Photovoltaic Water Pumping System for Small Power Conventional AC Pumps

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Abstract. The interest of photovoltaic (PV) water pumping systems with standard components is increasing as a low cost and independent solution over dedicated systems. However, one of the challenges of this alternative is the fact that small power systems to drive power pumps require a small number of PV modules and the PV string voltage is, usually, not enough to feed the frequency converter. This paper presents an approach to the drive, using a DC/DC converter with maximum power point tracking (MPPT). The overall system has been tested on a real experimental platform.

Keywords: Water Pumping System, Conventional Components, Low Power Pumps, Maximum Power Point Tracking

1 Introduction

The use of photovoltaic energy for water pumping systems is a solution that has been widely researched and implanted [1], [2]. DC motor driven pumps are already in use in several countries, but some problems (mostly maintenance due the presence of commutator and brushes) have made researchers to find other solutions [3].

One of this solutions is a water pumping system equipped with AC motors due to their advantages, mainly their reliability and low cost [2]. However, one problem is the fact that the market is being controlled by few manufacturers able to afford the continuous technology development, causing low spare availability and relatively high prices for dedicated systems [4]. Hence, AC drive systems with fully standard components become attractive [4], [5].

Dedicated PV water pumping systems are formed typically by a power converter, DC motor and PV string for power generation. Low power PV water pumping systems based on standard AC motors are not usual, because a higher voltage is needed to power the motor, which requires a string with a large number of PV modules. Standard Frequency Converters (SFCs) and AC motors are extensively used in industrial applications and they have been seldom used in PV water pumping systems [4], [5]. The main advantages of this approach in comparison to dedicated systems include manufacturers' independence and better component availability, lower cost because the components are manufactured in large quantities and increased reliability of the system because they are designed to work in industrial environment [5].

SFCs are produced for AC standard voltage of the grid (single or three-phase) and, therefore, needs a minimum voltage level on their DC-link for proper operation. One initial problem is the fact that a large number of PV modules are needed to reach this minimum operating voltage. For small power systems, where the power of the motor is below 1,5 kW, this large number of PV modules implies a high value of surplus power installed. On the other hand, the number of necessary PV modules to generate the rated power of the pump implies a undervoltage value to operate the SFC. Another problem, pointed by Ramos [5], is the lack of maximum power point tracking (MPPT). This paper presents an approach with a DC/DC converter as a solution of these two problems. The proposed solution integrates a step-up converter with MPPT which has been implemented is implemented using a real platform.

2 Photovoltaic Water Pumping System

As demonstrated by Abella [4], a PV array can be directly connected to a SFC to drive an AC pump. The SFC needs a minimum DC-link voltage level to operate in normal conditions. This value varies depending on the type of converter (single-phase or three-phase). Table 1 presents the AC and DC link voltage ranges, for rated power, of the single-phase SFC ACS355. The DC values are, approximately, the peak values of the AC voltage. For lower power (i. e., lower radiation), the DC voltage will also be lower, and, consequently, the speed of the AC motor will be smaller than the rated one, due to scalar control. The system proposed is shown on Figure 1.

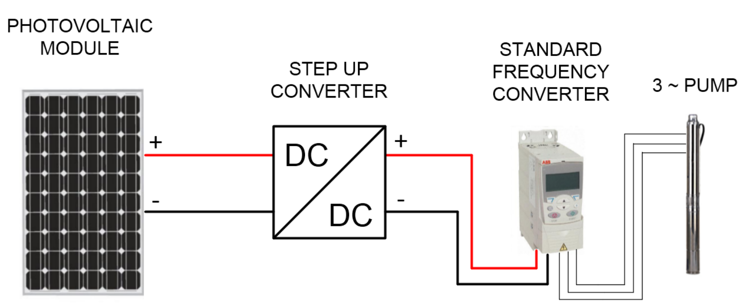

Fig. 1. Configuration of proposed PV water pumping system.

Table 1: Single-phase SFC ACS355.

