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# Nonlinear Hierarchical Easy-to-Implement Control for DC MicroGrids

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**Abstract:** It was considered in this work the connection of a photovoltaics (PV) solar plant to the main grid through a Direct Current (DC) MicroGrid and a hybrid storage system, composed of a battery and a supercapacitor, in order to satisfy constraints of grid connection (the so-called Grid-Codes). The objective, and main contribution of this paper, is to stabilize the DC MicroGrid voltage in spite of large variations in production and consumption, using a nonlinear hierarchical easy-to-implement control strategy. Here it is presented the MicroGrid's control design based on detailed models of the photovoltaic energy sources and the storage systems. Such DC grids may present an unstable behavior created by the PV's intermittent output power, by switching ripples from the power converters and their power electronics, and oscillatory currents produced by some types of loads. Therefore the system is subject to both fast and slow variations, and its stabilization is based on different technologies of storage, such as battery and supercapacitor, and control algorithms designed thanks to the use of time-scale separation between different components of the storage systems. The obtained nonlinear results are stronger than current linear controllers, allowing to keep operating margins around the voltage reference. At the same time in this work, insights from power systems practice have been used, aiming to obtain a very simple and easy-to-implement control scheme. Detailed simulation results are provided to illustrate the behavior and effectiveness of the proposed stabilization technique.

**Keywords:** Microgrids; Power System Stability; Nonlinear control systems; Lyapunov methods; Power generation control

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The integration of renewable energy sources (renewables) and modern loads on a large scale is a challenging task due to their intermittent nature. As a consequence, the power grid becomes vulnerable and subject to instability issues. In particular, the presence of Distributed Generation (DG) such as solar energy, or modern loads as electric vehicles and intelligent buildings in a distribution network creates challenges that can be addressed by the concept of MicroGrids [1], [2]. In MicroGrids, storage devices are used to compensate for intermittent behavior and then secure grid integrity concerning the increase in the number of DG elements [3]. They allow for the possibility to design control systems to ensure stability during the injection and consumption of intermittent power.

The present paper focuses on stabilizing voltage on a Direct Current (DC) MicroGrid, used to integrate renewable power. This stabilization is obtained by designing a hierarchical control strategy that considers the power balance between the energy sources and loads. The nonlinear control scheme has been developed for a DC MicroGrid composed of photovoltaic (PV) panels, two storage devices (a battery and a supercapacitor)

35 acting at different time scales, a DC load and its connection to an Alternate Current (AC)  
36 grid.

37 In the field of MicroGrids, linear control methods are generally used, as in [4], [5],  
38 [6], [7] and [8]. These works use the small signal model of converters, and apply the  
39 industrial standard PI control, mostly addressing the stabilisation of the MicroGrid's  
40 DC voltage. On those workd, the control voltage performances are acceptable in terms  
41 of voltage overshoot and settling time, and stabilization of the whole DC MicroGrid  
42 is attained. Nevertheless, such control methods can correctly stabilize a MicroGrid  
43 only in steady state, when parameters do not vary much. On the other hand, if several  
44 parameters are time-varying, such linear controllers can not ensure good performance  
45 (sometimes not even stability) for the several operating points associated with such vari-  
46 ations. Therefore, developing new control structures to improve systems' performance  
47 is necessary.

48 On another hand, ([9],[10], [11]) propose new control strategies based on nonlinear  
49 control theory, using state average model of converters. On those, the control strategy  
50 is designed globally with high level controller, and act locally on converters with local  
51 control algorithm. With this control strategy the system should be able to balance supply  
52 power and demand load in order to obtain a good performance in transient conditions  
53 and steady-state. Nevertheless, such results are rather complex, with algorithms that  
54 are difficult to implement in small and low-cost micro-controllers, distributed on a  
55 large number of components. The now proposed control philosophy is also based on a  
56 Systems of Systems approach, where each brick is designed to participate in ensuring  
57 the stability of the whole DC voltage system. This control strategy was developed in  
58 ([12], [13], [14], [15], [16], [17]), addressing different applications. In the present paper,  
59 such techniques were used to design a control strategy to stabilize the DC MicroGrid  
60 voltage through a control algorithm that defines priorities in relation to the photovoltaic  
61 system, load, and constraints for storage system operation.

62 Other articles (see [18], [19], [20], [21]) have also proposed a hierarchical control  
63 scheme focusing on a centralized supervisory control level and a distributed lower level  
64 control, based on nonlinear theory. These controllers present rigorous analysis of the  
65 interaction between the different dynamics, and aim to stabilize the whole system, even  
66 when large variations of power production and consumption occur, and to ensure power  
67 quality while providing power to the main AC grid. Differently to those results, the  
68 present paper has used assumptions coming from the physics of power systems to reduce  
69 the complexity of the control design procedure. However, these assumptions make  
70 stability analysis to hold inside a smaller operation region than more complex results.  
71 Nevertheless, these insights from power systems' practice allow simpler algorithms, well  
72 suited for a distributed implementation in low-cost micro-controllers in a low voltage  
73 grid, and still allow to stand large disturbances inside a well-defined operation region.

74 In this scheme, the higher-level controller provides reference values for the local  
75 controllers. Thereafter, we develop these distributed controllers using backstepping,  
76 feedback linearization, and Lyapunov-based control techniques. Power system stability  
77 is analyzed by intermediate Lyapunov functions provided for each step to construct  
78 a composite Lyapunov function for the overall stability analysis. The local controllers  
79 are implemented at the actuators' level on each device's power converters (PV panel,  
80 battery, supercapacitor). The reference is obtained by a Maximum Power Point Tracking  
81 (MPPT) algorithm concerning the PV power source. The supervisory higher-level  
82 controller is allowed to reduce the power reference in case of overproduction. The  
83 higher-level controller provides power references for the storage devices to cope with  
84 power unbalance in the whole system.

85 This paper is organized as follows. In Section I, the model for the DC MicroGrid is  
86 introduced; in Section II the DC MicroGrid Control strategy is drawn; in Section III low  
87 level control laws for each subsystem are designed; in Section IV the stability analysis for

88 the overall interconnected system is done; Section V provides simulation results about  
89 the connected system behavior; finally, Section VI presents the conclusions.

## 90 1. DC Microgrid Model

91 A general DC MicroGrid as in Figure 1 is composed of Distributed Generation (DG)  
92 such as photovoltaic arrays, energy storage elements like supercapacitors and batteries,  
93 DC loads and grid-tied converters [22]. The energy storage elements play an important  
94 role for the entire power management of the DC MicroGrid as mentioned. They ensure  
95 a secured network, provide high quality power and maintain the common DC grid  
96 voltage stable [23]. Bidirectional converters are used to charge or discharge the energy  
97 storage elements such as the battery and the supercapacitor. The load (an electric vehicle  
98 charge station for example) is modelled as a variable resistance, which in the present  
99 case are more delicate than constant power loads.

100 In the following, the different components of the DC MicroGrid are described.

### 101 1.1. PV System Modeling

#### 102 1.1.1. Solar Array

103 A complete solar panel model with series and parallel connection is proposed  
104 [24],[25]. The PV is represented as a current source. Due to the variations of the tem-  
105 perature and the solar radiance, the current and the voltage generated by the PV panel  
106 vary.

107 The PV DC/DC boost converter operates following references given by a standard  
108 MPPT algorithm (not discussed in this paper) under varying levels of irradiation and  
109 temperature [25],[26] and [24].

#### 110 1.1.2. DC/DC Boost Converter

111 The DC/DC converter used to control the PV array is an unidirectional boost  
112 converter. It is represented by three state variables: the voltages on the capacitors  $C_1$  and  
113  $C_2$  and the current in the inductance  $L_1$ .

114 The mathematical model for the DC/DC boost converter that interconnects the PV  
115 to the DC grid is obtained based on power electronics averaging technique (see [27], [28],  
116 [29], [30]), and is given by (1).

### 117 1.2. Storage system

118 The hybrid storage system (battery-supercapacitor) adopts the advantages of both  
119 technologies, high power density from the supercapacitor and high energy density  
120 from the battery. The proposed hybrid storage consists of a lead acid battery and a  
121 supercapacitor, as in [31], [32],[3] and [33].

#### 122 1.2.1. Battery model

123 The chosen model for the study is based on the resistive Thevenin model for a Lead  
124 Acid Battery, considered as a voltage generator [34].

#### 125 1.2.2. Supercapacitor

126 The Supercapacitor is modelled by the so-called three-branch model, extracted from  
127 the transmission line modelling. It is connected to the DC grid by a DC/DC bidirectional  
128 boost converter as in [35] and [36].

