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Extremal control of DC/DC Converters in photovoltaic configurations*

Crina-Loredana Torous, Dumitru Popescu, Catalin Petrescu, Dragos-Viorel Balan

***Abstract* — The paper proposes an extremal control method through the design of a RST controller for a step-down DC-DC Buck Converter fed by a BGSP - P225 PV array. The input voltage for the converter is kept at the photovoltaic panel's maximum value by means of search algorithms for determining the Maximum Power Point. The algorithms used are Coggin's algorithm for the single variable dependent model P(U) and the gradient algorithm is used for the P(I,U) model. The voltage value can after that be identified again for different irradiance and temperature conditions. This gives the converter an extremal input voltage. Next, a dynamic model has been determined for the closed loop control system, starting from the converter's electrical components equations. A numerical RST controller used to achieve the performances of the system, was designed. A robustness analyses and correction has been performed for the RST polynomial control. The achieved performances of the DC-DC converter are validated through simulation by using the MATLAB / SIMULINK environment and the WinReg dedicated software. The novelty of the paper resides in the design of the RST controller for a photovoltaic panel and the robustness analysis.**

I. Introduction

Switched DC-DC converters are increasingly used in power electronic circuits, due to their simplicity in converting one level of electrical voltage into another level, by switching action. The operation regimes of switch controlled converters are characterized as follows: every moment, the power devices are either blocked – which means the current is null – or saturated – indicating a very low voltage on the device. The consequence is that the power dissipated by the devices is very small, while the conversion efficiency is high [1],[11].

Among the known DC-DC converter schemes, three versions are used most frequently: "step-down" voltage ("buck"), "step-up" voltage ("boost") and reverse ("inverter" or "buck-boost"). For the switching converters, the main factors that need to be considered are their analysis, design, control and stabilization [2],[7].

The DC-DC converter was tested in a photovoltaic configuration, which inputs into the converter the maximum voltage corresponding to a temperature and solar irradiation under standard test conditions: T=25^0 C and E=800 W/m^2. The maximum output power for the case study is P_{MAX}=186.4429 W, at a maximum power point (I_{MP},U_{MP})= (6.58 A; 28.35 V). These values have been determined using the polynomial interpolation algorithm (Coggin's) and the optimal gradient algorithm (Cauchy), see [4], [9], [10].

One of the usual converters is Buck converter. It is a controlled step-down converter which is supplied by an incoming unstabilized DC voltage, converting it to a regulated DC output, at a lower voltage [3].In the control of switch mode DC-DC, many control methods have been proposed and implemented, each having both advantages and disadvantages. A DC-DC converter will provide a regulated DC output voltage, based on feedback control. Depending on the application where it is applied, the effectiveness of the control method can be determined

In a photovoltaic power generation system, the photovoltaic power energy is taken over by the DC-DC converter, providing a desired output voltage. This output voltage can supply a DC load, or, through the medium of an inverter, the renewable energy is injected into the main power supply, or provided to AC load (Fig.1) [3].

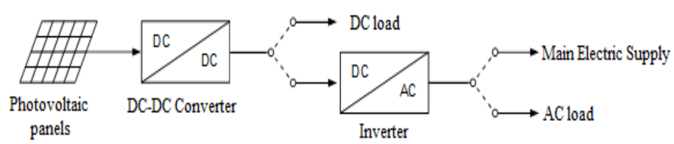

Fig. 1. Simplified renewable energy consumption schema

DC autonomous systems are the simplest achievable configurations, being intended to supply individual DC equipment (such as traffic light systems, lamps for public lighting, weather stations, etc.).AC autonomous systems are used for supplying the isolated consumer housing. The installed power is higher than for DC systems, the current and voltage for these systems being 230V / 50Hz (according to the European standard).Networked systems are used where the access to the electricity grid is available. The energy

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generated from renewable sources is introduced directly into the power grid as AC energy.[7]

.The electrical structure of DC-DC Buck converter consists of power MOSFET transistor (the switching element), diode, inductor and capacitor, as shown in Fig. 2.

