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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

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

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

1. DC Microgrid Model

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

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

1.1. PV System Modeling

1.1.1. Solar Array

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

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

1.1.2. DC/DC Boost Converter

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

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

1.2. Storage system

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

1.2.1. Battery model

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

1.2.2. Supercapacitor

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

1.2.3. Bidirectional Boost Converters

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

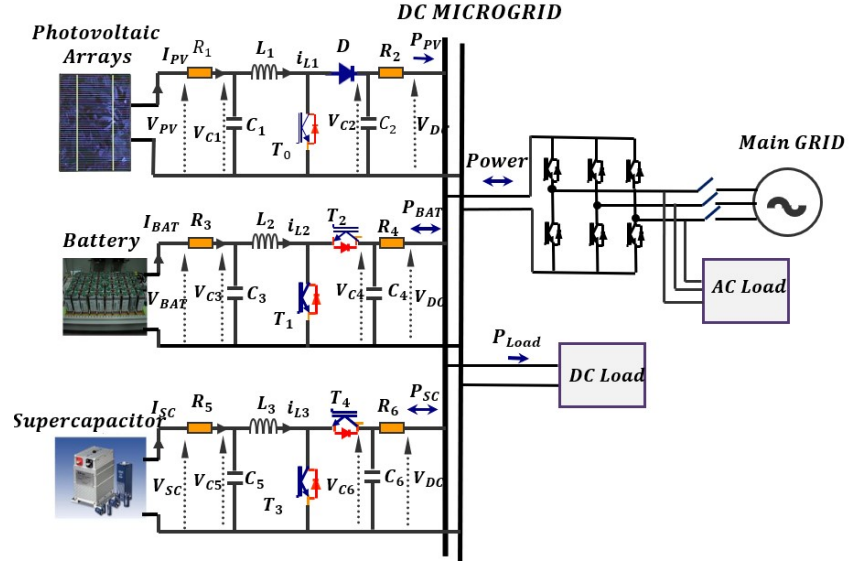


Figure 1. The considered DC MicroGrid.

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]:

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

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

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

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

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

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

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

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

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

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

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 values of resistances, inductances and capacitors respectively, and P_{load} represents the DC demanded power load. To model the switches, small resistances ($R_{01}, R_{02}, R_{03}, R_{04}, R_{05}$ and R_{06}) are included to take into account conduction losses. V_{PV}, V_{BAT}, V_{SC} and V_{DC} are the photovoltaic panel, battery, supercapacitor and DC MicroGrid voltages, respectively. 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 V_{DC} . The control inputs u_1, u_2 and u_3 represent the duty cycles of each converter. Equation (4) describes by Kirchhoff's law the voltage variation due to the sum of all currents in the DC bus V_{DC} .