#### 129 1.2.3. Bidirectional Boost Converters

130 The bidirectional boost converter controlling the battery is given by (2), based on  
131 the voltages on the capacitors  $C_3$  and  $C_4$  and the current in the inductance  $L_2$  (see [37],  
132 [29,32] and [30]).

133 The bidirectional boost converter controlling the supercapacitor is modelled based  
 134 on the voltages on the capacitors and the current in the inductance  $C_5$ ,  $C_6$ ,  $L_3$ , shown by  
 135 (3), (see [29], [32] and [30]).

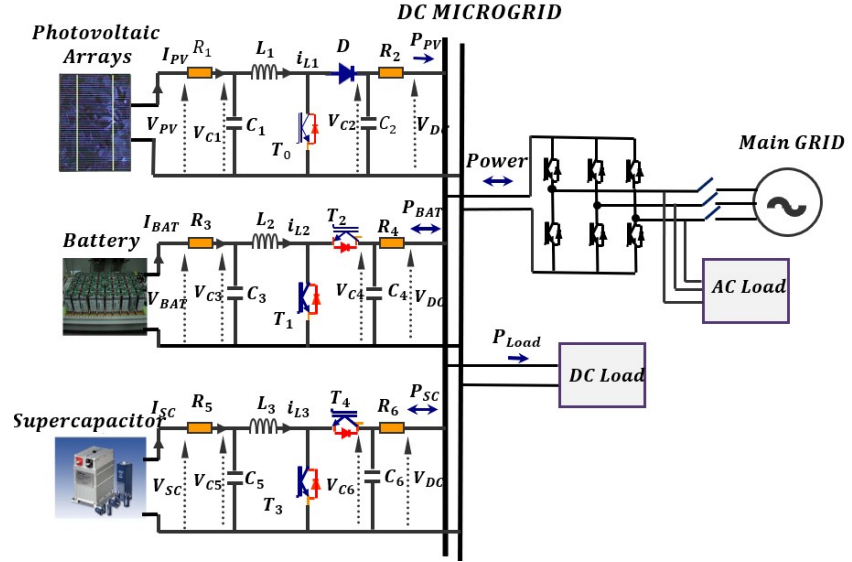


Figure 1. The considered DC MicroGrid.

### 136 1.3. Interconnected Model

137 The mathematical model for the DC grid in Figure 1 is obtained based on the power  
 138 electronics averaging technique [27]:

$$\dot{V}_{C1} = -\frac{1}{R_1 C_1} V_{C1} - \frac{1}{C_1} i_{L1} + \frac{1}{R_1 C_1} V_{PV} \quad (1a)$$

$$\dot{V}_{C2} = -\frac{1}{R_2 C_2} V_{C2} + \frac{(1-u_1)}{C_2} i_{L1} + \frac{1}{R_2 C_2} V_{DC} \quad (1b)$$

$$i_{L1} = \frac{1}{L_1} V_{C1} - \frac{(R_{01} - R_{02})u_1 + R_{02}}{L_1} i_{L1} - \frac{(1-u_1)}{L_1} V_{C2} \quad (1c)$$

$$\dot{V}_{C3} = -\frac{1}{R_3 C_3} V_{C3} - \frac{1}{C_3} i_{L2} + \frac{1}{R_3 C_3} V_{BAT} \quad (2a)$$

$$\dot{V}_{C4} = -\frac{1}{R_4 C_4} V_{C4} + \frac{(1-u_2)}{C_4} i_{L2} + \frac{1}{R_4 C_4} V_{DC} \quad (2b)$$

$$i_{L2} = \frac{1}{L_2} V_{C3} - \frac{(R_{03} - R_{04})u_2 + R_{04}}{L_2} i_{L2} - \frac{(1-u_2)}{L_2} V_{C4} \quad (2c)$$

$$\dot{V}_{C5} = -\frac{1}{R_5 C_5} V_{C5} - \frac{1}{C_5} i_{L3} + \frac{1}{R_5 C_5} V_{SC} \quad (3a)$$

$$\dot{V}_{C6} = -\frac{1}{R_6 C_6} V_{C6} + \frac{(1-u_3)}{C_6} i_{L3} + \frac{1}{R_6 C_6} V_{DC} \quad (3b)$$

$$i_{L3} = \frac{1}{L_3} V_{C5} - \frac{(R_{05} - R_{06})u_3 + R_{06}}{L_3} i_{L3} - \frac{(1-u_3)}{L_3} V_{C6} \quad (3c)$$

$$\dot{V}_{DC} = \frac{1}{C_{DC}} \left[ \frac{1}{R_2} (V_{C2} - V_{DC}) + i_{L2} + i_{L3} - \frac{P_{load}}{V_{DC}} \right] \quad (4a)$$

140 where  $R_1, R_2, R_3, R_4, R_5, R_6, L_1, L_2, L_3, C_1, C_2, C_3, C_4, C_5, C_6$  and  $C_{DC}$  are known positive  
 141 values of resistances, inductances and capacitors respectively, and  $P_{load}$  represents the DC  
 142 demanded power load. To model the switches, small resistances ( $R_{01}, R_{02}, R_{03}, R_{04}, R_{05}$   
 143 and  $R_{06}$ ) are included to take into account conduction losses.  $V_{PV}, V_{BAT}, V_{SC}$  and  $V_{DC}$  are  
 144 the photovoltaic panel, battery, supercapacitor and DC MicroGrid voltages, respectively.  
 145 The measured output vector is composed by  $V_{C1}, V_{C2}, V_{C3}, V_{C4}, V_{C5}, V_{C6}, i_{L1}, i_{L2}, i_{L3}$  and  
 146  $V_{DC}$ . The control inputs  $u_1, u_2$  and  $u_3$  represent the duty cycles of each converter.  
 147 Equation (4) describes by Kirchoff's law the voltage variation due to the sum of all  
 148 currents in the DC bus  $V_{DC}$ .

## 149 2. DC MicroGrid Control strategy

150 The target for the controller is to stabilize the DC bus voltage around the desired  
 151 value, then ensuring power quality and allowing the DC MicroGrid to manage the  
 152 desired amount of power. The proposed control will be based on two control layers (see  
 153 Figure 2). First, we define the high level controller to give reference values for lower local  
 154 controllers. Thereafter, we develop a local control using backstepping and Lyapunov  
 155 based techniques.

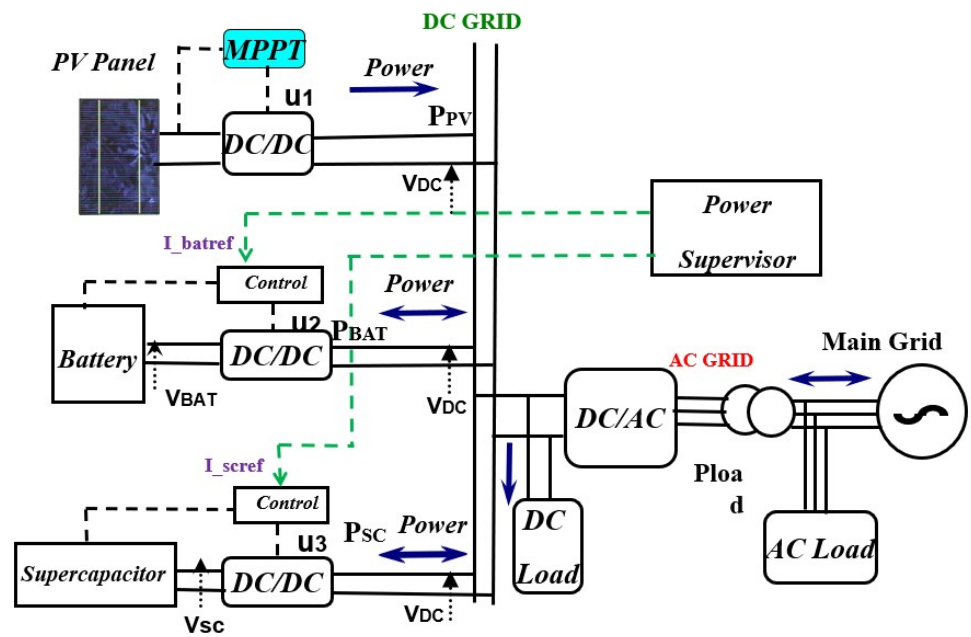


Figure 2. DC MicroGrid Control strategy.