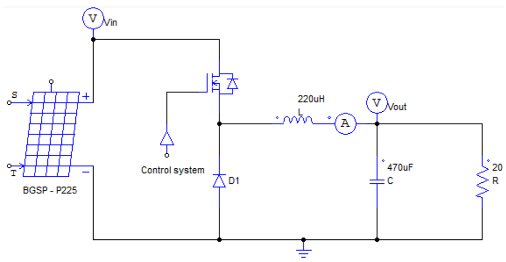

Fig. 2. DC-DC Buck converter (psim simulation schema)

The Buck converter belongs to the class of “chopper" circuits, or attenuation circuits. It actually multiplies the constant input voltage by a scalar factor (D), smaller than unity, at the output:

$$V_{out} = \mathrm{D} \cdot V_{in} \qquad (1)$$

where D is the duty ratio of the converter. Therefore, by adjusting the duty ratio (D), the output voltage can be regulated [1].The power transistor can be associated to an ideal switch, and thus, depending on its state (closed/open), results the electrical behavior of the Buck converter.

II. PHOTOVOLTAIC CONFIGURATION

A. Panel model

The photovoltaic cell panel model, which will be detailed in the present paper is the one diode extended model, also known as a L4P [4]. The abbreviation stands for Lumped, 1 Mechanism model with 4 Parameters, where Lumped refers to the type of approximation used and 1 Mechanism refers to the degree of approximation used to model a cell with an equivalent electrical circuit, presented in Fig. 3.

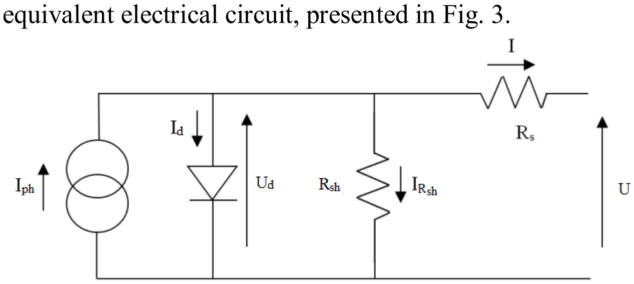

Fig. 3. L4P cell model

In order to estimate the I(U) and P(U) characteristics, we start with the solar cell nonlinear equation, which is presented below:

$$I = I_{ph} - I_0 * \left(e^{\left(\frac{q}{n*N_s*K*T}*(U+I*R_s)\right)} - 1 \right) - \frac{U+I*R_s}{R_{sh}} \qquad (2)$$

Where:
I_{ph} – photovoltaic current
I_0 – saturation current for the diode
R_s – series resistance
R_{sh} – shunt resistance
q – electron charge constant, 1.602 x 10^{-19} C
n – shape factor (1 for ideal cell)
N_s – number of cells wired in series
K – Boltzmann constant, 1.381 x 10^{-23} J/K
T – cell temperature (K)

B. Photovoltaic characteristics

For simplicity, the L4P model provides a good approximation of a photovoltaic cell and will be used further in the simulation of the photovoltaic panel. Equation (2) is also known as the 5 parameter model for photovoltaic cells; the 5 parameters in this case are: I_{ph}, I_0, n, R_s, R_{sh}..

The simplified model of the photovoltaic panel was used in simulation to obtain the characteristics for one panel, having 60 cells connected in series and parallel, for a voltage range of 1-40 V. In the figures that follow, it can be noticed that the model offers a good approximation of the real one. The results of the tests are presented below in Fig. 4 and Fig. 5.