AC Supply voltage [Min-Max]	200 - 240 V
DC-link voltage (on DC Bus) [Min-Max]	280 - 340 V

For proper functioning, the DC-link voltage obtained from the PV string must attend the minimum value of the SFC and the input voltage must be close to the maximum power point voltage of the PV string [5]. To attend the required voltage at the DC-link of the SFC, a DC/DC step-up converter which rises the voltage level at its output is the proposed solution in this paper. The step-up converter is controlled by a Proportional-Integrative (PI) controller which generates the Pulse-Width Modulation (PWM) pulses. The reference voltage (V_{ref}) is defined by a MPPT algorithm as described later.

For the SFC operation, the so-called PID Macro is utilized for control. This macro, which has a pre-parametrized list of parameters, is available from the manufacturers for closed-loop process control. In this application, the process variable is the DC-link voltage. So, the SFC imposes the DC voltage according to an external reference value (set-point). This reference is set to 300 V. This means that the SFC works with a fixed DC-link voltage and the reference voltage of the PV string is imposed by the step-up converter according to the MPPT algorithm.

To operate in this way, the SFC requires the configuration of a set of parameters, such as the operation method that will be used, analog and digital input and output terminals, acceleration and deceleration times, and mainly the PID parameters: Proportional Gain (K_p), integral time (T_i) and derivative time (T_d) [5].

2.1 Maximum Power Point Tracking

A general issue in PV generation is tracking the maximum power available at the PV string output. The need of an algorithm to track the Maximum Power Point (MPP) comes from the non-linearity of the I-V curve of a PV module. The MPPT technique consists in adjusting the output voltage of the PV string to extract the maximum power independently of any changes in the irradiation or temperature.

In this work, the MPPT method implemented was the P&O algorithm, due to its simplicity and low computational resources [6]. P&O is the most common method of MPPT algorithms, since it is widely used in the control of the power converters in PV applications and does not require any information about the PV modules characteristics to perform the maximum power point tracking [8].

Basically, the P&O algorithm perturbs the voltage and analyses the change on the power value. These perturbations on the voltage are successive steps on the operation point that creates a change in power. If this change is positive, the perturbations are applied on the same direction, otherwise the perturbations are applied on the opposite direction. The steps followed by the algorithm are illustrated on the flow chart of the Figure 2 with the variables defined in the Table 2.

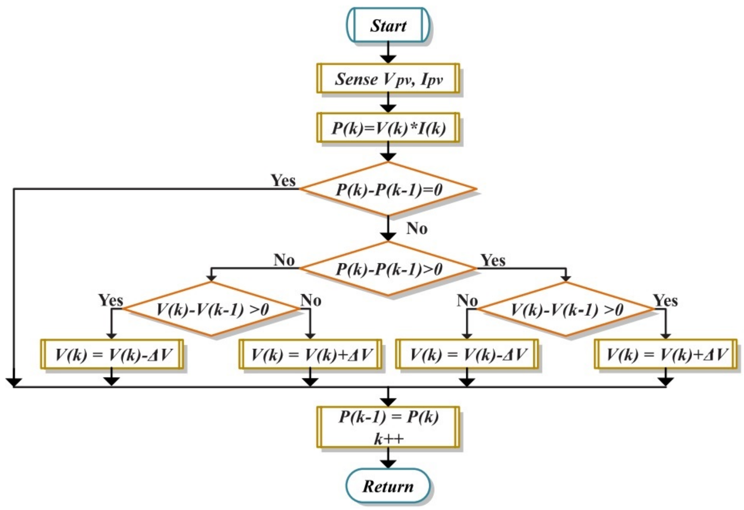

Fig. 2. State flow chart of P&O MPPT algorithm [6].

Table 2: Description of variables presented in flow chart of Figure 2 [6].

