Robust voltage regulation of boost converters in DC microgrids *

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Abstract—This paper deals with the design of a robust decentralized control scheme for voltage regulation in boost-based DC microgrids. The proposed solution consists of the design of a suitable manifold on which voltage regulation is achieved, even in presence of unknown load demand and modelling uncertainties. A second order sliding mode control is used to constrain the state of the microgrid to this manifold by generating continuous control inputs that can be used as duty cycles of the power converters. The proposed control scheme has been validated through experiments on a real DC microgrid.

I. INTRODUCTION

Nowadays, due to economical, technological and environmental reasons, the most relevant challenge in power grids deals with the transition from the traditional power generation and transmission systems towards the large scale introduction of smaller Distributed Generation units (DGUs) [1]. Moreover, due to the ever-increasing energy demand and the public concern about global warming and climate change, much effort has been focused on the diffusion of environmentally friendly Renewable Energy Sources (RES) [2]. In this context, in order to integrate different types of RES, the so-called microgrids have been proposed as a new concept of electric power systems [3]. Microgrids are electrical distribution networks, composed of clusters of DGUs, loads, energy storage systems and energy conversion devices interconnected through power distribution lines [4].

Since electrical Alternating Current (AC) has been widely used in most industrial, commercial and residential applications, AC microgrids have attracted the attention of many control system researchers [5]–[10]. However, several advantages of DC microgrids with respect to AC microgrids are well known [11]. The most important advantage relies on the natural interface of many types of RES, energy storage systems and loads with DC network, through DC-DC converters. For this reason, lossy conversion stages are reduced and consequently DC microgrids are more efficient than AC microgrids. Furthermore, control systems for a DC microgrid are less complex than the ones required for an AC microgrid, where several issues such as synchronization, frequency regulation, reactive power flows, harmonics and unbalanced loads need to be addressed.

Two main control objectives in DC microgrids are voltage regulation and current or power sharing. Typically, both objectives are simultaneously achieved by designing hierarchical control schemes. In the literature, these control problems have been addressed by different approaches [12]–[18]. All these works deal with DC-DC buck converters or do not take into account the model of the power converter. However, considering that many battery-powered applications (e.g., electric vehicles and lighting systems) often stack cells in series to increase the voltage level, DC-DC boost converters can be used in order to achieve higher voltage and reduce the number of cells. In this paper a Sliding Mode (SM) control scheme is proposed to regulate the voltage of boost converters within a DC microgrid, which is experimentally shown to be compatible with additional secondary controllers.

The sliding mode control methodology [19] is well known for its robustness properties and, belonging to the class of Variable Structure Control systems, has been extensively applied to power electronics, since it is perfectly adequate to control the inherently variable structure nature of power converters. In this paper we propose robust decentralized primary controllers, relying on a Second Order SM (SOSM) control methodology, capable of dealing with unknown load and input voltage dynamics, as well as uncertain model parameters, without requiring the use of observers. Due to its decentralized and robust nature, the design of each local controller does not depend on the knowledge of the whole microgrid, making the control synthesis simple and the control scheme scalable. The proposed controllers generate continuous inputs that can be used as duty cycles, in order to achieve constant switching frequency. The proposed control scheme has been validated through experimental tests on a real DC microgrid test facility at Ricerca sul Sistema Energetico (RSE), in Milan, Italy [20], showing good closed-loop performances.

II. DC MICROGRID MODEL

The considered low-voltage DC network is represented by a connected and undirected graph $G = (V, E)$, where the nodes $V = \{1, ..., n\}$, represent the DGUs and the edges $E = \{e_{ij} \in E \mid e_{ij} = 1\}$.
\[ I_t = R_t^{-1} (u \circ V + V_{DC}) \]

where \( R_t \) is the line resistance, \( u \) is the control input, and \( V_{DC} \) is the voltage source.

The symbols used in (1) and (2) are described in Table I.

