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Power sharing of parallel operated DC-DC converters using current-limiting droop control

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***Abstract*— In this paper, a nonlinear current-limiting droop controller is proposed to achieve accurate power sharing among parallel operated DC-DC boost converters in a DC micro-grid application. In particular, the recently developed robust droop controller is adopted and implemented as a dynamic virtual resistance in series with the inductance of each DC-DC boost converter. Opposed to the traditional approaches that use small-signal modeling, the proposed control design takes into account the accurate nonlinear dynamic model of each converter and it is analytically proven that accurate power sharing can be accomplished with an inherent current limitation for each converter independently using input-to-state stability theory. When the load requests more power that exceeds the capacity of the converters, the current-limiting capability of the proposed control method protects the devices by limiting the inductor current of each converter below a given maximum value. Extensive simulation results of two paralleled DC-DC boost converters are presented to verify the power sharing and current-limiting properties of the proposed controller under several changes of the load.**

I. INTRODUCTION

The rapid advancement of the smart grid and renewable energy generation units has increased the need for enhanced efficiency and quality in the power supply [1], [2]. In contrast with the AC networks, DC micro-grids can viably enhance the power quality, diminish energy conversion steps, decrease power losses and running expenses, and boost the value and benefits of distributed energy. In the interim, due to the DC nature of the power, synchronisation and instability issues can also be avoided [3]. Therefore, DC power distribution represents a promising technology that has been widely applied in large-scale data centres, shipboard systems, electric vehicles [4], [5], etc.

Nevertheless, the stability of a DC micro-grid continues to remain a main concern during its design, due to the operation of the power electronic converters, which represent the basic units for achieving the integration between distributed generations and loads. These power converters can suitably adjust the voltage levels required by each device in the network. In islanded DC micro-grids without communication among the units, the system often operates in a distributed control scheme where each unit has a controller whose decision is based on the available local variables. In this case, the stability needs to be guaranteed by the sources that operate in parallel and control the bus voltage cooperatively. A common practice to accomplish this task without overloading some sources is to introduce virtual resistances in the output of the power converters, a technique also known as droop control [6], [7], [8].

The droop control is mostly used in parallel operated converters to achieve power sharing and increase the reliability of the system. In fact, the droop control is a type of distributed control method that can realise the power sharing by the located electrical variables. Its main drawback is represented by the poor voltage regulation. To this end, several improvements for droop methods have been developed in [9], [10], [11], [12], [13], trying to restore the voltage to the rated value. However, another critical issue is that traditional droop control results in inaccurate power sharing when the output or line impedances of the paralleled converters are different. To improve the power sharing and increase the reliability of a system, droop control techniques that are mainly based on virtual impedances have been proposed in the literature [14], [15]. One of the techniques to achieve accurate power sharing is based on the concept of the robust droop controller, which acts independently from the line impedances, focusing only on the output parameter to be regulated, i.e. the load voltage [16], [17].

However, the stability analysis of droop controlled-converters in DC micro-grids has not been adequately addressed. Most of the existing approaches rely on the small-signal model of the power converters and on linearization methods, ignoring the nonlinear dynamics of the devices [18], [19]. In addition, another critical issue that is related to the stability of the micro-grid and corresponds to the technical requirements of each distributed generation unit is the current-limiting capability of the converters. Current limitation as described in [20], [21], protects the equipment without violating certain boundaries, as imposed by the technical limits of the converters. Hence, except from the theoretical proof of stability, which should be based on the accurate nonlinear dynamic model of the dc/dc power converters, the devices must be protected at all times and must satisfy some technical limitations. This is a crucial matter especially during transients, faults and unrealistic power demands. Although the converter is often protected using additional fuses, circuit breakers and relays, there is an increased interest in designing control methods that can guarantee an inherent current limitation [22]. Traditional current-limiting control strategies suitably change the original control structure to the current-limiting control structure [23]. However, closed loop stability cannot be analytically guaranteed and the original controller can suffer from integrator windup and latch-up issues that may lead to instability [23]. Hence,