Variable	Description
V_{pv}	Voltage measured from the PV Panel
I_{pv}	Current measured from the PV Panel
$P(k)$, $V(k)$	Power and Voltage in present iteration
$P(k-1)$, $V(k-1)$	Power and Voltage in past iteration
ΔV	Voltage increment
$k++$	Change for next iteration

The MPPT algorithm generates the reference voltage value (V_{ref}) for the step-up converter. This value is the reference for the PI controller, which reads the actual voltage value of V_{pv}, the reference voltage (given by MPPT algorithm) and generates the pulses of the duty-cycle for the switch of the step-up.

3 Proposed Solution

As an approach to solve the problems referred in previous sections, a DC/DC step-up converter is applied to implement the MPPT and operate the PV string with a large range of voltages.

DC/DC converters are power electronic circuits for power processing that convert a DC voltage value to another level, higher or lower, depending on the converter. There are many types of converters, which are used in large scale in different areas, like UPS, electrical drives, renewable energy systems, DC motor control systems and so on [7]. The step-up converter, or booster converter, is a switching circuit that elevates the value of the input voltage to the output. The electrical scheme of this type of converter is shown on Figure 3.

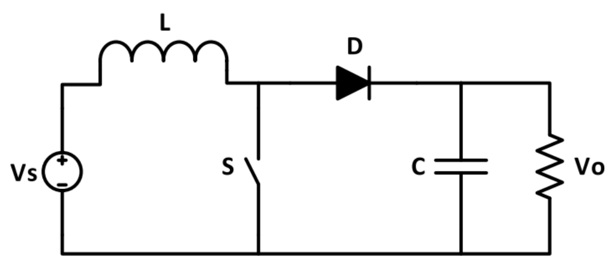

Fig. 3. Step-up converter.

The electric scheme of the proposed PV water pumping system is shown in Figure 4. The step-up is installed between the PV string and the DC-link of the SFC. It is composed by an inductor, a diode and a power switch (IGBT). The block diagram of step-up control with MPPT implemented is shown on Figure 5.

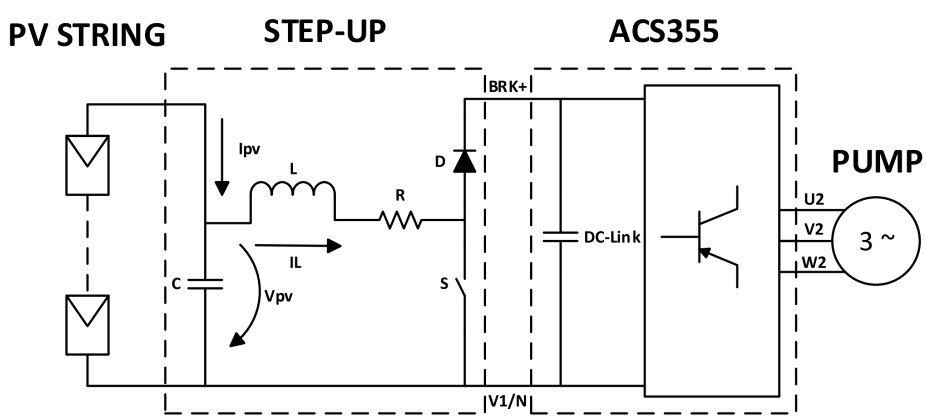

Fig. 4. Proposed PV water pumping system.

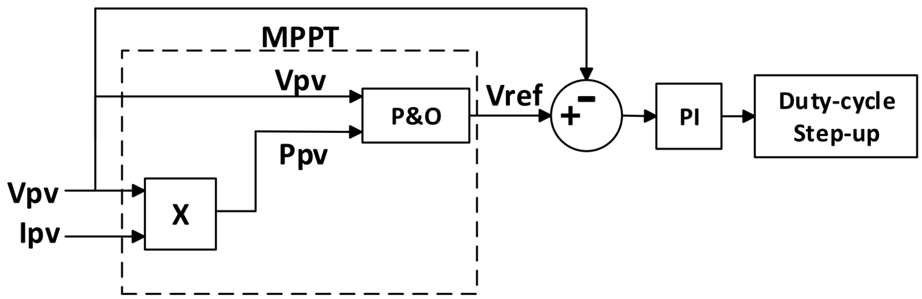

Fig. 5. Step-up control with MPPT.