### TABLE I
**DESCRIPTION OF THE USED SYMBOLS**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_{li} )</td>
<td>Inductor currents</td>
</tr>
<tr>
<td>( V_i )</td>
<td>Boost output voltage</td>
</tr>
<tr>
<td>( L_{ij} )</td>
<td>Inductor currents</td>
</tr>
<tr>
<td>( R_t )</td>
<td>Filter resistance</td>
</tr>
<tr>
<td>( L_t )</td>
<td>Filter inductance</td>
</tr>
<tr>
<td>( C_t )</td>
<td>Shunt capacitor</td>
</tr>
<tr>
<td>( R_{ij} )</td>
<td>Line resistance</td>
</tr>
</tbody>
</table>

**Remark 1 (Kron reduction)** In (1), the load currents are located only at the Point of Common Coupling (PCC) of each DG. However, by using the Kron reduction method, it is possible to map arbitrary interconnections of DGs and loads, into a reduced network with only local loads.

**Remark 2 (Decentralized control)** Since, according to Assumption 2, the values of \( I_{li} \) and \( V_i \) are available at the \( i \)-th DG, the control scheme to regulate the voltages needs to be fully decentralized.

**Remark 3 (Varying uncertainty)** The uncertain terms are required to be constant (Assumption 1) only to allow for a steady state solution and to theoretically analyze its stability.
The second line of (4) implies that at the steady state the total generated current \( I_L \) is equal to the total current demand \( I_L \). To formulate the control objective, aiming at voltage regulation, it is assumed that for every DGs, there exists a desired reference voltage \( V^* \).

**Assumption 2 (Desired voltage)** There exists a constant reference voltage \( V^*_i \) at the PCC, for all \( i \in V \).

The objective is then formulated as follows: Given system (3), and given a \( V^* = [V^*_1, \ldots, V^*_n]^T \), we aim at designing a fully decentralized control scheme capable of guaranteeing voltage regulation, i.e.

**Objective 1 (Voltage regulation)**

\[
\lim_{t \to \infty} V(t) = V = V^*. \tag{5}
\]

### IV. THE PROPOSED SOLUTION

In this section a fully decentralized SSM controller is proposed in order to achieve Objective 1, providing a continuous control input. As a first step, system (3) is augmented with additional state variables \( \theta_i \) for all \( i \in V \), resulting in:

\[
L_t^i \dot{I}_t = -R_i I_t - u \circ V + V_{DC}
\]

\[
C_t \dot{V} = u \circ I_t - BR^{-1}B^T V - I_L
\]

\[
\dot{\theta} = -(V - V^*). \tag{6}
\]

The additional state \( \theta \) will be coupled to the control input \( u \) via the proposed control scheme, and its dynamics provide a form of integral action that is helpful to obtain the desired voltage regulation.

Now, to facilitate the discussion, some definitions are recalled that are essential to SM control. To this end, consider system

\[
\dot{x} = \zeta(x, u), \tag{7}
\]

with \( x \in \mathbb{R}^n, u \in \mathbb{R}^m \).

**Definition 1 (Sliding function)** The sliding function \( \sigma(x) : \mathbb{R}^n \to \mathbb{R}^m \) is a sufficiently smooth output function of (7).

**Definition 2 (Sliding manifold)** The \( r \)-sliding manifold \( \mathbb{M} \) is given by

\[
\{ x \in \mathbb{R}^n, u \in \mathbb{R}^m : \sigma = L^r_\zeta \sigma = \cdots = L^{(r-1)}_\zeta \sigma = 0 \}, \tag{8}
\]

where \( L^{(r-1)}_\zeta \sigma \) is the \( (r-1) \)-th order Lie derivative of \( \sigma \) along the vector field \( \zeta \). With a slight abuse of notation, also \( L_\zeta \sigma = \dot{\sigma} \), and \( L^{(2)}_\zeta \sigma = \ddot{\sigma} \) are used in the remainder.

**Definition 3 (Sliding mode order)** An \( r \)-sliding mode is enforced from \( t = T_r \geq 0 \), when, starting from an initial condition, the state of (7) reaches the \( r \)-sliding manifold, and remains there for all \( t \geq T_r \). The order of a sliding mode controller is identical to the order of the sliding mode that it is aimed at enforcing.

