A SRM for a PV Powered Water Pumping System Based on a Multilevel Converter and DC/DC Dual Output Converter

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Abstract- This paper focuses on a proposal for a system based on a photovoltaic (*PV*) supply for a powered water pumping. The system consists in a switched reluctance machine (*SRM*) controlled by a multilevel converter and fed by *PV* panels associated to a *DC/DC* converter. The multilevel power converter proposed to control the *SRM* was designed to minimize the switches and to support the balance of the two input capacitors. The *DC/DC* converter consists in a hybrid solution that merges a Buck-Boost converter with a *Sepic* converter. They use a topology solution in which the input current presents a reduced ripple and only requires one switch. This *DC/DC* converter is also characterized by a dual output to adapt to the multilevel converter. The control system and a maximum power point tracking (*MPPT*) algorithm are also presented. The operation of this system will be verified by tests that are done by computer simulations.

Keywords- Water pumping system, *PV*, *SRM*, *DC/DC* converter, Dual output.

1. INTRODUCTION

Water pumps are used in almost all the places. They are used in industry, commerce, agriculture and residential. One of the applications in which this system is extremely important but where there are problems regarding the electrical power supply is in rural and remote areas. In order to overcome these problems these systems have been associated with solar photovoltaic (*PV*) supply [1-4]. The system consists of several components, being the electrical machine one of them. There are many types of electrical machines that can be used in this system. However, one of the machines that have been considered very interesting for this application is the switched reluctance machine (*SRM*) [5-9].

To control and to feed the *SRM* a power electronic converter should be associated with it. Several power electronic converters have been proposed for this machine. Most of the topologies that have been used and proposed are characterized by two voltage levels [10,11]. However, in the last years, many multilevel topologies have also been proposed. Some of these topologies are a derivation of the classical multilevel topologies used in inverters, like the Neutral Point Clamped Asymmetric Half-Bridge (*NPC-AHB*) and asymmetric flying capacitor [12,13]. However, other topologies have been proposed, having some of them the purpose to reduce the number of switches [14-17]. Nonetheless, the minimization of the switches could affect the performance of the motor. For example, the topology described in [15] does not allow independently magnetizing and demagnetizing of motor windings. In this way, it is not possible to demagnetize the motor winding with the maximum voltage, by which there is an increase of the torque ripple.

Another aspect associated to these *PV* Powered Water Pumping System is the *DC/DC* converters connected to the *PV* panels and associated to a maximum power point algorithm (*MPPT*). Many *DC/DC* converters have been proposed for these *PV* systems [18-20]. However, many SRM drives, inclusive with multilevel topologies, require *DC/DC* converters with dual output. Thus, several topologies with this characteristic have been presented [21 23]. Nevertheless, integrated solutions in which an *SRM* drive with a multilevel topology is used have been scarcely addressed.

In this paper, an integrated solution for *PV* powered water pumping system with a *SRM* is proposed. The proposed solution is comprised by a *SRM* drive with a multilevel topology and a *DC/DC* converter with a dual output. The multilevel topology is designed with a reduced number of switches but without losing the capability to independently magnetize and demagnetize two motor windings and maintain the balance of the *DC* power supplies. The *DC/DC* converter is also designed to use a reduced number of switches, presented Buck-Boost characteristic and provide reduced input current ripple. The solution will be tested by results obtained by simulations.

2. POWER CONVERTER SYSTEM FOR THE PV POWERED WATER PUMPING

The application under consideration is a *PV* powered water pumping system. For this system the *SRM* was adopted as the electrical machine. To control this machine a multilevel converter is proposed. Between the *PV* modules and this converter a *DC/DC* converter with dual output was adopted. The full scheme of the power electronic converters for this system is presented in Fig. 1. The multilevel converter requires 14 fully controlled power switches. It is designed in a way that helps the balance of the capacitors of the *DC/DC* converter. On the other hand, the *DC/DC* converter requires only one fully controlled power switch. This converter can be seen as the merge of a Buck-Boost with a Zeta converter. In this way it will be obtained a Buck-Boost characteristic. However, it was designed to provide continuous input current which is important for the *PV* panel. Although it uses only one switch, it provides a dual output to connect the *SRM* drive.

