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SRG Load Voltage Control Strategy Based on Turn- Off Angle Modifying

[2]A. W. F. V. Silveira, [1,3]A. Fleury, [2]D. A. Andrade, [2]Gomes, L. C., [1]W. R. H. Araújo, [4]H. dePaula, [1]R. J. Dias
[1]Pontifícia Universidade Católica de Goiás, [2]Universidade Federal de Uberlândia, [3]Universidade Estadual de Goiás,
[4]Universidade Federal de Minas Gerais
Praça Universitária, 1440, CEP 74000, Goiânia, Goiás, Brasil
Phone: +55 14 62 3946 1426
afleury@terra.com.br, gutofleury@gmail.com

Abstract. This paper presents a control strategy for the Switched Reluctance Generator (SRG) output voltage. The developed technique uses a PI controller to vary the magnetization angle of the machine phases, acting on the value of the turn off angle in one of the switches of the half-bridge converter, allowing the inclusion of a freewheeling step between the magnetization and demagnetization of the phases. This strategy was implemented both in simulation (Matlab/ Simulink®) and experimentally (through DSP). Results with and without the freewheeling step were compared, showing that its addition for the SRG magnetization control substantially increases the energy conversion capability. Besides, the obtained results demonstrated that the proposed strategy is also able to perform an accurate control of the generator output voltage, even in transient situations.

Key words

Switched reluctance, load voltage control strategy, turn off angle modifying.

1. Introduction

The switched reluctance generator (SRG) has been aim of studies for applications which require variable speed, where its constructive characteristics make it commercially competitive [1]. So far, the applications where the SRG has been more exploited are: electricity generation in aircrafts [2], vehicles [3-4] and wind farms [5]. In automotive and aircrafts applications, operation in high speeds are generally required, which is not a problem for the switched reluctance machine (SRM), since there are no permanent magnets and no windings on the rotor, allowing that the machine rotate in ultra high speeds [3]. Concerning wind generation, the demanded operation characteristics are different, since the machine operates in low speed and with high torque in the shaft [5].

The control issues regarding the several applications for the SRG are also different. In wind applications, for instance, the control must ensure that the machine operate in its optimum point from the electric generation perspective. When it comes to embedded applications, as the automotive, for example, the demand of generated power tends to oscillate abruptly with the connection and disconnection of loads, which represents proportionally large transients for the electric system. In this way, the precise voltage control on the load bus becomes necessary [6]. Besides, studies have been pointing for the increasing of the DC bus voltage, from 14 to 42 V, to supply the crescent demand for power required by the new electromechanical and electronic equipments incorporated to the vehicles, in order to increase comfort and safety [7]. In this context, new research lines aiming to improve the embedded generation for vehicles have raised. New machines are being studied and compared [4], in order to find the one most suited to this new scenerio, being the SRG a strong candidate to be employed in the new projects of vehicular electric systems [3].

Within this context, this paper presents a study with the SRG operating in closed loop control of the generated voltage on the load. The strategy developed is firstly presented and latter validated through simulation and experimental results. Results showing the generator efficiency performing in closed loop on different operation speeds are presented as well. Figure 1 illustrates the SRG block diagram being used for generation on vehicles equipped with DC bus of 42 V.

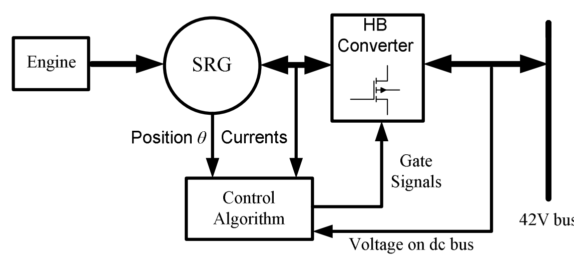

Fig.1. Schematic of a SRM connected to an automotive DC bus.

2. Variable Reluctance Machine

The reluctance machine has windings only on the stator. The absence of windings on the rotor allows that high speeds be achieved. Figure 2 shows the representation of a SRM with one of the phase windings.

