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Design, implementation and evaluation of a control system to optimize the performance of a Permanent Magnet Synchronous Motor (PMSM) supplied by a stand-alone Photovoltaic System without batteries

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Abstract.

This paper lays out the problem of powering a Permanent Magnet Synchronous Motor (PMSM) by means of a photovoltaic (PV) generator without any battery or any other kind of energy accumulation system and develops a simple and efficient solution for it.
The solution has been made by the implementation of a Proportional-Integral Controller (PI) based on Arduino platform as well as an appropriate tuning of its control parameters utilizing the tuning method known as AMIGOf (Approximate M-constrained Integral Gained Optimization based on frequency response).
The controller allows the motor to rotate at a speed range from repose state to the maximum speed that can be reached when the photovoltaic generator operates at its maximum power point (MPP).
In order to assess the system operation, it has been built up an experimental system composed on the motor, an e-bike inverter and a small photovoltaic generator. Start-up and sudden drop of the available PV power tests have been carried out. The obtained results show a successful system behaviour, providing quick start-up without oscillations and a fast response to a drop of the available power. The generator voltage is always kept close to the control setpoint value, avoiding sharp voltage drops which could turn out the system to be unstable.

Key words

Stand-alone photovoltaic system, Permanent Magnet Synchronous Motor, PID controller, Photovoltaic pumping system

1. Introduction

Photovoltaic energy has experienced a great development during the last few years, being nowadays one of the main renewable energy sources [1] and the one which shows better future prospects [2].

The photovoltaic systems connected to the grid (on-grid systems) have been the ones that have experienced the greatest development [3]-[4], since these systems harness the entire generated energy without the necessity of installing energy accumulation systems. This fact has meant that the photovoltaic generation capacity connected to the grid in the most advanced countries is already on the order of GW [5], with an increasing number of photovoltaics plants that exceed a MWp.
Photovoltaic energy is also useful in places where they do not have access to the conventional grid (off-grid or stand-alone systems) as, for instance, the rural electrification systems [6]-[7]. By its own nature, PV energy generation is discontinuous and highly dependent on the time of the day and weather conditions. This fact makes that off-grid applications, where it is required a constant energy supply, need the design of a hybrid system with a non-renewable energy source [8] or the use of a system that allows to store the exceeding energy produced on higher irradiance hours in order to use it when generated energy is insufficient or null. Energy storage systems present problems of price, viability and maintenance necessities [9]-[10], and they are the main obstacle to the growth of installed power in photovoltaic systems outside the grid.
Even so, there are applications that do not require of a steady energy supply and, hence, do not need energy storage systems and suit better to the stand-alone PV systems characteristics. Among these applications, it has to be highlighted the photovoltaic pumping systems (PVPS) that climb water to a tank at variable water flow. This application was originally developed to provide potable water in developing countries [11], but currently its utilization is spreading to irrigation systems [12], whose energy requirements are quite large. This is the reason that currently are being designed PVPS with installed power higher than 1 MWp, on the same order than systems connected to the grid.

Although the first PVPS were driving by direct current motors [13] directly connected to PV generator or through DC-DC converters [14], the most common system nowadays is the asynchronous induction motor driven by a standard frequency inverter [15].
These kind of PVPS work executing a proportional-integral-derivative (PID) control algorithm, whose control variable is the PV generator voltage and whose output variable is the motor rotation frequency.
The System performance depends essentially on the proper adjustment of the PID control parameters, process known as tuning [16].
Nowadays, the fast development of electric vehicles (EVs) has contributed to a great improvement in electric motors features, mainly the permanent magnet synchronous motor (PMSM) [17], also known as brushless DC motors (BLDC). Compared to induction motors, PMSM motors have a better power-to-weight ratio and a better dynamic response.
This improved performance is a powerful argument to consider the use of this kind of motors in the PVPS, since it would allow to increase the robustness of the system in the face of sudden drop of irradiance (cloud pass), one of the main problems to be solved in this systems [18].
This paper deals with the optimization of the operation of a PMSM motor directly powered by a PV generator without any energy accumulation element, by means of an appropirate tuning of the control parameters. Its performance has been assessed in the two most critical process: the start-up and the response to a sudden drop of the available PV power.