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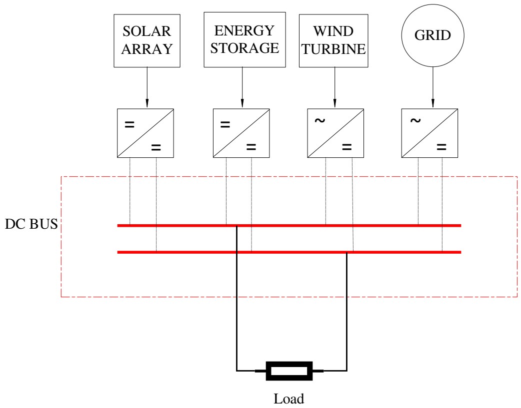


Fig. 1: Typical topology in a DC micro-grid system

the design of a droop control structure for power converters in a DC micro-grid to achieve accurate power sharing and guarantee closed-loop system stability with a given current limitation is of significance.

To this end, in this paper, a nonlinear controller equipped with the robust droop control structure is developed for parallel operated DC/DC boost converters to guarantee accurate power sharing among the paralleled units in proportion to their power ratings. Based on the nonlinear dynamics of the converters and using input-to-state stability theory, it is proven that the proposed controller imposes an inherent current-limiting strategy for each converter. Hence, the current drawn from each source does not violate certain boundaries specified by the technical limits of each power electronic device, and therefore accurate power sharing is accomplished while ensuring the full protection of DC micro-grid. Extensive simulation results of two parallel operated DC/DC boost converters are provided to demonstrate the effectiveness of the proposed approach.

The remainder of the paper contains a brief description in Section II regarding the conventional droop control method and the main challenges that exist in a DC micro-grid. In Section III, the DC power system under consideration is introduced and analysed. Using nonlinear theory, it is shown that both power converters introduce the desired current limitation. Simulation results are provided in Section V, while the conclusions are pointed out in Section VI.

II. Problem description and objectives

In Fig. 1, a typical islanded DC micro-grid is depicted consisting of various DC/DC or AC/DC power converters connected in parallel to a common DC bus and feeding a load. Power sharing without the need of communication among the different converters is often achieved via droop control [24], [11]. In the conventional droop control strategy, each one of the m parallel-operated power converters introduces an output voltage V_i of the form:

$$V_i = V_{ref} - n_i i_i, \tag{1}$$

where i_i is the output current of each converter, n_i is the droop coefficient and $i \in \{1, 2, \ldots, m\}$. However, conventional droop control suffers from poor voltage regulation and cannot achieve accurate power sharing when each converter introduces a different output impedance [16], [17]. One of the recently developed methods to address these issues is based on a robust droop strategy, which achieves accurate power sharing and tight voltage regulation [16], [17]. The robust droop controller takes the form

$$\dot{V}_i = k_e(V_{ref} - V_o) - n_i i_i, \tag{2}$$

where V_o is the load voltage and k_e is a constant gain. At the steady-state, there is

$$n_1 i_1 = n_2 i_2 = \ldots = n_m i_m.$$

By multiplying this expression with the load voltage V_o in each part of the equation, it yields

$$n_1 P_1 = n_2 P_2 = \ldots = n_m P_m,$$

where $P_i = V_o i_i$ is the power injected to the load by the i-th converter. This guarantees the power sharing in the DC micro-grid.

Although accurate power sharing is achieved independently from the power requested by the load, the technical limitations of each converter are not taken into account. Given the power rating P_n of a converter and the rated output voltage V_{ref}, a limitation for the output current (and consequently the input current) of each converter is introduced. To ensure protection to the generating circuit or the transmission system from harmful effects in cases of significant changes in the load demand, a current-limiting property is required. Hence, imposing an upper limit for the current that may be delivered to a load and making sure that certain boundaries are not violated represents another major challenge in a DC micro-grid operation.

