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Drive the switched Reluctance Generator with mesh load Voltage Control

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Abstract. This paper will present a voltage control strategy applied to the load for a triphasic variable reluctance generator 6x4. The developed strategy is based on the use of a proportional integral controller which generates a reference signal for a hysteresis controller, used to control the magnetization current. This signal is proportional to the difference between the voltage applied to the load and its reference value. This strategy uses an internal current control loop which has as its main advantage the possibility to aggregate protection routines to the control strategy. The strategy was implemented and tested through computational simulation and experimentally using the DSP platform.

Key words

Switched reluctance generator, half-bridge converter, load voltage control.

1. Introduction

Known since the 19th century, the variable reluctance machine (VRM) showed a slow development, and it is placed among the machines that most favored themselves with the power electronics advance, sensoring, micro processing, and signal digital processing. Those characteristics made them more viable, trusty and efficient [1].

According to the electronic technology advances, variable reluctance machines became more competitive when compared with other types of machines [2], despite the fact that it works best in some specific applications. Those applications operate with variable speed [3], and always seeking electric machines working with the best efficiency [4].

The variable reluctance machine works following the maximum stored energy principle in a magnetic circuit, which means, least reluctance. In a simpler way, the drive systems for variable reluctance machines are made of an energy converter, a control system, and a measuring system for electric and mechanical values.

As said before, a variable reluctance machine has a good performance with variable speed, and this feature made the study of the machine promising for applications in wind power generation. The variable reluctance generator has become more competitive, and it is due the fact that the induction motor needs a power electronic converter to be turned on, and a commutation box to be able to regulate in a certain speed [5].

After a bibliographic search, it was found that the best converter for a VRM drive system operating as a generator would be the half-bridge, which is characterized for having two controlled switches in series with the machine phase, and two diodes that are used to demagnetize the coil of the phase after its own magnetization period.

It is hard to control the current during the operation as a generator, and that is because the back electromotive force in a generating operation works as a voltage source, which helps to increase the current flow through the phase. Even during the demagnetization, the current keeps going up, so it is necessary to set a voltage control strategy in the load unlike the motor operation.

Once the control strategies for the variable reluctance generator (VRG) were little explored, and since it is difficult to control, this article presents a study made using the VRG operating in a closed-loop voltage generated in the load. The designed strategy is presented, and validated over simulations and experiments.

2. Variable Reluctance Generator Characteristics

The principle of the variable reluctance machine uses the maximum stored energy fundament in the magnetic circuit, which means, least reluctance, and when a certain phase of the machine is energized, the rotor tends to shift to a position where the reluctance is minimal, and it corresponds to a position where the stator excited coil inductance is maximum [6].

The variable reluctance machine is basically made by laminated rotor and stator, with salient poles and coils restricted to it. There is a bunch of VRM configurations that can be studied. Figure 1 presents the structure of a tree-phase machine containing six poles in its stator and four poles in its rotor.

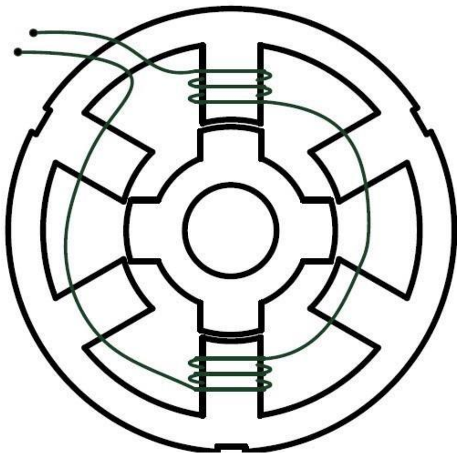

Fig. 1. Drawing of the 6x4 VRM transverse section showing one of the three phases' winding.

The variable reluctance machine is an electromechanical converter made of simple structure, and it can work either as a generator or motor, depending on the drive angle of the electronic converter switch as showed in figure 2 [7].