In relation to the machine operation, if a rotor pole aligns with an energized stator pole, the position is of stable equilibrium. Thus, in the reluctance machine, there is a natural tendency of the mobile part to rest on the maximum inductance position of the excited coil. If the rotor is in the position of unstable equilibrium in relation to a certain phase, and this one is energized, the rotor tends to rotate for the equilibrium position, featuring a motor operation. On the other hand, if the rotor is in the equilibrium position and it is forced to rotate by an external agent, the produced torque is restorative and results in a back electromotive force additive to the voltage, and the machine generates electricity. In a switched reluctance machine, the mechanical energy received from a primary machine is transformed into electric energy forcing the rotor pole and the energized stator pole to leave the aligned position. Figure 3 illustrates, for one phase, the regions in relation to the inductance variation where the SRM operates as a motor or generator.

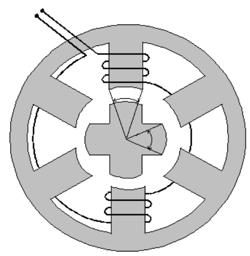

Fig.2. Switched reluctance machine – 6 x 4.

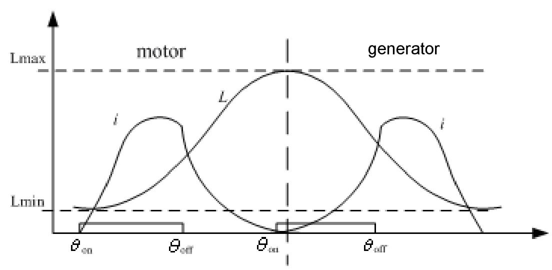

Fig.3. Phase current and inductance variation as a function of the rotor position.

A. Mathematical Modeling

The electric circuit for a phase of the SRM can be solved as:

$$v = Ri + L\frac{di}{dt} + i\omega\frac{dL}{d\theta} \tag{1}$$

where v is the applied voltage, i is the phase current, R is the phase resistance, L is the phase inductance and θ is the angular position of the rotor. The third term on the right side of the equation is the back electromotive force e, that can be written as:

$$e = i\omega\frac{dL}{d\theta} \tag{2}$$

where $\omega = d\theta/dt$ is the angular speed of the rotor.

The mechanic torque produced by the SRM, disregarding the losses, can be expressed by (3).

$$T(\theta, i) = \frac{1}{2} i^2 \frac{dL}{d\theta} \tag{3}$$

Some conclusions can be made from the above equation. The mechanic torque produced by the machine is independent of the current signal that is flowing in the phase; thus, the applied current on the phase can be unidirectional. The torque signal is given by the variation of the inductance in relation to the rotor position and was calculated in the simulations taking into account the friction D and the inertia J, according to (4).

$$T_m = T_{emag} - J\frac{d\omega}{dt} - D\omega \tag{4}$$

Considering three phases with different inductances and instantaneous currents, the electromagnetic torque can be written as:

$$T_{emag} = \frac{1}{2}\left(i_a^2 \frac{dL_a}{d\theta} + i_b^2 \frac{dL_b}{d\theta} + i_c^2 \frac{dL_c}{d\theta} \right) \tag{5}$$

The equation of the rotor speed (6) completes the dynamic description of the machine.

$$\omega = \frac{d\theta}{dt} \tag{6}$$

The mathematical model, considering the three phases, is finally presented by (7).

$$\begin{bmatrix} v_a \\ v_b \\ v_c \\ T_m \\ 0 \end{bmatrix} = \begin{bmatrix} R_a & 0 & 0 & 0 & 0 \\ 0 & R_b & 0 & 0 & 0 \\ 0 & 0 & R_c & 0 & 0 \\ i_a r_1 & i_b r_2 & i_c r_3 & D & 0 \\ 0 & 0 & 0 & -1 & 0 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \\ \omega \\ \theta \end{bmatrix} + \begin{bmatrix} L_a & 0 & 0 & 0 & i_a \frac{dL_a}{d\theta} \\ 0 & L_b & 0 & 0 & i_b \frac{dL_b}{d\theta} \\ 0 & 0 & L_c & 0 & i_c \frac{dL_c}{d\theta} \\ 0 & 0 & 0 & J & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{i}_a \\ \dot{i}_b \\ \dot{i}_c \\ \dot{\omega} \\ \dot{\theta} \end{bmatrix} \tag{7}$$