III. Nonlinear Model of two parallel DC/DC boost converters

Fig. 2 shows the configuration of a DC micro-grid consisting of two DC/DC boost converters connected in parallel and feeding a common load, which is assumed as resistive. Although for simplicity, the investigation is restricted in two paralleled converters, it can be easily expanded to the cases of m boost converters in a DC micro-grid. Using Kirchhoff laws and average analysis [25], the dynamic model of the entire system including the nonlinear behaviour of the boost converter becomes

$$L_{in1}\dot{i}_{in1} = U_1 - r_{in1}i_{in1} - (1-u_1)V_1 \tag{3}$$
$$C_1\dot{V}_1 = (1-u_1)i_{in1} - i_1 \tag{4}$$
$$L_1\dot{i}_1 = V_1 - (i_1+i_2)R - R_1 i_1 \tag{5}$$
$$L_{in2}\dot{i}_{in2} = U_2 - r_{in2}i_{in2} - (1-u_2)V_2 \tag{6}$$
$$C_2\dot{V}_2 = (1-u_2)i_{in2} - i_2 \tag{7}$$
$$L_2\dot{i}_2 = V_2 - (i_1+i_2)R - R_2 i_2. \tag{8}$$

Here L_{in1}, L_{in2} are the boost converter inductances with parasitic resistances r_{in1} and r_{in2}, respectively, and C_1, C_2 represent the output capacitors the converters. The output

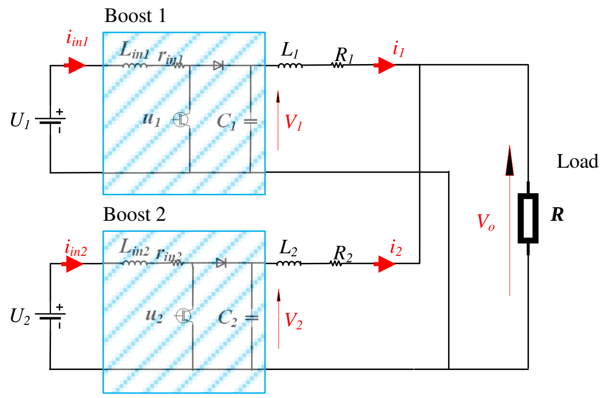


Fig. 2: Proposed network configuration for parallel operation

impedances or line impedances of the converters are introduced by the inductances L_1, L_2 and the resistances R_1, R_2, while R is the common load. The state vector of the system consists of the inductor currents i_{in1}, i_{in2} in the input of every converter, the output voltages V_1, V_2 and the line currents i_1, i_2. The control input vector consists of the duty-ratio inputs of each converter u_1 and u_2, which by definition should remain bounded in the set $[0, 1]$. The DC input voltages of the converters are given as U_1 and U_2, and represent constant inputs for the system (uncontrollable), as shown in Fig. 2.

It can be observed, that system (3)-(8) is nonlinear, since the control inputs u_1 and u_2 are multiplied with the system states. In addition, in the case where $u_1 = 1$ or $u_2 = 1$, at the steady-state, the inductor currents i_{in1} and i_{in2} take the values $i_{in1} = \frac{U_1}{r_{in1}}$ and $i_{in2} = \frac{U_2}{r_{in2}}$, respectively. Since r_{in1} and r_{in2} are parasitic resistances and therefore very small, then the two input currents reach very high values that can cause damage to the boost converter devices. Hence, there is a clear challenge to achieve the desired operation of the DC micro-grid system, i.e. accurate power sharing, while maintaining the currents below the converters' rated values. Such a controller that can achieve these tasks is investigated in the sequel.

IV. Proposed current-limiting droop controller

A. Controller design and analysis

In order to achieve the desired power sharing and voltage regulation, while maintaining a limited current for each boost converter, the robust droop control concept given in (2) is implemented as a dynamic virtual resistance for each converter, opposed to the original design which is applied directly to the voltage. Hence, the duty-ratio input of each boost converter takes the form

$$u_i = 1 - \frac{w_i}{v_i} i_i, \tag{9}$$

where $i = \{1, 2\}$ indicates the converter number and w_i represents a virtual resistance for i-th converter. In order to incorporate the robust droop control concept, the virtual resistance is proposed to follow the nonlinear dynamics:

$$\dot{w}_i = -c_i w_{qi}^2 \left[k_e(V_{ref} - V_o) - n_i i_i \right] \tag{10}$$

$$\dot{w}_{qi} = c_i \left[k_e(V_{ref} - V_o) - n_i i_i \right] \frac{(w_i - w_{mi})w_{qi}}{\triangle w_{mi}} - k_{qi} \left(\frac{(w_i - w_{mi})^2}{\triangle w_{mi}} + w_{qi}^2 - 1 \right) w_{qi}, \tag{11}$$