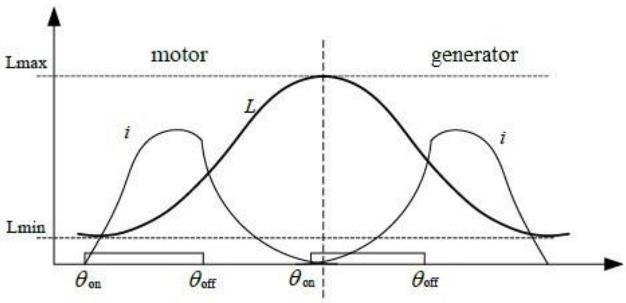

Fig. 2. Variation of VRM's one phase inductance

A. Mathematics Modeling

Working the equations, an equivalent elementary circuit can be obtained neglecting the mutual inductance between phases. So, the voltage in a winding terminals of a variable reluctance machine can be written as:

$$v = R_f i + \frac{\partial \lambda(\theta, i)}{\partial t} \quad (1)$$

Where v and i are the machine voltage and the current flowing in the machine windings, respectively, R_f is the winding resistance and $\lambda(\theta, i)$ is the flow enclosed by the winding. These parameters refer to one phase, and vary according to the rotor position in relation to time t, except the resistance R_f .

The current in the circuit relates to the magnetic flow through its own inductance, as can be verified:

$$\lambda(\theta, i) = L(\theta, i) i \quad (2)$$

Replacing the equation (2) in equation (1) and considering that L is a function of the rotor and current angular position (teta), in the time domain the voltage can be written as:

$$v = R_f i + L(\theta, i) \frac{\partial i}{\partial t} + i \frac{\partial L(\theta, i)}{\partial \theta} \frac{\partial \theta}{\partial t} \quad (3)$$

Considering that the rotor angular variation over time is the angular speed, the equation (3) can be written as:

$$v = R_f i + L(\theta, i) \frac{\partial i}{\partial t} + i \omega \frac{\partial L(\theta, i)}{\partial \theta} \quad (4)$$

The three terms on the right side of the equation (4) express the voltage drop in the winding resistance, the inductive voltage drop, and the back electromotive force dependent of the inductance variation in relation to the speed angular position and the current, respectively. That is why driving an VRM as a generator is complex [4].
Replacing the above equations in the input power equation results in:

$$pe = vi = R_f i^2 + L(\theta, i) i \frac{\partial i}{\partial t} + i^2 \frac{\partial L(\theta, i)}{\partial t} \quad (5)$$

Using terms already known, the above equation is:

$$pe = R_f i^2 + \frac{\partial}{\partial t}\left(\frac{1}{2} L(\theta, i) i^2\right) + \frac{1}{2} i^2 \frac{\partial L(\theta, i)}{\partial t} \quad (6)$$

The last term of this equation represents the air gap power, expressing the time in terms of rotor position and speed, the air gap power can be written as follows:

$$p_{ent} = \frac{1}{2} i^2 \frac{\partial L(\theta, i)}{\partial \theta} \omega_n \quad (7)$$

Once the air gap power is the electromagnetic torque times the rotor speed, it results that torque is given by:

$$c_{emag} = \frac{1}{2} i^2 \frac{\partial L(\theta, i)}{\partial \theta} \quad (8)$$

So, a general expression of torque per phase is:

$$c_{emag} = \frac{1}{2} i_a^2 \frac{\partial L_a}{\partial \theta} + \frac{1}{2} i_b^2 \frac{\partial L_b}{\partial \theta} + \frac{1}{2} i_c^2 \frac{\partial L_c}{\partial \theta} \quad (9)$$