One challenge is the adjust of the dynamics between the two power stages: the step-up converter and the SFC. The step-up performs the MPPT algorithm with a determined frequency, and the PID macro of the SFC adjusts the speed of the pump to maintain the voltage on the DC-link equal to reference (V_{SP}).

Hence, the PID macro parameters K_p and T_i, acceleration and deceleration times of the SFC, must be adjusted to match the dynamics between these two power stages. According to the tests achieved on the experimental platform, the values of these parameters used in this work are show on Table 3.

Table 3: Experimental parameters of the step-up and SFC.

Parameter	**Value**
Step-up PI Controller	$K_p = 500\text{x}10^{-6}$; $K_i = 0{,}10$
SFC PID Controller	$K_p = 0{,}2$; $T_i = 2$ s; $T_d = 0$
SFC Acceleration time	0.1 s
SFC Deceleration time	0.1 s

3.1 Experimental Platform

To evaluate the functioning and performance of the system proposed in this work, a solar photovoltaic water pumping system at the Polytechnic Institute of Bragança has been used. The system is composed by the elements described on Table 4.

Table 4: Components of the system.

Component	**Description**
Pump	Termar B20 3∼ 1.5 kW - Submersible
Standard Frequency Converter	ABB ACS355-01E-07A5-2
Step-up Power Switch and Diode	Two IGBTs of Mitsubishi PM75RLA120
Step-up Inductor	Mundorf BT140 12 mH/0,45 Ohm
Photovoltaic Modules	Fluitecnik's FTS-220P

The experimental platform components utilized in this work are shown on Figure 6. The PV modules are installed on the roof of the laboratory. The step-up was implemented in Simulink and the real time control was performed using the 1103 controller board from dSPACE.

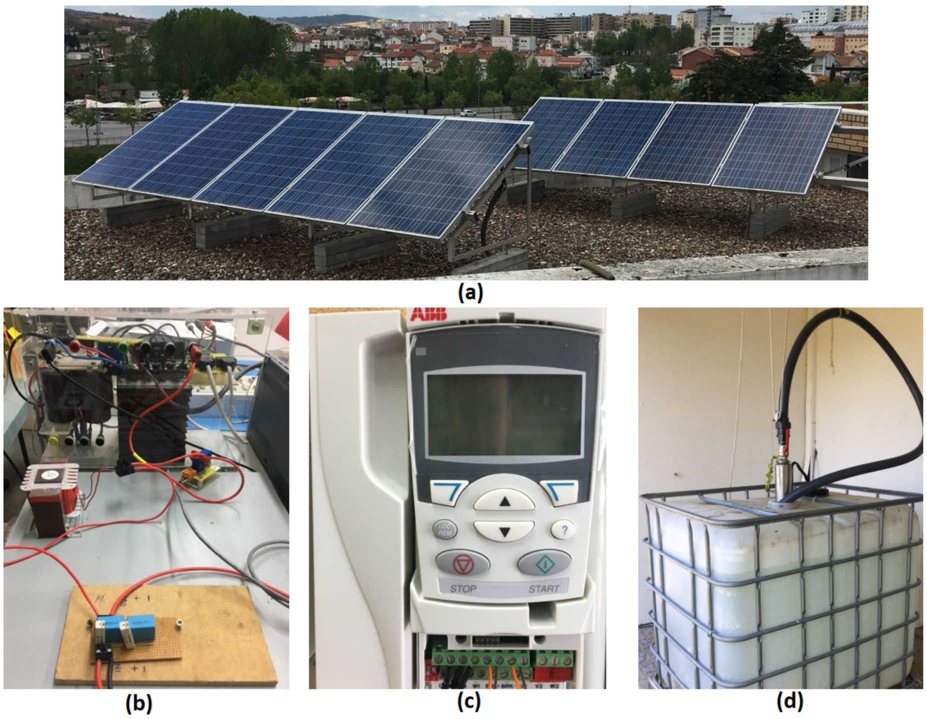

Fig. 6. Experimental platform, (a) PV string, (b) step-up converter, (c) single-phase ACS355, (d) water tank and pump.

