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Power Controller Design and Stability Analysis of a Photovoltaic System with a dc/dc Boost Converter

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***Abstract*—The challenging issue of designing stable active power controllers for photovoltaic (PV) systems interfaced to the load with dc/dc boost converters is addressed in this paper. In particular, exploiting the inherent voltage and current ripple of power converters, a new proportional-integral (PI) controller with error variable the power-voltage gradient is proposed which is capable to ensure maximum power point (MPP) operation. Taking into account the nonlinear model of the PV source and the accurate nonlinear dynamics of the dc/dc boost converter an extensive stability analysis is addressed. Based on the singular perturbation theory and Lyapunov's direct method, it is proven that for appropriate values of the PI controller gains, stability and convergence to the MPP can be guaranteed. The excellent performance of the proposed PI controller is evaluated through simulations results and it is compared with the commonly used perturb and observe algorithm and the conventional MPP method based on ripple correlation control.**

I. INTRODUCTION

The demands for sustainable and environmentally friendly electric power generation have decisively lead to an increased use of photovoltaic (PV) systems as a basic renewable energy source [1]. This wide penetration of PV systems in the electricity grid creates some other technical requirements related to the good performance and increased efficiency. On the other hand, it is well known that the power delivered from PV systems varies and depends not only from the environmental conditions but also from the operating point. However, for a particular irradiance and temperature value, it is shown that there exists a unique operating point for a PV system, defined as maximum power point (MPP), where PV deliver the maximum power [2]. As a result, a continuous tracking to the MPP should be one of the main tasks of a controlled PV system.

To achieve operation at the MPP, power electronic converters are used to interface the PV system with the electrical grid or the load, simultaneously providing a fast and reliable control input. In particular, the switching signals (duty-ratios) of power converters are properly regulated to drive the system operation point at the MPP [3]. Therefore, the design and implementation of efficient control schemes, which provide the appropriate switching signals has become a challenging target.

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Most of the commonly used control schemes for MPP tracking are heuristic and are comprised by an external perturbation and an algorithmic method. In this category belong the perturb and observe (P&O) [4] and the incremental conductance methods [5]. Also fuzzy and intelligent techniques have been reported in [6], [7]. The main drawback of these methods is that stability cannot be guaranteed. As it is reported in [8], bad tuning of the control parameters of the P&O method can cause unstable operation, even chaotic behavior. Still, at steady state, oscillations are appeared, as a result of the external perturbation needed for these MPP tracking methods.

In order to provide a stable controller under operation with the MPP tracking control, the so-called extremum seeking (ES) method has been developed and applied on PV systems. In [9] an extensive theoretical analysis has been conducted for the ES scheme, where stability is proved under some assumptions. In [10] and [11] the ES technique was tested experimentally for a PV array supplying a dc/dc power converter under different operating conditions. Although ES can guarantee stable operation under some constraints, a main drawback is that an external triggering perturbation again is needed. In other cases, [12], [13], sliding mode controllers have been proposed based on a time-varying sliding surface. However, the selection of a time-varying surface is a difficult task for PV systems, while the appearance of chattering, as a result of imperfect control switching, is an additional problem.

A new methodology, namely the ripple correlation control (RCC) promises effective operation with no need of external perturbations [14], [15]. The fundamental principle of the method is based on the fact that, as it is well known, power converters impose a voltage and current ripple even in steady state, due to the switching mechanism. The device's inherent ripple is exploited as a natural perturbation, thus avoiding to generate a forced external perturbation. The method uses the power-voltage gradient to obtain the MPP. The performance of a RCC technique is presented in [16] and verified experimentally for a stand-alone PV system. Moreover, when the stability is investigated, it is conducted for an ideal source, modeled by a dc voltage source in series with a resistance [17], while the PV nonlinearities are not taken into account.