The mathematics model of variable reluctance motor, considering the three phases is given in equation 10, where:

$$r_1 = \frac{1}{2} i_a^2 \frac{\partial L_a(\theta)}{\partial \theta} \qquad r_2 = \frac{1}{2} i_b^2 \frac{\partial L_b(\theta)}{\partial \theta} \qquad r_3 = \frac{1}{2} i_c^2 \frac{\partial L_c(\theta)}{\partial \theta}$$

$$\begin{bmatrix} v_a \\ v_b \\ v_c \\ C_m \\ 0 \end{bmatrix} = \begin{bmatrix} r_a & 0 & 0 & 0 & 0 \\ 0 & r_b & 0 & 0 & 0 \\ 0 & 0 & r_c & 0 & 0 \\ r_1 & r_2 & r_3 & -D & 0 \\ 0 & 0 & 0 & -1 & 0 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \\ \omega_m \\ \theta \end{bmatrix} + \begin{bmatrix} L_a & 0 & 0 & 0 & i_a \frac{\partial L_a(\theta)}{\partial \theta} \\ 0 & L_b & 0 & 0 & i_b \frac{\partial L_b(\theta)}{\partial \theta} \\ 0 & 0 & L_c & 0 & i_c \frac{\partial L_c(\theta)}{\partial \theta} \\ 0 & 0 & 0 & -J & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{i}_a \\ \dot{i}_b \\ \dot{i}_c \\ \dot{\omega}_m \\ \dot{\theta} \end{bmatrix} \qquad (10)$$

The matrices designated by [V],[R],[I],[L],[I] appear following the order in (10), so the state matrix of the variable reluctance motor has the form below:

$$\left[\dot{I}\right] = [L]^{-1}[V] - [L]^{-1}[R][I] \qquad (11)$$

B. Computational Modeling

In order to simulate the 6x4 variable reluctance machine operating as a generator, it was used the software Matlab/Simulink. The data related to the scaling of the simulated machine can be seen in table 1, and they come from a projected machine to do the experiments (Fig. 3). More details related to the modeling can be found in [4].

Fig. 3. Variable reluctance machine used to obtain the parameters to the simulation.

The variable reluctance generator, as any other electrical machine is an energy electromechanical converter. In order to get the variable reluctance motor to operate as a generator, it is necessary to magnetize the machine phases during the decreasing of the inductance value in relation to the variation of rotor position.

Table I. - Parameters of the variable reluctance machine.

Parameters	Value
Conduction Angle	30 degrees
Viscous Friction	0.026 N.m.s
Breech Stator	12 mm
Breech Rotor	12,4 mm
Laminated battery's Length	107 mm
Stator Teeth	22,5 mm
Rotor Teeth	11,7 mm
Stator Diameter	140 mm
Rotor Diameter	70 mm
Air Gap	0,4 mm
Inductance (aligned position)	36 mH
Inductance (misaligned position)	3 mH
Stator Teeth's Width	19 mm
Rotor Teeth's Width	20 mm
Moment of Inertia	0,0028 kg.m^2
Number of Coils per Phase	100 turns/phase

The figure 4 shows the block diagram of the half-bridge converter adapted to a variable reluctance motor to operate as a generator. The figure 5 represents the magnetization circuit, free-wheeling, and demagnetization of the variable reluctance machine phases operating as a generator, respectively.

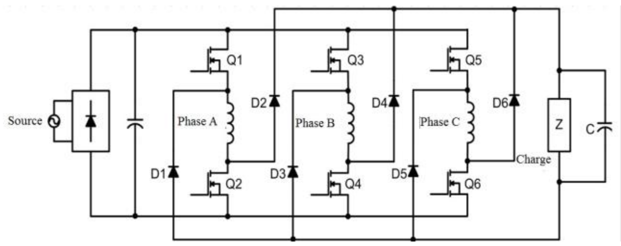

Fig. 4. Block diagram of the *half-bridge* converter computational simulation.