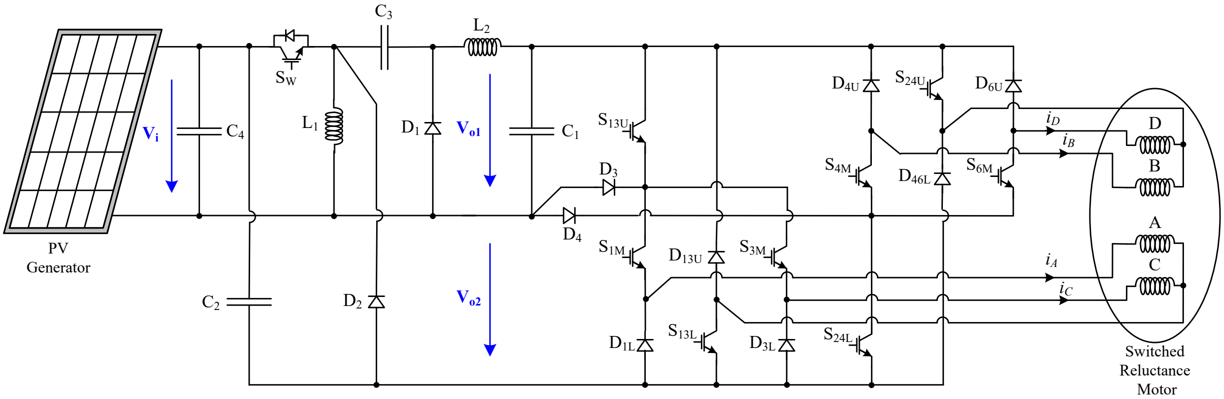
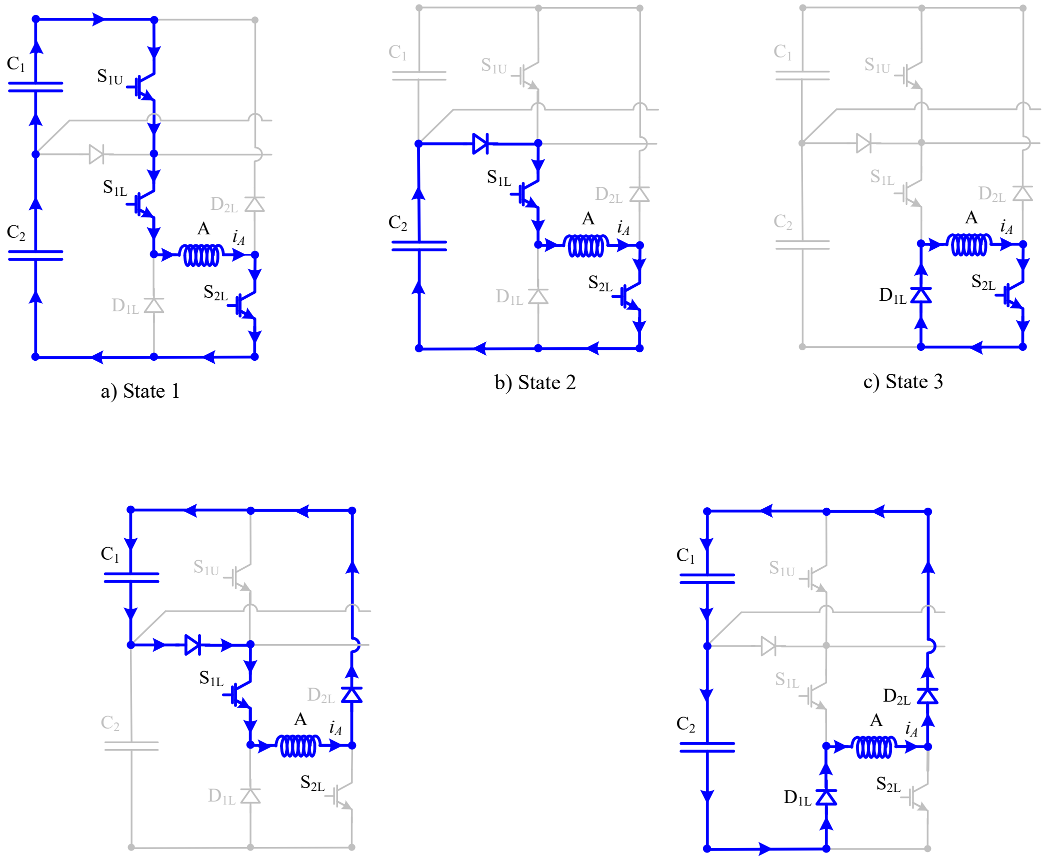