The experimental results were carried out with 4, 6 and 8 PV modules available on the roof of the laboratory. All tests were performed under same solar radiation and temperature levels, acquired by the measuring system present on the laboratory. These values are shown on Table 5.

Table 5: Tests conditions.

Condition	**Value**
Radiation level	G = 810 W/m^2
Ambient Temperature	T_a = 28°C
PV Module Temperature	T_{pv} = 45°C

4 Practical Implementation of the System and Evaluation of the Results

Figures 7, 8 and 9 show the V_{pv}, V_{dc}, I_{pv} and P_{pv} curves for 4, 6 and 8 PV modules, respectively. V_{SP} is set 300 V and the MPPT is running two times per second with voltage increment of 1 V.

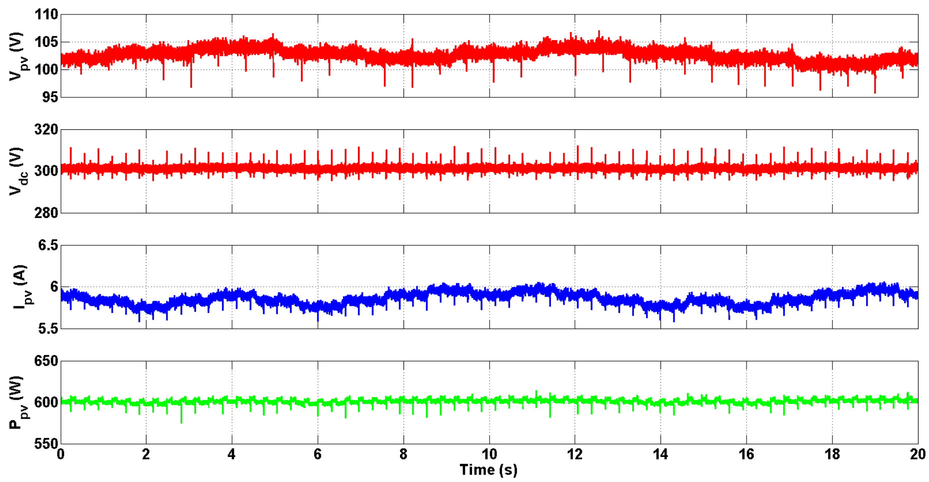

Fig. 7. V_{pv}, V_{dc}, I_{pv} and P_{pv} for 4 PV modules.

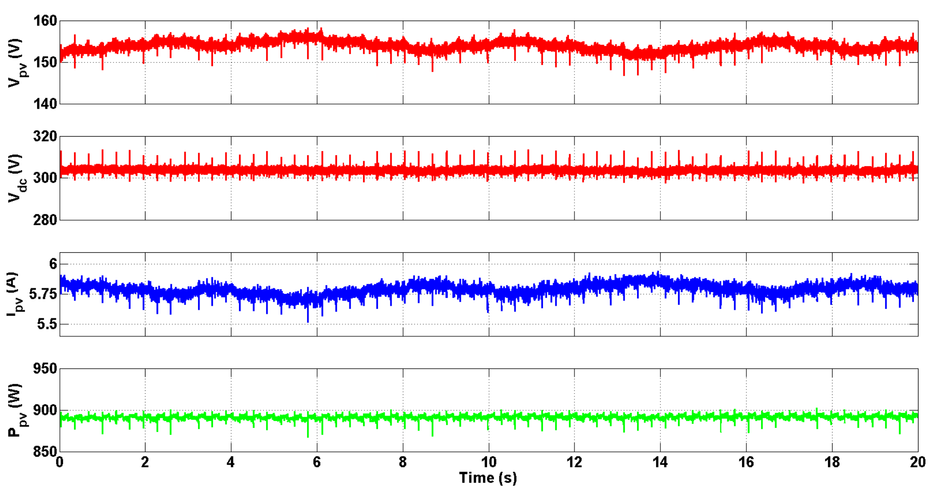

Fig. 8. V_{pv}, V_{dc}, I_{pv} and P_{pv} for 6 PV modules.