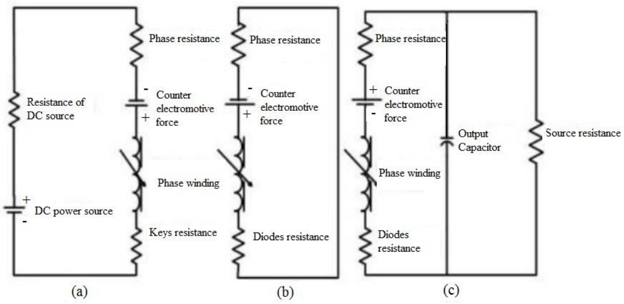

Fig. 5. Demagnetization circuit, free-wheeling circuit, and coils demagnetization circuits.

C. Variable Reluctance Generator Control

The current control of the variable reluctance machine during its operation as a generator is a hard task, once the back electromotive force is a voltage source acting to increase the current flow in the phase. Even during the demagnetization step the current keeps growing, and it is necessary a voltage control strategy in the load, different from the motor operation.

The variable reluctance generator can be controlled to produce a desired power in the load, what happens in applications where it is interesting to use the variable reluctance generator operating in its great point [7], or it can be controlled to produce a constant voltage in the load side, changing the power when the resistance load changes. For embedded systems, for example, it is necessary to avoid big changes in the direct current at the bus voltage.

Given these information, and aiming to check the variable reluctance generator's operability while operating in voltage closed-loop generated on the load side, a strategy to control it based on the use of a hysteresis magnetization current controller, will be presented, simulated and experimentally tested.

The strategy of voltage control on the load for the variable reluctance generator uses a IP controller, in order to generate a reference signal to the hysteresis controller, used to control the magnetize current in each phase. This signal is proportional to the error between the voltage reference on the load, and its calibrated value as shown in figure 6.

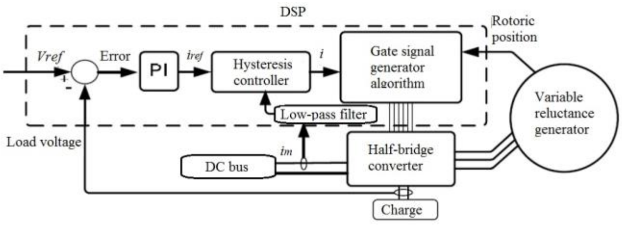

Fig. 6. Block diagram of voltage control on the load.

From the figure we can see that the outermost mesh - responsible for the voltage control on the load, it generates a reference signal to the internal mesh hysteresis controller, which has to control the current that comes from the cc bus (im), used to magnetize each phase. Though, for a better operation of the current controller, the magnetization current flows through a low-pass filter to introduce a little delay in the input current signal.

The delay is needed because of a switched voltage is injected when magnetizing the variable reluctance generator of the phases, and that way, the current im used for magnetization goes down to zero instantly when the upper switch related to one phase opens. When the low-pass filter goes in it is permitted to use the hysteresis controller in an effective way, and a proper switching.

3. Simualtions Results

In order to validate the developed strategy, tests and simulations were done following few criteria: the variable reluctance generator operated in closed-loop, and it was controlled using the control strategy described in this article. The cc bus voltage that feeds the half-bridge converter was set to 42 V, and an operation speed of the machine set to be constant at 1350 rpm. The machine was tested for eight seconds, and submitted to a load transitional resistance coupled to the variable reluctance generator, where the resistance was reduced from 20 ohms to 15 ohms in three seconds, and after six seconds the load resistance came back to its initial value.

From figure 7, it is noticed that in the whole simulation the control kept the voltage in the load with a value close to the reference of 42 V.

The figure 8 shows the phases' amplitudes currents of the variable reluctance generator that was simulated for eight seconds. While the variable reluctance generator was operating according to the control strategy, the current phase fluctuated, however from figure 7 it can be seen that those oscillations do not affect the oscillations found in the voltage load signal.

The figure 9 shows the current curve from one of the phases along with a gate signal to a phase magnetize cycle, where it verifies the gate signal applied to the converter upper switch related to the certain phase to get the free-wheeling, what improves the electrical energy capacity.

It can be observed from figure 10 that the voltage signal in one of the three phases, from the variable reluctance generator feeds the resistive load of 20 ohms.