Now, a suitable sliding function \( \sigma(I_t, V, \theta) \) for system (6) will be introduced, which permits to prove the achievement of Objective 1. The sliding function \( \sigma : \mathbb{R}^{3n} \to \mathbb{R}^n \) is given by

\[
\sigma(I_t, V, \theta) = M_1 I_t + M_2 (V - V^*) - M_3 \theta, \tag{9}
\]

where \( M_1, M_2 \) and \( M_3 \) are positive definite diagonal matrices (e.g., \( M_1 = \text{diag}(m_1, \ldots, m_n) \)) suitable selected in order to assign the dynamics of system (3) on the manifold \( \sigma = 0 \). Since \( M_1, M_2, M_3 \) are diagonal matrices, \( \sigma, i \in V \), depends only on the state variables locally available at the \( i \)-th node, facilitating the design of a decentralized control scheme (see Remark 2). By regarding the sliding function (9) as the output function of system (3), it appears that the relative degree \( \rho \) of the system is one. This implies that a first order SM controller can be naturally applied [19] in order to attain in a finite time the sliding manifold \( \sigma = 0 \). In this case, the discontinuous control signal generated by a first order SM controller can be directly used to open and close the switch of the boost converter.

**Remark 4 (Duty cycle)** By using a discontinuous SM control law to open and close the switch of the boost converter, the Insulated Gate Bipolar Transistors (IGBTs) switching frequency cannot be a-priori fixed and the corresponding power losses could be very high. Usually, in order to achieve a constant IGBTs switching frequency, boost converters are controlled by implementing the so-called Pulse Width Modulation (PWM) technique. To do this, a continuous control signal that represents the so-called duty cycle of the boost converter is required.

In order to obtain a continuous control signal, the procedure suggested in [23] is adopted, yielding for system (6):

\[
L_t^i \dot{I}_t = -R_i I_t - u \circ V + V_{DC}
\]

\[
C_t \dot{V} = u \circ I_t - BR^{-1}B^T V - I_L
\]

\[
\dot{\theta} = -(V - V^*)
\]

\[
\dot{u} = h, \tag{10}
\]

where \( h \in \mathbb{R}^n \) is the new (discontinuous) SM control input. From (10) one can observe that the system relative degree (with respect to \( h \)) is two. Then, it is possible to rely on a second order SM control strategy in order to steer the state of system (10) to the sliding manifold \( \sigma = \dot{\sigma} = 0 \) for all \( t \geq T_r \). Now, a specific second order SM controller is discussed, namely, the well known Suboptimal SSM (SSSM) controller proposed in [23]. Define \( d_i \) equal to \( \sum_{j \in \mathcal{N}_i} I_{ij} \), with \( I_{ij} \) given by (2). For each node two auxiliary
variables are defined, $\xi_1 = \sigma_i$, $\xi_2 = \dot{\sigma}_i$, $i \in \mathcal{V}$, and the so-called auxiliary system is build as follows:

$$
\dot{\xi}_1 = \xi_2,
\dot{\xi}_2 = \phi_i(I_{L_i}, V_i, \dot{d}_i, u_i) - \gamma_i(I_{L_i}, V_i) h_i
$$

(11)

where $\xi_2$, is not measurable since $I_{L_i}$ is unknown and the parameters of the model are uncertain. Bearing in mind that $\dot{\xi}_2 = \dot{\sigma}_i = \phi_i + \gamma_i h_i$, the expressions for $\phi_i$ and $\gamma_i$ are straightforwardly obtained from (9) by taking the second time derivative of $\sigma_i$. The following assumption is made on $\phi_i$ and $\gamma_i$, $i \in \mathcal{V}$:

**Assumption 3 (Bounded uncertainty)** $\phi_i$ and $\gamma_i$ in (11) have known bounds, i.e.,

$$
|\phi_i(\cdot)| \leq \Phi_i, \quad \forall i \in \mathcal{V}
$$

(12)

$$
0 < \Gamma_{\min} \leq \gamma_i(\cdot) \leq \Gamma_{\max}, \quad \forall i \in \mathcal{V},
$$

(13)

$\Phi_i$, $\Gamma_{\min}$ and $\Gamma_{\max}$, being positive constants.

