# DSP Based SRG Load Voltage Control

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*Abstract*— **The aim of this paper is to present a three-phase 6x4 switched reluctance generator load voltage control. The showed strategy uses a PI controller to vary the magnetization level of the phases during the magnetization period using a PWM signal. This strategy was simulated and than tested in a bench. Results of both simulations and tests are presented here. It was used a low cost fixed-point DSP and a half-bridge converter. The results got showed that this strategy successfully controls the generated voltage applied to the load. Strategies for switched reluctance generator voltage control are important for vehicular applications.**

***Keywords* - switched reluctance generator, half-brige converter, voltage control strategy.**

## I. Introduction

Nowadays there is a great deal of interest in the development of an integrated starter/generator (ISG) for vehicular applications. ISG is an electric subsystem in which the functions of the starting engine and the embedded electric power generator are fulfilled by just one electrical machine, instead of two separated electric machines as it is usual until now in traditional automotive vehicles [1]. The development of the ISG for automotive application will result in a vehicle with improved electric system performance and expected lower weight and cost.

Moreover, automotive industry has experienced an increasing demand for electrification in cars over the past decade [2-3]. The introduction of electronically driven systems such as power steering, active suspension, air conditioning, and another comfort and safety electrical devices, have opened a new field of research on alternatives for vehicles power systems, including the replacement of the 14V DC bus for a 42V DC bus to allow the safe growth of the power demand in the automobiles with lower currents preserving the wire gauge and avoiding weight and costs increase [3-5]. Besides, ISG technology can be used to implement stop and go systems in vehicles contributing to reduce polluting emissions in urban traffic [5-6] and to implement middle hybrid vehicles [6-8].

This scenario, stimulates investments to develop the ISG technology and many works suggested the use of switched reluctance machine (SRM) in this application due to it's robustness, fault tolerance, absence of permanent magnets and windings in the rotor, compatibility to operate at very wide speed range, simple control and low manufacture costs [1-3].

The work reported in [9], showed that a 6x4 switched reluctance generator (SRG) designed for this work presented its best performance at speeds above 1200rpm, and that after reaching its peak performance, at around 1300rpm, the power generated decreases slowly with speed growth. This characteristic is important in automotive applications since the combustion engine operates with variable speed at around 600 to 6000rpm (1:10).

When the switched reluctance integrated starter/generator (SRISG) operates in generator mode for vehicles applications it's necessary to implement a close loop load voltage control to keep the electric vehicle DC bus with voltage constant under variable load and speed conditions.

This work presents a strategy of load voltage control to be used in the generator mode of the SRISG. The strategy described here was simulated and tested using a DSP to demonstrate its applicability in this context.

## II. Energy conversion

The following nomenclature is used in the text:

| | |
|---|---|
| $v$ | Applied voltage. |
| $i$ | Phase current. |
| $R$ | Phase resistance. |
| $L$ | Phase inductance. |
| *cemf* | Back electromotive force. |
| $\omega$ | Rotor angular speed. |
| $C_m$ | Applied mechanical torque. |
| $C_{emag}$ | Electromagnetic torque. |
| $J$ | Moment of inertia. |
| $D$ | Coefficient of friction. |
| $\lambda$ | Flux linkage. |
| $\theta$ | Rotor angular position. |
| $W_x^{co}$ | Co-energy of the phase *x*. |
| $t$ | Time |
| $n$ | Number of phases |

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In a SRISG operating in the generator mode mechanical power achieved from a prime mover through a shaft is converted into electrical power. When a pole of the rotor is aligned with the excited pole of the stator, there is a state of stable equilibrium. Thus, in the machine there is a natural tendency to align the rotor and the stator active poles, in order to maximize the inductance of that phase and to establish a minimal reluctance. When an external mechanical agent forces the rotor to leave the stable equilibrium position, the electromagnetic torque produced results in a back electromotive force that increases the applied voltage. In this way the machine generates electrical power.

The electrical equation for a phase of the generator is:

$$v = Ri + L\frac{di}{dt} + cemf \tag{1}$$

The back electromotive force is given by:

$$cemf = i \cdot \omega \cdot \frac{\partial L}{\partial \theta} \tag{2}$$

where: $\omega = \frac{d\theta}{dt}$.