### 156 2.1. High Level Controller for PV array source

157 A Maximum Power Point Tracking (MPPT) algorithm is used to extract the maxi-  
 158 mum power from a photovoltaic array of solar cells. To accomplish this task, a  $V_{C1}^*$  time  
 159 varying (piecewise constant) desired voltage reference is provided by the MPPT. In this  
 160 paper, the Incremental Conductance method is applied (see [25], [38] and [39]).

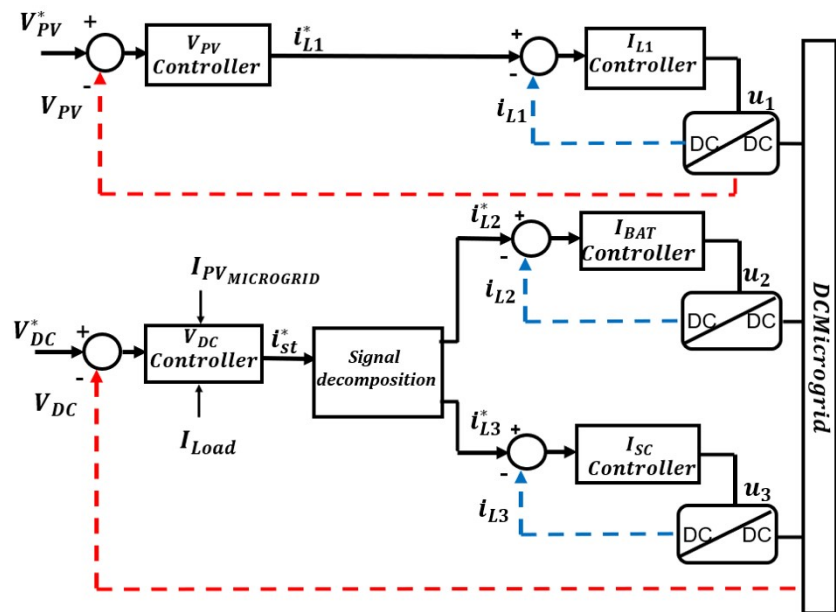
### 161 2.2. High Level Controller for Storage system

We rely on the storage system (battery + supercapacitor) to act as a buffer to absorb the current (power) variations and stabilize the DC bus. Based on the physical characteristics of the storage components, and in particular on the current limitations from the battery, we indicate: 1- to consider a current reference  $i_{ST}^*$  based on power balance equations for the whole system; 2- to use a time-scale separation to decompose it in two components, a fast one ( $i_{L3}^*$ ) and a slow one ( $i_{L2}^*$ ), as shown in Figure 3. The slow component will be used as the reference for the battery's power supply, while the fast

component will be the reference power for the supercapacitor. This time scale separation is obtained by the introduction of a first order low pass filter that decomposes the current reference in two references for the battery and supercapacitor [40]

$$i_{ST}^* = i_{L2}^* + i_{L3}^* \quad (5)$$

162 The two components are chosen to keep sufficient time-scale separation between  
 163 the lower and higher level control objectives (see [41]), and to ensure that the battery  
 164 does not need to react faster than its specifications allow. Therefore, we target to extend  
 165 the lifespan of the battery [10].



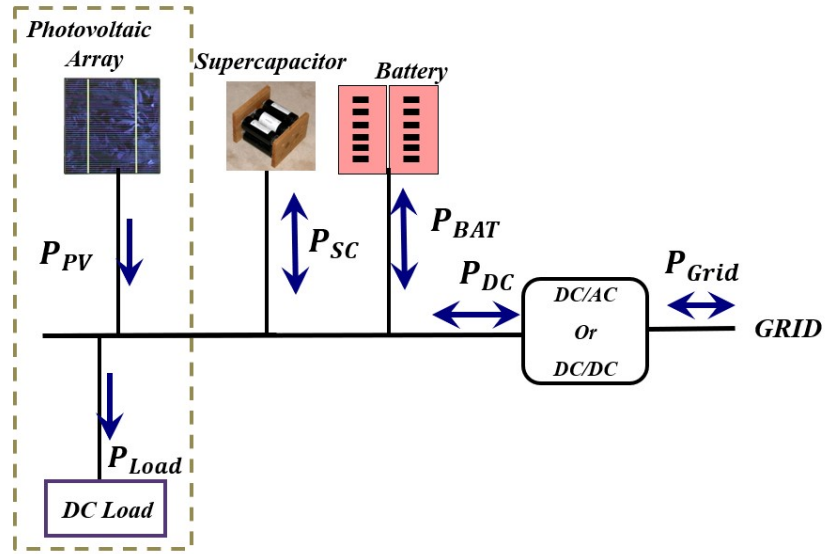
**Figure 3.** The adopted time-scale depending control strategy.

The power flow of the different elements of DC MicroGrid (see [22]) will depend on the grid topology. Most works consider a radial DC MicroGrid for its simplicity while yet capturing most challenges existing in DC MicroGrids. Radial systems are easier for installation and operation and meet the objective of designing a plug and play system which allows a larger penetration of renewable energy into the network. The proposed control strategy is also applicable for ring or bus [42] topologies (which are simpler than radial), and may also be implemented in meshed ones. For the latter it would be necessary to prevent congestion problems, that is not addressed in the present paper, and is usually dealt with higher-level controllers, closer to optimization and communication techniques. Bus topology is currently used in residential buildings, where low voltage DC bus is preferred to match the voltage level of many appliances and to avoid extra DC-DC conversion stages. Also in such systems, loads and AC grid interface can be located close to each other in order to reduce the distribution losses [43]. A radial grid is shown in Figure 4 while a ring DC MicroGrid is shown in Figure 5. The sum of the output power of all generating units (photovoltaic system in the present case), all loads and the storage system is defined as follows:

$$P_{DC} = P_{PV} + P_{Load} + P_{ST} \quad (6)$$

166 with  $P_{ST} = P_{BAT} + P_{SC}$ , where  $P_{PV}$  is the PV power,  $P_{ST}$  is the storage power,  $P_{BAT}$  is  
 167 the battery power,  $P_{SC}$  is the supercapacitor power,  $P_{Load}$  is the load power and  $P_{DC}$  is  
 168 the DC grid power.

169 In general, the DC MicroGrid is connected to the main AC Grid then  $P_{DC} = P_{GRID}$ ,  
 170 and the balance power is supplied to or obtained from the AC Grid ( $P_{GRID}$  being the



**Figure 4.** The Power Flow scheme.

171 power from or to the AC grid). In the present paper, we investigate the more difficult  
 172 case corresponding to when the DC MicroGrid is in islanded mode, and we can not rely  
 173 on the AC network to balance the DC grid. In this case, any unbalance on the power  
 174 flow will create a voltage excursion on the DC grid.

The energy storage elements can switch between charge and discharge mode in order to maintain the DC grid power balance.  $V_{DC}(t)$  must be kept around its nominal value  $V_{DC}^*$  and inside voltage limits following the power balance given by equation (4). It is possible to rewrite equation (4) as:

$$\dot{V}_{DC} = \frac{1}{C_{DC}} \left[ \frac{1}{R_2} (V_{C2} - V_{DC}) + \frac{P_{ST} - P_{Load}}{V_{DC}} \right] \quad (7)$$

175 In the following,  $i_{ST}^*$  as in (5) is designed for  $i_{L2}$  and  $i_{L3}$ , in order to steer  $V_{DC}$  to its  
 176 reference  $V_{DC}^*$  using backstepping techniques [44]. Let us define the output tracking error  
 177  $e_{V_{DC}} = (V_{DC} - V_{DC}^*)$ . Based on the error dynamics, we suggest the following current  
 178 reference:

$$i_{ST}^* = \frac{P_{Load}}{V_{DC}} - \frac{1}{R_2} (V_{C2} - V_{DC}) - C_{DC} (K_{10} e_{V_{DC}} + \bar{K}_{10} \alpha_{10}) \quad (8)$$

with:

$$\dot{\alpha}_{10} = K_{10}^\alpha e_{V_{DC}}$$

179 where  $\alpha_{10}$  represents an integral error term, and  $K_{10}$ ,  $\bar{K}_{10}$  and  $K_{10}^\alpha$  are positive tuning  
 180 gain parameters.