In this paper, based on the RCC technique an appropriate proportional-integral (PI) controller with error variable the power-voltage gradient is proposed and analyzed in detail. At this point, it is noted that PI controllers have been used in PV applications, only for regulating the output voltage [18], and to our knowledge, it is the first time that the PI controller concept is combined with the RCC technique to provide an MPP tracking controller with guaranteed stability. To this

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end, based on the singular perturbation method and taking into account the nonlinear model of the PV source, i.e. considering the output voltage-current nonlinear dependence, as well as the accurate nonlinear dynamics of the power converter, an extensive stability analysis is conducted for the closed-loop system. In particular, using suitable Lyapunov techniques, it is proven that there exists a wide range of appropriate gain values for the PI controller applied on the complete nonlinear system, which can guarantee asymptotic stability at the MPP.

The remaining of the paper is organized as follows. In Section II, the nonlinear model of a stand-alone PV system is provided. In Section III, the applied PI controller is proposed, while in Section IV, an extensive stability analysis is presented. In Section V, simulations results are carried out and finally, in Section VI, some conclusion are drawn.

II. STAND-ALONE PV SYSTEM MODEL

A stand-alone PV system is depicted in Figure 1. This system consists of a PV source, a battery storage, a dc/dc boost converter and an inductance-resistance load.

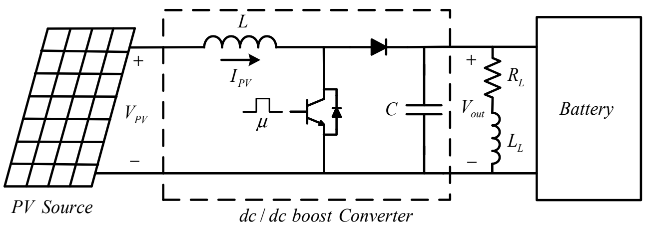

Figure 1. A stand-alone PV System.

A PV cell can be modeled as a photo-current source I_{SC}, that produces a current proportional to the sun irradiance, which is in parallel with a diode D and a resistor R_P, which in turn is in series with a resistor R_S. The equations of the PV cell output current $I_{PV,cell}$ and voltage $V_{PV,cell}$ are given by the following equations [19]:

$$I_{PV,cell} = I_{SC} - I_D - V_D / R_P,$$

$$I_D = I_0 \left(e^{V_D/V_T} - 1 \right)$$

$$V_{PV,cell} = V_D - R_s I_{PV,cell}$$

A PV module composed of 36 PV cells connected in series is regarded. As PV source of the stand-alone system, a PV string, consisting of m PV modules in series, is considered. The output voltage and current of the PV string are denoted by V_{PV} and I_{PV}, respectively. Voltage-current (dash lines) and power-current (solid lines) characteristics for the PV string is depicted in Figure 2 for three different irradiance levels G. One can observe the nonlinear dependence of the output voltage and power with respect to the PV string current and the solar irradiation. It is pointed out that the power produced by the PV string for a given irradiance has a unique maximum point defined as MPP. The maximum power produced, as well as, the current and voltage at that point, are denoted as P_{PV}^{MPP}, I_{PV}^{MPP} and V_{PV}^{MPP}, respectively. The short-circuit of the PV string is defined as I_{SC} and the open-circuit as V_{OC}.

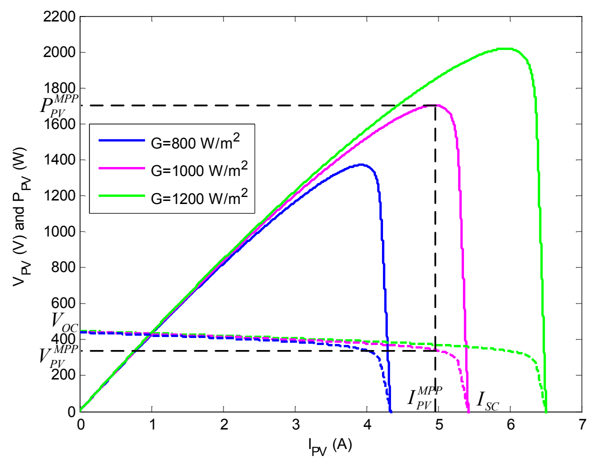

Figure 2. $V_{PV} - I_{PV}$ (dash lines) and $P_{PV} - I_{PV}$ (solid lines) characteristics for different irradiance levels (G) of a PV string.

