Maximum Power Point Tracking: Platform for simulation and noise immune RCC implementation

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***Abstract*—A simulation platform for testing Maximum Power Point Tracking (MPPT) techniques is presented. It receives Irradiation and Temperature curves, and outputs a comparison between the MPPT and the maximum power levels that could be extracted from the panel. A mathematical implementation of Ripple Correlation Control (RCC) method is simulated on the platform. Noise filters are added to the system, and an interesting result on the response of the system to signals with low frequency filtering is presented.**

I. Introduction

Efficiency is a key parameter for photovoltaic applications. Obtaining more power from smaller areas is one of the key challenges for this industry, in order to achieve even more relevance in the market of electric generation from renewable sources.

MPPT techniques have an important incidence on the performance of photovoltaic cells. The study and development of those control strategies is quite difficult since the characteristic $I(V)$ equation of a solar panel is implicit and non-linear, and the control must work properly over the entire range.

In this paper, two topics are presented, which may be useful for anyone interested in the development of a system with MPPT capability.

In the first part, a very simple and effective simulation platform for testing any kind of MPPT technique is presented for *MathWorks Simulink*®. It provides an environment for the control system, with the typical inputs (panel voltage and current) and output (duty cycle for a switched converter), and a simple model for the load that allows a fast simulation and relevant results independent from the final converter to be used.

The platform receives any kind of curve of irradiance and temperature for the panel as the input, and generate output curves that show the performance of the method compared to an ideal calculated output for each provided input, as a function of time. The results are also written to a file that can be loaded in Matlab®for further analysis.

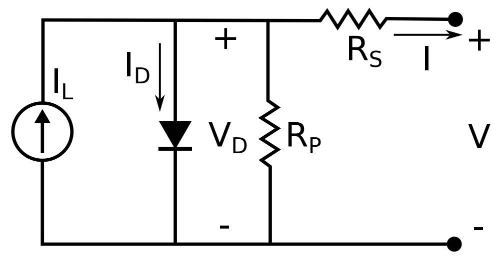

Fig. 1. Solar cell equivalent circuit.

In the second part, a mathematical version of the RCC method is implemented on this platform and it is shown how the parameters and some variations of this method impact on the efficiency, stability and response time of the control system. Although this abstract version cannot be directly applied in hardware, its simplicity makes it ideal to understand the behaviour of the entire system as a function of general parameters that could be present in any final implementation: gain of each subsystem, saturations, signal filtering.

Finally, an interesting result is observed in the behaviour of this method, by applying an important filtering to the input signals, which improves the convergence of the method under noisy conditions (one of the main problems of RCC due to the time derivatives present in the control law), even when the cut-off frequency is to the left of the ripple's fundamental frequency.

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A. Photovoltaic Solar Panel Characteristics

A typical silicon Solar Cell of a photovoltaic panel can be modelled like the equivalent circuit shown in Fig.1 [3].

An array of identical solar cells disposed in shunt and series of equal length (which would be the equivalent of a complete solar panel) can also be modelled as the same

circuit, with an obvious adjustment in the values of the components, compared to each individual cell in that panel [6].
This non-linear circuit yields to the following characteristic equation for a single solar cell or a complete solar panel, which is parametric with irradiance (proportional to I_L) and temperature (mainly through V_{th}) [6], [1]

$$\boxed{I = I_L - I_S(e^{(V+I.R_S)/V_{th}} - 1) - \frac{(V + I.R_S)}{R_P}} \quad (1)$$

This non-linear equation, correspond to a characteristic I-V curve as shown in Fig.2.

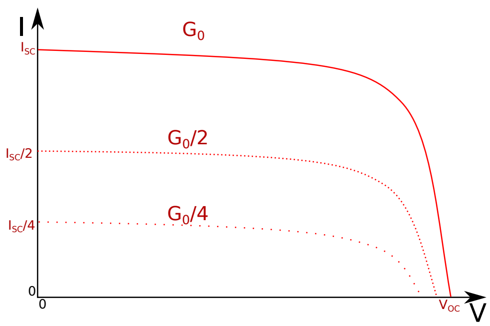

Fig. 2. Characteristic I-V curve for a solar cell or solar panel.