The stator winding is fed in DC. As $\omega$ and $i$ are both positive, the sign of $e$ is the same as that of $\partial L/\partial\theta$. From (2) it can be seen that when $\partial L/\partial\theta>0$ the back electromotive force is positive. In this case, electric power is converted to mechanical power and the machine works as a motor. But when $\partial L/\partial\theta<0$ the back electromotive force is negative and it increases the current converting mechanical power into electrical power.

The dynamic mechanical equation for the SRISG is given by (3). It is to be noted that the electromagnetic torque $C_{emag}$ comes as a negative quantity, i. e., acting against the rotor mechanical speed.

$$C_m - C_{emag} + J\frac{d\omega}{dt} + D.\omega = 0 \tag{3}$$

The co-energy of a phase of this machine is given by:

$$W^{co} = \int_0^i \lambda di \tag{4}$$

And the corresponding electromagnetic torque for an $n$ phase SRISG is given by:

$$C_{emag} = \sum_{x=1}^{n} \frac{\partial W_x^{co}}{\partial \theta} \tag{5}$$

The mathematical model of the SRISG regarding a three phase prototype is shown below:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \\ C_m \\ 0 \end{bmatrix} = \begin{bmatrix} R_a & 0 & 0 & 0 & 0 \\ 0 & R_b & 0 & 0 & 0 \\ 0 & 0 & R_c & 0 & 0 \\ -r_a/i_a & -r_b/i_b & -r_c/i_c & D & 0 \\ 0 & 0 & 0 & -1 & 0 \end{bmatrix} \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \\ \omega \\ \theta \end{bmatrix} +$$

$$+ \begin{bmatrix} L_a & 0 & 0 & 0 & i_a\frac{\partial L_a}{\partial \theta} \\ 0 & L_b & 0 & 0 & i_b\frac{\partial L_b}{\partial \theta} \\ 0 & 0 & L_c & 0 & i_a\frac{\partial L_a}{\partial \theta} \\ 0 & 0 & 0 & J & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \dot{i}_a \\ \dot{i}_b \\ \dot{i}_c \\ \dot{\omega} \\ \dot{\theta} \end{bmatrix} \tag{6}$$

where:

$$r_a = \frac{\partial W_a^{co}}{\partial \theta};\ r_b = \frac{\partial W_b^{co}}{\partial \theta} \text{ and } r_c = \frac{\partial W_c^{co}}{\partial \theta} \tag{7}$$

If the matrices above are designated $[V]$, $[R]$, $[I]$, $[L]$ and $[\dot{I}]$ exactly in the order they appear in (6), the matrix of states for the SRG has the form:

$$[\dot{I}] = [L]^{-1}[V] - [L]^{-1}[R][I] \tag{8}$$

## III. COMPUTING MODEL

To construct the mathematical model, a three-phase 6/4 prototype was considered. Measurements of the flux linkage *($\lambda$)* were done for many rotor positions *($\theta$)*, also considering different current values for each one of them. These measurements resulted in a large data bank of the function $\lambda(\theta,i)$. Using this data bank, a program for polynomial interpolation was developed to represent the inductance of a phase as a function of its current and the instantaneous rotor position. Figure 1 shows the inductance of a phase obtained from the polynomial equation for $L(\theta,i)$. The half-bridge converter designed to drive a starter generator (Fig. 2) was used to drive de SRISG operating in generation mode and the Mathlab/Simulink was used to implement the simulation program.

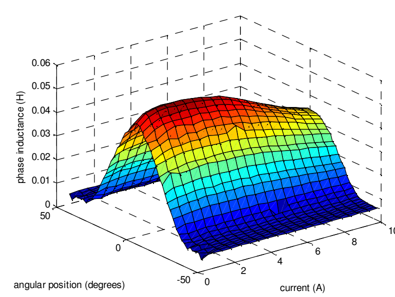


Fig. 1. Winding inductance obtained experimentally as function of phase current and rotor angular position.