2. DC MicroGrid Control strategy

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

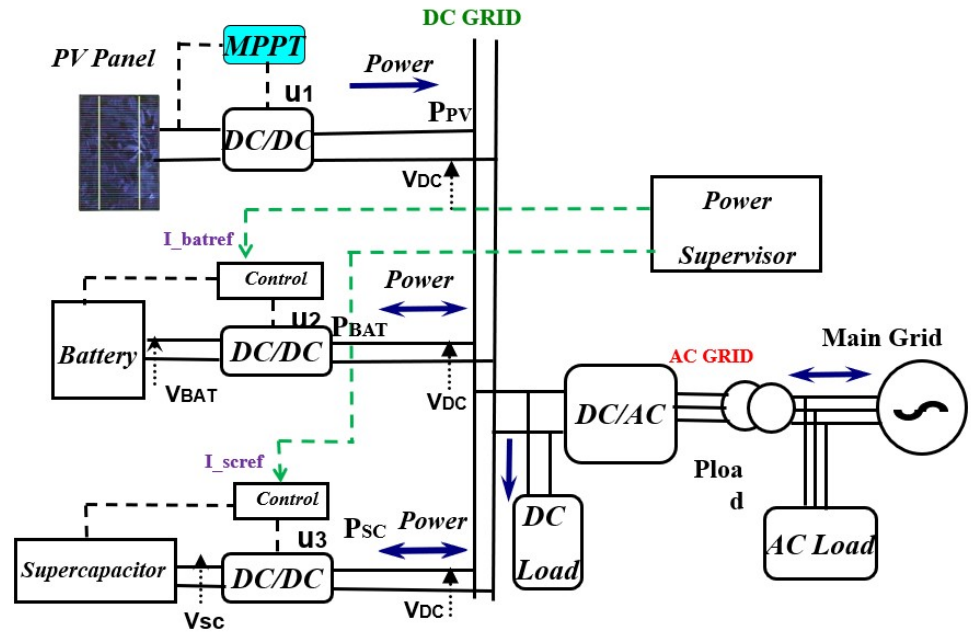


Figure 2. DC MicroGrid Control strategy.

2.1. High Level Controller for PV array source

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

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].

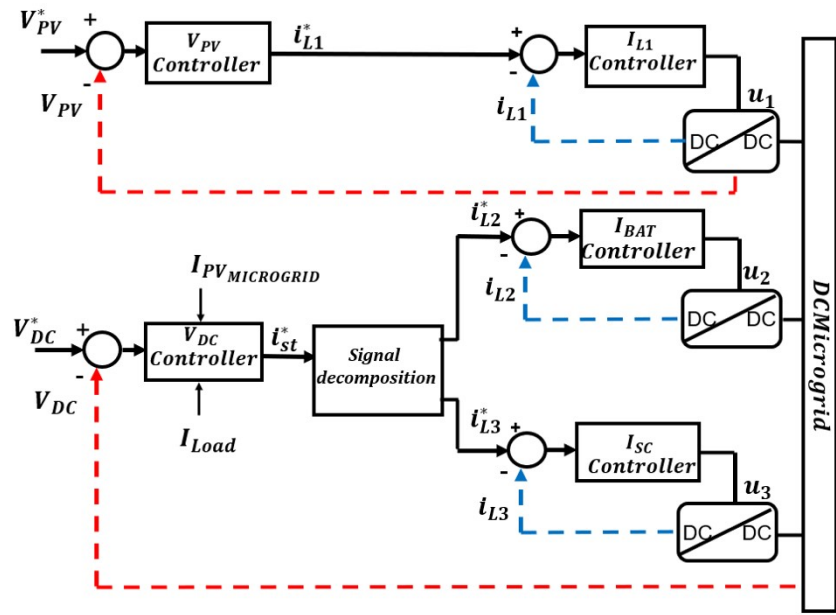


Figure 3. The adopted time-scale depending control strategy.

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

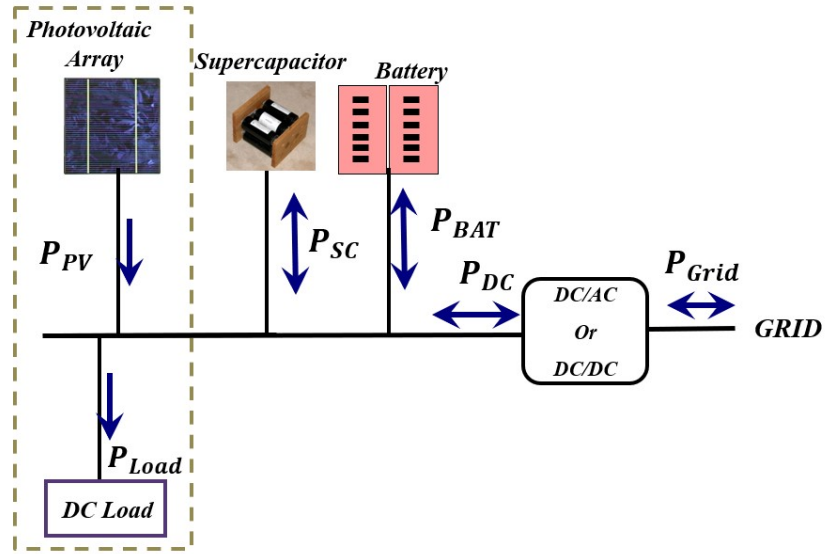


Figure 4. The Power Flow scheme.