If the power as a function of voltage or current is calculated, the plot shown in Fig.3 [1] is obtained. Both curves change in different ways as a function of the temperature and irradiance received by the cell. Also, the ageing process of the cells in the panel also change the curves.
With those considerations, it can be understood that the voltage or current that shall be extracted from the panel in order to get the maximum power (Maximum Power Point or MPP), depends on an unpredictable set of conditions that change over time. That is why it is necessary to implement some kind of technique to control the output of the panels, particularly to follow this point, so that the panel is efficiently used.
There are a number of available techniques to achieve that, some of them are explained in [5]. For each of the techniques, there are a large number of parameters and decisions to be taken when implementing a real system with MPPT capability, and it is very difficult to predict exactly the output of the system as a function of each of those variables. That is why it is convenient to have a platform for testing simulated implementations of a particular technique being considered, from the design phase to the adjustment procedure.

II. Testing Platform

Simplifications have to be made in order to simulate the system where the MPPT will operate. A basic diagram of such system can be seen in Fig.4.

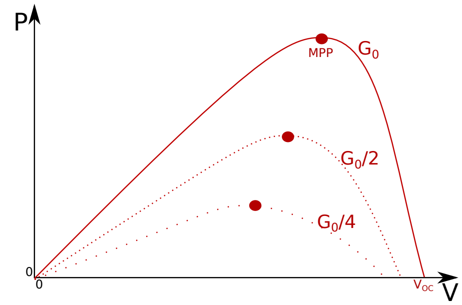

Fig. 3. Power as a function of V or I in a solar cell or solar panel.

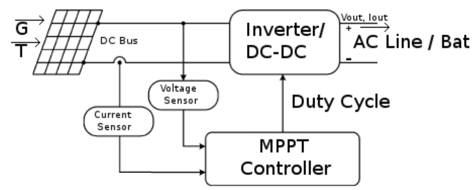

Fig. 4. Basic diagram of the system where the MPPT controller will operate.

Simulating a complete power converter such as an Inverter or a DC-DC, would be difficult to implement in the simulator and very slow to run, and would only have sense to test very particular characteristics of that implementation. Otherwise, it is not necessary to develop the entire system, as far as the DC Bus in the output of the panel behaves similarly to the input port of the power converter to be used.
In this paper, it will be considered a very simple model for a switching converter, that is equivalent from the point of view of the panel, since it has a DC level and a ripple component in the DC Bus where it is connected.
The model is a Capacitor that maintains the voltage at the DC Bus, and a series switch and resistor, which provides a variable load, by changing the duty cycle of the switch. That combination not only provides a variable mean load in a time interval, but also introduces ripple to the bus, which is a necessary condition for the RCC method to work.

The complete platform is shown in Fig.5 and fully described in [6]. There are some auxiliary elements in this diagram: a thermal model for the solar panel, which calculates the cell temperature as a function of the environment temperature and the power dissipated in the panel, two look-up tables with preloaded values of the calculated MPP (V_{MPP} and I_{MPP}) for each combination of irradiance and temperature, a PWM generator to convert the duty cycle value into the electrical command signal for the switch, voltage and current sensors which are eventually mixed with additive noise and provide the inputs to the MPPT control, and all the relevant signals are also registered in an output file that can be loaded in Matlab®.