Figure 1. Full scheme of the power electronic converters for the *PV* powered water pumping system.

Analysing the proposed multilevel converter to control the SRM, it is possible to verify that associated to each motor winding there are five possible states. Those five states can be seen in Fig. 2, where is possible to verify that in accordance with the switch conditions different voltages are applied to the motor winding. The different voltages that are possible to apply are ($+V_{o1}+V_{o2}$), ($+V_{o1}$), 0, ($-V_{o1}$) and ($-V_{o1}-V_{o2}$). So, if S_{13U}, S_{1M} and S_{13L} are *ON* the maximum positive voltage is applied to the motor winding. If switches S_{1M} and S_{13L} are *ON* then the intermediate positive voltage is applied ($+V_{o1}$). If only S_{13L} is *ON* the zero voltage level is applied. In the case of only S_{1M} is *ON* then the intermediate negative voltage level is applied ($-V_{o2}$). Finally, if none of the switches is *ON* then the maximum negative voltage is applied ($-V_{o1}-V_{o2}$).



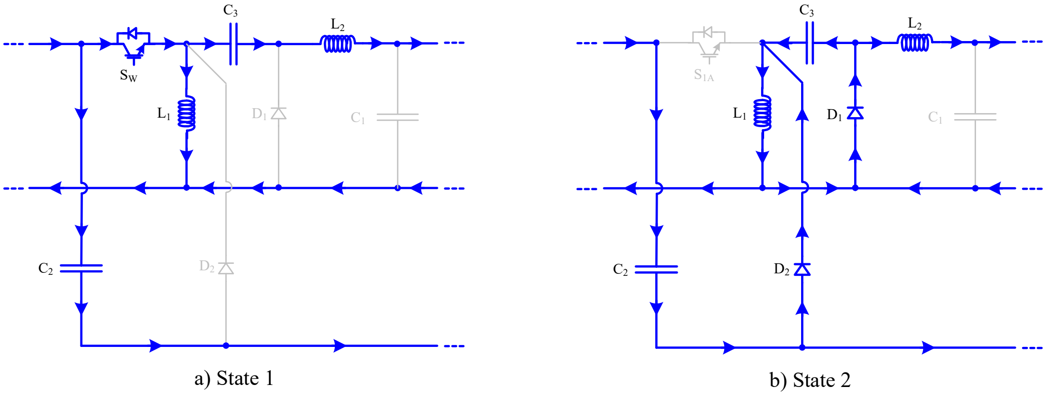
a) State 1 b) State 2 c) State 3

d) State 4 e) State 5

Figure 2. Possible states for the proposed multilevel converter.

Regarding the proposed DC/DC converter, considering that it operates in continuous conduction mode (CCM) there are only two possible states. These two possible states are presented in Fig. 3. So, the first state is when the switch SW is ON. In this case the energy is transferred to the inductors L1 and L2 by which the current through them will increase. Capacitor C_2 will discharge for the load and capacitor C_3 will be charged.

When the switch SW turns OFF the inductors will be discharged. In this way, the currents through them will decrease. Capacitor C_2 will now be charged and the current through them will flow through inductor L_1. Regarding capacitor C_3 the current through it will also flow through inductor L_1 and diode D_1.



a) State 1

b) State 2

Figure 3. Possible states for the proposed DC/DC converter.