For the dynamic analysis of the dc/dc boost power converter the average modeling technique is adopted. This model description has been extensively used in the literature for pulse width modulation (PWM) regulated systems to transform an essentially discrete-time nonlinear control design problem into an equivalent continuous time nonlinear control problem [20]. Hence, taking into account that the output voltage is constant due to the presence of the battery, one can obtain the following nonlinear differential equation for the dc/dc boost converter, fed by the PV system:

$$L\dot{I}_{PV} = -(1-\mu)V_{out} + V_{PV} \tag{1}$$

where now I_{PV} is the input inductor current, V_{out} is the constant output voltage and V_{PV} is the input voltage of the dc/dc converter. The converter inductance is represented by L and μ denotes the duty-ratio representing the switching cycle ratio in a period. It should be noted that μ is a continuous function that takes values in the range $[0,1]$ and constitutes the controlled input of the system, while V_{PV} is considered as an unknown disturbance input. Its value is determined each time instant by the solar irradiation and the operation point achieved by the controller on the $V_{PV} - I_{PV}$ curve.

III. THE PROPOSED PI CONTROLLER FOR MPP OPERATION

A main task of controlling a PV system is to drive it continuously to operate on MPP. However, this is not an easy task due to the fact that the MPP is unknown and changes with environmental conditions. This obstacle is usually overcomed by a cascaded control scheme. This scheme includes a fast inner-loop controller, whose reference value is determined by a slower outer-loop MPP tracking method. The outer-loop consists usually of an algorithmic method, used to track the MPP by perturbing the PV string voltage or current reference value. Particularly, if the power produced by the PV string is increased, this means that the operating point is approaching the MPP, therefore the reference value should be perturbed in the same direction. If the power is decreased, then the reference value must be perturbed in the opposite direction.

The reference value provided from the outer-loop is then used as input to the inner-loop controller in order to stabilize the system at the desired operating point. There are many control laws proposed in the literature for the inner-loop, as given for example in [21], [22]. However, as mentioned in the introduction, stability of the total system cannot be guaranteed, due to the heuristic nature of the MPP tracking methods used in the outer-loop.

On the other hand, ES control schemes have been applied in PV systems to track the set point which maximizes the delivered power. The ES method uses a sinusoidal perturbation signal in order to drive the PV system to the MPP, thus substituting the outer-loop of the controller. Depending on whether the sinusoidal perturbation is in or out of phase with the power delivered from the PV system, the operating point can be determined with respect to the MPP. However a main drawback of this technique is that an external perturbation is again needed, which causes oscillations around the MPP at steady state.

To overcome these drawbacks, in this paper based on the RCC principle, we obtain an appropriate error signal which can be used as input for a PI controller. Particularly, the gradient of the power-voltage curve dP_{PV} / dV_{PV} is considered as input error signal. One can easily observe that when the error signal equals to zero the desired operating point, namely the MPP, is established. Thus, we propose the following PI controller:

$$\mu = 1 - k_p \frac{dP_{PV}}{dV_{PV}} - k_I \int \frac{dP_{PV}}{dV_{PV}} dt \tag{2}$$

where k_p, k_I are positive constants.

Establishing a mathematical description for the closed-loop system, a stability analysis is now possible for the total system. In the next section, a complete stability analysis is carried out for the stand-alone PV system, which takes into account the nonlinear model of the PV source and the nonlinear dynamics of the boost converter.

IV. Stability Analysis of the Closed-Loop System

In order to proceed with our analysis, the mathematical model of the closed-loop system is given by the nonlinear differential equations (1) and (2). Defining $z = k_I \int \frac{dP_{PV}}{dV_{PV}} dt$ we arrive at the following state-space representation for the closed-loop system:

$$L\dot{I}_{PV} = -(1-\mu)V_{out} + V_{PV} \tag{3}$$

$$\dot{z} = k_I \frac{dP_{PV}}{dV_{PV}} \tag{4}$$

with $\mu = 1 - k_p \frac{dP_{PV}}{dV_{PV}} - z$

System (3)-(4) for k_I small enough consists a standard singular perturbation model with I_{PV} the fast variable, z the slow variable and k_I the perturbation parameter. The two time-scale property of the standard model is a fundamental characteristic and the analysis is divided into two steps. First the boundary-layer (fast system) is examined and then the reduced model (slow system) is analyzed. Thus, we start from the boundary-layer model which is obtained from (3) by substituting the slow variable z with a frozen parameter z^*. Therefore, one obtains:

$$L\dot{I}_{PV} = -k_p V_{out} \frac{dP_{PV}}{dV_{PV}} - z^* V_{out} + V_{PV} \tag{5}$$