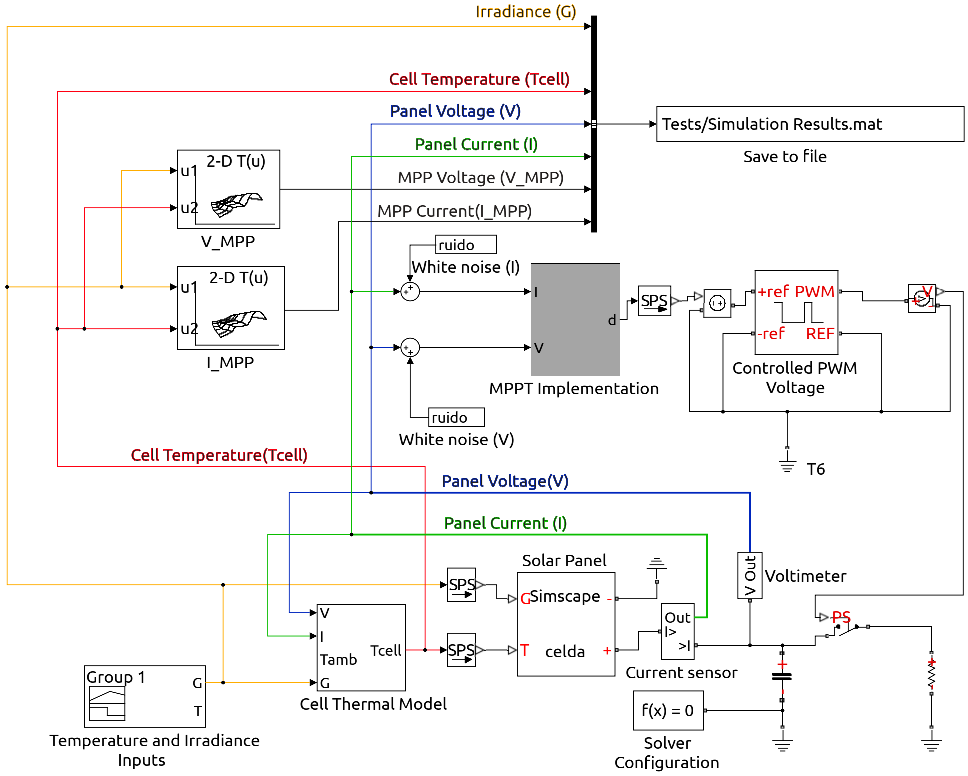

Fig. 5. Testing Platform for MPPT algorithms implemented in Simulink®.

III. RCC Implementation

A. RCC Fundamentals

A complete explanation of the RCC algorithm fundamentals is presented in [2], and this particular implementation is better described in [6].
The idea is that, according to Fig.3, the relation between small signal changes in voltage and power, can be resumed by the following relations:

$$V < V_{MP} \Rightarrow dP.dV > 0 \Longrightarrow \frac{dP}{dt}.\frac{dV}{dt} > 0$$
$$V > V_{MP} \Rightarrow dP.dV < 0 \Longrightarrow \frac{dP}{dt}.\frac{dV}{dt} < 0$$
$$V \approx V_{MP} \Rightarrow dP \approx 0 \Longrightarrow \frac{dP}{dt}.\frac{dV}{dt} \approx 0$$

Making use of this relations, the following control law can be used for the duty cycle command of a switching converter:

$$d(t) = k \int \dot{p}\dot{v}dt \qquad (2)$$

In order for this method to work, the signals shall have some kind of variations in order to have a non null derivative, otherwise the law control would not work. The ripple generated by any switched converter is enough in order to keep this method working, and that is the reason of its name. The integral result will approach to a constant (null integrand) when the voltage approaches V_{MP}.
The sign of k depends on the converter: if an increment in duty cycle corresponds to an increment in voltage, it shall be positive, otherwise negative (like the model used in this paper, where the resistance's mean value goes down with an increment in duty cycle, and also the voltage in the capacitor).

In Fig.6, it is shown a very simple and general implementation of the RCC algorithm in *Simulink*®. Using this simple model, the most important parameters of the system, which should be present in any possible implementation, could be adjusted to observe their effect in the output.

The magnitude of k (total gain of the system) is one of the parameters which is interesting to adjust through simulation, since it has an important role in the response time of the system, but also the stability of the duty cycle. This is shown in Fig.7, where simulation results are presented for the values $k = 10$ and $k = 100$. In a real power converter, it is usually desirable that the duty cycle reaches a stable value.