with c_i, k_{qi}, k_e, w_{mi}, $\triangle w_{mi}$ being positive constants. It is highlighted that a second controller state w_{qi} is introduced to define the dynamic structure of the virtual resistance and to maintain a given bound for w_i. To further explain this, the nonlinear controller dynamics w_i and w_{qi} are investigated. Considering the following Lyapunov function candidate for system (10)-(11):

$$W_i = \frac{(w_i - w_{mi})^2}{\triangle w_{mi}^2} + w_{qi}^2, \tag{12}$$

then by calculating its time derivative and using the controller equations (10)-(11), it yields:

$$\begin{aligned} \dot{W}_i &= \frac{2(w_i - w_{mi})\dot{w}_i}{\triangle w_{mi}^2} + 2w_{qi}\dot{w}_{qi} \\ &= -2c_i w_{qi}^2 \frac{w_i - w_{mi}}{\triangle w_{mi}^2} \left[k_e(V_{ref} - V_o) - n_i i_i \right] \\ &\quad +2c_i w_{qi}^2 \frac{w_i - w_{mi}}{\triangle w_{mi}^2} \left[k_e(V_{ref} - V_o) - n_i i_i \right] \\ &\quad -2k_{qi} \left(\frac{(w_i - w_{mi})^2}{\triangle w_{mi}} + w_{qi}^2 - 1 \right) w_{qi}^2 \\ &= -2k_{qi} \left(\frac{(w_i - w_{mi})^2}{\triangle w_{mi}^2} + w_{qi}^2 - 1 \right) w_{qi}^2. \end{aligned} \tag{13}$$

From the expression (13), one can notice that $\dot{W}_i$ becomes zero on the ellipse

$$W_{i0} = \left\{ w_i, w_{qi} \in \mathbb{R} : \frac{(w_i - w_{mi})^2}{\triangle w_{mi}^2} + w_{qi}^2 = 1 \right\}, \tag{14}$$

or at the horizontal axis $w_{qi} = 0$ on the $w_i - w_{qi}$ plane (Fig. 3). This indicates that if the initial conditions of the controller states w_{i0} and w_{qi0} are chosen on the ellipse W_{i0}, i.e. they satisfy

$$\frac{(w_{i0} - w_{mi})^2}{\triangle w_{mi}^2} + w_{qi0}^2 = 1$$

then from (13) there is

$$\dot{W}_i(t) = 0, \ \forall t \geq 0,$$

which results in

$$W_i(t) = W_i(0) = 1, \ \forall t \geq 0,$$

leading to the result that w_i and w_{qi} will start and remain on the ellipse W_{i0} for all $t \geq 0$, as shown in Fig. 3. Hence, a typical choice for the initial conditions is $w_{i0} = w_{mi}$, $w_{qi0} = 1$.

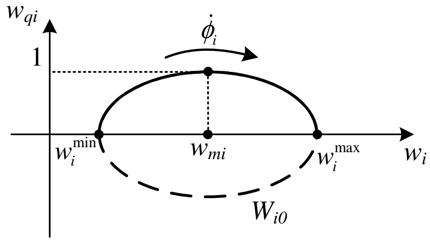


Fig. 3: Phase portrait of the controller dynamics

Since the controller states operation is restricted on the ellipse W_{i0}, then $w_i \in [w_i^{min}, w_i^{max}] = [w_{mi} - \Delta w_{mi}, w_{mi} + \Delta w_{mi}]$ and $w_{qi} \in [0, 1]$ for all $t \geq 0$. If the positive constants w_{mi} and Δw_{mi} are chosen to guarantee

$$w_{mi} > \Delta w_{mi}$$

then $w_i^{min} > 0$, which means that the ellipse W_{i0} is located on the right-half plane of $w_i - w_{qi}$ and therefore $w_i \in [w_i^{min}, w_i^{max}] > 0, \forall t \geq 0$, introducing a positive virtual resistance. Using the transformation

$$\begin{aligned} w_i - w_{mi} &= \Delta w_{mi} \sin\phi \\ w_{qi} &= \cos\phi \end{aligned}$$