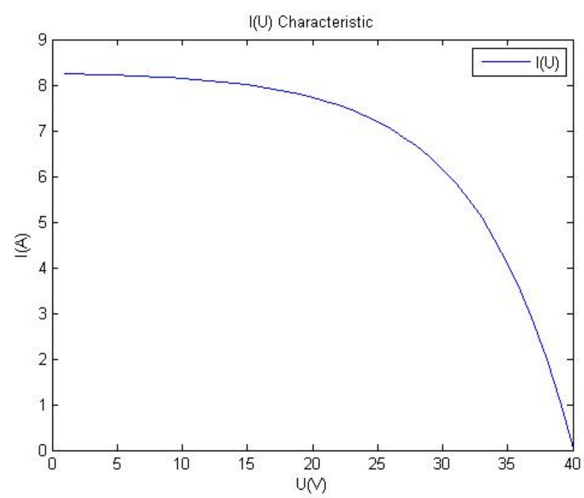

Fig. 4. Simulated I(U) Characteristic

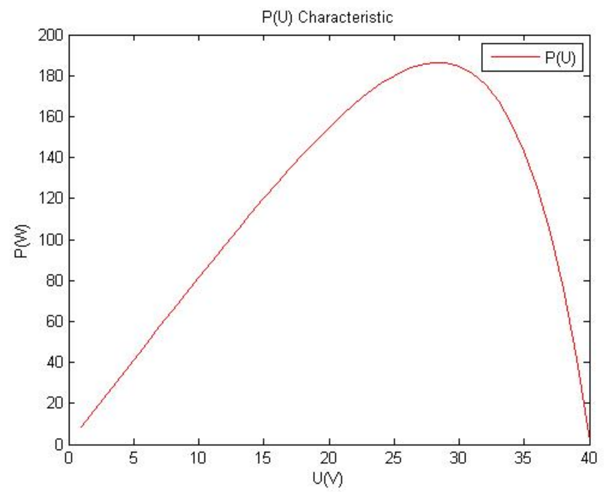

Fig. 5. Simulated P(U) Characteristic

III. THE BUCK CONVERTER

For designing the DC-DC Buck converter we have chosen the standard catalogue values for the electrical components, presented in Table I.

Parameter	Value
L	220µH
C	470µF
R	20Ω

Table I. DC-DC Buck Converter – Electrical components

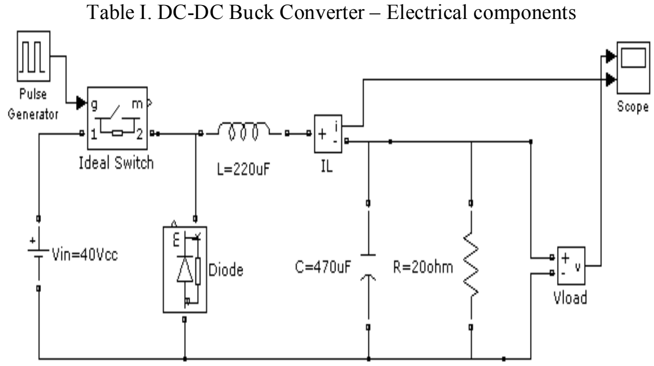

Fig.6. DC-DC Buck converter: Simulink model

A. DC-DC Buck Converter dynamic model

The ideal representation of the DC-DC Buck converter is shown in Fig. 7, in which the transistor was replaced by the ideal switch k. The situation when the transistor conducts is modeled by k=1. k=0 represents the converter with the transistor blocked.

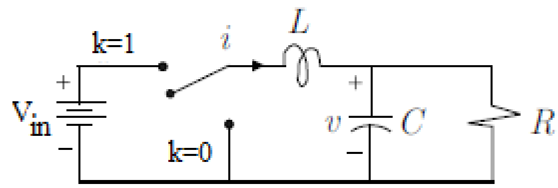

Fig.7. DC-DC Buck converter – Switching scheme

By applying Kirchhoff's theory, with respect to the voltage law, in both cases (k=1 and k=0) it has been obtained [3]:

$$L\frac{di}{dt} = -v + k \cdot V_{in} \quad (3)$$

$$C\frac{du}{dt} = i - \frac{v}{R} + k \cdot V_{in} \quad (4)$$

The open-loop line-to-output transfer function is given by:

$$G_p(s) = \frac{V_{in}}{LCs^2 + \frac{L}{R}s + 1} \quad (5)$$

where the input of the transfer function is the duty ratio and the output is the output voltage given by the Buck converter. Considering 40V a maximum value for V_{in}, and taking into account the values from Table I, from equation (4), the dynamic model is:

$$G_p(s) = \frac{40}{10.34 \cdot 10^{-8} s^2 + 11 \cdot 10^{-6} s + 1} \quad (6)$$

The step response of the DC-DC Buck Converter dynamic model is shown in Fig. 8:

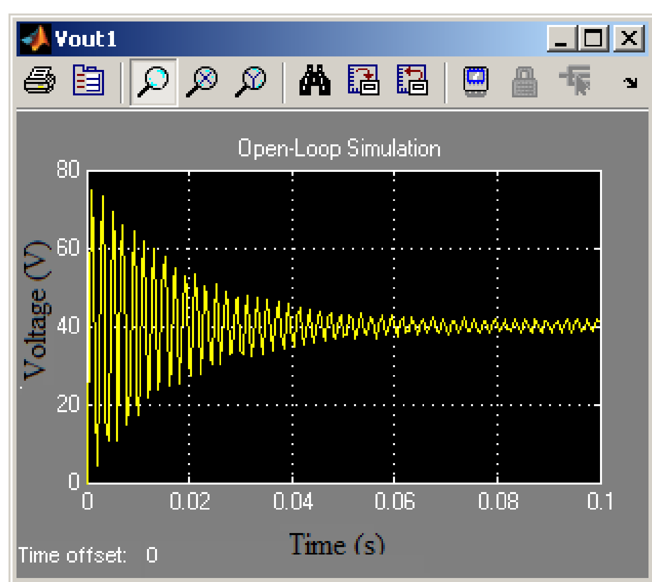

Fig. 8. DC-DC Buck Converter – Step response for dynamic model

Figure 8 shows a strong oscillatory character of the dynamic model. The controller should fix this issue, by placing the poles of the closed-loop system at specified locations.

B. RST controller design

Classic PID controllers are designed starting from linear models, thus tending to focus on only one regulation problem and that is obtaining the desired output voltage V_{out}.

The RST controller overcomes this weakness, offering good performances both in regulation and in tracking. The RST controller provides the desired system behavior in tracking (when changing the reference voltage) independently of his behavior in regulation (disturbances rejection) [5],[6],[8].

Fig. 8 shows the classical scheme of a system with an RST controller. To be noted that the tracking and regulation with independent objectives method that will be used leads to simplifying the zeros of the DC-DC Buck model.

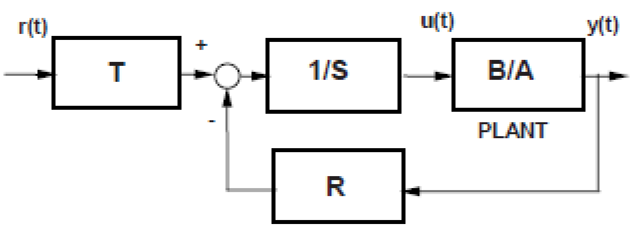

Fig. 8. RST standard control system

The R, S, T blocks of the controller can be written in a polynomial form:

$$R(z^{-1}) = r_0 + r_1 \cdot z^{-1} + \dots + r_{nr} \cdot z^{-nr}$$

$$S(z^{-1}) = s_0 + s_1 \cdot z^{-1} + \dots + s_{ns} \cdot z^{-ns} \qquad (7)$$

$$T(z^{-1}) = t_0 + t_1 \cdot z^{-1} + \dots + t_{nt} \cdot z^{-nt}$$

Finally, the RST controller will have the following command:

$$u(k) = \frac{T(z^{-1})}{S(z^{-1})} \cdot r(k) - \frac{R(z^{-1})}{S(z^{-1})} \cdot y(k), \qquad (8)$$

where r(k) is the reference and y(k) represents the output of the system.

The RST design method remains the poles placement with independent objectives in reference trajectory tracking and regulation. The characteristic polynomial $P(z^{-1})$ can be written as follow:

$$P(z^{-1}) = A(z^{-1}) \cdot S(z^{-1}) + B(z^{-1}) \cdot R(z^{-1}) \qquad (9)$$

where $A(z^{-1})$ and $B(z^{-1})$ are the polynomials that describe the system, by discretizing the continuous model with a proper sampling period Ts [6].

Having the pair (ζ, ω_n), by discretization, one can determine the characteristic polynomial $P(z^{-1})$, and from equation (9) one can compute the R and S polynomials. The $T(z^{-1})$ polynomial is computed to ensure an unitary static gain between the desired trajectory and the output of the system.

In a first stage, to determine the polynomials R and S (regulation performances), we have established the regulation performances which include open loop. Thus, we have allocated the dominant poles given by ($\omega_n = 1500$ rad/s and $\zeta = 0.9$), starting from the polynomial characteristic of the system $P(z^{-1})$:

$$P(z^{-1}) = 1 - 1.929 \cdot z^{-1} + 0.931 \cdot z^{-1} \qquad (10)$$

By using WinReg software tool for system control design and analysis, we determined the (R, S, T) polynomials. For computing the T polynomial, we have imposed the tracking given by ($\omega_n = 39.5$ rad/s and $\zeta = 0.9$).