The static voltage gain of this *DC/DC* converter in *CCM* can be obtained considering that the average voltage in the inductors over one cycle is zero, by which:

$$\begin{cases} \frac{1}{T}\int_0^T v_{L_1}dt = \frac{1}{T}\left[\int_0^{\delta T}(V_i)dt + \int_{\delta T}^{T}(-V_{C_2})dt\right] = 0 \\ \frac{1}{T}\int_0^T v_{L_1}dt = \frac{1}{T}\left[\int_0^{\delta T}(V_i)dt + \int_{\delta T}^{T}(-V_{C_3})dt\right] = 0 \\ \frac{1}{T}\int_0^T v_{L_2}dt = \frac{1}{T}\left[\int_0^{\delta T}(V_i - V_{C_3} - V_{o1})dt + \int_{\delta T}^{T}(-V_{o1})dt\right] = 0 \end{cases} \tag{1}$$

Solving the integral expressions given by (1) it is possible to determine the average voltage at each converter output:

$$\begin{cases} V_{o1} = \frac{\delta}{1-\delta}V_i \\ V_{o2} = \frac{\delta}{1-\delta}V_i \end{cases} \tag{2}$$

3. CONTROL OF THE PROPOSED SYSTEM

As verified before, this system consists in several components, by which there is the need to implement several controllers. In Fig. 4 the full system is presented, in which it is possible to verify that there is a controller for the *DC/DC* converter and a controller for the motor converter. The controller for the *DC/DC* converter should take into consideration the maximum power point algorithm (*MPPT*) in order to extract the maximum energy from the *PV* panels. The balance between the energy that is generated by the *PV* panels and the motor consumption is ensured by a voltage controller. This controller will maintain the output voltages of the *DC/DC* converter stable at a reference value.

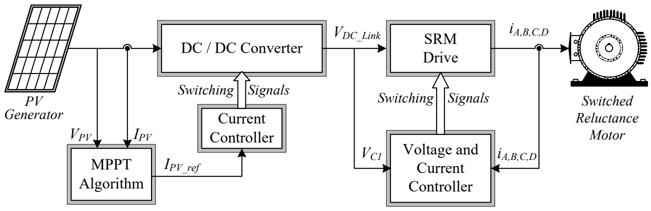


Figure 4. Full scheme of the power electronic converters for the PV powered water pumping system.

In order to extract the maximum energy from the *PV* panels, many *MPPT* algorithms have been developed. The ones that are considered as classical are the *Perturb & Observe* [25] and the incremental conductance [26]. There are many other algorithms but their complexity is being increased. In this work, the development of an algorithm that maintains the simplicity of those ones, but can be implemented through a simple integral was adopted. It is based on the time derivative of the power and voltage by which singularities are avoided. When the derivative of power with voltage or current is used, singularities can appear [24-26]. In this case, the control of the *DC/DC* converter attached to the *PV* panels through its input current was adopted. In this way, the *MPPT* should give the input current converter reference. The current controller will be the simple hysteretic controller.

For the proposed *MPPT* it is considered the *PV* panel characteristic, namely the shifting of the operating point taking into consideration the variation of the power and voltage. In accordance with this it is possible to conclude about which variation should have the *PV* panel current in order to move to the maximum power point (*MPP*). This can be defined by the following conditions:

$$\begin{cases} \left(\dfrac{dP}{dt} > 0 \; and \; \dfrac{dV}{dt} > 0\right) or \left(\dfrac{dP}{dt} < 0 \; and \; \dfrac{dV}{dt} < 0\right), decrease \, I_{PH} \\ \left(\dfrac{dP}{dt} > 0 \; and \; \dfrac{dV}{dt} < 0\right) or \left(\dfrac{dP}{dt} < 0 \; and \; \dfrac{dV}{dt} > 0\right), increase \, I_{PH} \end{cases} \tag{3}$$

The *MPPT* will then be developed from the conditions described by (1). In fact, in accordance with this, it is possible to establish a law, function of the time derivative of the power and voltage that defines the *MPPT*. This can be ensured by the control law for the reference current definition expressed by (4).