inside the controller dynamics (10)-(11), after a few calculations it results in

$$\dot{\phi}_i = \frac{c_i w_{qi}^2}{\Delta w_{mi}} \left[k_e(V_{ref} - V_o) - n_i i_i\right] \tag{15}$$

which proves that the controller state trajectory on the $w_i - w_{qi}$ plane will move on the ellipse W_{i0} with an angular velocity $\dot{\phi}_i$ given by (15). It is highlighted that the angular velocity becomes zero when: i) $k_e(V_{ref} - V_o) - n_i i_i = 0$, which guarantees the accurate power sharing and the desired tight voltage regulation, or ii) $w_{qi} = 0$, which leads to $w_i = w_i^{min}$ or $w_i = w_i^{max}$, corresponding to the current-limiting capability as explained in the sequel.

B. Current limitation

By substituting the expression of the proposed controller (9) into the inductor current equations (3) and (6), the closed-loop dynamics of the inductor current become for each converter:

$$L\dot{i}_{ini} = -\left(w_i + r_{ini}\right) i_{ini} + U_i. \tag{16}$$

By introducing the following Lyapunov function candidate

$$V_i = \frac{1}{2} L_i i_{ini}^2 \tag{17}$$

and computing its time derivative, after using (16), the expression of $\dot{V}$ becomes

$$\dot{V}_i = L_i i_{ini} \cdot \dot{i}_{ini} = -\left(w_i + r_{ini}\right) i_{ini}^2 + U_i i_{ini} \tag{18}$$

Taking into account that $w_i \in [w_i^{min}, w_i^{max}] > 0, \forall t \geq 0$, as proven in the previous subsection then

$$\begin{aligned} \dot{V}_i &\leq -\left(w_i^{min} + r_{ini}\right) i_{ini}^2 + U_i i_{ini} \\ &\leq -\left(w_i^{min} + r_{ini}\right) \left|i_{ini}\right|^2 + \left|U_i\right| \left|i_{ini}\right| \end{aligned} \tag{19}$$

Thus

$$\dot{V}_i < 0, \forall |i_{ini}| > \frac{U_i}{w_i^{min} + r_{ini}} \tag{20}$$

which means that system (16) is input-to-state stable with respect to the uncontrollable constant and positive input U_i. Therefore, if initially $|i_{ini}(0)| \leq \frac{U_i}{w_i^{min} + r_{ini}}$, then

$$|i_{ini}(t)| \leq \frac{U_i}{w_i^{min} + r_{ini}}, \forall t \geq 0. \tag{21}$$

By selecting w_i^{min} as

$$w_i^{min} = \frac{U_i}{i_{ini}^{max}} \tag{22}$$

where i_{ini}^{max} represents the maximum input current allowed to flow through the converter according to the converter ratings, then by substituting (22) into (21), it yields

$$|i_{ini}(t)| \leq \frac{U_i}{\frac{U_i}{i_{ini}^{max}} + r_{ini}} = \frac{1}{1 + r_{ini}\frac{i_{ini}^{max}}{U_i}} i_{ini}^{max} < i_{ini}^{max}, \ \forall t \geq 0 \tag{23}$$

which guarantees the desired current-limiting capability of each boost converter separately.

It is highlighted that the current-limiting property of each converter is accomplished independently from the power sharing function $k_e(V_{ref} - V_o) - n_i i_i$ than needs to be regulated to zero. This means that each converter has as the first priority to protect itself from high currents that can damage the device. When the current is below the maximum value, then power sharing can be achieved. This will be illustrated in the simulation results that follows.

V. Simulation results

A DC micro-grid with two parallel DC/DC boost converters, similar to the one presented in Fig. 2, is simulated using Simpower Systems toolbox of Matlab/Simulink to evaluate the proposed control strategy. A switching frequency of $100kHz$ was used for the pulse-width-modulation of both converters. The system and controller are displayed in Table I. The main task is to achieve accurate power sharing among the paralleled converters and regulation of the common load voltage to the rated value $V_{ref} = 300V$, while maintaining the inductor currents below their maximum values independently from the load changes. Here it is assumed that $P_{n2} = 2P_{n1}$ and hence the load should be shared in a 2:1 ratio.