Due to time-scale consideration between the voltage and current dynamics, in the sequel we consider  $V_{DC}$  as a zero dynamics of the system, so  $i_{ST}$  can be considered already equal to  $i_{ST}^*$ , such that inside an operation region ( $\mathcal{D} = \{e_{V_{DC}} \in \mathbb{R} \mid e_{V_{DC}} \leq V_{DC_{Max}}\}$  for a desired constant  $V_{DC_{Max}}$ ) and we can write:

$$\begin{bmatrix} \dot{\alpha}_{10} \\ \dot{e}_{V_{DC}} \end{bmatrix} = \begin{bmatrix} 0 & K_{10}^\alpha \\ -\bar{K}_{10} & -K_{10} \end{bmatrix} \begin{bmatrix} \alpha_{10} \\ e_{V_{DC}} \end{bmatrix}$$

181 As a consequence, the closed-loop dynamics of  $V_{DC}$  results to be linear and expo-  
 182 nentially stable, with desired dynamics given by the stable poles assigned by the tuning



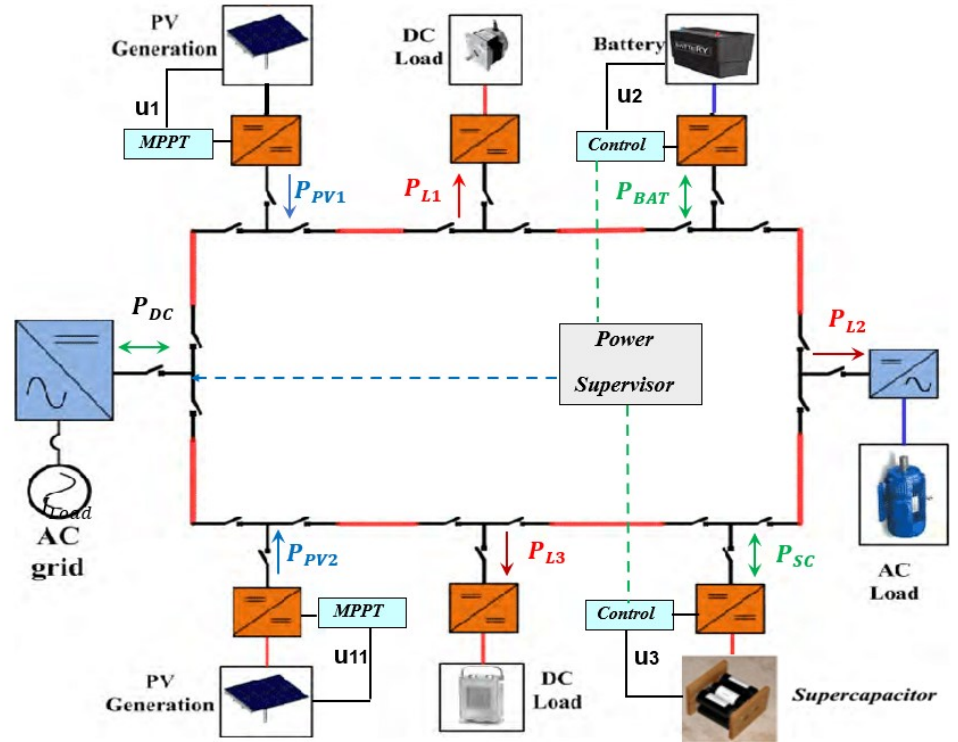


Figure 5. Ring DC MicroGrid Topology

183 gains. Then, there exists  $P_{10} = P_{10}^T > 0$  such that  $P_{10}A_{10} + A_{10}^T P_{10} = -I_2$ , where  $I_2$  is the  
 184 identity matrix in  $\mathbb{R}^2$ , such that the Lyapunov function:

$$W_{10} = [\alpha_{10} e_{V_{DC}}]^T P_{10} [\alpha_{10} e_{V_{DC}}] > 0 \quad (9)$$

185 exists, which time derivative is negative definite:

$$\dot{W}_{10} = -\alpha_{10}^2 e_{V_{DC}}^2 - \alpha_{10}^2 < 0. \quad (10)$$

### 186 3. Local Control Level

#### 187 3.1. Storage System Control

##### 188 3.1.1. Battery Control Law

Taking the  $i_{L2}^*$  reference value for  $i_{L2}$ , it is possible to compute the control law by feedback linearization. First, we define the output tracking error:

$$e_{i_{L2}} = (i_{L2} - i_{L2}^*)$$

189 and consider the control law [11]:

$$u_2 = \frac{1}{(V_{C4} + (R_{04} - R_{03})i_{L2})} \left[ -(V_{C3} - V_{C4}) + R_{04}i_{L2} - L_2(K_6(i_{L2} - i_{L2}^*) + \bar{K}_6\alpha_6) + i_{L2}^* \right] \quad (11)$$

where  $i_{L2}^*$  is obtained through a derivative filter,  $\alpha_6$  represents an integral term and  $K_6$ ,  $\bar{K}_6$  and  $K_6^\alpha$  are the positive tuning gain parameters. By technological reasons, the following condition is always fulfilled:

$$V_{C4} + (R_{04} - R_{03})i_{L2} \neq 0. \quad (12)$$

190 Consequently, the closed loop system is shown to be linear and exponentially stable [11]:

$$\begin{aligned}\dot{\alpha}_6 &= K_6^\alpha e_{i_{L2}} \\ \dot{e}_{i_{L2}} &= -K_6 e_{i_{L2}} - \overline{K}_6 \alpha_6\end{aligned}\quad (13)$$

### 191 3.1.2. Supercapacitor Control Law

192 We define the output tracking error  $e_{i_{L3}} = (i_{L3} - i_{L3}^*)$  and its derivative  $\dot{e}_{i_{L3}} =$   
193  $(\dot{i}_{L3} - \dot{i}_{L3}^*)$ .

194 As in the previous case, we consider a control law  $u_3$  by input/output feedback  
195 linearization such as to steer  $i_{L3}$  towards its reference  $i_{L3}^*$ , imposing the desired dynamic  
196 closed-loop behaviour, where  $\alpha_9$  represents an integral error term and  $K_9, \overline{K}_9$  and  $K_9^\alpha$  are  
197 the positive tuning gain parameters:

$$\begin{aligned}u_3 &= \frac{1}{(V_{C6} + (R_{06} - R_{05})i_{L3})} [-V_{C5} + V_{C6} + R_{05}i_{L3} \\ &\quad - L_3(K_9(i_{L3} - i_{L3}^*) + \overline{K}_9\alpha_9 + \dot{i}_{L3}^*)]\end{aligned}\quad (14)$$

198 Consequently, the closed loop system results linear and exponentially stable [11]:

$$\begin{aligned}\dot{\alpha}_9 &= K_9^\alpha e_{i_{L3}} \\ \dot{e}_{i_{L3}} &= -K_9 e_{i_{L3}} - \overline{K}_9 \alpha_9\end{aligned}\quad (15)$$

We remark that  $i_{L3}^*$  is obtained as  $i_{L2}^*$  in (11), and we need to consider a condition similar  
to the one in with (12) (always fulfilled by technological reasons):

$$V_{C6} + (R_{06} - R_{05})i_{L3} \neq 0. \quad (16)$$

199 The control inputs  $u_2$  and  $u_3$  feedback linearize the dynamics of  $i_{L2}$  and  $i_{L3}$ . Because  
200 of the linearity of the stable closed loop system, there exist matrices  $P_{6,9} = P_{6,9}^T > 0$   
201 such that  $P_{6,9}A_{6,9} + A_{6,9}^T P_{6,9} = -I_2$ , where  $I_2$  is an identity matrix in  $\mathbb{R}^2$ . Therefore, we  
202 introduce the candidate Lyapunov function:

$$W_{69} = [\alpha_6 \ e_{i_{L2}}]^T P_6 [\alpha_6 \ e_{i_{L2}}] + [\alpha_9 \ e_{i_{L3}}]^T P_9 [\alpha_9 \ e_{i_{L3}}] \quad (17)$$

203 which time derivative is:

$$\dot{W}_{69} = -e_{i_{L2}}^2 - \alpha_6^2 - e_{i_{L3}}^2 - \alpha_9^2 < 0. \quad (18)$$

### 204 3.2. PV System Control

Based on (1), the control target for the PV array is to stabilize the voltage capacitor  
 $V_{C1}$  around the time varying (piecewise constant) reference value  $V_{C1}^*$ , provided by the  
MPPT algorithm. Similarly to [10], we state the assumption that the current can be set to  
have much faster dynamics than the capacitances' voltages. This allows the current and  
voltage regulation to be in a cascaded control scheme, with an inner current loop and an  
outer voltage loop. Consequently, a reference  $i_{L1}^*$  for  $i_{L1}$  will be designed to steer  $V_{C1}$  to  
its reference  $V_{C1}^*$ . To this purpose, we define the tracking errors:

$$e_{V_{C1}} = (V_{C1} - V_{C1}^*) \text{ and } e_{i_{L1}} = (i_{L1} - i_{L1}^*).$$