power from or to the AC grid). In the present paper, we investigate the more difficult case corresponding to when the DC MicroGrid is in islanded mode, and we can not rely on the AC network to balance the DC grid. In this case, any unbalance on the power 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:

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

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

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

where α_{10} represents an integral error term, and K_{10} , \bar{K}_{10} and K_{10}^α are positive tuning 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:

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

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

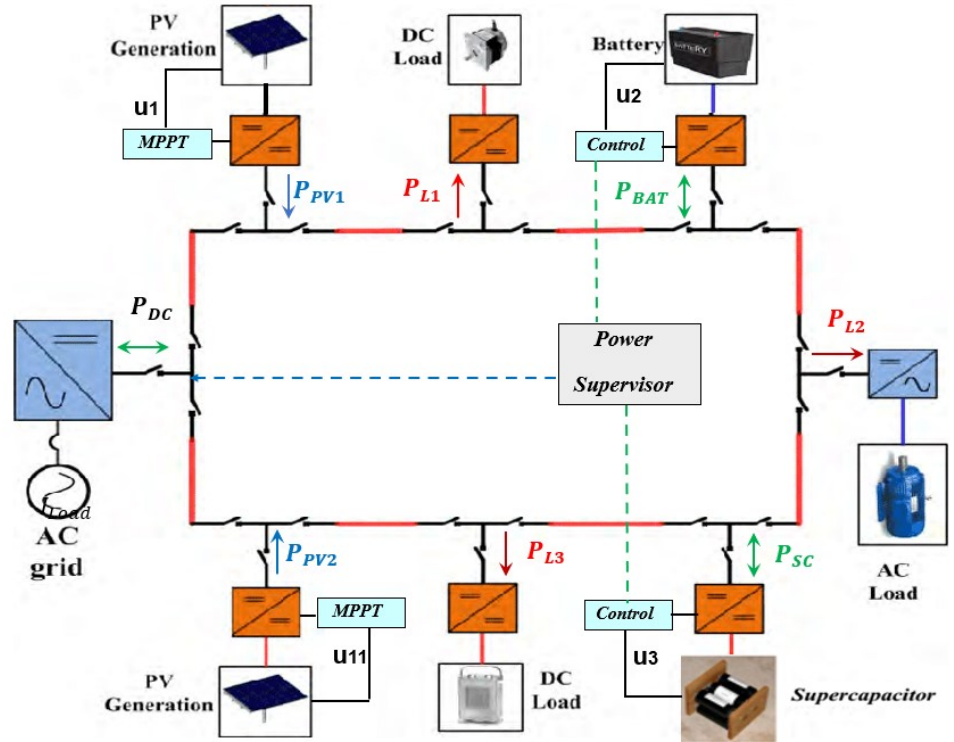


Figure 5. Ring DC MicroGrid Topology

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 identity matrix in \mathbb{R}^2 , such that the Lyapunov function:

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

exists, which time derivative is negative definite:

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

3. Local Control Level

3.1. Storage System Control

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:

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

and consider the control law [11]:

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

where i_{L2}^* is obtained through a derivative filter, α_6 represents an integral term and K_6 , \bar{K}_6 and K_6^α are the positive tuning gain parameters. By technological reasons, the following condition is always fulfilled:

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

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

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

3.1.2. Supercapacitor Control Law

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

As in the previous case, we consider a control law u_3 by input/output feedback linearization such as to steer i_{L3} towards its reference i_{L3}^* , imposing the desired dynamic closed-loop behaviour, where α_9 represents an integral error term and K_9 , \bar{K}_9 and K_9^α are the positive tuning gain parameters:

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

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

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

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

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

The control inputs u_2 and u_3 feedback linearize the dynamics of i_{L2} and i_{L3} . Because of the linearity of the stable closed loop system, there exist matrices $P_{6,9} = P_{6,9}^T > 0$ 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 introduce the candidate Lyapunov function:

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

which time derivative is:

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

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:

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

205 and the control law:

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

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where α_1 and α_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^α 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 $P_{1,3}A_{1,3} + A_{1,3}^TP_{1,3} = -I_2$, 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}	0.001Ω	R_1	0.1Ω	C_1	$0.1F$
R_{02}	0.002Ω	R_2	0.001Ω	C_2	$0.01F$
R_{03}	0.001Ω	R_3	0.5Ω	C_3	$0.1F$
R_{04}	0.0015Ω	R_4	0.01Ω	C_4	$0.01F$
R_{05}	0.001Ω	R_5	0.4Ω	C_5	$0.1F$
R_{06}	0.0015Ω	R_6	0.01Ω	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

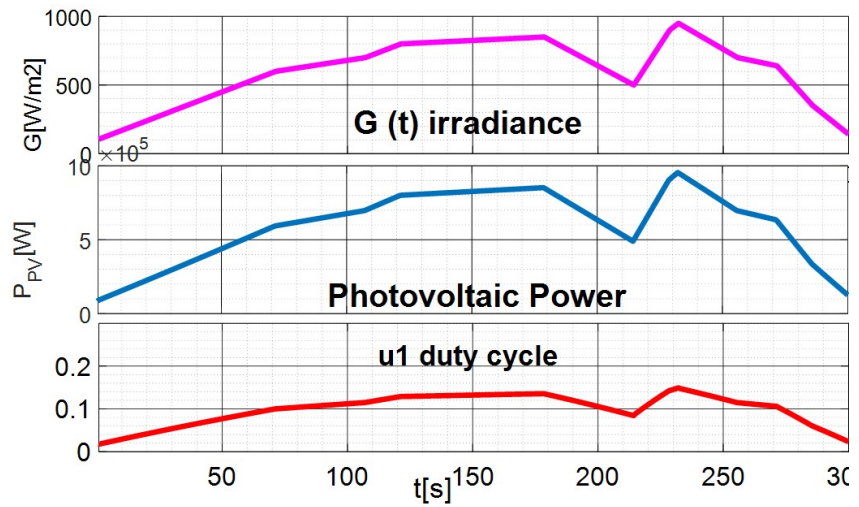


Figure 6. PV with Varying Irradiance.

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.

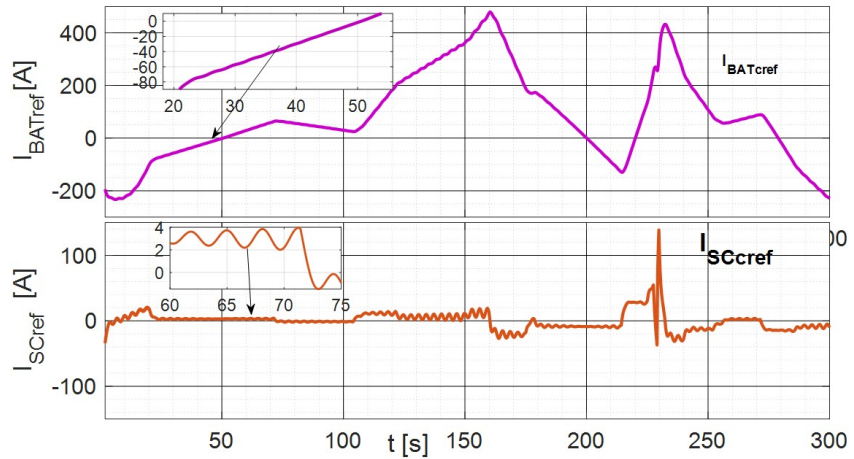


Figure 7. Power reference components (top graph: i_{L3}^* , bottom graph: i_{L2}^*).

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.