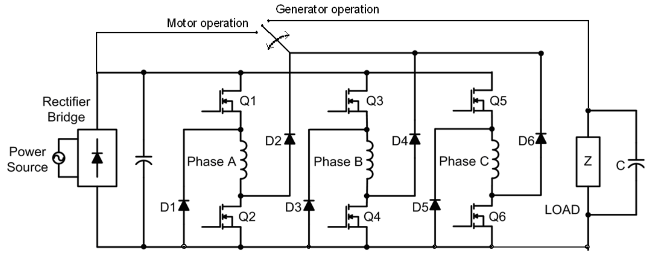

Fig. 2. Electrical scheme of the half-bridge converter used to generator mode.

The power applied to half-bridge converter comes from an AC source, which, along with a rectifier bridge, excites the SRISG. As a result it supplies the load through its windings. The excitation period of each phase begins when its switches are turned on and they start to conduct. During this time the inductance is still increasing, the diodes are not conducting and the phase windings generate a positive back electromotive force. The generating period starts when the controlled switches are turned off, the phase current is deviated to the load through the diode and the phase windings generate a negative back electromotive force due to the change of $\partial L/\partial \theta$ sign. The load voltage is obtained from equation (2). Fig. 3(a) and Fig. 3(b) show the active circuit during the excitation and the generation periods.

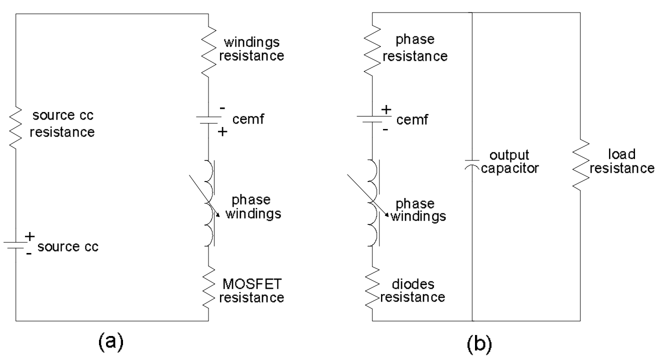

Fig. 3.Electrical scheme of the excitation (a) and generation (b) circuits of the HB and RC converters.

## IV. SIMULATIONS RESULTS

The strategy to control the voltage generated by the SRISG was simulated. The block diagram of the strategy can be seen in Fig. 4, and some simulations results will be present here. Fig. 5 shows the behavior of the voltage generated that is used to supply a resistive load, adopting the strategy described above. The reference of 42 V was adopted and the generated voltage converged to a value near the reference, as can be observed. When the time of simulation reached 3s, the resistance of load was reduced from 20 Ω to 15 Ω, and at 6 s, returned to the resistance value of 20 Ω. This transient test demonstrated that this strategy of control can keep the generated voltage around the reference during the transient of load. The current in one of the phases of the machine can be seen in Fig. 6, demonstrating that this strategy controls the voltage in a resistive load with good accuracy and without large ripples in the current magnitude.

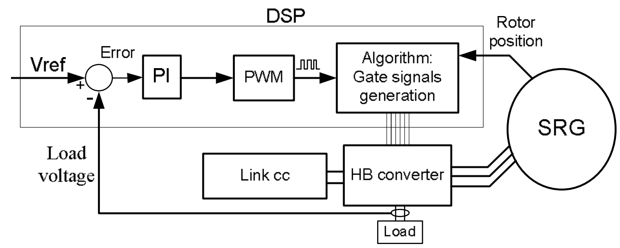

Fig. 4. Block diagram of the control strategy.

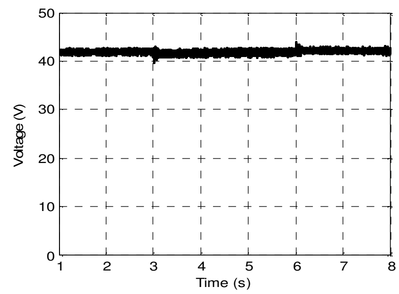

Fig. 5: Generated voltage.

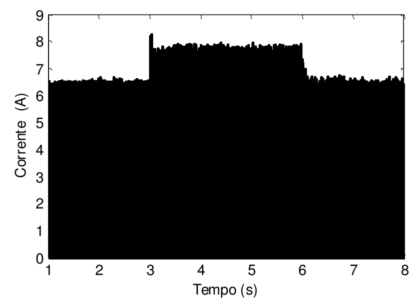

Fig.6: Current in one phase of SRISG.