Each converter is equipped with the proposed controller and both controllers are initialized at $0.3s$. The initial transient is caused by the uncharged dc capacitors C_1 and C_2. At first the load is $R = 300\Omega$. As it can be seen in Fig. 4b, accurate power sharing is achieved since at the steady state the output currents i_1 and i_2 satisfy $i_2 = 2i_1$. Fig. 4c illustrates that the load voltage is regulated very close to the rated value $V_{ref} = 300V$, while the line voltages V_1 and V_2 are also regulated

TABLE I: Controller and system parameters

Parameters	Values	Parameters	Values
L_1	$0.2mH$	L_2	$0.21mH$
R_1	2Ω	R_2	1.5Ω
L_{in1}, L_{in2}	$2.2mH$	U_1	$200V$
r_{in1}, r_{in2}	0.5Ω	U_2	$100V$
R	300Ω	C_1, C_2	$560\mu F$
n_1	1	k_{q1}, k_{q2}	1000
n_2	2	k_e	10
P_{n1}	$0.5kW$	t_s	$0.05s$
P_{n2}	$1kW$	i_1^{min}, i_2^{min}	$100\mu A$
c_1	$1.6 \cdot 10^5$	i_{in1}^{max}	$2.5A$
c_2	$3.1 \cdot 10^5$	i_{in2}^{max}	$10A$
w_{m1}	10^6	w_{m2}	$5 \cdot 10^5$

close to the rated value to achieve the desired power sharing. Fig. 4a depicts the inductor currents i_{in1} and i_{in2} which stay below the limit imposed by the system's parameters.

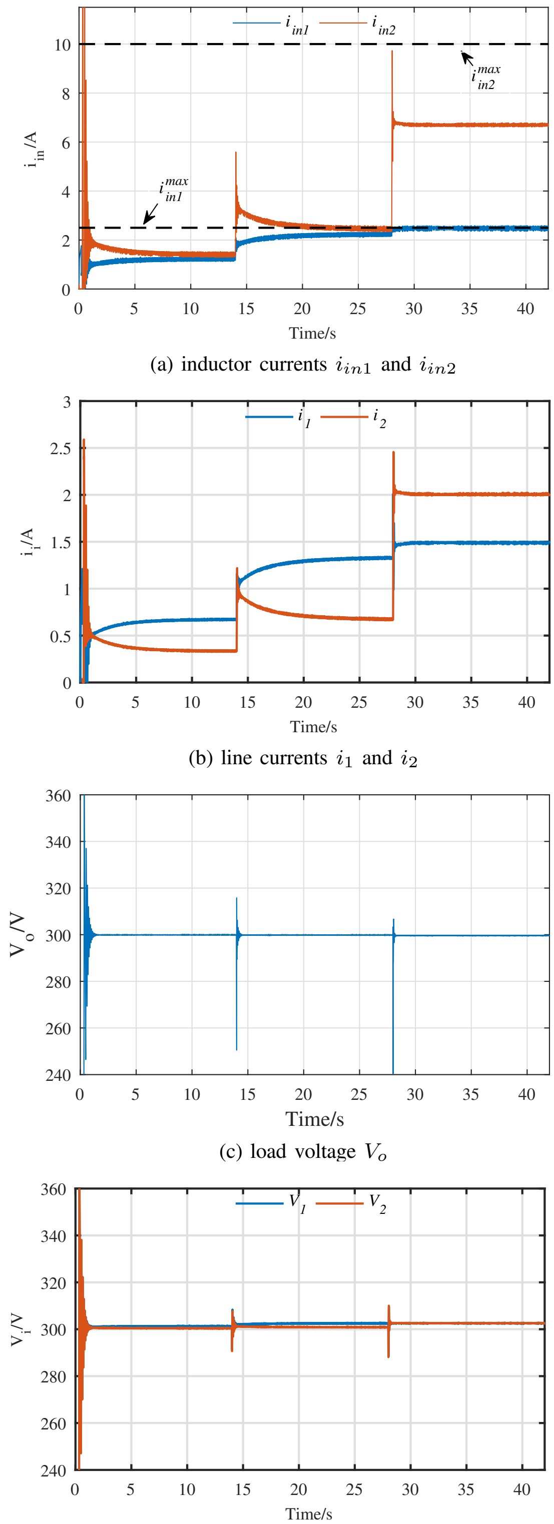
At $t = 14s$, a load change is applied and the resistive load changes to 150Ω. It can be observed in Fig. 4d, after a small transient, the line voltages slightly increase and the load voltage V_o remains close to the $300V$ value as desired (Fig. 4c). The inductor currents and the line currents increase due to the increase of the power demand but the accurate power sharing is maintained, since $i_1 = 0.67$ and $i_2 = 1.33$ at the steady state, i.e. $i_2 = 2i_1$, as shown in Fig. 4b. The inductor currents still remain below their maximum values (Fig. 4a).