The calculus and simulation led to:

$$R(z^{-1}) = -1.307 + 1.063 \cdot z^{-1} + 0.899 \cdot z^{-2}$$

$$S(z^{-1}) = 77.899 - 3.971 \cdot z^{-1} - 73.927 \cdot z^{-2} \qquad (11)$$

$$T(z^{-1}) = 1 - 0.411 \cdot z^{-1} + 0.067 \cdot z^{-2}$$

Also, for assuring steady state error zero, we have introduced the integrator component $(1 - z^{-1})$ in the pre-specification of the polynomial S [5].

The step response of the system is shown in Fig. 9.

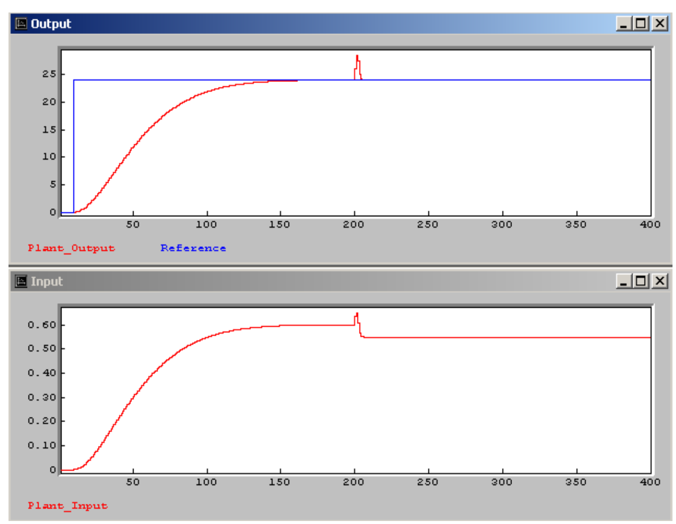

Fig. 9. Step response of the system (with RST controller)

We can observe that the response of the system achieve both performances in tracking and in regulation.

C. Robustness analysis

We want a robust controller for our DC-DC Buck converter. Therefore, we have analyzed the control specification in terms of the Modulus Margin $|\Delta M(j\omega)|$ and the maximum of the disturbance-output transfer sensitivity function, S_{py}. They have the following values:

$$|\Delta M(j\omega)| = 0.286 \tag{12}$$

and

$$\max|S_{py}| = 10.868\ dB \tag{13}$$

respectively.

These values are unsatisfactory in terms of the robustness. Therefore we improved the classical RST controller, by specifying additional fixed parts in the pre-specification of the polynomial R and S [5], [6]. In order to take into account the additional fixed parts of R and S, they will be factorized as follow:

$$R(q^{-1}) = R'(q^{-1})H_R(q^{-1})$$

$$S(z^{-1}) = S'(z^{-1})H_S(z^{-1}) \tag{14}$$

where $H_R(z^{-1})$ and $H_S(z^{-1})$ are predefined polynomials.

We want to improve the Modulus Margin, as follows:

$$|\Delta M(j\omega)| \geq 0.5 \tag{15}$$

and

$$\max|S_{py}| \leq 6\ dB \tag{16}$$

In order to modify the command in terms of the robustness, we added an additional complex pole in the characteristic polynomial $P(z^{-1})$ (for regulation specification) and we have specified 3 additional complex poles in the pre-specification of R, as can be seen in (17). To be noted that the additional poles are “faster” than the dominant ones.

$$H_R(z^{-1}) = (1-z^{-1} + 0.4\cdot z^{-2})\cdot(1-0.03\cdot z^{-1} + 0.417\cdot z^{-2})\cdot(1-0.8\cdot z^{-1} + 0.5\cdot z^{-2}) \tag{17}$$