where:

$$r_1 = \frac{1}{2}\frac{dL_a}{d\theta}; \quad r_2 = \frac{1}{2}\frac{dL_b}{d\theta}; \quad r_3 = \frac{1}{2}\frac{dL_c}{d\theta} \tag{8}$$

Designating by [V], [R], [I], [L] and [$\dot{I}$] the matrixes in the same order that appear in (7), the states matrix of the SRM has the following form:

$$[\dot{I}] = [L]^{-1}[V] - [L]^{-1}[R][I] \tag{9}$$

B. Computational Modeling

The Matlab/Simulink® software was used to develop the simulations, taking into consideration the magnetic saturation of a 1 h.p., 6x4 reluctance machine, operating as generator. The data of the simulated machine and further details about the simulation can be found in [8]. The converter used to drive the SRM is the half-bridge (Fig. 4), commonly used for this application. Fig. 5 shows the (a) magnetization circuit, (b) freewheel and (c) the demagnetization of the coils.

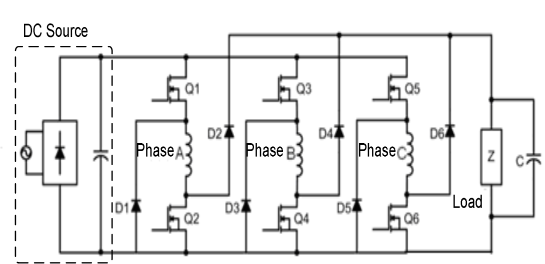

Fig.4. Asymmetrical half-bridge converter for the SRG.

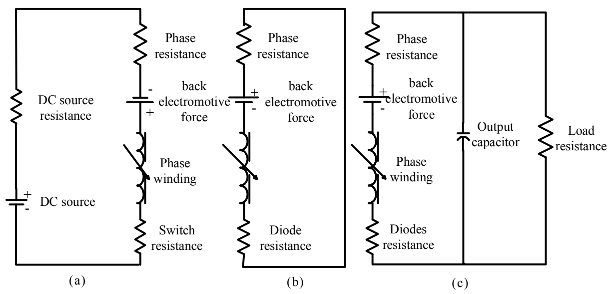

Fig. 5. (a) Magnetization, (b) freewheelling and (c) demagnetization steps.

C. SRG control

The switched reluctance generator can be controlled to deliver a desired power to the load or to apply on it a constant voltage, varying the output power according to the load resistance. In embedded applications in general, including the automotive, it is necessary that the voltage on the DC bus be kept nearly constant, even with the generator operating under variable speed and with variations on the equivalent impedance of the combined loads connected to its output.

Firstly, to understand the proposed strategy, it is necessary a better comprehension of the three-phase, 6x4 machine employed on the study and the way that it is driven as a generator. From Fig. 6, it is possible to observe the machine current curve for the operation as generator and the gate signals applied to one of the phases. This is done when the variation of the inductance in relation to the rotor position is negative. For the 6x4 SRG employed here, when operating under open loop, the conduction angle or excitation ($\theta_{cond} = \theta_{off} - \theta_{on}$) of each phase should be of 30°, to generate the maximum power in nominal operation. In this case, both switches used to control the phase magnetization are driven by a single pulse and remain closed during all the excitation period (30°).