Then, similarly to [11], we consider the tracking reference as:

$$i_{L1}^* = \frac{1}{R_1}(V_{PV} - V_{C1}) + C_1 K_1 (V_{C1} - V_{C1}^*) + C_1 \overline{K}_1^\alpha \alpha_1 \quad (19)$$

205 and the control law:

$$\begin{aligned}
u_1 = & \frac{1}{V_{C2} + (R_{02} - R_{01})i_{L1}} [V_{C2} - V_{C1} \\
& + R_{02}i_{L1}L_1(K_3e_{i_{L1}} + \bar{K}_3\alpha_3) \\
& - C_1\bar{K}_1K_1^\alpha e_{V_{C1}} \\
& + (C_1K_1 - \frac{1}{R_1})(K_1e_{V_{C1}} + \bar{K}_1\alpha_1)] \quad (20)
\end{aligned}$$

206

where  $\alpha_1$  and  $\alpha_3$  represent the integral terms assuring zero error in steady state between the dynamics of the states and their references:

$$\dot{\alpha}_1 = K_1^\alpha e_{V_{C1}} \quad \text{and} \quad \dot{\alpha}_3 = K_3^\alpha e_{i_{L1}}$$

and where  $K_1, \bar{K}_1, K_1^\alpha, K_3, \bar{K}_3$  and  $K_3^\alpha$  are positive tuning gain parameters. As before, the control input  $u_1$  feedback linearizes the dynamics of  $V_{C1}$  and  $i_{L1}$ , and the closed loop results to be linear and exponentially stable [11]:

$$\dot{e}_{V_{C1}} = -K_1e_{V_{C1}} - \bar{K}_1\alpha_1 \quad (21)$$

$$\dot{e}_{i_{L1}} = -K_3e_{i_{L1}} - \bar{K}_3\alpha_3 \quad (22)$$

As a consequence, there exist matrices  $P_{1,3} = P_{1,3}^T > 0$  such that  $P_{1,3}A_{1,3} + A_{1,3}^T P_{1,3} = -I_2$ ,  $I_2$  is an identity matrix in  $\mathbb{R}^2$ . Then, we introduce the Lyapunov function for the dynamics of  $V_{C1}$  and  $i_{L1}$  and its derivative as:

$$W_{13} = [\alpha_1 \ e_{V_{C1}}]^T P_1 [\alpha_1 \ e_{V_{C1}}] + [\alpha_3 \ e_{i_{L1}}]^T P_3 [\alpha_3 \ e_{i_{L1}}] \quad (23)$$

207

$$\dot{W}_{13} = -e_{V_{C1}}^2 - \alpha_1^2 - e_{i_{L1}}^2 - \alpha_3^2 < 0. \quad (24)$$

#### 208 4. Stability study of the interconnected system

209 It is possible to split the states into controlled variables  $V_{C1}, i_{L1}, i_{L2}, i_{L3}$  and  $V_{DC}$  and  
210 the zero dynamics (uncontrolled variables)  $V_{C2}, V_{C3}, V_{C4}, V_{C5}$  and  $V_{C6}$ . With respect to  
211 the equilibrium points given by the references, the calculation of the missing equilibrium  
212 points  $V_{C2}^e, V_{C3}^e, V_{C4}^e, V_{C5}^e$  and  $V_{C6}^e$  can be easily done by steady-state considerations for  
213 the closed loop system.

214 **Lemma 4.1.** *Under the assumption that for each time the conditions:  $V_{C2} + (R_{02} - R_{01})i_{L1} \neq$   
215  $0, V_{C4} + (R_{04} - R_{03})i_{L2} \neq 0$  and  $V_{C6} + (R_{06} - R_{05})i_{L3} \neq 0$ , there exist control laws  $u_1, u_2$   
216 and  $u_3$  given by (20), (11) and (14) such that the system (1), (2), (3), (4), has in closed loop an  
217 equilibrium point  $x_e$  and any initial condition exponentially converges to it.*

218 **Proof.** The proof is based on a Lyapunov function  $W$ , which is a composition of the  
219 previous Lyapunov functions. We consider the closed loop system with respect to the  
220 control inputs  $u_1, u_2$  and  $u_3$  already defined for controlling the dynamics of  $V_{C1}, i_{L1},$   
221  $i_{L2}, i_{L3}$  and  $V_{DC}$ . They were proven to be stable by the Lyapunov functions  $W_{1,3}, W_{6,9}$   
222 and  $W_{10}$ . These Lyapunov functions, provided for each step, will be used for the entire  
223 system by a composite Lyapunov function. The Lyapunov function  $V$  is then defined as:

$$W = W_{13} + W_{69} + W_{10} + W_{23456} \quad (25)$$

where  $W_{13}, W_{69}$  and  $W_{10}$  have already been introduced and  $W_{23456}$  refers to dynamics  $V_{C2}, V_{C3}, V_{C4}, V_{C5}$  and  $V_{C6}$ . We introduce the errors  $e_{V_{C2}}, e_{V_{C3}}, e_{V_{C4}}, e_{V_{C5}}$  and  $e_{V_{C6}}$  between

the remaining voltage dynamics and their equilibrium points, and consider a candidate Lyapunov function  $W_{23456}$  as:

$$W_{23456} = \frac{R_2 C_2}{2} e_{V_{C2}}^2 + \frac{R_3 C_3}{2} e_{V_{C3}}^2 + \frac{R_4 C_4}{2} e_{V_{C4}}^2 + \frac{R_5 C_5}{2} e_{V_{C5}}^2 + \frac{R_6 C_6}{2} e_{V_{C6}}^2.$$

224

Its time derivative is:

$$\dot{W}_{23456} = -e_{V_{C2}}^2 - e_{V_{C3}}^2 - e_{V_{C4}}^2 - e_{V_{C5}}^2 - e_{V_{C6}}^2 < 0$$

225

Finally, we consider the composition of the Lyapunov functions for the whole system:

226

$$\begin{aligned} W_{1\dots 10} &= ([\alpha_1 e_{V_{C1}}]^T P_1 [\alpha_1 e_{V_{C1}}]) + ([\alpha_2 e_{i_{L1}}]^T P_2 [\alpha_2 e_{i_{L1}}]) \\ &+ \frac{R_2 C_2}{2} e_{V_{C2}}^2 + \frac{R_3 C_3}{2} e_{V_{C3}}^2 + \frac{R_4 C_4}{2} e_{V_{C4}}^2 \\ &+ ([\alpha_6 e_{i_{L2}}]^T P_6 [\alpha_6 e_{i_{L2}}]) + \frac{R_5 C_5}{2} e_{V_{C5}}^2 + \frac{R_6 C_6}{2} e_{V_{C6}}^2 \\ &+ ([\alpha_9 e_{i_{L3}}]^T P_9 [\alpha_9 e_{i_{L3}}]) + ([\alpha_{10} e_{V_{DC}}]^T P_{10} [\alpha_{10} e_{V_{DC}}]) > 0 \end{aligned}$$

227

which time derivative is:

$$\begin{aligned} \dot{W}_{1\dots 10} &= -e_{V_{C1}}^2 - \alpha_1^2 - e_{i_{L1}}^2 - \alpha_2^2 - e_{V_{C2}}^2 \\ &- e_{V_{C3}}^2 - e_{V_{C4}}^2 - e_{i_{L2}}^2 - \alpha_6^2 - e_{V_{C5}}^2 - e_{V_{C6}}^2 - e_{i_{L3}}^2 \\ &- e_{V_{DC}}^2 - \alpha_9^2 - \alpha_{10}^2 < 0 \end{aligned}$$

228

Then, exponential convergence of all states of the interconnected system towards their equilibrium points is ensured.  $\square$

229

## 230 5. Simulation Results

231

In this section we present simulations using detailed switching models on Simscape Electrical from Matlab Simulink. These simulations allow to isolate the control and dynamic response phenomena, while still representative for the remaining power electronic aspects.

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$R_{01}$	$0.001\Omega$	$R_1$	$0.1\Omega$	$C_1$	$0.1F$
$R_{02}$	$0.002\Omega$	$R_2$	$0.001\Omega$	$C_2$	$0.01F$
$R_{03}$	$0.001\Omega$	$R_3$	$0.5\Omega$	$C_3$	$0.1F$
$R_{04}$	$0.0015\Omega$	$R_4$	$0.01\Omega$	$C_4$	$0.01F$
$R_{05}$	$0.001\Omega$	$R_5$	$0.4\Omega$	$C_5$	$0.1F$
$R_{06}$	$0.0015\Omega$	$R_6$	$0.01\Omega$	$C_6$	$0.01F$
$L_1$	$0.0033H$	$L_2$	$0.0033H$	$L_3$	$0.0033H$
$V_{PV}$	$1000V$	$P_n$	$1MW$	$V_{DC}$	$1000V$
$V_{SC}$	$500V$	$V_{BAT}$	$500V$	$V_{DC}$	$1000V$

Table 1: Simulation parameters.