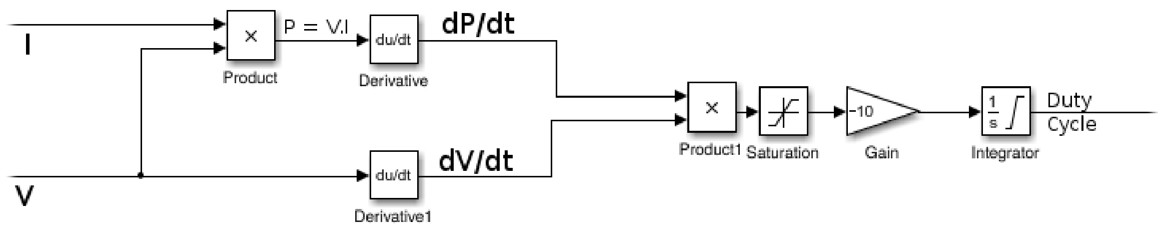

Fig. 6. Abstract implementation of RCC algorithm in Simulink®.

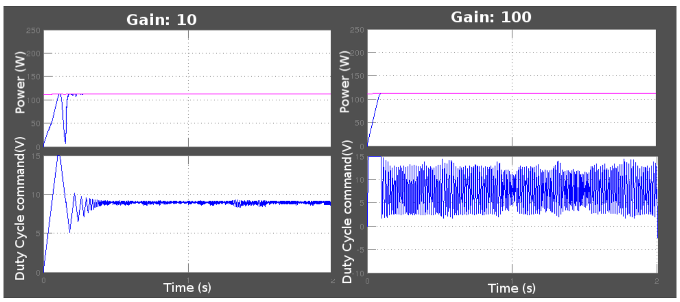

Fig. 7. Stability of the duty cycle as a function of RCC gain (k)

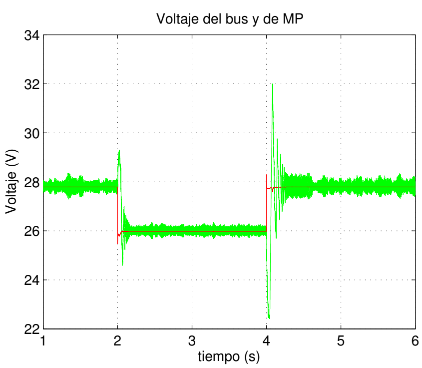

Fig. 8. RCC system response to increasing and decreasing Irradiance steps (red line is theoretical MPP).

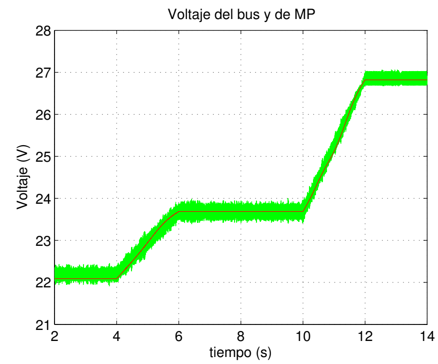

Fig. 9. RCC system response to increasing ramps in Irradiance (red line is theoretical MPP).

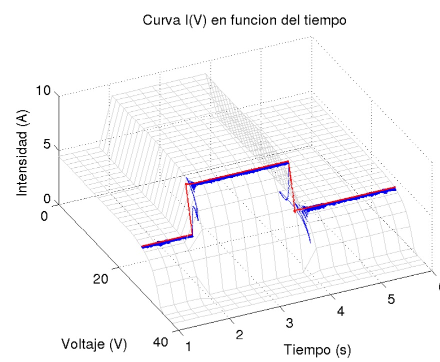

Fig. 10. Voltage response to increasing and decreasing Irradiance steps

B. RCC Simulations

Several simulations were run with this system, applying selected inputs of irradiance and temperature, which produce different kinds of shifting in the V_{MP} and I_{MP}. Fig.8 shows how the voltage is adjusted when applying a step input in irradiance from $500W/m^2$ to $1000W/m^2$, compared to the theoretical V_{MPP} calculated (red line). It can be observed that the response curve follows with great accuracy the red line, with the corresponding ripple introduced by the load switching, and some oscillations after step inputs.