2. Work Methodology

A. Theory fundamentals

The control aim of a motor directly powered by a PV generator consists of achieving that, in every moment, the motor rotates at its maximum possible speed, taking advantage of all energy available in the generator. PMSM motors require an electronic system to convert the direct current supplied by the generator into alternate current, usually three-phase current, needed to produce its movement. This system is usually known as inverter. In the simplest inverters, the power applied to the motor is regulated by means of an analog control signal or by a PWM control signal.
In order to power the PMSM motor with the PV generator is necessary to implement a control electronic system whose input signal is the DC voltage in the generator and whose output is the control signal applied to the inverter input to regulate the power supplied to the motor. The control setpoint will be a specific voltage value of the PV generator, which will be optimal when it matches with the voltage from its maximum power point (MPP).
The control that has to be carried out must be reverse, that is, if the generator voltage is higher than the setpoint voltage (negative error), the output must be increased so that the power applied to the motor is also increased, causing a reduction in the generator voltage and in the error. On the other hand, if the generator voltage is lower than the setpoint (positive error), the power applied to the motor must be decreased to increase the voltage of the generator, approaching again to the setpoint value.
The basic requirements that must satisfy this control system are:

1. The maximum power point tracking (MPPT) in order to set up a setpoint that maximizes the energy supplied by the PV generator.
2. A quick, soft and damped response to sudden changes of the irradiance (cloud pass) or of the setpoint (motor starter up).
3. For some applications, it is necessary to regulate the motor speed from stop to its maximum value. To achieve this, it must be possible to adjust the setpoint between the open circuit voltage (V_{OC}) and the MPP voltage (V_{MPP}).

The key element to obtain the optimal system performance is the proper adjustment of the proportional-integral-derivative (PID) control parameters. Due to the electromagnetic noise existing inherently in motor power regulation systems, it is usual to null the derivative control, carrying out just a proportional-integral (PI) control.

B. Hardware

It has been designed and built up an experimental prototype for assessing the tuning method and the performance of a PMSM motor supplied by a PV generator. In order to ensure that tests can be reproducible, it has been used devices easily accessible in the market such as:

- Photovoltaic modules model A-10J of Atersa.
- Control module Arduino UNO.
- E-bike inverter Nine Continent CE6-17A.
- E-bike motor Nine Continent RH205B assembled to a 26” wheel.

Figure 1 shows a block diagram of the system.

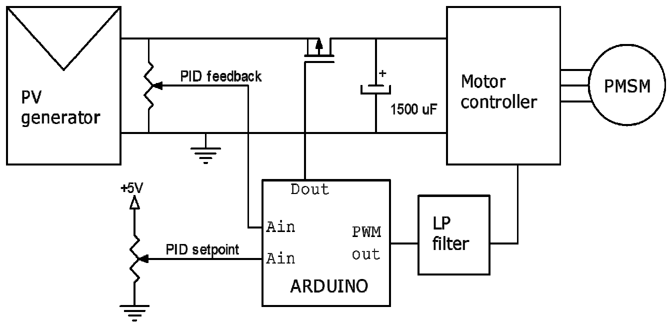

Fig. 1. System hardware

The PV generator has been made with 6 modules configured in two parallel strings of 3 modules each, reaching a peak power of around 60 W. Its characteristics in STC are:
V_{OC} = 62,1V; I_{SC} = 1,36A; V_{MPP} = 48,9V; I_{MPP} = 1,22A.
The control system is based on an Arduino UNO platform that executes the PID control algorithm.
The control input is the PV generator voltage, which is applied to an analogical input of this controller through a voltage divider.
The output should be an analog signal with a range between 1V and 4V, which is what the inverter control

input requires. The problem is that Arduino UNO does not include any D/A converter that provides that signal. The immediate solution would be to add an external D/A converter, although we have implemented another simpler solution. The analog signal was obtained by applying a second order low pass filter to one of the Arduino PWM outputs. This filter works as a PWM/analog converter, providing an analog signal with a voltage proportional to the duty cycle of the PWM input signal.
According to this, the controller output is a PWM signal with a frequency of 32 kHz, which is applied to the inverter control input through a LP filter with 50 Hz cut-off frequency.
The setpoint of the PID control must be adjustable in order to regulate the motor speed. A potentiometer has been used to perform this function. Its behaviour is described below:

- When it is at minimum, the setpoint must be equal to V_{OC}. The power delivered by the PV generator at this voltage is null and the motor will remain stopped.
- When it is at maximum, setpoint must be equal $V_{MPP.}$ The power delivered by the PV generator at this voltage will reach its maximum value and the motor will rotate at the maximum possible speed.
- Any intermediate value of the potentiometer will correspond linearly with a setpoint voltage between V_{OC} and V_{MPP}.

It is important to take into account that these voltage values are not constant, but depends highly on the generator temperature. Therefore, its values must be periodically updated.
Figure 2 shows the current/voltage (blue) and power/voltage (red) curves of a typical PV generator, in which it can be seen the adjust range of the PID control setpoint.

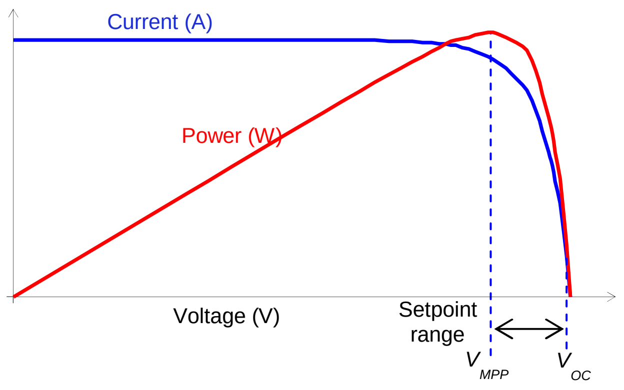

Fig. 2. I/V and P/V curves of a PV generator

To obtain $V_{OC,}$ the disconnection of the PV generator from the rest of the circuit must be possible. The MOSFET located at the PV generator output (showed in Figure 1), whose state is controlled by an Arduino digital output, performs this function.
An important feature from the inverter used in this project is that the supply voltage must always be greater than 30 V, otherwise it cuts off the energy supplied to the motor and it consequently stops. This fact might be a major problem in some applications, such as in PVPS. A sudden motor stop can cause serious problems to the installation, fundamentally the phenomena known as "water hammer". This could happened in the short time interval in which generator is disconnected to update the V_{OC} value. In order to avoid the energy lost in the inverter in that moment, a 1500 µF capacitor was attached to its power input (also showed in Figure 1).
To fill out the experimental design, a PMSM motor assembled to a bike wheel and compatible with the inverter has been used. The whole assembly has been mounted on a cycling roller equipped with a magnetic brake with adjustable intensity, which has allowed carrying out the tests with different load values.

Software

The software has been made in Arduino programming environment. Its main purposes are:

- Maximum power point estimation.
- Control voltage setpoint set up.
- Carry out PID control.

To be able to set up the setpoint it is needed to know V_{OC} and V_{MPP} values. The V_{OC} can be directly obtained measuring the PV generator voltage when it has been disconnected from the rest of the circuit by the MOSFET. The V_{MPP} cannot be measured directly nor can't it be obtained implementing a MPPT algorithm, since this kind of algorithm demands that the generator works continuously around this operating point. For that reason it is necessary to make an approximate estimation of its value. To achieve it, it has been taken into account the fact that the ratio between V_{MPP} and V_{OC} is roughly constant in a wide temperature range. To find this ratio for the PV generator used in this project, the values of V_{OC} y V_{MPP} for various temperatures were measured, obtaining the following relationship:

$$\boldsymbol{V_{MPP} \cong 0.78 * V_{OC}} \quad (1)$$

The estimation of V_{OC} and V_{MPP} should be periodically done to take into account the temperature effects in the PV generator.
The Arduino-PID library [19] has been used to implement the PID control of the system. This control has been simplified to a PI control (cancelling the derivative gain) to avoid phenomena as "Derivative Kick", which causes instability in systems with high electromagnetic noise, such as caused by PWM signals used in motor power regulation.
The key of a good system operation is the proper tuning of the PI controller, which consists of obtaining the optimal values of tuning parameters: proportional gain and integral time.
Although there are many methods, both analytical and empirical, to achieve the tuning, in this paper the AMIGO (*Approximate M-constrained Integral Gained Optimization*) tuning rules based on frequency response modelling [20]-[21] has been applied, since they have been recently assessed as the most suitable for this kind of systems [16].
After the control parameters have been configured following these tuning rules, a fine adjustment has been

made by testing the start-up process. The desired objective is to obtain a fast, smooth and damped response to the sudden change in the setpoint produced in this process.