To obtain the equilibrium point of (5) we set $\dot{I}_{PV} = 0$ and solving with respect to V_{PV} one arrives at:

$$V_{PV} = k_p V_{out} \frac{dP_{PV}}{dV_{PV}} + z^* V_{out} \tag{6}$$

The above algebraic equation is nonlinear and cannot be solved analytically. To overcome this problem, one can observe that (6) can be written as:

$$V_{PV} = f(V_{PV}) \tag{7}$$

If function f consists a contraction mapping then one can conclude that there exists exactly one solution V_{PV}^* that satisfies (7). In order to prove this property for function f, its derivative with regard to V_{PV} is calculated:

$$\frac{df(V_{PV})}{dV_{PV}} = k_p V_{out} \frac{d^2 P_{PV}}{dV_{PV}^2} \tag{8}$$

Since $d^2 P_{PV} / dV_{PV}^2$ is bounded there exists k_p small enough such that:

$$\left| k_p V_{out} \frac{d^2 P_{PV}}{dV_{PV}^2} \right| < 1$$

As a result for sufficiently small k_p, function f is a contraction, which indicates that there exists a unique solution V_{PV}^* satisfying (7). From the $I_{PV} - V_{PV}$ characteristic the solution V_{PV}^* corresponds to a unique value I_{PV}^* for the PV current. Therefore, the boundary-layer model (5) has a unique equilibrium point I_{PV}^*.

Let us shift the equilibrium point to the origin via the following change of variables $\tilde{I}_{PV} = I_{PV} - I_{PV}^*$, then the corresponding boundary-layer becomes:

$$L\dot{\tilde{I}}_{PV} = -k_p V_{out} \frac{dP_{PV}}{dV_{PV}} - z^* V_{out} + V_{PV} \tag{9}$$

Now defining for (9) the Lyapunov function:

$$V_1 = \frac{1}{2} L\tilde{I}_{PV}^2$$

its time derivative can be calculated as

$$\dot{V}_1 = L\tilde{I}_{PV}\dot{\tilde{I}}_{PV} = \tilde{I}_{PV}\left(-k_p V_{out}\frac{dP_{PV}}{dV_{PV}} - z^* V_{out} + V_{PV}\right) \quad (10)$$

In order to prove that $\dot{V}_1$ is negative definite we add and subtract the term $k_p V_{out}\, dP_{PV} / dV_{PV}\big|_{V_{PV}=V_{PV}^*}$, to obtain

$$\begin{aligned}\dot{V}_1 = \tilde{I}_{PV}(&-k_p V_{out}\frac{dP_{PV}}{dV_{PV}} + k_p V_{out}\left.\frac{dP_{PV}}{dV_{PV}}\right|_{V_{PV}=V_{PV}^*} \\ &-k_p V_{out}\left.\frac{dP_{PV}}{dV_{PV}}\right|_{V_{PV}=V_{PV}^*} - z^* V_{out} + V_{PV})\end{aligned} \quad (11)$$

Since the equilibrium point V_{PV}^* must satisfy (6) one gets for (11)

$$\dot{V}_1 = \tilde{I}_{PV}\left(-k_p V_{out}\frac{dP_{PV}}{dV_{PV}} + k_p V_{out}\left.\frac{dP_{PV}}{dV_{PV}}\right|_{V_{PV}=V_{PV}^*} - V_{PV}^* + V_{PV}\right)$$

or equivalalently

$$\dot{V}_1 = \tilde{I}_{PV} k_p V_{out}\left(\left.\frac{dP_{PV}}{dV_{PV}}\right|_{V_{PV}=V_{PV}^*} - \frac{dP_{PV}}{dV_{PV}}\right) + \tilde{I}_{PV}\left(V_{PV} - V_{PV}^*\right) \quad (12)$$