Fig. 7 shows the characteristic of current and gate signal, applied to the superior switches of the converter, to one phase, when the SRISG was operating in the generator mode and in close loop using the described strategy. The signal of voltage in one phase can be visualized in Fig. 8.

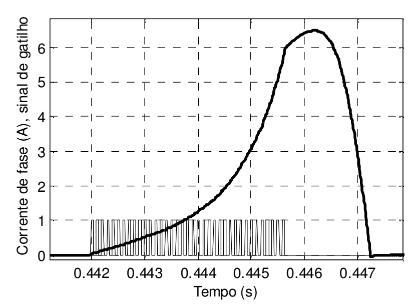

Fig. 7. Phase current and gate signal.

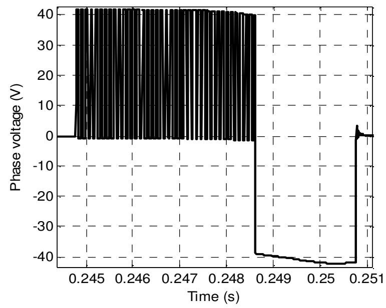


Fig. 8. Voltage in one phase of SRISG.

## V. EXPERIMENTAL RESULTS

A three phases, 1 HP, SRM prototype designed and constructed was used to get the experimental results. It was controlled to operate as generator. The half-bridge converter described in section two was implemented to drive this machine. A four poles, 2 HP, three-phase induction machine driven by a vector controlled inverter was used as the primary power source machine. The control of the SRISG was programmed using a TMS320F2812 fixed point DSP showed in Fig. 9. For all experimental results of the SRISG phase current, 1 V is equivalent to 4 A. The coefficients of the PI controller, used to implement the load voltage control strategy, ware set through trial and error. The value of $K_p$ is 2 and $K_i$ is 0.8.

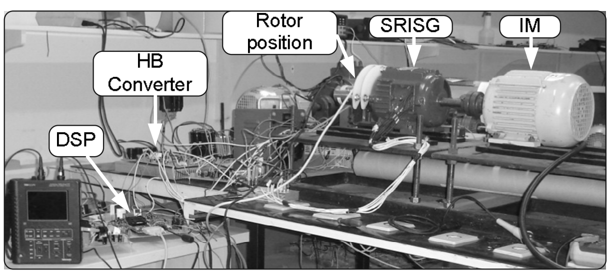


Fig. 9. Picture of the experimental setup.

Some preliminary experimental results were got using the strategy presented in Fig. 4. It is based on switching the excitation voltage applied to the phases during a fixed conduction angle, 30° for all the phases (fixed $\theta_{on}$ and fixed $\theta_{off}$), to control the magnetization of the phases. These results are presented in Fig. 10. It shows the load voltage response when the reference drops from 42V to 30V in a single step. As expected, the load current followed the voltage.

Otherwise Fig. 11 presents the curves of load voltage and current when the resistance of the load is reduced to 75% of its initial value. As seen the controller is able to keep the voltage at the set reference.

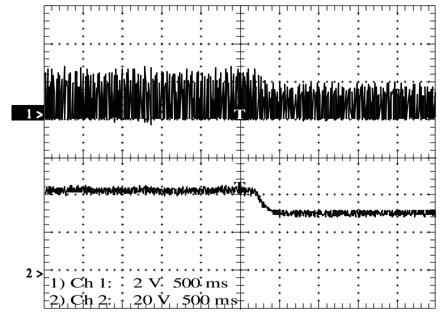


Fig. 10. Current magnitude and load voltage during a reference transient (1 V - 4 A).

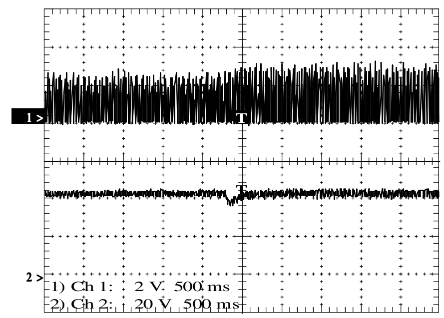


Fig. 11. Current magnitude and load voltage during a load transient.