Knowing the appropriate conduction angle to magnetize the SRG phases, in order to implement the magnetization strategy acting on the value of θ_{off}, it was defined that the PI controller should only change the turn off angle of the top switch of the converter, allowing that a freewheelling step be performed, keeping the lower switch of the converter closed until the 30º are completed. Only then the converter lower switch is opened, making possible that the power storage in the phase winding be delivered to the load. Fig. 7 shows the block diagram of the developed strategy, while Fig. 6 presents a simulation result of the SRG operating in closed loop, illustrating the voltage and current curves on phase A and the gate signals of the top (Q1) and low (Q2) switches of the half-bridge converter (Fig. 4). The positive part of the voltage on the phase refers to the applied voltage by the DC source, when Q1 and Q2 are closed (magnetization period); the negative part occurs when Q1 and Q2 open, polarizing directly the diodes D1 and D2 and making that the storaged power on the phase windings be delivered to the load.

During the freewheeling step, when only Q2 stays closed, thus keeping the current flowing through the diode D2, the voltage on the phase becomes slightly negative due the voltage drop on the phase resistance. Within this step, the current is still increasing due the electromechanical energy conversion, since the primary machine is forcing the misalignment between the rotor pole and the energized stator pole.

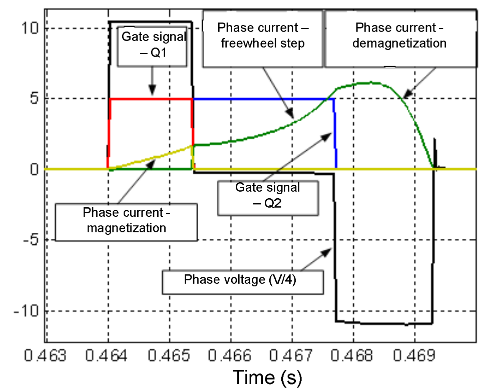

Fig. 6. Phase A voltage, current and gate signals (Q1 and Q2).

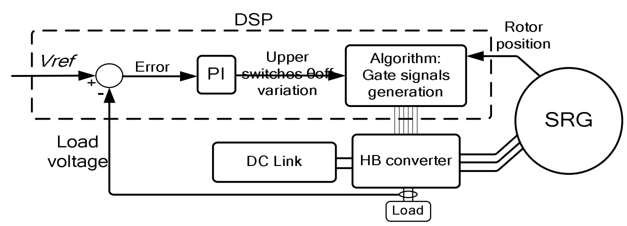

Fig. 7. Control strategy based on the variation of the magnetization period, by acting on the upper switches θ_{off} value.

Equation (11) expresses the energy balance in the conversion process:

$$E_{load} = E_{magnetization} + E_{converted} - E_{losses} \qquad (11)$$

where: E_{load} is the energy delivered to the load in one generation cycle of the phase, $E_{magnetization}$ is the energy spent by the source to magnetize the phase, $E_{converted}$ is the energy converted from mechanic into electric and E_{losses} is the combination of all the losses during the generation process of a phase.

3. Simulation Results

In order to validate the developed strategy, simulation tests were conducted as described in the sequence. The reluctance generator operated in closed loop, being controlled by the proposed strategy; the voltage on the bus that supplies the HB converter was defined as 42 V; the machine speed was set to be constant at 1350 rpm. The SRG was submitted to an electric load transient at 3 s of simulation time, defined by a reduction of its resistance from 20 to 15 Ω; at 6 s, its original value was restored.

The current behavior during the load transient is depicted in Fig. 8. When the load resistance is reduced, the controller actuates in order to provide more current and to sustain the output voltage; once the original load value is restored, the controller acts to bring the current amplitude back to its initial value.

The gate signal of the switches related to phase A of the SRG, along with the current on the same phase, can be visualized in Fig. 9. It can be observed that the gate of the top switch (Q1) has variable width, controlled by the output of the PI, while the gate of the bottom one remains with fixed width in relation to the angular displacement of the rotor. This figure corresponds to the situation where the SRG supplies a load of 20 Ω, runs at 1350 rpm and a reference of 42 V on the load is set.

Fig. 10 presents the graphs of the gate signals and the current in phase A, for the case where a load of 15 Ω is connected to the SRG output, under the same conditions described previously. It can be noted that the controller action on the width of Q1 gate is to increase the generator magnetization, thus keeping the load voltage value close to the reference.