We examine the first term of (12). To prove that it is negative definite we exploit the fact that the $P_{PV} - V_{PV}$ curve nonlinearities imply convexity and therefore it holds true that $d^2 P_{PV} / dV_{PV}^2 < 0$ in $[0, V_{OC}]$. Using the mean value theorem one can prove that there exists a $V_{PV} = c_1$, with $c_1 \in (0, V_{OC})$ such that:

$$\frac{dP_{PV}/dV_{PV} - dP_{PV}/dV_{PV}\big|_{V_{PV}=V_{PV}^*}}{V_{PV} - V_{PV}^*} = \left.\frac{d^2 P_{PV}}{dV_{PV}^2}\right|_{V_{PV}=c_1} < 0 \quad (13)$$

Multiplying (13) by $-\left(V_{PV} - V_{PV}^*\right)^2$ we obtain:

$$\left(V_{PV} - V_{PV}^*\right)\left(\left.\frac{dP_{PV}}{dV_{PV}}\right|_{V_{PV}=V_{PV}^*} - \frac{dP_{PV}}{dV_{PV}}\right) \geq 0$$

Since the PV current and PV voltage are inversely related it is straightforward to conclude that:

$$\tilde{I}_{PV} k_p V_{out}\left(\left.\frac{dP_{PV}}{dV_{PV}}\right|_{V_{PV}=V_{PV}^*} - \frac{dP_{PV}}{dV_{PV}}\right) \leq 0 \quad (14)$$

Therefore applying (14) into (12) one arrives at

$$\dot{V}_1 \leq (I_{PV} - I_{PV}^*)\left(V_{PV} - V_{PV}^*\right) \quad (15)$$

One can easily see from (15) that $\dot{V}_1$ is negative definite, which implies asymptotic stability at the origin. However, in order to prove exponential stability at the origin we take into account that for the $V_{PV} - I_{PV}$ characteristic it holds true that

$$\frac{dV_{PV}}{dI_{PV}} < 0 \text{ in } [0, I_{SC}] \quad (16)$$

Inequality (16) implies that there exists a positive constant $\delta > 0$ which satisfies the relation $\frac{dV_{PV}}{dI_{PV}} \leq -\delta$ in $[0, I_{SC}]$.

The mean value theorem implies that there exists $I_{PV} = c_2$, with $c_2 \in (0, I_{SC})$ such that for any $I_{PV} \in [0, I_{SC}]$

$$\frac{V_{PV} - V_{PV}^*}{I_{PV} - I_{PV}^*} = \left.\frac{dV_{PV}}{dI_{PV}}\right|_{I_{PV}=c_2} \leq -\delta \quad (17)$$

Multiplying inequality (17) by $(I_{PV} - I_{PV}^*)^2$ one arrives at

$$\left(I_{PV} - I_{PV}^*\right)\left(V_{PV} - V_{PV}^*\right) \leq -\delta\left(I_{PV} - I_{PV}^*\right)^2 \quad (18)$$

Hence from (15) and (18) we obtain

$$\dot{V}_1 \leq -\delta\left(I_{PV} - I_{PV}^*\right)^2 \quad (19)$$

Clearly (19) proves exponential stability of the unique equilibrium point of the boundary-layer model (5). According to [23], if the equilibrium point of (5) is exponentially stable in the frozen parameter z^*, then it will remain exponentially stable when this parameter is replaced by the slowly varying variable z.

Proceeding with our analysis we will now examine the corresponding reduced system which is given by

$$\dot{z} = k_I \frac{dP_{PV}}{dV_{PV}} \quad (20)$$

with V_{PV} being equal to

$$V_{PV} = k_p V_{out}\frac{dP_{PV}}{dV_{PV}} + z V_{out} \quad (21)$$

Solving (21) with respect to the slow variable z we arrive at

$$z = \frac{V_{PV}}{V_{out}} - k_p \frac{dP_{PV}}{dV_{PV}} \quad (22)$$

Introducing the time scale $t = \tau / k_I$ we define the nonlinear differential equation (20) of z in the new time scale as

$$z' = \frac{dz}{d\tau} = \frac{dz}{dt}\frac{dt}{d\tau} = \frac{1}{k_I}\dot{z} = \frac{1}{k_I}\left(k_I \frac{dP_{PV}}{dV_{PV}}\right) = \frac{dP_{PV}}{dV_{PV}} \quad (23)$$

where " $'$ " represents the time derivative in the new time scale.