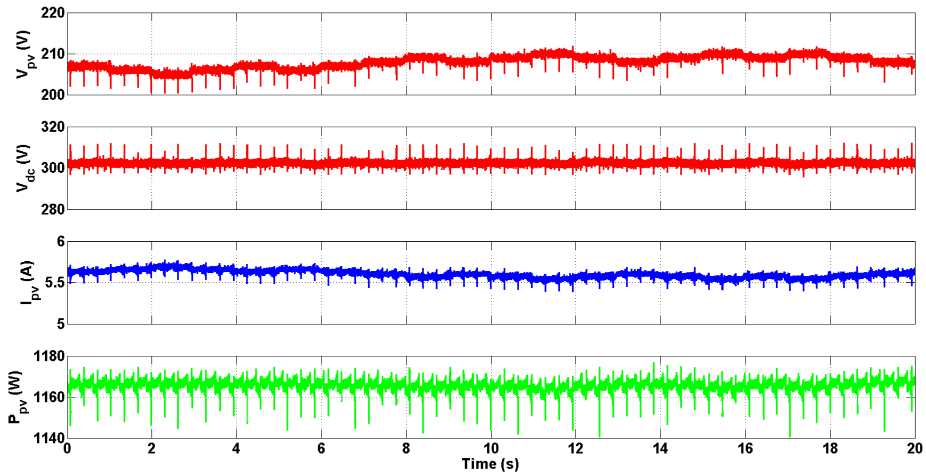

Fig. 9. V_{pv}, V_{dc}, I_{pv} and P_{pv} for 8 PV modules.

For all conditions V_{dc} is 300 V and V_{pv} varies according to the MPPT algorithm, validating the parameters of PID controller of the SFC and the required dynamics between these two power stages. The PV power curve as well as the water pump operation are in agreement with the expected results, showing that the step-up controls the PV string voltage using the MPPT algorithm applying successive steps in order to operate in MPP. The SFC PID macro controls the DC-link voltage indirectly by adjusting the speed of the motor.

These results show that the step-up allows driving low power pumps (up to 1,5 kW) minimizing the necessary number of PV modules. For comparison, Table 6 shows the power and voltage (in MPP) provided by each set of PV modules tested.

Table 6: Comparison of the power and voltage for each set of PV modules.

Size of PV string	**Power and Voltage**
4 PV modules	P = 880 W and V_{pv} = 117 V
6 PV modules	P = 1320 W and V_{pv} = 176 V
8 PV modules	P = 1760 W and V_{pv} = 235 V

From the analysis of the results of Table 6 and Figure 9, with 8 PV modules, it is possible to verify that the power is greater than the 1,5 kW (beyond the necessary) and the PV voltage level is less than the minimum value required from the SFC, i. e., 280 V (Table 1): V_{pv} varies between 200 V - 210 V and V_{dc} is fixed at 300 V for rated operation of the SFC, validating the solution proposed.

5 Conclusions

SFCs can be used in PV pumping applications driven by AC motors. This alternative offers significant advantages compared with those based on PV dedicated controller and pumps. Indeed, SFCs are widely available all over the world at significantly lower costs than those of PV dedicated power inverters. To solve the problem of the number of PV modules on low power systems and the implementation of a MPPT, the addition of a DC/DC converter has been proven to operate as expected. The validity of these proposals have been evaluated experimentally in a real system.

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