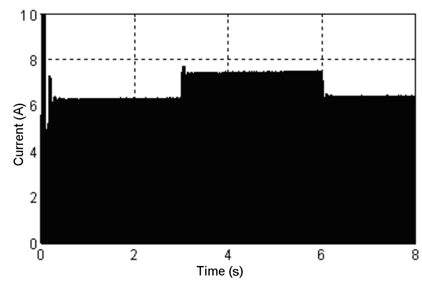

Fig. 8. Current in one phase of the SRG.

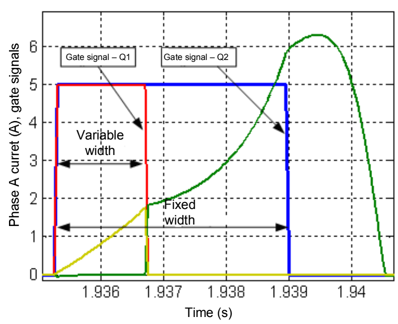

Fig. 9. Phase A current and gate signals (Q1 and Q2) with the SRG supplying a 20 Ω resistor.

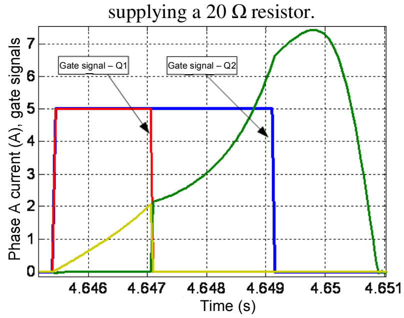

Fig. 10. Phase A current and gate signals (Q1 and Q2) with the SRG supplying a 15 Ω resistor.

Fig. 11 presents the generator output voltage profile, where slight oscillations can be observed in the simulated load transients (t = 3 s and 6 s). Besides, oscillations during the steady state operation can also be seen, which is expected for this type of machine; it can be reduced by increasing the output filter capacitor.

The strategy proposed here shows advantages in relation to that where the controller acts simultaneously on the top and bottom switches of the half-bridge converter. This can be observed in Fig. 12, which shows the phase A current and gate signals with the PI controller acting on both switches, without the freewheeling period. This result was obtained with the SRG operating under the same conditions of load and voltage reference of Fig. 9. Notice that these plots are in the same time scale and that the gate signal applied on both switches of phase A has a bigger width than that of the top switch of the same phase, in red, in Fig. 10. This indicates that a higher energy descendant from the DC source, used in the magnetization, is necessary when the freewheel is not used. Therefore, concerning the SRG operation in closed loop, one can conclude that the freewheelling step increases the electric energy generation capability.

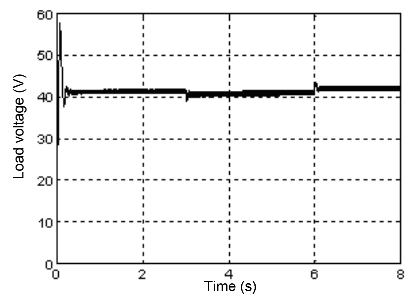

Fig. 11. SRG load voltage during the load resistance transient.

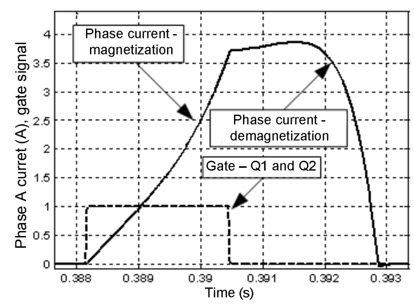

Fig. 12. Phase A current and gate signals (Q1 and Q2), being the SRG controlled without the freewheeling step and supplying a 20 Ω resistor.

4. Experimental Results

In order to experimentally validate the presented control strategy, the 1 h.p. SRG was coupled to a three-phase, 2 h.p. induction motor, driven by a commercial frequency converter. The HB converter presented in Fig. 4 was built to drive the SRG, being the control strategy implemented in a TMS320F2812 DSP. The rotor position information, required for the application of the gate signals during the magnetization period of the phases, was obtained using a position sensor coupled to the SRG shaft. The picture of the the laboratory setup is shown in Fig. 13.