**Remark 5 (Unknown bounds)** Note that in practical cases the bounds in (12) and (13) can be determined relying on data analysis and physical insights. However, if these bounds cannot be a-priori estimated, the Adaptive SSOSM algorithm [24] can be used to dominate the uncertainty.

With reference to [23], for each DGU $i \in \mathcal{V}$, the control law that is proposed to steer $\xi_1$, $\xi_2$, to zero in a finite time can be expressed as

$$
h_i = \alpha_i H_{\max} \text{sgn} \left( \xi_i - \frac{1}{2} \xi_{1,\max}, \right)
$$

(14)

with

$$
H_{\max} > \max \left( \frac{\Phi_i}{\alpha_i \Gamma_{\min}}, \frac{4 \Phi_i}{3 \Gamma_{\min} - \alpha_i \Gamma_{\max}} \right),
$$

(15)

$$
\alpha_i \in (0,1] \cap \left( 0, \frac{3 \Gamma_{\min}}{\Gamma_{\max}} \right)
$$

(16)

$\alpha_i$ switching between $\alpha_i^*$ and 1, according to [23, Algorithm 1]. Note that the control input $u_i(t) = \int_0^t h_i(\tau) d\tau$, is continuous. Then, $\delta_i = 1 - u_i$ can be used as duty cycle of the $i$-th boost converter. Note also that the design of the local controller for each DGU is not based on the knowledge of the whole microgrid, making the control synthesis simpler and the proposed control scheme scalable. We refer to [25] for the stability analysis of the controlled systems, but the main result is stated here for the sake of exposition.

**Theorem 1 (Local exponential stability)**. Let Assumptions 1-3 hold. The desired operating point $(\bar{T}_i, V^*, \bar{\theta})$ of system (6) can be made locally exponentially stable on the sliding manifold characterized by $\sigma = \bar{\sigma} = \bar{0}$, by choosing the entries of $M_2$ sufficiently large.

V. EXPERIMENTAL RESULTS

In order to verify the proposed control strategy, experimental tests are carried out using the DC microgrid test facility at RSE, shown in Figs. 2 and 3. The RSE’s DC grid is unipolar with a nominal voltage of 380 V, including a resistive load (Node 1) with a maximum power of 30 kW at 400 V, a DC generator (Node 3) with a maximum power of 30 kW (used as PV emulator) and two energy storage systems (Node 2 and Node 4), based on high temperature NaNiCl batteries, each of them with an energy of 18 kW h and a maximum power of 30 kW for 10 s. These components

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V^*$</td>
<td>380 V</td>
<td>DC nominal voltage</td>
<td></td>
</tr>
<tr>
<td>$V_{DC_i}$</td>
<td>≈270 V</td>
<td>DC input voltage</td>
<td></td>
</tr>
<tr>
<td>$R_{12}$</td>
<td>125 mΩ</td>
<td>Tie-Line resistance 1-2</td>
<td></td>
</tr>
<tr>
<td>$R_{13}$</td>
<td>19.5 mΩ</td>
<td>Tie-Line resistance 1-3</td>
<td></td>
</tr>
<tr>
<td>$R_{34}$</td>
<td>125 mΩ</td>
<td>Tie-Line resistance 3-4</td>
<td></td>
</tr>
<tr>
<td>$L_{12}$</td>
<td>70 µH</td>
<td>Tie-Line inductance 1-2</td>
<td></td>
</tr>
<tr>
<td>$L_{13}$</td>
<td>43 µH</td>
<td>Tie-Line inductance 1-3</td>
<td></td>
</tr>
<tr>
<td>$L_{34}$</td>
<td>70 µH</td>
<td>Tie-Line inductance 3-4</td>
<td></td>
</tr>
<tr>
<td>$C_{1i}$</td>
<td>6.8 mF</td>
<td>Output capacitance</td>
<td></td>
</tr>
<tr>
<td>$L_{2i}$</td>
<td>1.12 mH</td>
<td>Input inductance</td>
<td></td>
</tr>
<tr>
<td>$f_{sw}$</td>
<td>4 kHz</td>
<td>Switching frequency</td>
<td></td>
</tr>
</tbody>
</table>