Fig.9 also shows the voltage response of the system to increasing ramps in irradiance.

Fig.10 is intended to show the path described by the controller when reaching the MPP, so it is also displayed the family of characteristic curves for each input as a function of time. In this case, the input is the same as in Fig.8.

When the incident irradiance level changes in the panel, the I_L current changes proportional to this variable, while the voltage V_{th} does not change significantly, nor the open-circuit voltage. Changes in temperature have exactly the complimentary effect, affecting significantly the open-circuit voltage, but not the short-circuit current of the panel. In Fig.11 it is shown the response of the system and the variation in the I-V and P-V curves with a step in ambient temperature, from $293K$ to $313K$.

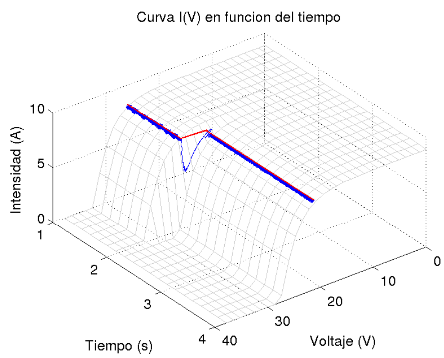

Fig. 11. Voltage response to an increasing temperature step

C. RCC Noise filtering

When testing the noise tolerance of the RCC method, it was found that problems arise when the noise bandwidth is higher than the ripple frequency of the system, due to the presence of the derivators, which in this case are ideal and so the gain of the system is higher for high frequencies. The algorithm was not able to converge to the MPP under this conditions after several simulation attempts, even with low noise amplitudes compared to the ripple signal.

An alternative implementation was proposed, first substituting the ideal derivators by real high pass filters, with a defined cut-off frequency f_d, and then low pass filters were added (cut-off frequency f_b), in order to attenuate the additive noise in the higher frequencies.

It was found that with some values of f_b near the ripple frequency, the system finally converged to the MPP.
During the testing, the amplitude of the noise was increased, and the cut-off frequency of the low-pass filters were reduced in order to counteract this effect, and it was surprisingly found that the control system was able to work properly even when the cut-off frequency was much lower than the ripple's fundamental harmonic, with the only side effect that the response curve was slower.
The explanation found to this effect is that although the ripple is being filtered, the slower changes in the voltage of the DC Bus due to any adjustment in the duty cycle, are enough to provide non null-derivatives in the integrator, allowing it to converge to the duty cycle value that keeps the system working in the MPP.
Table I shows the efficiency measured for the system in steady state, with a ripple frequency of $1kHz$, a noise bandwidth of $10kHz$, and the low pass filters of first and second order, with the shown cut-off frequencies.

Low-pass filter order	f_d	f_b	Efficiency (%)
First order	400 Hz	200 Hz	68.55
Second order	400 Hz	200 Hz)	74.31

TABLE I
RCC EFFICIENCY WITH $1kHz$ RIPPLE, ADDED WITH $10\ kHz$ BANDWIDTH NOISE OF $0.1\ mW/Hz$ SPECTRAL DENSITY, USING NON-IDEAL DERIVATORS AND LOW-PASS FILTERS WITH FREQUENCY LOWER THAT THE RIPPLE'S FUNDAMENTAL.

IV. Conclusions

A simulation platform for testing the impact of general parameters of MPPT techniques, is very useful during the development and adjustment phase of a system implementing such a control system, since the non-linearity of the solar panel curve makes it very difficult if not impossible to predict precise results in a theoretical manner.

The utility of such platform was proved simulating an implementation of the RCC algorithm, and a surprising result was found changing some parameters of the filters used, which provides a solution to the lack of stability of this method under noisy conditions.

RCC method provides not only a very fast response and simple control system (it can be implemented only with analogical devices), but can also be easily modified and adjusted according to the conditions of the real system to be implemented: higher noise tolerances could be reached at the cost of a quite slower response system, resulting in a very versatile method.

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