$$d = k\int \frac{dP}{dt}\frac{dV}{dt}\,dt \tag{4}$$

The control law given by (4) can even be simplified considering the signal of the two derivatives. Thus, the *MPPT* will be defined by the control law (5). The advantage of this control law is that its implementation is very simple and can stay at the *MPP* of the *PV* panel.

$$d = k\int sign\left(\frac{dP}{dt}\right) sign\left(\frac{dV}{dt}\right) dt \tag{5}$$

Another aspect that should be addressed is the balance of the energy that is generated and the one that is delivered to the load. This will be achieved through the stabilization of the output voltages of the *DC/DC* converter. A controller is developed to control that voltage, function of the *SRM* currents. Thus, a voltage controller that will give the current references of the *SRM* is used. For this voltage controller it was adopted a *PI* compensator. The motor currents will be defined by a typical hysteretic controller. This voltage controller, associated to the *SRM* controller, is presented in Fig. 5.

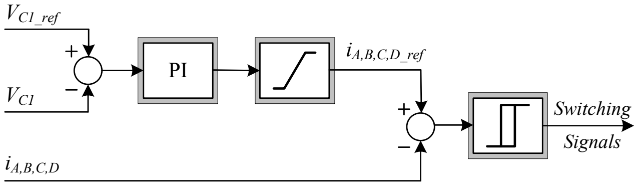


Figure 5. Voltage controller associated to the *SRM* controller.

4. SIMULATION RESULTS

The proposed integrated solution for *PV* powered water pumping system with a *SRM* was simulated by the Matlab/Simulink program. The parameters that were used for the *DC/DC* converter and multilevel converter are presented in Table I. The reference for the voltages of each output is 200 V. At the input of the *DC/DC* converter it was connected five *PV* panels in serial connection. The characteristics of each *PV* panel used in this pumping system can be seen in table II.

Initially the system was tested for an irradiance of 600 W/m2 and considering a temperature of 25 ºC. The results of the voltage applied to winding A and currents in all windings are presented in Figs. 6 and 7. These figures show the multilevel characteristic (voltage) of the *SRM* converter and that the currents in the motor windings are completely controlled. Another result that is presented and related with this first test is the output voltages of the *DC/DC* converter (applied to the *SRM* drive). Fig. 8 shows this result, being possible to verify that 200 V is obtained at each output and that they are balanced.

Table I: Power converters and *SRM* used in the pumping system characteristics

Parameter	Value
Inductor (L1)	5 mH
Inductor (L2)	5 mH
Capacitor (C1)	20 µF
Capacitor (C2)	1000 µF
Capacitor (C3)	1000 µF
SRM	8/6

Table II: *PV* panels used in the Pumping System Characteristics

Electrical performance under STC	
Maximum Power	320 W
Maximum Power Voltage	37.4 V
Maximum Power Current	8.56 A
Open Circuit Voltage	46.7 V
Short Circuit Current	9.10 A

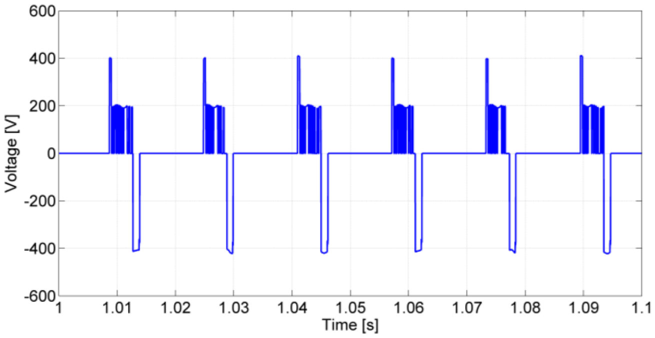


Figure 6. Voltage across winding *A* of the *SRM*.

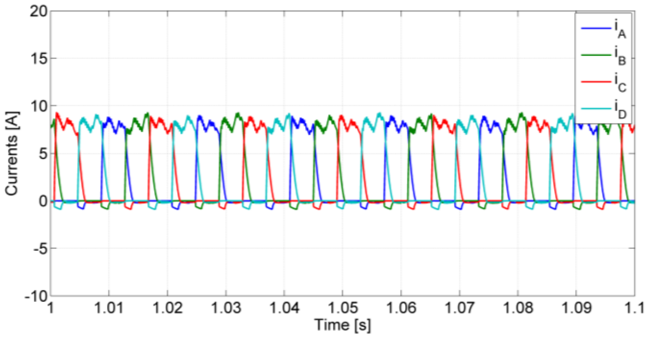


Figure 7. Currents through the winding of the *SRM*.