A load transient test, similar to the simulated one, was performed, where the load resistance was reduced from 20 to 15 Ω. The voltage reference on the load was chosen as 42 V. In this test, the SRG was set to run at 1350 rpm and, from Fig. 14, it can be observed that the current signal increases after the reduction of the load resistance; the voltage signal shows a fast drop right after the transient, returning to the reference value some time latter. Fig. 15 presents the gate signals of the phase A top switch (Q1 in Fig. 4) and the corresponding current signal, from which is possible to visualize all the converter operation steps: magnetization, freewheel and demagnetization. This figure was obtained before the load transient depicted in Fig. 14. The corresponding graphs after the load transient can be visualized in Fig. 16.

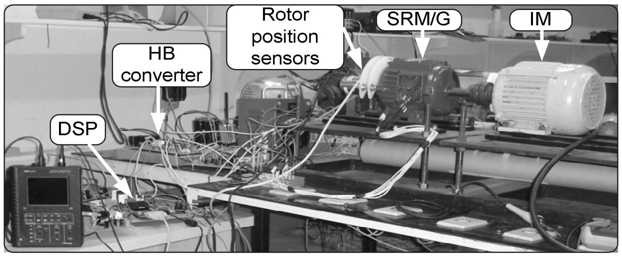

Fig. 13. Picture of the experimental setup.

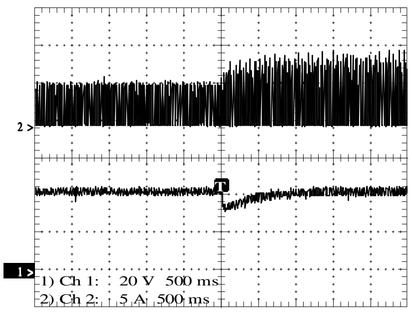

Fig. 14. Current and load voltage during a load transient.

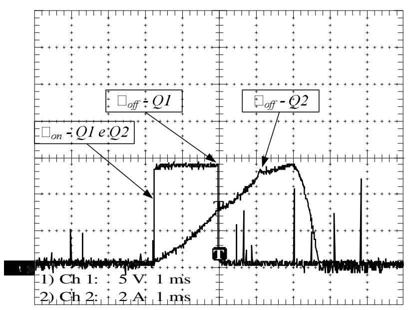

Fig. 15. Current in one of the phases and gate signal for a voltage reference of 42 V and a load of 20 Ω.

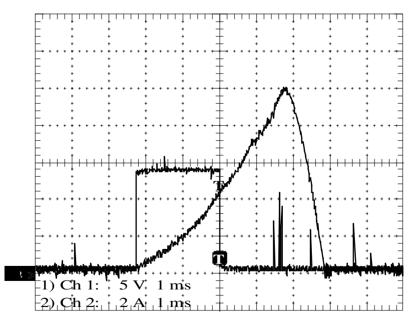

Fig. 16. Current in one of the phases and gate signal for a voltage reference of 42 V and a 15 Ω load.

Fig. 17 shows the gate signal of the converter top switch and the current signal in one phase, for the case where the voltage reference is 30 V and the load resistance in the machine output is 20 Ω.

From Fig. 15, Fig. 16 and Fig. 17, it is possible to observe the controller action on the turn off angle value of the phases top switch, varying, in this way, the SRG magnetization, from the DC link.

A test submitting the controller to a reference voltage step transient was also performed (from 42 to 30 V). The current behavior for this situation is presented in Fig. 18, where a reduction in its amplitude can observed along with the load voltage signal, which converges to the reference value applied to the controller.

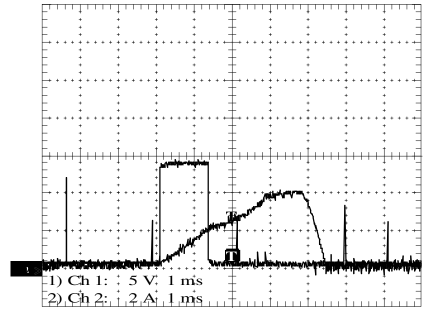

Fig. 17. Current in one of the phases and gate signal for a voltage reference of 30 V and a load of 20 Ω.