Hence, in order to obtain the derivative of the power P_{PV} with respect to the state variable z we write

$$\frac{dP_{PV}}{dV_{PV}} = \frac{dP_{PV}}{dz}\frac{dz}{dV_{PV}} \tag{24}$$

From (22) the derivative of the state z with respect to the PV voltage can be found to be

$$\frac{dz}{dV_{PV}} = \frac{1}{V_{out}} - k_P \frac{d^2 P_{PV}}{dV_{PV}^2} \tag{25}$$

Since $d^2 P_{PV} / dV_{PV}^2 < 0$ it can be easily seen that $\frac{dz}{dV_{PV}} > 0$.

Now, we are ready to introduce the following Lyapunov function for the reduced system (23) defined in the new time scale

$$V_2 = \frac{1}{2}\left(z - z_{MPP}\right)^2$$

where z_{MPP} is the equilibrium point of (23) corresponding to $V_{PV} = V_{PV}^{MPP}$ and $I_{PV} = I_{PV}^{MPP}$. From (22) it can be found that when $V_{PV} = V_{PV}^{MPP}$, then $z_{MPP} = \frac{V_{PV}^{MPP}}{V_{out}}$. On the other hand: $V_{PV} > V_{PV}^{MPP}$ implies $z > z_{MPP}$ and conversely, while the time derivative of the Lyapunov function V_2 can be found as

$$V_2' = \frac{dz}{dV_{PV}}\left(z - z_{MPP}\right)\frac{dP_{PV}}{dz} \tag{26}$$

From (26) it is straightforward to conclude that the equilibrium point z_{MPP} is asymptotically stable. However, in order to prove exponential stability for the reduced system (23), we consider the two following cases:

i) When $z \le z_{MPP}$ it holds true that $dP_{PV} / dz \ge 0$, with $dP_{PV} / dz = 0$ if and only if $z = z_{MPP}$. Hence, there exists a positive constant $\varepsilon_1 > 0$ such that the inequality $\frac{dP_{PV}}{dz} \ge -\varepsilon_1\left(z - z_{MPP}\right)$ is satisfied, which indicates that

$$\left(z - z_{MPP}\right)\frac{dP_{PV}}{dz} \le -\varepsilon_1\left(z - z_{MPP}\right)^2 \tag{27}$$

ii) When $z \ge z_{MPP}$ with a similar analysis one can conclude that there exists a positive constant $\varepsilon_2 > 0$ for which it holds true that:

$$\left(z - z_{MPP}\right)\frac{dP_{PV}}{dz} \le -\varepsilon_2\left(z - z_{MPP}\right)^2 \tag{28}$$

Taking into account both cases, one can obtain from (27) and (28) that $\left(z - z_{MPP}\right)\frac{dP_{PV}}{dz} \le -\min(\varepsilon_1, \varepsilon_2)\left(z - z_{MPP}\right)^2$ Therefore (26) becomes

$$V_2' \le -\frac{dz}{dV_{PV}}\min(\varepsilon_1, \varepsilon_2)\left(z - z_{MPP}\right)^2 \tag{29}$$

Inequality (29) indicates exponential stability of the reduced system (23). Hence, it is proven exponential stability for both the boundary-layer model and the reduced system at their respective equilibrium points. Based on the singular perturbation theory [23], one can conclude that for sufficiently small k_p there exists $k_{I\max} > 0$ such that, for all $k_I \in (0, k_{I\max})$ the equilibrium point $\left(V_{PV}^{MPP}, I_{PV}^{MPP}, z_{MPP}\right)$ of the initial closed-loop system (3)-(4) is asymptotically stable.

V. Simulation Results

To verify the stability analysis presented in the previous Section and to examine the controller performance, the stand-alone PV system, depicted in Figure 1, is simulated for the case where a step change occurs for the irradiance. A string of four PV modules is used as input for the dc/dc boost converter. The nominal values (for irradiance $G = 1000W/m^2$) for each PV module are: $V_{MPP} = 17.2V$, $I_{MPP} = 4.95A$, $I_{SC} = 5.45A$ and $V_{OC} = 22.2V$. The parameters of the dc/dc boost converter are $L = 20mH$ and $C = 200\mu F$, while the output voltage of the battery is considered to be $V_{out} = 100V$. The proposed PI controller is applied on the PV system and compared with the MPP tracking controller using RCC adopted in [16] and with the commonly used P&O method.