Another test was realized to verify the voltage control associated to the *SRM*. In Fig. 9 the output voltages of the *DC/DC* converter when the system is suddenly connected is shown. Although the capacitors of the *DC/DC* converters are initially discharged (zero output voltage) the voltages applied to the *SRM* converter will rise from zero to the reference value (200 V). It is also possible to confirm that these two voltages became balanced.

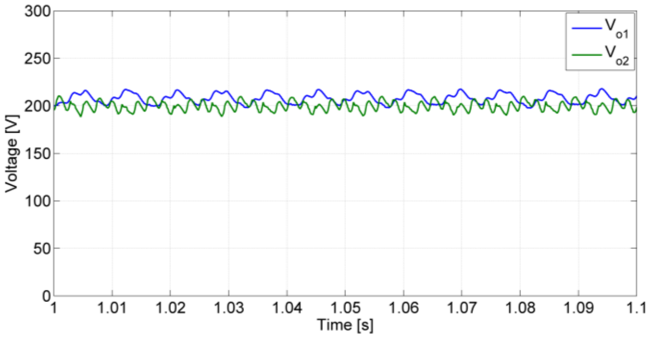


Figure 8. Voltages applied to the multilevel converter.

To see the behaviour of the proposed *MPPT* a transient test was also developed. In this case it was considered that initially the system is disconnected and suddenly became connected. As shown by the result presented in Fig. 9, the performance of the proposed *MPPT* is very interesting. In fact, it is possible to verify that during the turn on of the pumping system the generated power increases immediately to the *MPP*. Moreover, it stays stable at that point. The stabilization of the voltages applied to the multilevel converter during this turn on process of the system is also shown in Fig. 10. Again, it is possible to conclude that after the transient process those voltages stabilize in the reference value and in a balanced way.

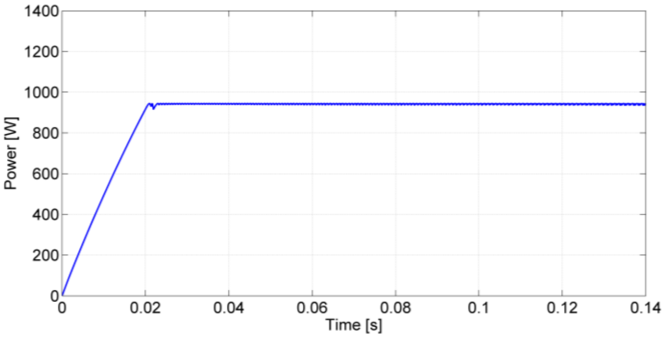


Figure 9. *PV* power during the turn on of the system.

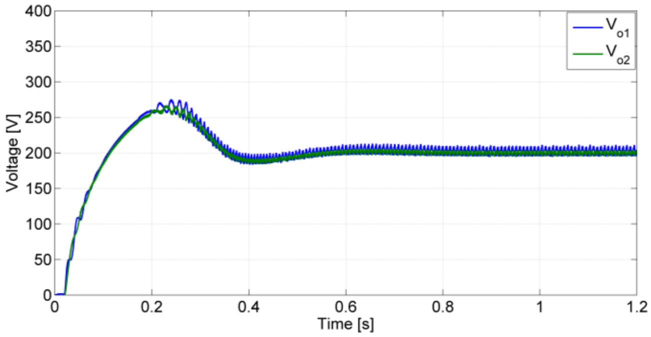


Figure 10. Voltages applied to the multilevel converter during the turn on of the system.