3. System testing and results

Figure 3 shows a picture from experimental system used to assess system operation.

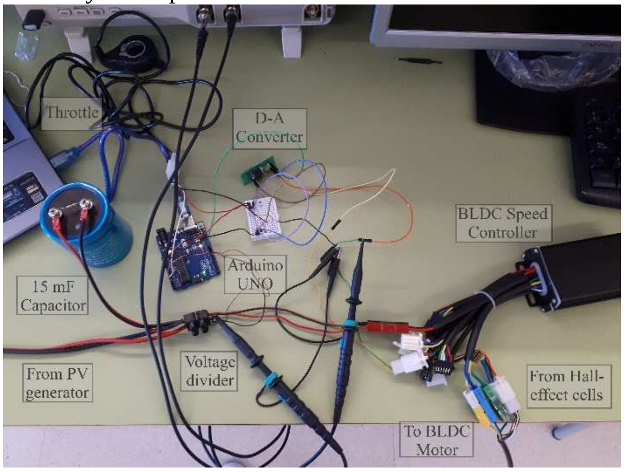

Fig. 3. Laboratory experiment

First of all, it has been carried out tuning tests by means of the frequency response analysis. To apply this method, it has to be done two tests.

In the first instance, the open-loop static transfer function of the system has been obtained. For this, a set of values of the control feedback variable (voltage measured on Arduino input corresponding to the voltage of the PV generator) versus the output variable of the controller (LP filter output voltage) have been obtained experimentally. The slope of this curve is the static gain (k_s) of the process. Figure 4 shows the static transfer function for this test.

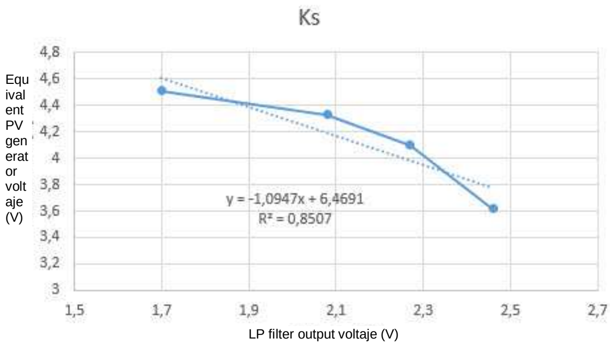

Fig. 4. Open-loop static transfer function

As can be observed, the function is not linear, which means that this system control is a complex problem: it does not exist an optimal set of parameters for all operating points, so it is necessary to find the set that provide the most suitable performance in the most critical circumstances. To establish the k_s value, an adjustment by the minimum squares method has been made, obtaining the following result:

- $k_s = 1.0947$

As a clarification, the absolute value of the slope is shown, since the control is reverse and its curve has a negative slope. Secondly, a closed-loop pure proportional control was configured, cancelling the integral and derived gains. The tuning method consists of increasing the proportional gain value (K_P) until both the feedback signal and the system control output reach a stable oscillation. Then, the K_P value must be decreased until the oscillation disappears.

The lowest value for which the oscillation is obtained is known as critical gain (K_C). The period of this oscillation is called the critical period (T_C).

Figure 5 shows the feedback signal oscillation (yellow signal) and the output (blue signal) for K_P = 2.7.