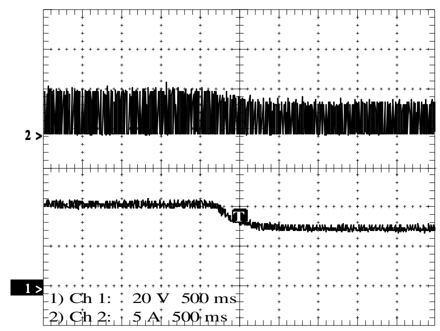

Fig. 18 . Voltage applied to the load and current magnitude in one phase of the machine, during a control voltage reference transient (42 to 30 V).

Another test was realized, now with respect to speed reference step imposition. The SRG controlled in closed loop with reference of 42 V was accelerated from 800 rpm to 2000 rpm. Fig. 19 brings the corresponding result, showing that the voltage signal value was kept around the reference. It is worthy to mention that the load voltage oscillation amplitude reduced with the increasing of the speed, which was expected, since this type of machine presents larger torque ripples in lower operation speeds. Regarding this issue, other works have proposed techniques to minimize it, as [9].

In [10] the authors investigates the problem of optimal control for accomplishing maximum energy conversion in SRG by determining the optimal turn-on and turn-off angles.

As a final comment regarding the general controller performance, the results presented so far showed that an accurate control of the load voltage was reached even under different operation transients.

In order to prove the superior efficiency of the strategy based on the variation of the conduction angle, which includes the freewheeling step, another experimental test was conducted. In such test, the SRG was set to run under different speeds, controlled with variable magnetization angle in two different ways: with and without the freewheeling step. In both cases, the controller voltage reference was adjusted as 42 V and the load resistance was of 20 Ω.

Fig. 20 shows the obtained result, where the generated power is taken as the difference between the output power delivered to the resistive load and the electric power drawn from the DC excitation supply.

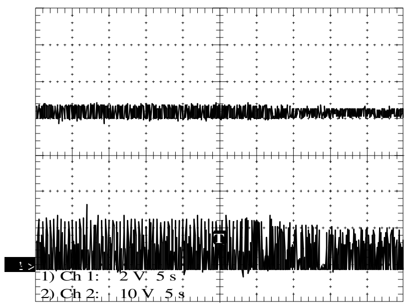

Fig. 19. Load voltage and current in one phase of the closed loop controlled SRG, for the case of a speed transient.

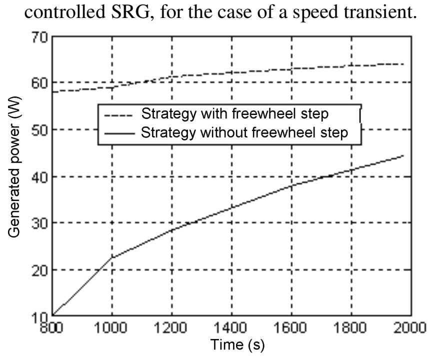

Fig. 20. Generated power by the SRG, supplying a load resistance of 20 Ω.

5. Conclusion

A strategy for the switched reluctance generator load voltage control, based on the variation of the magnetization angle, including a freewheeling step, was proposed in this paper. This technique varies only the closure angle of the top switches of the half-bridge converter, allowing that the electromechanical energy conversion continue until the lower switches are opened with fixed angle (determined for the machine 6x4 configuration, as employed on this work). The control strategy proposed was implemented both computationally (Matlab/Simulink®) and experimentally (using DSP). The obtained results showed that the proposed technique is able to accurately control the load voltage even under the different transient conditions tested in this paper (step variation of the load resistance and of the speed and output voltage references). Moreover, it was demonstrated that the inclusion of the freewheeling step improves the energy conversion efficiency of the system.

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