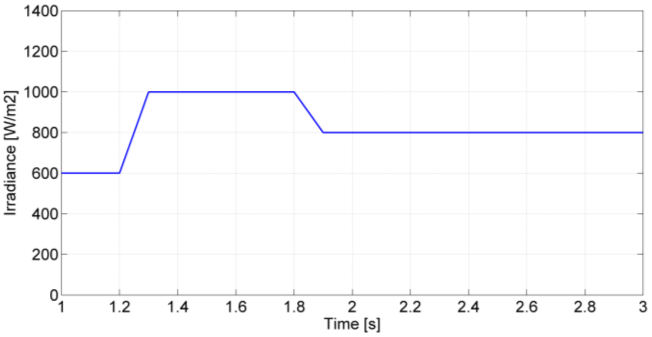


Figure 11. Profile of the solar irradiation applied to the *PV* panels.

Tests with changes in the applied solar irradiance to the *PV* panels were also performed. The result of a test in which the performance of the pumping system was analyzed is shown in Figs. 11 to 13. In Fig. 11 the variation of the applied solar irradiation is presented, namely starting with 600 W/m2, changing to 1000 W/m2 at 1.2 s and changing again to 800 W/m2 at 1.8 s. The obtained result for the *SRM* motor speed is presented in Fig. 12. This figure shows that with the increase of the irradiance the motor speed also increases. When the applied irradiance decreases the motor speed also reduces. Finally, in Fig. 13 it is presented the output voltages of the *DC/DC* converter, being possible to confirm that they maintain stable and balanced although there are some perturbations when there is a change in the irradiance.

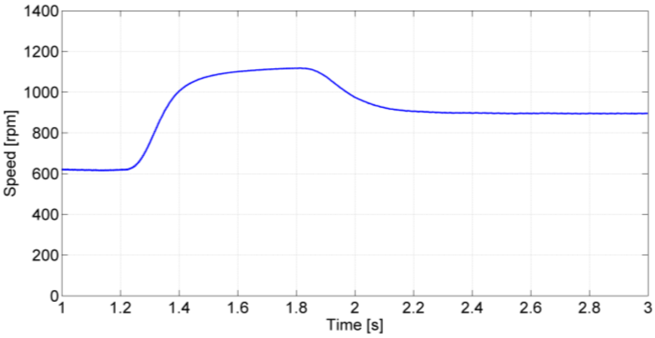


Figure 12. Speed of the *SRM* for the irradiation defined in Figure 11.

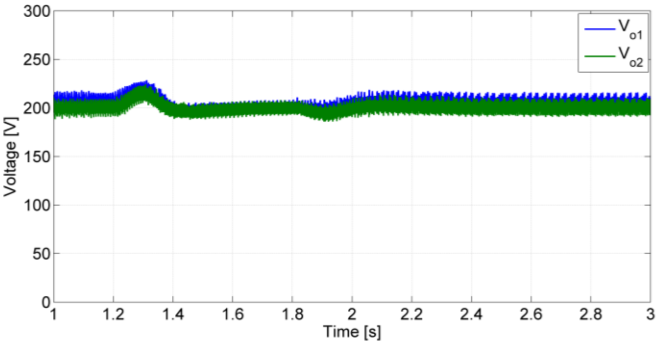


Figure 13. Voltages applied to the multilevel converter for changes in the irradiation.

5. CONCLUSIONS

This paper focused on a proposal regarding an integrated solution for *PV* powered water pumping system with a *SRM*. The proposed solution is composed by a *SRM* drive in which a multilevel topology and a *DC/DC* converter with a dual output are used. The proposed converter for the *SRM* drive, besides the voltage multilevel characteristics, was also designed with the purpose to reduce the number of switches but without losing the capability to independently magnetize and demagnetize two motor windings and maintain the balance of the *DC* power supplies. On the other hand, the *DC/DC* converter was also designed to use the minimal number of switches. Thus, a *DC/DC* converter with *Buck-Boost* characteristics and dual output that uses a single switch was proposed. Another feature associated to this system was the proposed *MPPT*. This algorithm is based in a control law that is function of the time derivative of the power and voltage. It resulted in a simple algorithm that easily can be implemented. Several tests were performed from computer simulations and showed the capabilities of the proposed *PV* powered water pumping system with a *SRM*.

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