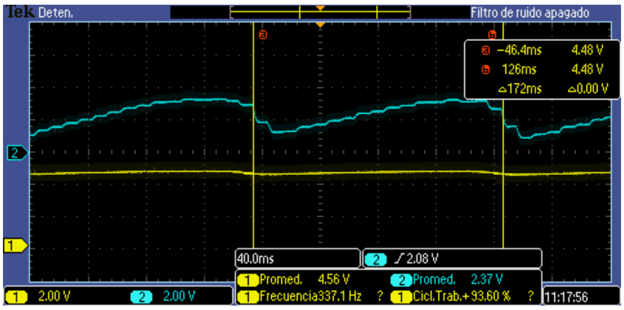

Fig. 5. Oscillation with K_P = 2.7

The definitive values of critical parameters obtained in this test are:

- K_C = 0.7
- T_C = 142 ms.

From the static gain and these values, the control system parameters can be deduced using the design rules described in the AMIGO tuning method:

$$K_P = 0{,}16 * K_C \qquad (2)$$

$$T_i = \frac{K_P}{K_i} = \frac{T_C}{1 + \frac{4{,}5}{K_C * k_s}} \qquad (3)$$

The following parameters are obtained by applying those rules:

- K_P = 0.112
- T_i = 0.0207 s.
- K_i = 5.42 s^{-1}

In [16] it is obtained that this tuning method provides the maximum acceptable value for K_P and the minimum acceptable value for T_i to control this type of non-linear systems. In addition, it was proposed to improve the response by performing a fine adjustment, which consists mainly of increasing T_i, although it may also be necessary to decrease the K_P. The start-up test is the most appropriate for this fine-tuning. In this test, the setpoint varies from the value corresponding to the V_{OC} (null speed) to the value corresponding to the V_{MPP} (maximum speed).

Figures 6a, 6b and 6c show several sequences of these tests with different T_i values until a start-up with no oscillations is achieved. In all these tests, the K_P value has remained constant at 0.112.

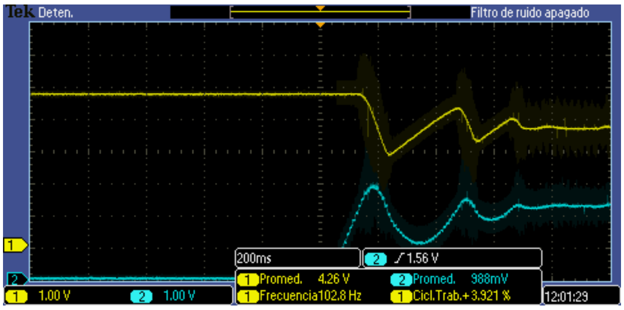

Fig. 6a. T_i = 20.7 ms

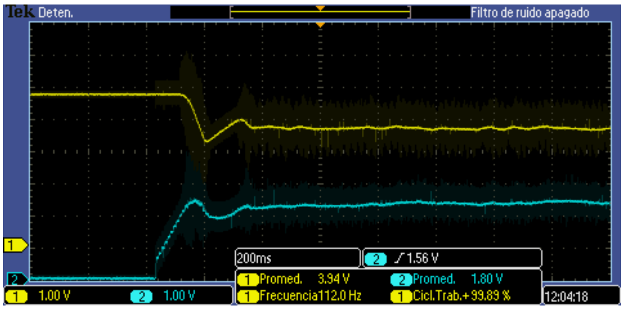

Fig. 6b. T_i = 28.0 ms

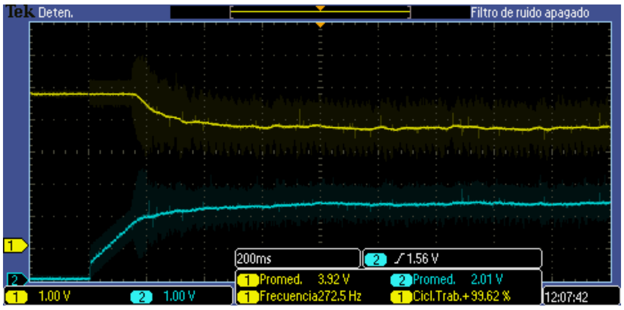

Fig. 6c. T_i = 44.8 ms

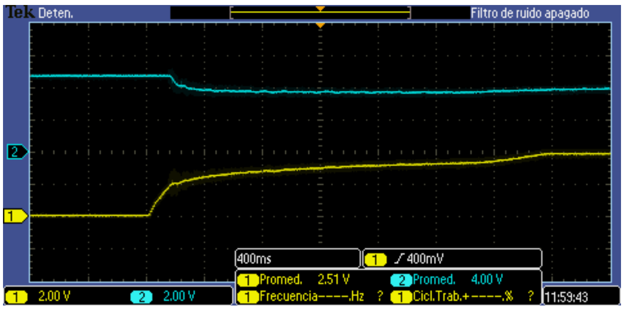

Fig. 6d. T_i = 56 ms

After this fine-tuning, these definitive control parameters were chosen:

- K_P = 0.112
- T_i = 0.0448 s.
- K_i = 2.5 s^{-1}

To check the suitability of this set of control parameters, the system response to a sudden drop in the available power in the PV generator (cloud pass) was tested. The photovoltaic generator was covered with a translucent object to simulate the passage of clouds. Figure 7 shows the changes in both the generator voltage and LP filter output signal obtained in this test.

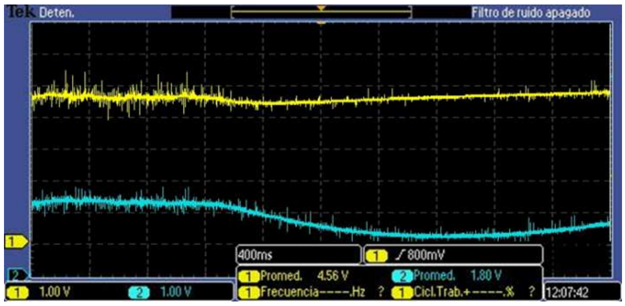

Fig. 7. Cloud pass test

4. Discussion.

Figures 6a, 6b and 6c show the signal corresponding to the PV generator voltage in yellow and the LP filter output signal, which regulates the motor rotary speed, in blue. In figure 6d the colours have been inverted. The captions show the setting of the T_i parameter.

Figure 6a shows a wide oscillation in both signals, which occurs with the values of the parameters obtained with the AMIGO tuning rules. Figure 6b shows how the oscillation is substantially damped with the increase in T_i and in figure 6c the oscillation disappears completely for T_i = 44.8 ms. Higher values of T_i, as shown in Figure 6d, also do not produce oscillation, but its start-up time is much longer. A longer start time causes the response time to abrupt changes in available power to be greater, so the value of T_i that provides the shortest start time without causing oscillations should be chosen.

Finally, figure 7 shows a sharp drop in available power in the PV generator. The yellow signal represents the PV generator voltage and the blue signal represents the LP filter output signal.

It can be seen that the output voltage of the filter drops quickly when the shading of the PV generator causes a sudden drop of the supply voltage. This causes a decrease in the motor rotation speed, which, in turn, causes the PV generator voltage to rise again and return to the setpoint, avoiding a fall below the critical level of 30 V.

4. Conclusions

This paper deals with the design, implementation and assessment of a PI controller, programmed in the Arduino platform, which allows to take advantage of the maximum available power in a stand-alone PV generator to directly power a PMSM motor, without the need to have any accumulation system of Energy.

Hardware and software elements have been described and a tuning method based on AMIGO tuning rules has been applied. It has been shown that the results of the direct application of the AMIGO tuning rules are a good starting point, but they do not provide an optimal result, because afterwards it has been necessary to make a fine adjustment to obtain the set of parameters that improve the behaviour of the system.

This fine adjustment of the parameters causes a notable increase in the time required for tuning, so that a substantial improvement in the industrial application of the system could be obtained if a new tuning method were developed that would avoid having to make such adjustment.

Finally, the tuned system has been tested in the start-up process and during a sudden change in the available power of the PV generator, caused by its shading. The result of the first test is a fast and smooth start of the motor without causing oscillations in its rotation speed or in the voltage of the PV generator. In the second test, the controller has caused a rapid rise in the PV generator voltage after its shading has occurred, preventing the voltage from falling below the system stop level.

A possible application of this project would be in stand-alone PVPS. In these systems, the motor almost universally used is the asynchronous induction motor. Taking into account that PMSM motors have a better dynamic response than induction motors, it is expected that the use of this type of motors will improve PVPS performance.

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