From figure 11 we can observe the input and output electrical power curves from the variable reluctance generator. It is verified that the VRG controlled by the strategy based on the utilization of the hysteresis-type magnetization current controller generates about 65 W, and it feeds a 20 ohms load.

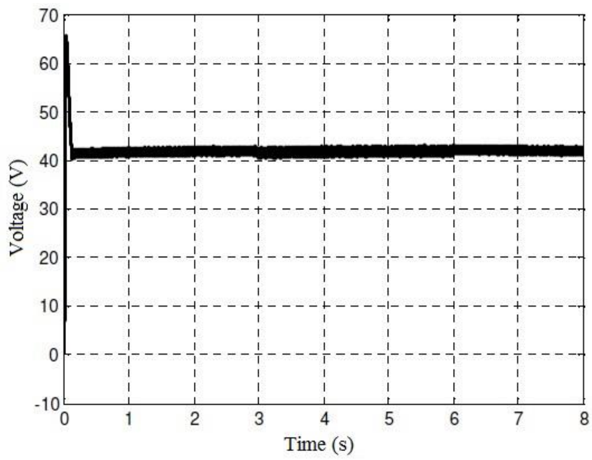

Fig.7. Voltage curve on the load during the transitory test of the load resistance (20 Ω - 15 Ω).

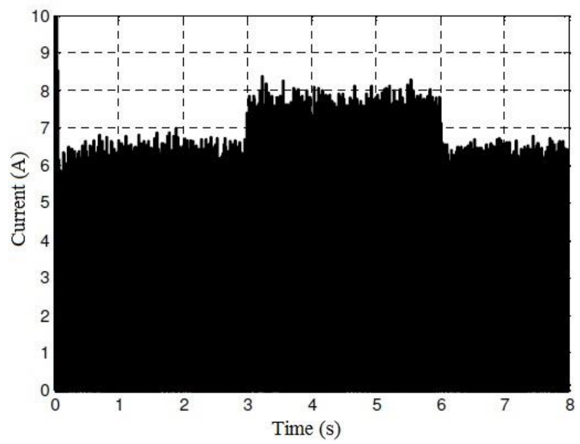

Fig. 8. Current curve in the phases during the simulation with load transitory.

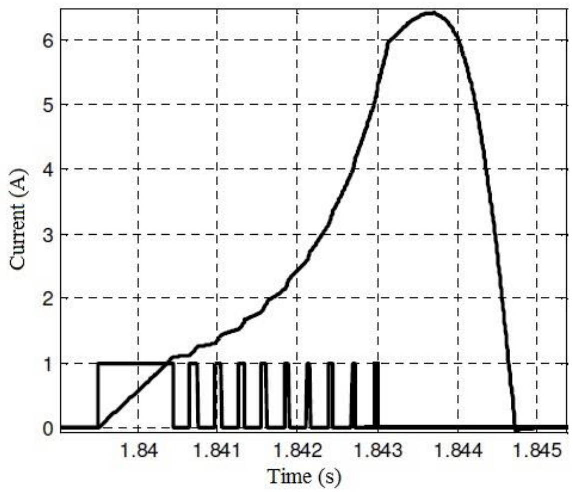

Fig. 9. Current curve, and gate signal to one of the VRG's phases.

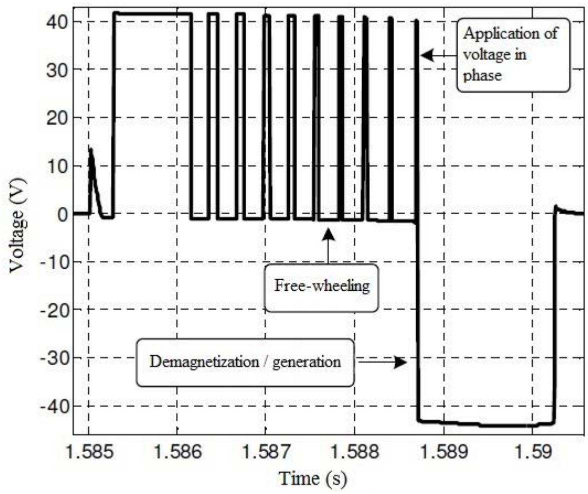

Fig. 10. Voltage curve on phase A.