235

Two simulations are presented. The first one is done during 300s of simulation time, and aims to show the system power characteristics and energy behavior. The second is done during 50s of simulation time, and focuses on the dynamic performance of the proposed control.

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Figure 6 in the left shows the output power for the photovoltaic system with varying irradiance. It can be seen that the output power follows the irradiance variations. Figure

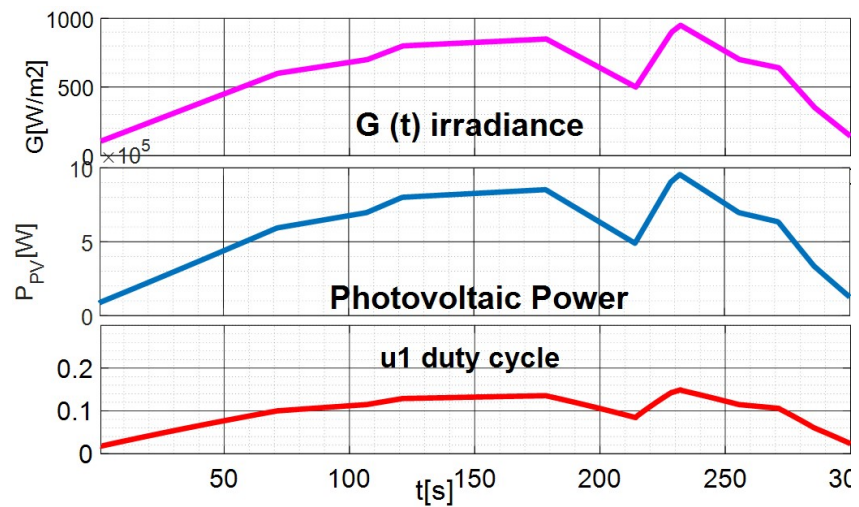


Figure 6. PV with Varying Irradiance.

241 6 in the right shows the control input  $u_1$ , which is bounded between zero and 1. One can  
 242 see that the local controller keeps the PV tracking its Maximum Power Point.

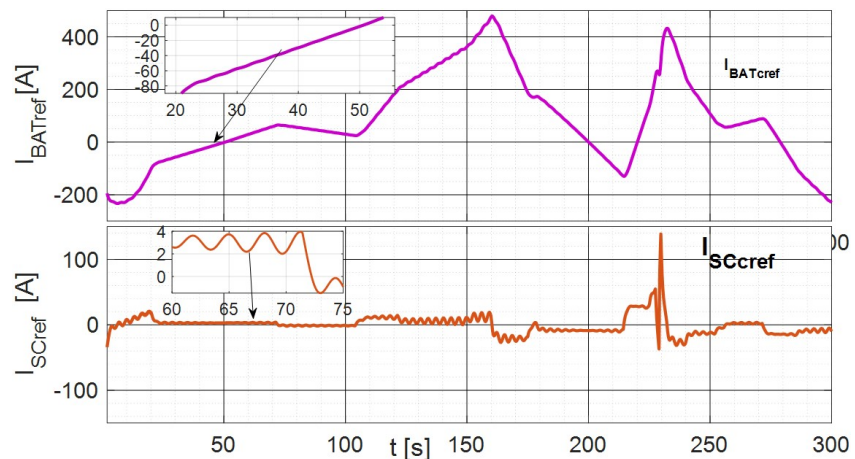


Figure 7. Power reference components (top graph:  $i_{L3}^*$ , bottom graph:  $i_{L2}^*$ ).

243 Figure 7 shows the signal decomposition from equation (5), with fast and slow  
 244 references shown in the top and the bottom figures respectively.

245 Figure 8 shows the control input  $u_2$  which is bounded between zero and one and  
 246 the output power from the battery.

247 Figure 9 shows the control inputs  $u_3$ , which are bounded between zero and one,  
 248 and the output power from the supercapacitor. The Figures 8 and 9 show the control  
 249 inputs are smooth except in the case of fast power variations of different elements of the  
 250 DC MicroGrid. Concerning the output power from the battery and the supercapacitor,  
 251 fast time-varying signals are instantaneously absorbed by the supercapacitor  $P_{SC}$ , such  
 252 that the battery can remain rather unchanged during fast perturbations. This is capital  
 253 to ensure a long lifespan for the battery. This one can then provide most of the energy  
 254 demanded by the load, allowing long term stability and the use of weather forecast and  
 255 load predictions in the higher level algorithms.

256 Figure 10 shows the output power for different elements of the DC MicroGrid.  
 257 We can remark that the variation of storage power follows the variation on PV and  
 258 load powers, illustrating how grid Voltage stabilization is reached by the storage power  
 259 response.

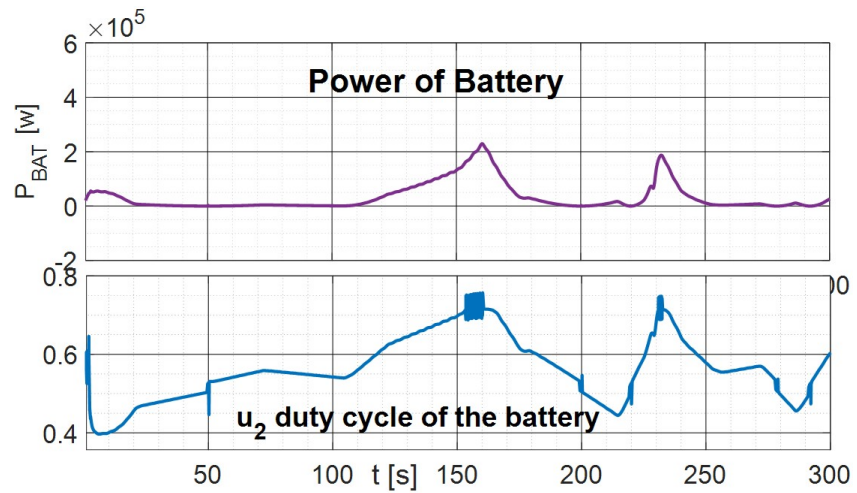


Figure 8. Control inputs  $u_2$  and Output power of the battery.

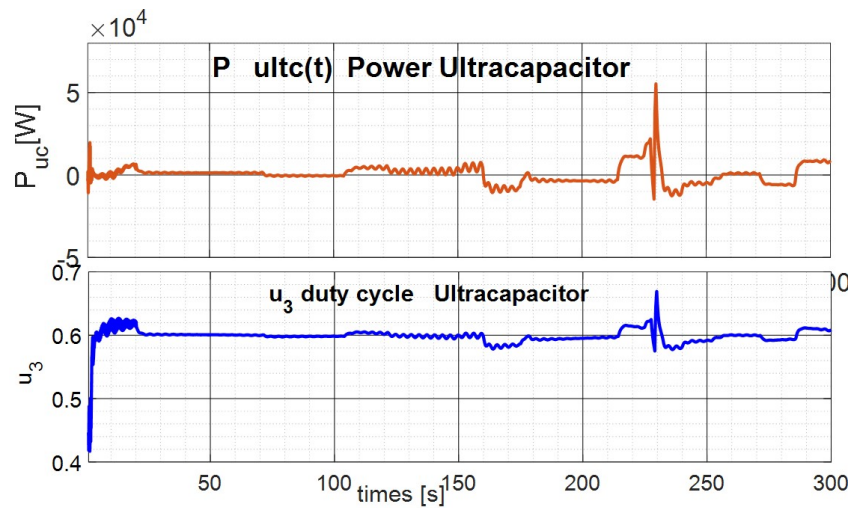


Figure 9. Control inputs  $u_3$  and output power of the supercapacitor.

260 Figure 11 presents the DC voltage  $V_{DC}$  response for this longer simulation with  
 261 slow power excursions. There, one may remark that the controller always keeps  $V_{DC}$   
 262 close to its nominal value despite these large power variations.