Fig. 12 shows the PWM controlled gate signal (Fig. 4) of the upper switch of one phase (Q1 in phase A – Fig. 2 – for example) and the corresponding current responsible for magnetize the phase. When Q1 and Q2 are turned off the phase begins its demagnetization and the generation occurs in the remaining period of the cycle. The upper signal in Fig. 13 shows the voltage in the phase during one cycle, being the continuous negative signal of the generated voltage. The bottom signal corresponds to the Q1 gate signal.

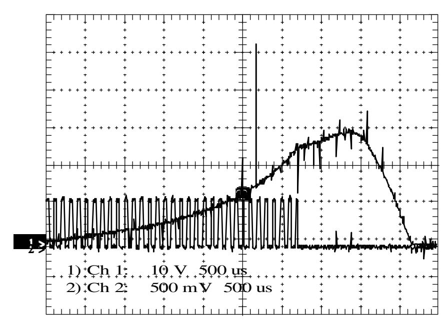


Fig. 12. PWM gate signal and current in one of the phases.

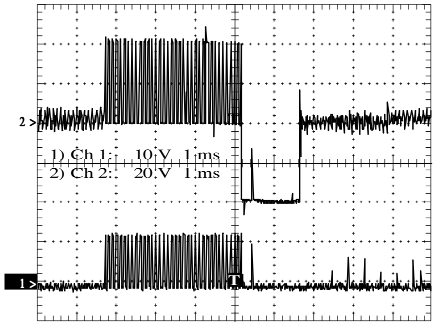


Fig. 13. Voltage in one phase and PWM gate signal.

Looking to Fig. 14 the behavior of the load voltage and phase current amplitude can be observed when the SRISG operates at a speed transient (800 rpm to 2200 rpm), demonstrating that the control strategy implemented also is efficient in speed transients. To investigate the efficiency of the control strategy proposed in this paper some tests were done.

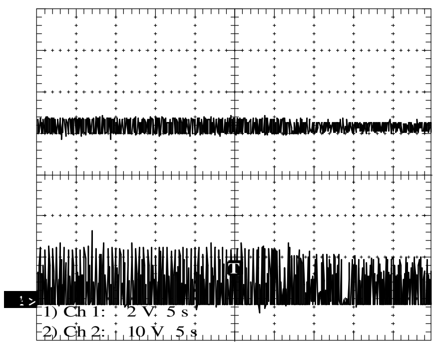


Fig. 14. Load voltage and current in one phase due SRG speed transient.

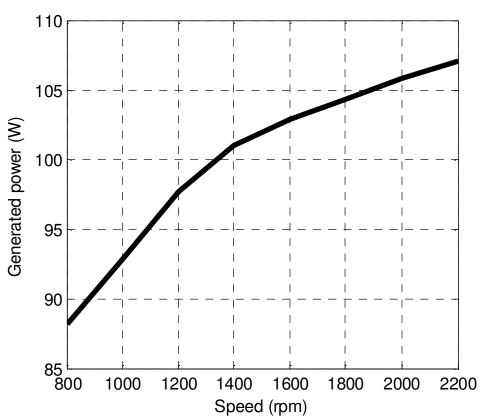


Fig. 15. Liquid power generated by the machine.

Fig. 15 depicts the curve of generated power by the machine for different speeds with 42 V of load voltage reference value and supplying a 20 Ω load. The power generated, converted from mechanical energy to electrical energy, is the power delivered to the load subtracted by the power-in (energy used to magnetize the phases) of the drive system. This curve indicate that, with the improve of speed, more mechanical energy is converted to electrical energy and lower electrical energy is used to magnetize the phases.

## VI. Conclusions

Operation of the 6x4 SRM in close loop load voltage was presented in this work. A strategy using PI controller to control de generated voltage applied to the load based on regulating the mean of the magnetization voltage was presented. It uses a PWM signal and it was implemented throw simulation using Mathlab/Simulink and tested using a fixed-point DSP board in a test bench. The results presented show that the strategy of close loop voltage control had a good performance during transients and so it can be used to implement an SRISG. More details of the prototype, experimentally analysis, characteristics and efficiency of the control strategy present in this work will be included in the final version.

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