The irradiance increases from $G = 800W/m^2$ to $G = 1000W/m^2$ at time instant $t = 1\sec$. To the best of the authors knowledge there is no a general method for tuning the parameters of the aforementioned controllers (only some methods based on small signal analysis, as given for example in [24], are referred). Therefore, the parameters where selected by trial and error to achieve optimal transient and steady-state performance. In particular, for the P&O method the sample time was chosen to be $T = 1ms$ and the duty cycle perturbation $\Delta\mu = 0.004$. For the RCC controller the gain was selected to be $k = 0.4$, while for the PI controller the gains were set at $k_P = 0.005$ and $k_I = 0.4$.

The response of the PV system is shown in Figures 3 and 4. All three controllers achieve to drive the PV system to the MPP. However, as expected, one can observe that for the proposed PI controller no oscillations at steady state appear in contrast with the P&O controller. The proposed PI controller performance seems to be very similar with that of the RCC, although during transients the first exhibits better responses. This is verified in both Figures 3 and 4. This can be explained by the fact that the basic idea of both controllers is very similar, while in the proposed scheme the proportional-integral structure introduced, rather improves the dynamic response of the system. Therefore, from Figure 4, one can see that the PV system driven by the PI controller, delivers more power at transient period compared to the other two controllers. Finally, from Figure 4, one can observe that at steady-state the RCC and the PI controller deliver exactly the same amount of power which is certainly greater than the one obtained when the PV system is driven by the P&O method.

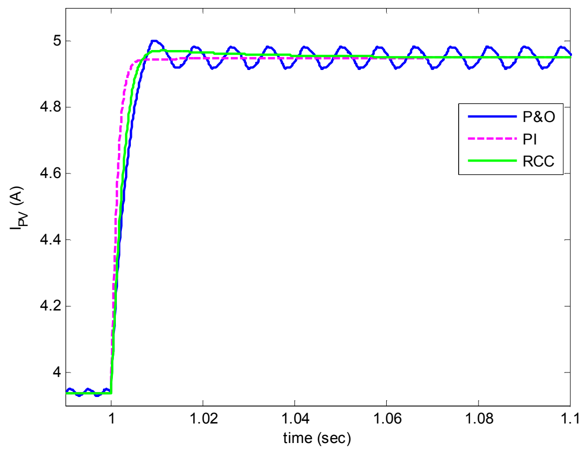

Figure 3. Response of the PV current in the case of irradiation change.

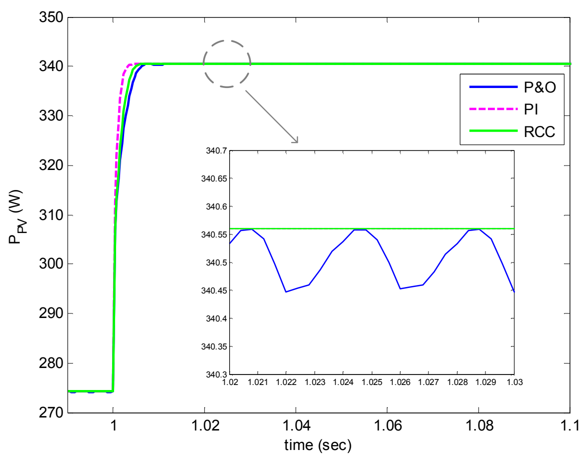

Figure 4. Response of the power delivered from the PV source in the case of irradiation change. At steady-state the power delivered with the PI controller and the RCC match exatcly.

VI. CONCLUSION

An appropriate PI controller is proposed to track the MPP of a PV system. For appropriate gain values of the PI controller, asymptotic stability of the closed loop system is proven. The effectiveness of the proposed controller is evaluated through simulations results and is compared with two commonly used MPP methods, namely the RCC and the P&O algorithm.

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