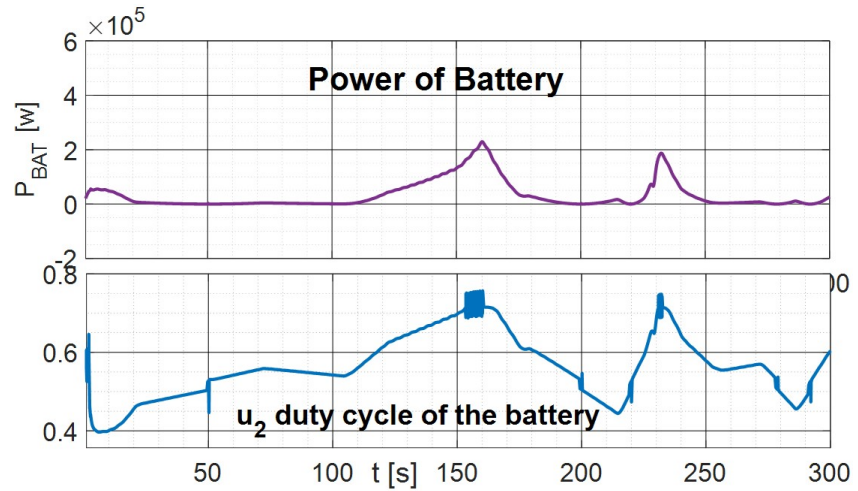


Figure 8. Control inputs u_2 and Output power of the battery.

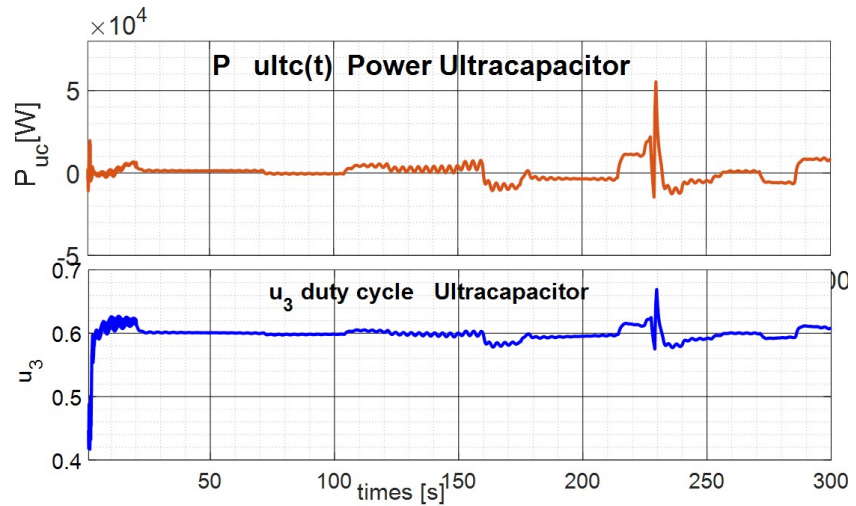


Figure 9. Control inputs u_3 and output power of the supercapacitor.

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

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

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

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

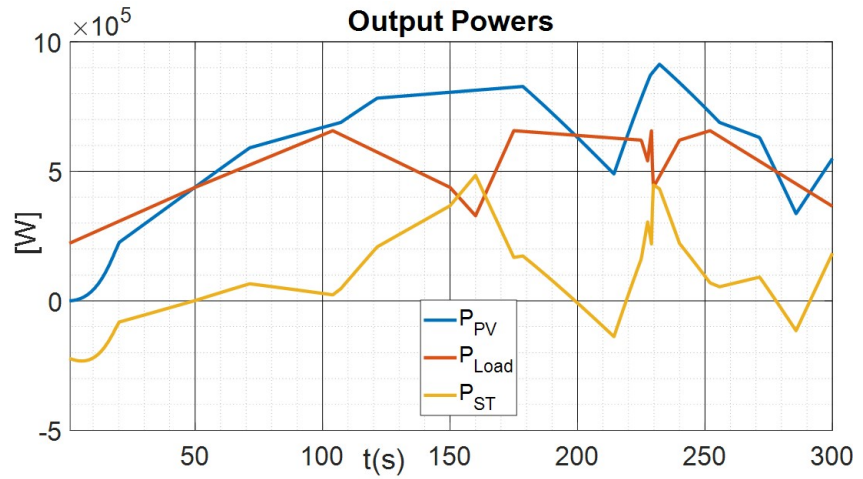


Figure 10. Output Power.

