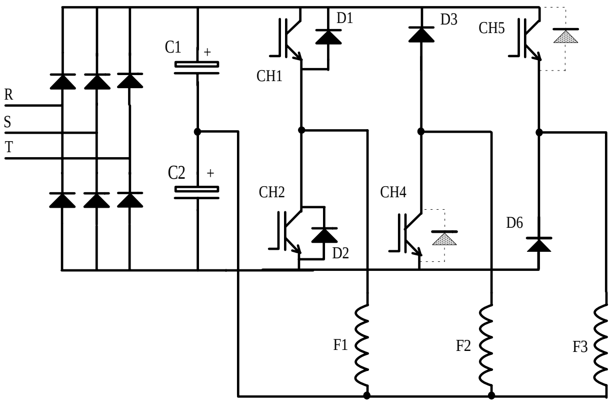

Fig. 10. Fault simulation in the power switches CH3 and CH6 of the three phase bridge inverter.

The loss of the power switches doesn't commit the maintenance of the voltage balance of the capacitors. The possibility to invert the current polarity in one phase of the machine still allows to maintain the balanced voltages. In the figure 11 the phase currents and capacitor voltages of the inverter DC bus are presented with the restriction that in the leg 2 and 3 of the inverter just the power switch CH4 and CH5, respectively, can be driven. This condition simulates the loss of the complemental switches CH3 and CH6, respectively. In the current curve can be observed that the only current that change of polarity during the machine operation is the current of the phase 1 (F1). The current of the other phases maintains its polarities along the operation.

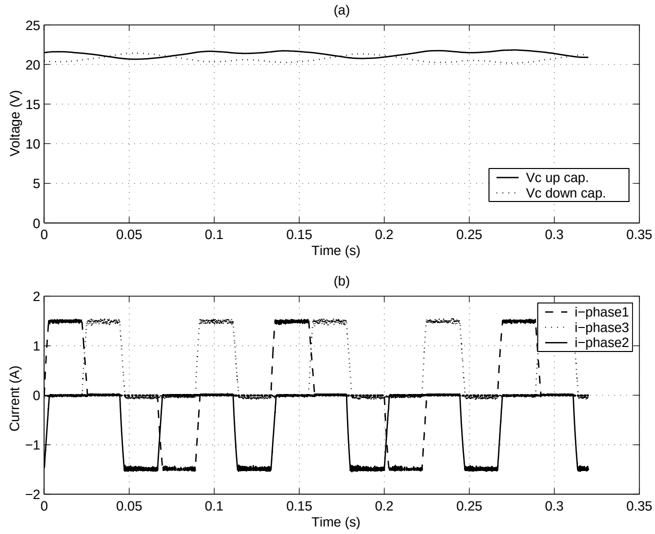

Fig. 11. Experimental results: Fault simulation in the CH4 and CH5 power switches - (a) Capacitor DC bus voltage and (b) Phase currents.

VI. Conclusion

In this paper the use of the three phase bridge inverter was discussed in the driven of switched reluctance motors (SRM), where the phase windings of the machine are connected in star. Previous studies had already determined the viability of use of the structure, presenting solutions to outline the inherent problems the structure in the instant of startup of the machine and when the same operates in very low speed.

The substitution of the relay used to put in short circuit one of the capacitors of the DC bus of the three phase inverter in the startup for the technique of energizing two phases at the same time, it allows to operate the machine in all speed range, as well as, with variable duty cycle, without loss of efficiency of the system, as observed with the use of the relay, when the three phase bridge inverter started to have an equivalent behavior to the of the R-Dump inverter.

With two phases of the machine energized at the same time the mutual coupling effect among the phases it is more visible. The effect appears in the form of a disturbance in the phase currents, demanding a larger effort of the current controllers used in SRM drive systems.

Regarding fault tolerance of the studied structure, it was shown that the same has conditions of maintaining the system operand with the same performance of before the fault and maintaining the voltage balance of the DC bus capacitors, same when two power switches of the inverter lose their command signs.

Appendix

Data of the SRM used experimentally

- Model: H55BMBJL
- r_s: 2.2 Ω
- L_s(aligned unsaturated inductance per phase): 52 mH
- L_s(unaligned inductance per phase): 8 mH
- J (rotor inertia): 1.07×10^{-3} kgm^2
- rated current: 2.5A
- rated voltage: 120 V (CC)
- Number of stator poles: 12
- Number of rotor poles: 8
- Number of stator phases: 3

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