![Fig. 2. Photo of the RSE’s DC microgrid adopted during the test.](image)

![Fig. 3. Layout of the RSE’s DC microgrid adopted during the test.](image)
are connected to a common DC link through four DC-DC boost synchronous converters of $35\,\text{kW}$. The DC-DC converters are distributed and connected to the DC link with power distribution lines, the parameters of which are reported in Table II. The control of each converter is realized through two dSpace controllers that measure the inductor current and the boost output voltage and drive the power electronic converters. The DC-DC load and generator converters are controlled in constant power mode and are treated as current disturbances. The battery converters are controlled through the proposed SSOSM control scheme described in Section IV, where the voltage reference is set equal to $380\,\text{V}$. For both the battery converters, the SSOSM control parameters are $m_1 = 0.01, m_2 = 0.1, m_3 = 1, H_{\text{max}} = 4$, and $\alpha^*_i = 0.05$. In order to test the performance of the proposed control approach, three different scenarios are implemented. Note that in the following figures we arbitrarily assume that the current entering any node is positive (passive sign convention).

**Scenario 1. Disturbance with a limited ramp rate power variation:** We assume that the system is in a steady state condition with zero power absorbed by the load or provided by the generator. At the time instant $t = 5\,\text{s}$ the power reference for the load converter (see Fig. 4) or for the generator converter (see Fig. 5) is set to $20\,\text{kW}$ and at the time instant $t = 35\,\text{s}$ is reset to $0\,\text{kW}$ with the ramp rate limited to $1\,\text{kW/}\text{s}$. The proposed control strategy is able to keep the output voltage of both the batteries DC-DC converter to their reference without any voltage variation.

**Scenario 2. Disturbance with a step power variation:** The tests in Scenario 1 are replicated without ramp rate limitation. In this case, due to the step power variation, one can observe a voltage transient, after which the system exhibits a stable performance thanks to the robustness of the proposed control approach (see Figs. 6 and 7).

**Scenario 3. Step variation of the voltage reference:** In this scenario the proposed primary controllers have been coupled with a secondary control scheme that calculates the voltage references for the battery converters in order

![Fig. 4. Scenario 1: system performance with a load variation of about 20 kW in case of ramp rate equal to 1 kW/s.](image4.png)

![Fig. 6. Scenario 2: system performance with a step load variation of about 20 kW.](image6.png)

![Fig. 5. Scenario 1: system performance with a generator variation of about 20 kW in case of ramp rate equal to 1 kW/s.](image5.png)

![Fig. 7. Scenario 2: system performance with a step generator variation of about 20 kW.](image7.png)
to achieve current sharing among the batteries (see Fig. 8). Although the analysis of a secondary control level is not discussed in this paper, Scenario 3 is aimed at showing that the proposed primary controllers, due to their robustness property in tracking the voltage references, can be coupled with any secondary control scheme that guarantees current or power sharing.

Finally, note that in the discussed scenarios, only the voltage of the battery nodes (Node 2 and Node 4) have been controlled with the proposed strategy. Nevertheless, the voltage deviations from the nominal value in the other two nodes (Node 1 and Node 3), depending on the line impedances, are always less than 3%.

VI. CONCLUSIONS

In this paper a robust control strategy has been designed to regulate the voltage in boost-based DC microgrids. The proposed control scheme is fully decentralized and is based on higher order sliding mode control methodology, which allows to obtain continuous control inputs. The latter can be used as duty cycles of the boost converters, achieving constant switching frequency and facilitating a PWM-based implementation. The proposed control scheme has been validated through experimental tests on a real DC microgrid, showing satisfactory closed-loop performances.

REFERENCES