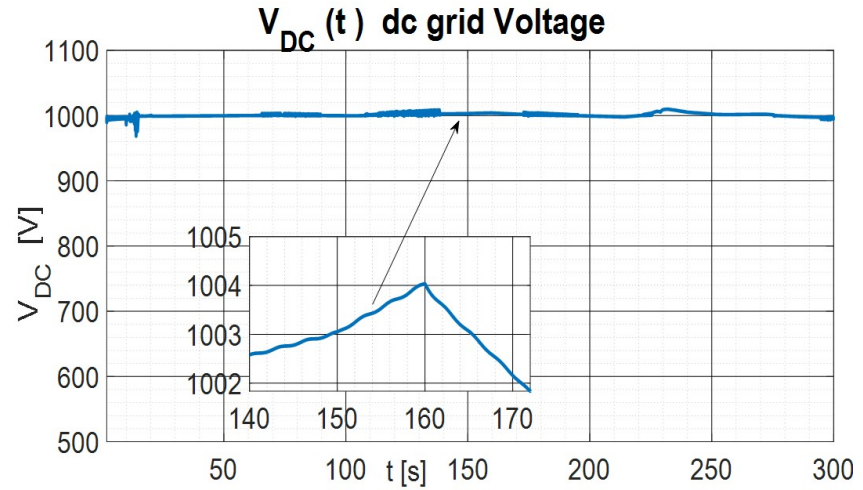


Figure 11. DC MicroGrid voltage.

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

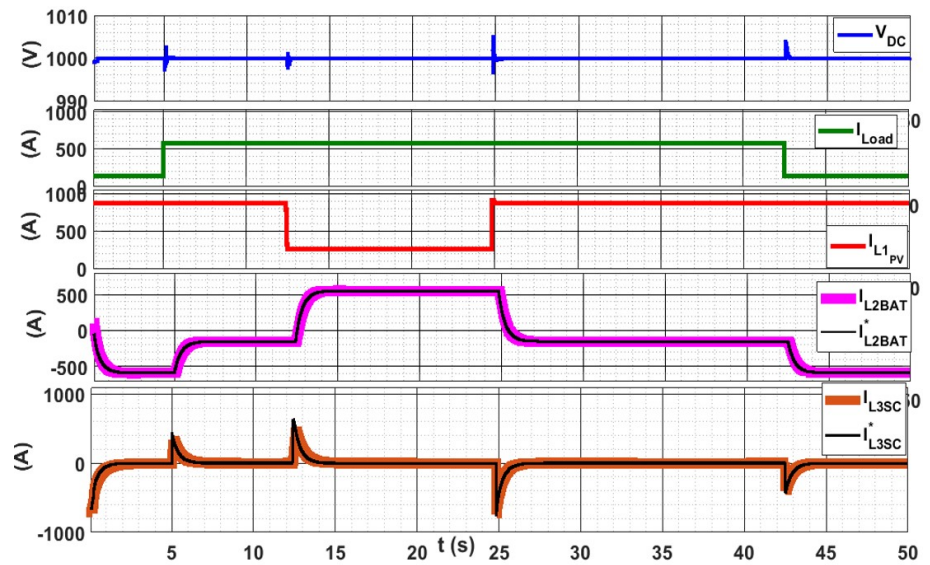


Figure 12. Dynamic response of the system.