Finally, at $t = 28s$ a second load change occurs and the resistive load becomes 85Ω. In this case, the power demand further increases requesting higher currents from each converter. As it is seen in Fig. 4a, the inductor current of converter 1 reaches the limit $i_{in1}^{max} = 2.5A$ based on the proposed current-limiting strategy, while the inductor current of the second converter still stays below its maximum value. Therefore, power sharing is sacrificed to protect the first power converter from damages, as it is shown in Fig. 4b. Nevertheless, the load voltage is still regulated close to the rated value as required (Fig. 4c).

The transient response of the virtual resistances is displayed in Fig. 5a. It is observed that as the load decreases and consequently the power demand increases, both virtual resistances decrease to allow a higher current flow. At the final change of the load, w_1 reaches its minimum value $w_1^{min} = \frac{U_1}{i_{1}^{max}} = 80\Omega$ which limits the inductor current i_{in1} below its given maximum value. The response of the additional controller states w_{q1} and w_{q2} is provided in Fig. 5b. By combining the values of w_i and w_{qi} given in Fig. 5a and Fig. 5b, it is verified that $\frac{(w_i - w_{mi})^2}{\triangle w_{mi}^2} + w_{qi}^2 = 1$ holds true, which validates the theoretical development.

VI. Conclusions

A current-limiting droop controller for achieving power sharing among two parallel operated DC-DC boost converters in a DC micro-grid application, was proposed. Based on the nonlinear dynamic model of the converters, it was proven that the proposed controller can guarantee accurate



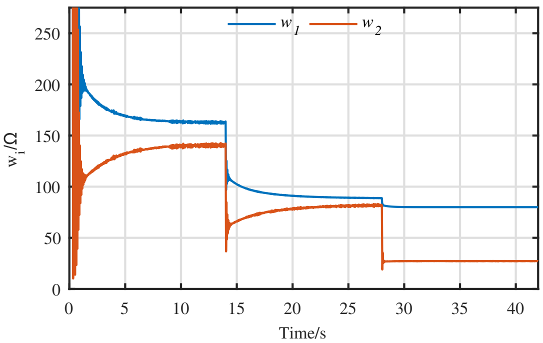
(a) inductor currents i_{in1} and i_{in2}

(b) line currents i_1 and i_2

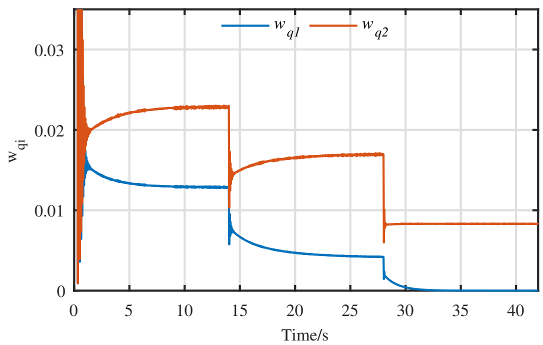
(c) load voltage V_o

(d) line voltages V_1 and V_2

Fig. 4: Simulation results of the system states of two parallel operated DC/DC boost converters under the proposed controller



(a) virtual resistances w_1 and w_2



(b) controller states w_{q1} and w_{q2}

Fig. 5: Simulation results of the controller states of two parallel operated DC/DC boost converters under the proposed controller

power sharing when the inductor currents of both converters remain below their maximum values. A detailed guidance for selecting the controller parameters was provided for a complete controller design. Extensive simulations were carried out and presented to validate the proposed control approach under several changes of the load demand.

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