263 Figure 12 on the opposite, shows fast (step) load power variations. It can be seen  
 264 how the DC bus voltage is kept stable inside its operation region, despite the fast  
 265 variations on load and PV currents. The load current is equal to  $576A$  for  $5s < t <$   
 266  $42.8s$  and is equal to  $138A$  elsewhere. The solar irradiance is kept at  $1000W/m^2$  for  
 267  $t < 12.4s$  and from  $t > 24.8s$  it is set to  $300W/m^2$ . One can remark very small DC bus  
 268 voltage variations following the transients, quickly recovering and stabilizing at the  
 269 rated ( $1000V_{DC}$ ) in about  $10ms$ . The maximum DC bus voltage error equals  $4V = 0.4\%$ ,  
 270 well inside the  $\pm 5\%$  desired operation region.

271 The reference and actual waveforms for the battery are shown in the fourth screen  
 272 from the top. Reference signal varies slowly for the battery resulting in very small errors.  
 273 The reference and actual waveforms for the supercapacitor are shown in the fifth screen  
 274 from the top. This reference varies much faster due to PV generation and load demand  
 275 variations, returning to  $0A$  after each transitory.

276 These results confirm that the proposed scheme is effective in achieving the goals  
 277 defined for this application.  
 278

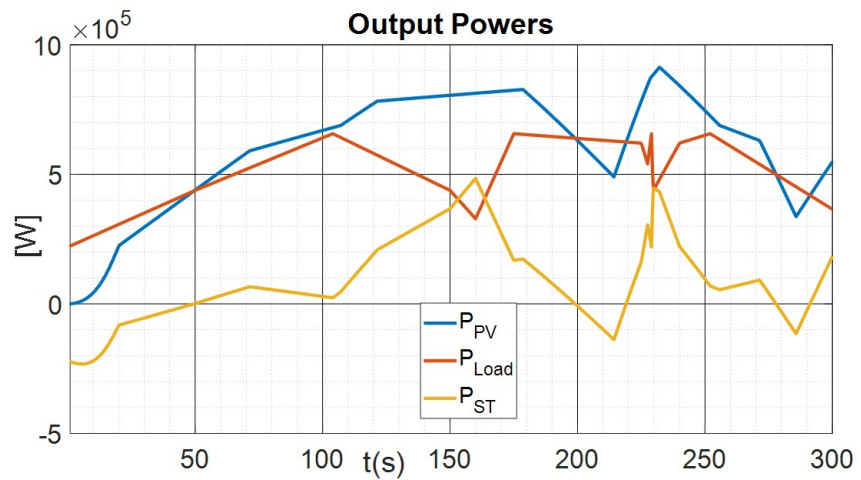


Figure 10. Output Power.

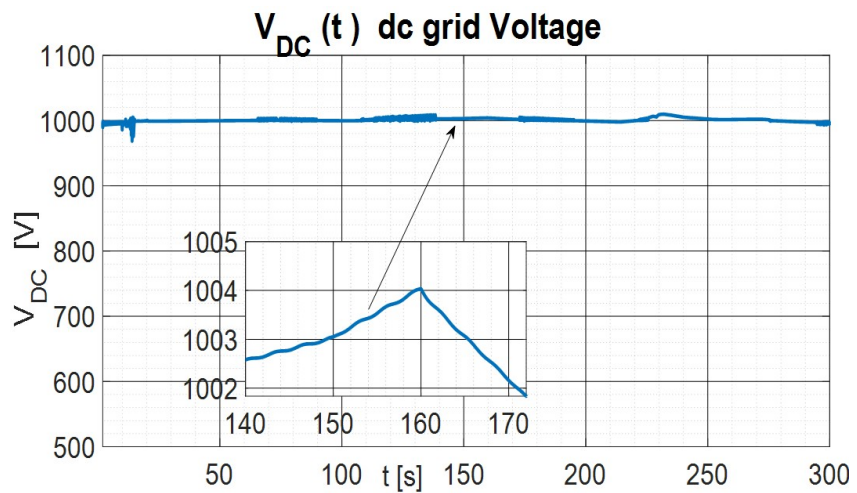


Figure 11. DC MicroGrid voltage.

### 279 5.1. Comparison with PI control

280 To illustrate the performance of the proposed controller, this one is compared to the  
 281 industrial standard PI control. The global objective is to stabilize the DC voltage as fast  
 282 as possible.

283 State space averaging method is used to obtain a Small Signal model for the con-  
 284 verter ([45–47]). The model is formulated under the assumption that all the converter  
 285 elements are ideal. The PI controllers are designed similarly to the ones presented in  
 286 [48,49],[50],[51],[52]

287 In general the DC MicroGrid is connected to the main AC Grid and then  $P_{DC} =$   
 288  $P_{GRID}$ , and balance power is supplied to or obtained from the AC Grid. In our work we  
 289 will study the more difficult case when the DC MicroGrid is in islanded mode, and we  
 290 can not rely on the AC network to balance the DC grid. In this case, any unbalance on  
 291 power flow will create a voltage excursion on the DC grid.

292 From equation (6) we define the dynamic equation of voltage of DC MicroGrid :

$$\dot{V}_{DC} = \frac{1}{C_{DC}} [I_{PV} + I_{BR} + I_{ST} + I_{Load}] \quad (26)$$

293 The energy storage elements can switch between charge and discharge mode in order to  
 294 maintain the DC grid power balance.  $V_{DC}(t)$  must be kept around its nominal value and  
 295 inside voltage limits following the power balance To present a performance comparison  
 296 of the proposed controller, Figure 13 shows the results for the same simulation as above

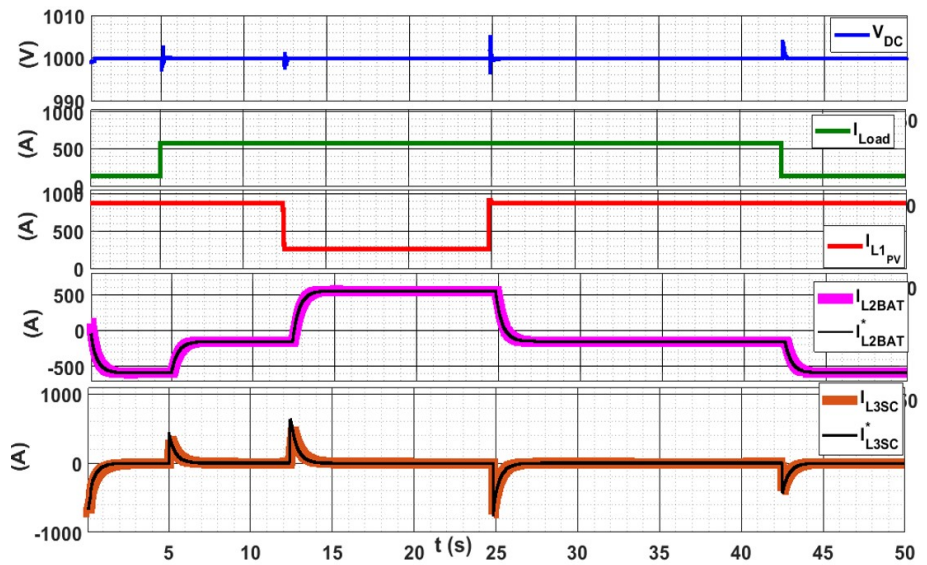


Figure 12. Dynamic response of the system.

297 using the industrial standard, a linear control (PI) for the DC MicroGrid voltage. The first  
 298 picture of Figure 13 shows how the DC bus voltage (top) varies as the load current and PV  
 299 current (following screens) vary. The load current is equal to 576A for  $5s < t < 42.8s$  and  
 300 is equal to 138A elsewhere. The solar irradiance was rated to  $1000W/m^2$  for  $t < 12.4s$   
 301 and  $t > 24.8s$ , and equal to  $300W/m^2$  otherwise. There, one sees that the DC bus voltage  
 302 varies briefly following the transients, recovering and stabilizing at the rated DC bus  
 303 voltage of 1000VDC in about 1s. The maximum DC bus voltage error is equal to 58V. The  
 304 battery's reference and actual waveforms are shown on the fourth screen from the top.  
 305 The reference signal varies slowly and the actual waveform follows it with a small  
 306 switching frequency ripple.

307 The supercapacitor's reference and actual waveforms are shown on the last screen  
 308 from the top. The reference signal varies fast and the actual waveform follows it to cope  
 309 with the generation and load variations, converging to 0A in steady state. One can also  
 310 remark that the PI linear control response has bigger overshoots in transients and slower  
 311 response.

312 Figure 14 presents a comparative study for the DC MicroGrid voltage. It can be seen  
 313 that the DC bus voltage varies following each disturbance, recovering and stabilizing  
 314 at the rated (1000V). The maximum DC bus voltage error is equal to 55V for linear  
 315 control in red. By using the PI linear control, the voltage  $V_{DC}$  oscillates during 1,2s  
 316 before reaching steady state while the steady state response for the proposed nonlinear  
 317 control is reached at 10ms as designed (it could be chosen to be faster though).