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

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

Figure 14 presents a comparative study for the DC MicroGrid voltage. It can be seen that the DC bus voltage varies following each disturbance, recovering and stabilizing at the rated (1000V). The maximum DC bus voltage error is equal to 55V for linear control in red. By using the PI linear control, the voltage V_{DC} oscillates during 1,2s before reaching steady state while the steady state response for the proposed nonlinear 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

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

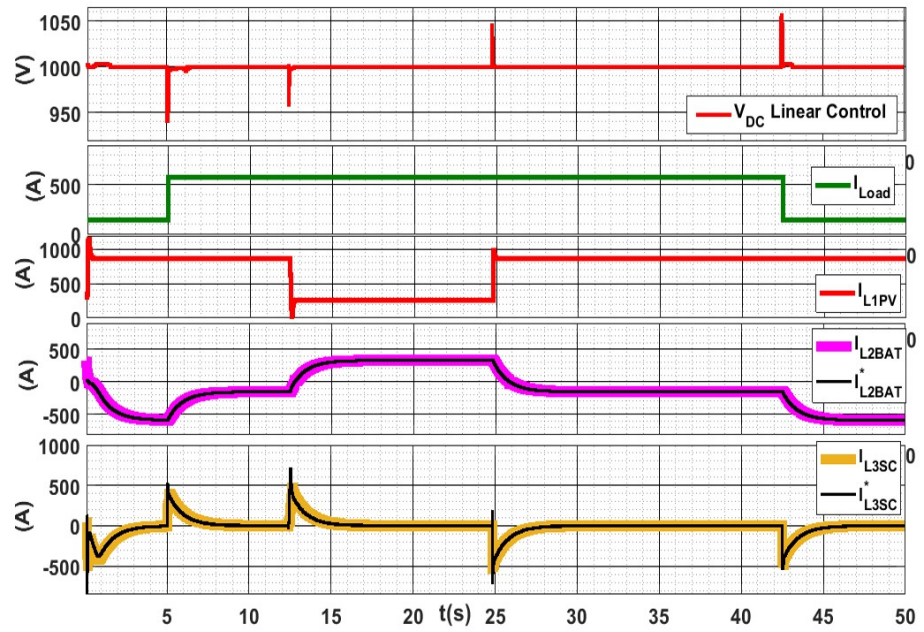


Figure 13. V_{DC} dynamics applying classical PI linear control.

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

6. Conclusion

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

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

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

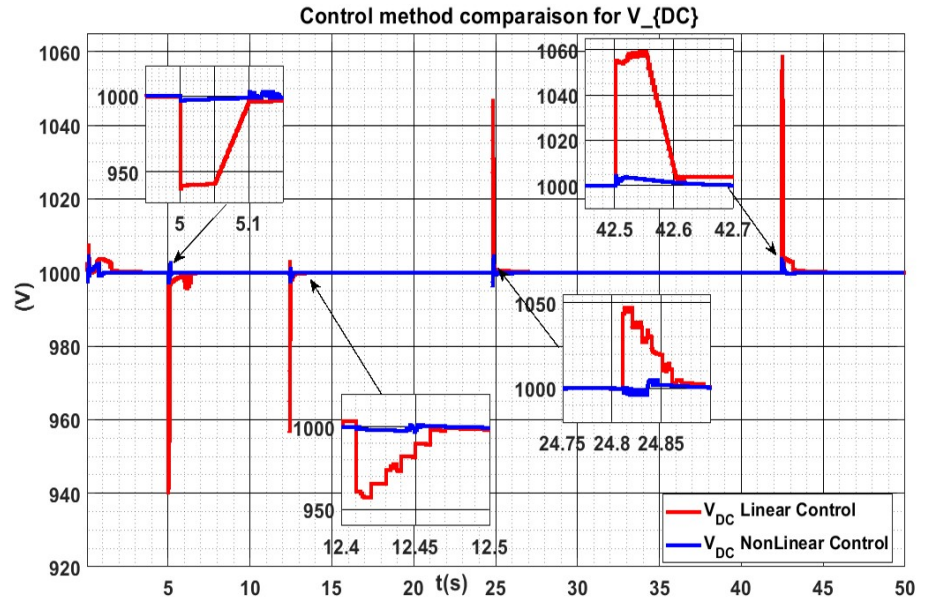


Figure 14. Comparison of the V_{DC} dynamics by applying nonlinear control (in blue) and classical PI control (in red).

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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