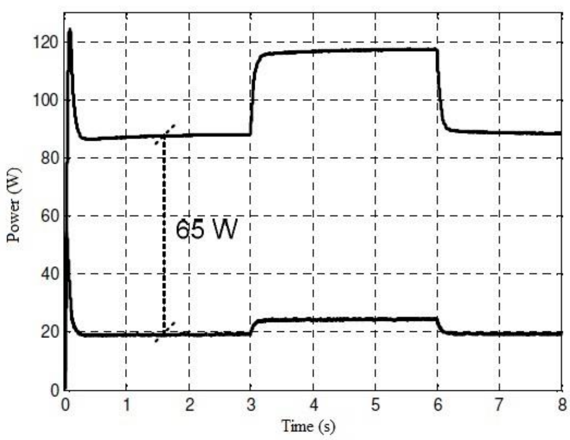

Fig. 11. VRG's input and output power.

This strategy of the voltage control on the VRG load uses an internal mesh of current. The perk of having this current mesh is the possibility of adding protection routines to the control strategy, and it will reduce the generator's magnetization in case the phase current get high values.

4. Experimental Results

In order to validate the control strategy used in the experiment, the VRG described before was coupled to a 2cv and 4 poles three-phase inductive motor, driven by a converter. The BH converter was built to drive the VRG, and the control strategy was set to be executed in a DSP TMS320f2812, used in the system. The position of the rotor, required to the application of the gate signals during the phases' magnetization period, was obtained using optic sensors combined to a disc. This disc represents the correct moment when each phase needs to be magnetized. The figure 12 shows a picture from the place where the test was done, in the lab.

The control strategy uses a IP controller, where it is necessary to convert this controller’s equation to the discrete-time domain, this way the controller could be implemented in the processor used. The equation of number 12 describe the controller in its discrete form.

$$U_{k+1} = K_p.E_{K+1} + K_p.\left(\frac{K_i}{K_p}.T_s - 1\right).E_k + U_k \qquad (12)$$

The IP controller used in the developed strategy was tuned using trial and error, and the coefficients were: Kp = 0.5 and Ki = 0.1.

The low-pass filter used to filter the input signal current of the half-bridge converter is represented by Laplace as shown in equation 13. This filter must be rewritten as a difference equation using the Z transforms (equation 14), in order to digitalize it.

$$S = \frac{2}{T_s}\frac{z-1}{z+1} \qquad (13)$$

$$U_{k+1} = \frac{\omega_c T_s}{2+\omega_c T_s} I_{k+1} + \frac{\omega_c T_s}{2+\omega_c T_s} I_k + \frac{2-\omega_c T_s}{2+\omega_c T_s} U_k \qquad (14)$$

Were Uk+1 is the filtered signal, Ik+1 is the input signal, Ik is the input signal in the previous sampling, Uk is the filtered signal in the previous sampling, and Ts is the sampling period.

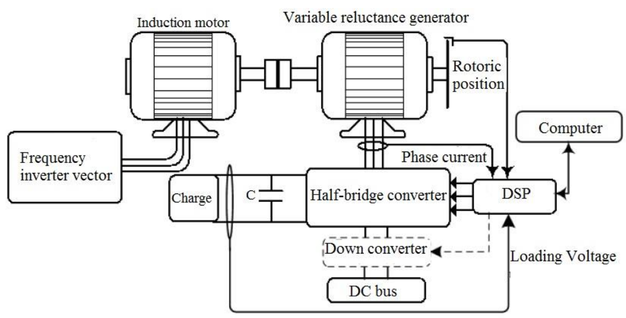

Fig.12. Experimental bench overview.