Steps	Peak overshoot Linear Control $V_{DC}$ [V]	Peak overshoot Non Linear Control $V_{DC}$ [V]	Settling time Linear Control [s]	Settling time Non Linear Control [s]
$t = 5s$	-58	-3	1.2	0.01
$t = 12.4s$	-45	-3	0.1	0.01
$t = 24.8s$	48	4	0.15	0.01
$t = 42.8s$	58	4	1	0.02

Table 2: Performance comparison with linear control and non linear control

318 Table (2) shows a comparison of voltage overshoot and settling time for several  
 319 step changes in load demand and photovoltaic power. There one may remark that the



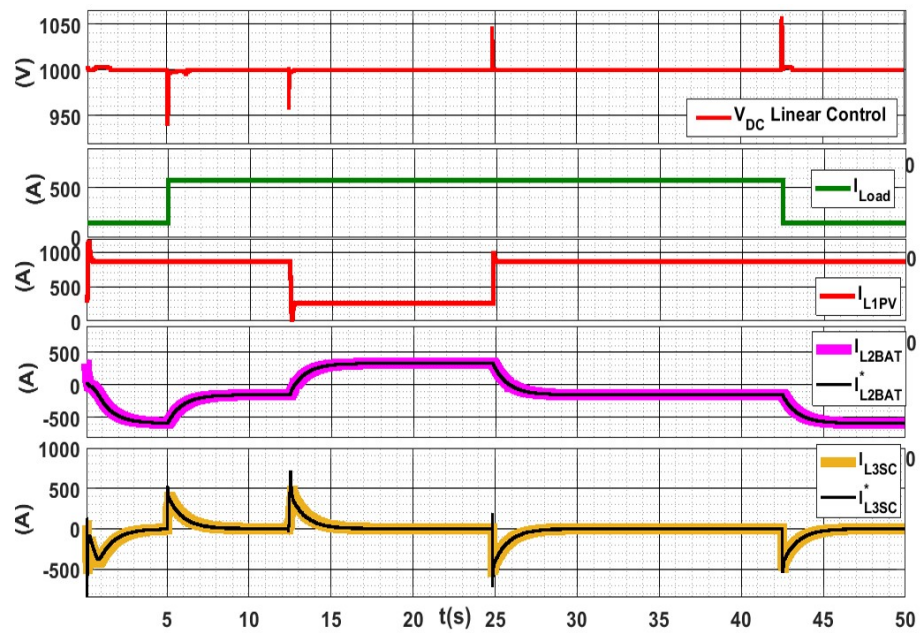


Figure 13.  $V_{DC}$  dynamics applying classical PI linear control.

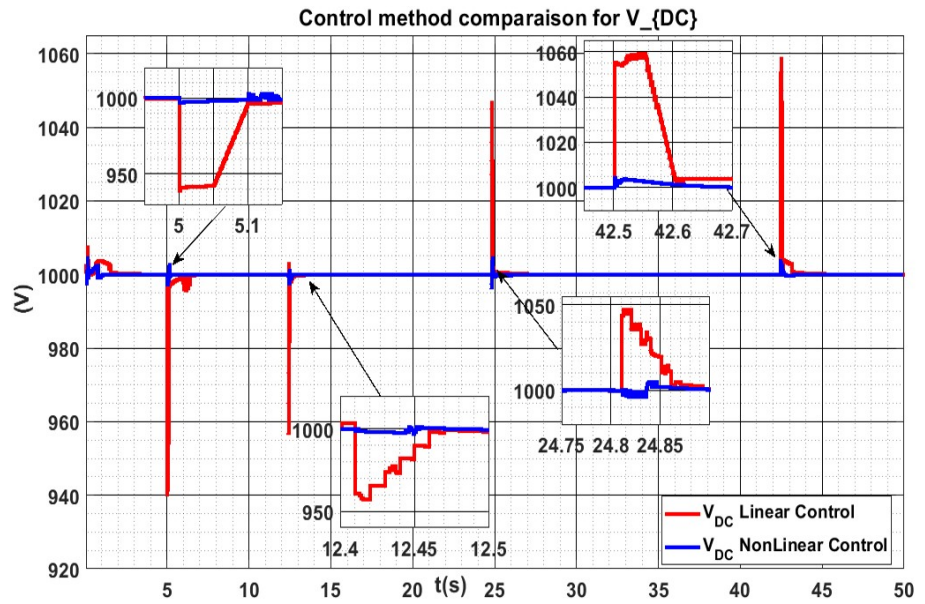
320 nonlinear control has a much smaller overshoot (10%) than the linear PI. In the same  
 321 way, settling time is much faster for the nonlinear control.

## 322 6. Conclusion

323 The efficient integration of distributed renewable power sources, especially fast  
 324 intermittent sources as solar, is an essential but difficult task. It depends on developing  
 325 flexible integration strategies to the network.

326 In this paper, a DC MicroGrid composed of PV panels and storage devices evolving  
 327 in different time scales is considered to favor this integration, and controllers for each  
 328 element are designed. A hierarchical control strategy is proposed such that it absorbs the  
 329 maximum available renewable power while keeping the DC grid's voltage stable with  
 330 respect to variations due to power production and consumption. The proposed control  
 331 algorithm splits the power reference into fast and slow components, to be tracked by  
 332 the supercapacitor and the battery respectively. As a consequence, the storage devices  
 333 keep the DC voltage at the desired value and guarantee the balance between power  
 334 generation and consumption. Moreover, in order to guarantee a suitable lifespan for the  
 335 battery, the control strategy respects physical constraints.

336 Detailed simulation results corroborate our claims, and illustrate the good behavior  
 337 of each element and the overall interconnected system. Compared to other results in  
 338 the literature, this paper focuses on proposing easily implementable control algorithms,  
 339 based on physical characteristics of the grid's elements, in order to obtain desired  
 340 closed-loop dynamics and a formal stability proof. Future works will be dedicated to  
 341 implementation in test-beds and the extension of the result to more complex meshed DC  
 342 grids.



**Figure 14.** Comparison of the  $V_{DC}$  dynamics by applying nonlinear control (in blue) and classical PI control (in red).

$I_{PV}$	Output current of solar cell
$P_{PV}$	Output power of solar cell
$V_{PV}$	Terminal voltage of PV cell
$I_{bat}$	Output current of the battery
$V_{bat}$	Output voltage of the battery
$P_{bat}$	Output power of the battery
$I_{sc}$	Output current of the super capacitor
$V_{sc}$	Output voltage of the super capacitor
$P_{sc}$	Output power of the super capacitor
$P_{DC}$	Output power of the DC microgrid
$T$	Cell's reference Temperature
$G$	Solar irradiation
$SOC$	State of charge of battery
$R_{01}, R_{02}$	internal resistances of DC/DC converter for the PV
$R_1, R_2$	resistances of DC/DC converter for the PV
$L_1$	inductance for the boost converter for the PV
$C_1, C_2$	capacitance of DC/DC converter for the PV
$V_{C1}, V_{C2}$	Voltage of capacitance $C_1$ and $C_2$ of DC/DC converter for the PV
$i_{L1}$	current of inductance $L_1$ for the boost converter for the PV
$R_{03}, R_{04}$	internal resistances of DC/DC converter for the battery
$R_3, R_4$	resistances of DC/DC converter for the battery
$L_2$	inductance for the boost converter for the battery
$C_3, C_4$	capacitance of DC/DC converter for the battery
$V_{C3}, V_{C4}$	Voltage of capacitance $C_3$ and $C_4$ of DC/DC converter for the battery
$i_{L2}$	current of inductance $L_1$ for the boost converter for the battery
$R_{05}, R_{06}$	internal resistances of DC/DC converter for the super capacitor
$R_5, R_6$	resistances of DC/DC converter for the super capacitor
$L_3$	inductance for the boost converter for the super capacitor
$C_5, C_6$	capacitance of DC/DC converter for the super capacitor
$V_{C5}, V_{C6}$	Voltage of capacitance $C_5$ and $C_6$ of DC/DC converter for the super capacitor
$i_{L3}$	current of inductance $L_1$ for the boost converter for the super capacitor
$C_{dc}$	DC-link capacitance of DC micro grid
$f$	Frequency of the AC grid
$f_c$	cutoff frequency for the filter
$K_1, \dots, K_{10}$	positive tuning gains parameters
$u_1, u_2$ and $u_3$	Duties cycle of DC/DC converter

Table 3: List of Symbols

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