The following RST controller was obtained:

$$R(z^{-1}) = -0.56 + 1.54\cdot z^{-1} - 1.53\cdot z^{-2} + 0.87\cdot z^{-3} + 2.18\cdot 10^{-4}\cdot z^{-4} - 0.33\cdot z^{-5} + 0.35\cdot z^{-6} - 0.17\cdot z^{-7} + 0.05\cdot z^{-8}$$

$$S(z^{-1}) = 77.89 - 144.97\cdot z^{-1} + 87.82\cdot z^{-2} + 18.01\cdot z^{-3} - 83.67\cdot z^{-4} + 79.47\cdot z^{-5} - 49.06\cdot z^{-6} + 18.76\cdot z^{-7} - 4.25\cdot z^{-8} \tag{18}$$

$$T(z^{-1}) = 1 - 1.48\cdot z^{-1} + 0.9\cdot z^{-2} - 0.23\cdot z^{-3} + 0.02\cdot z^{-4}$$

With the robust algorithm the Modulus Margin was increased. Also, by analyzing the disturbance output transfer function before and after correcting the command it can be noticed that the maximum amplitude of S_{yp} was decreased with approx. 50% (see Table II).

Parameter	Value

Before improving the command	
Modulus Margin	0.286
Max$\|S_{yp}\|$	10.868 dB
Gain Margin	1.41
Delay Margin	47.6 deg
Phase Margin	0.00340 sec
After improving the command	
Modulus Margin	0.490
Max$\|S_{yp}\|$	5.23 dB
Gain Margin	2.460
Delay Margin	59.1 deg
Phase Margin	0.00237 sec

Table II. Margins after improving the command

The disturbance-output transfer function is represented in Fig. 10.

In Fig. 11 it can be observed that the robust closed loop system preserves the imposed performances both in tracking and in regulation, the behavior being similar to that in Figure 9.

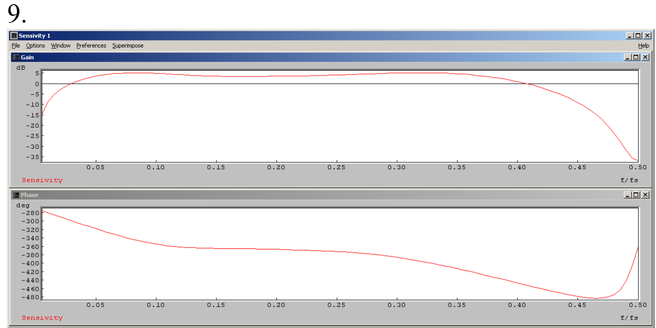

Fig. 10. Disturbance Output Transfer Function of the robust system, after improving the command

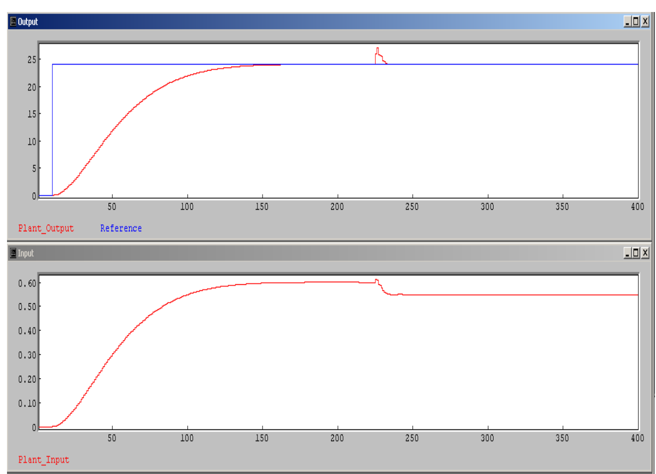

Fig. 11. Step response of the system (with RST controller), after improving the command

IV. CONCLUSION

Our research proposes an extremal control system for renewable energy systems. For the BGSP – P225 photovoltaic panel we use the Maximum Power Point and extract the maximum output voltage U_{MP} used for the tracking in the closed loop system. Thus, the converter output tracks the U_{MP} value.

We presented the modeling of a DC-DC Buck converter for a BGSP - P225 PV array. The model has a strong oscillatory character.

For this model, a polynomial RST algorithm was designed, which achieved performances in tracking and regulation. The RST controller meets both tracking and regulation requirements independently.

A robustness analysis was performed for the closed-loop system with RST control, and a robust command was designed ensuring robust performances. The nominal command was analyzed and improved, in order to compensate the non-linear behavior and parameter variations of the DC-DC Buck converter. Thus, satisfactory robustness indicators were obtained.

As a perspective of research, the performance of the robust control can be further improved by studying other system configurations, such as optimal control systems.

An experimental platform will be built in order to validate the results on actual photovoltaic installations.

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