The figure 13 shows one of the phases' current curves of the machine, and the voltage curve on the load side, in a test where the transitional reference goes from 42V to 30V. The control kept the voltage signal on the load side close to the reference value, and once analyzing the current signal in the phase it is observed the presence of amplitude oscillations that reflects the voltage signal on the load.

From figure 14 we can observe the voltage curves on the load, and the current in one of the generator's phases to testing with load transitional from 20 ohms to 15 ohms. The control keeps the voltage value on the load close to the reference value, however, when the load increases, the same thing happens to the current and voltage amplitude oscillations.

The figure 15 shows the current curves in one of the phases, and its respective gate signal of the upper switch to the VRG while operating with a 20 ohms load, and reference of 30V.

From figure 16, the voltage signal in one of the VRG's phases, and its respective gate signal is applied to the converter upper switch related to this phase.

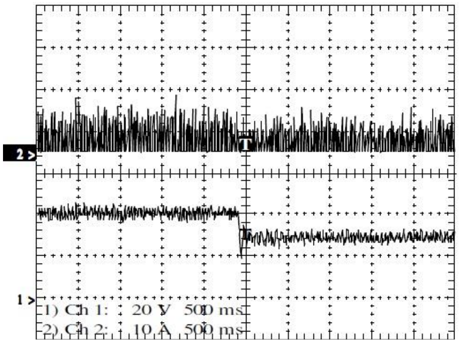

Fig.13. Current curve of one of the phases, and the controlled VRG's voltage curve on the load to be tested with transient reference.

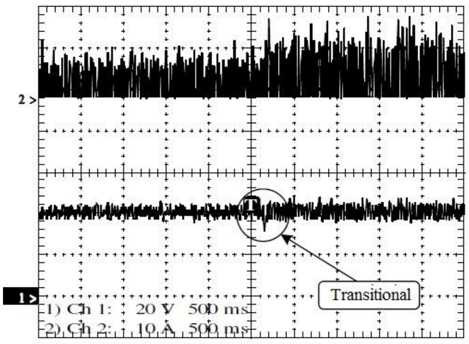

Fig.14. Current and voltage curve of one of the phases, and the controlled VRG's voltage curve on the load to be tested with transient load.

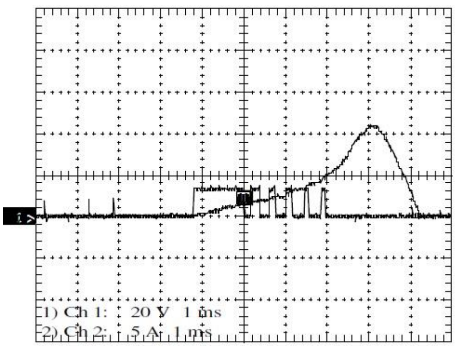

Fig. 15. Current curve of one of the VRG's phases, and the respective gate signal of the converter upper switch related to this phase.

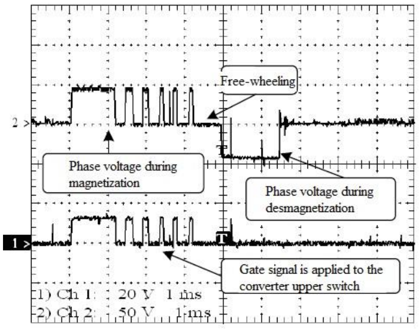

Fig. 16. Voltage curve in one of the phases, and the respective gate signal with 20 Ω load, and reference of 42V.

5. Conclusion

This article studied the 6x4 variable reluctance machine's operation, while working as a controlled generator in voltage closed-loop on the load side. It was tested a voltage control strategy on the load based on the use of a hysteresis magnetization current controller, through the simulation of an assembled prototype, and using a fixed point DSP. The results show that this technic controls the VRG very well, keeping the voltage value close to the reference, and presenting good results, especially when working with higher speed.

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