Distributed Cooperative Control of Hybrid AC/DC Microgrid

Preprint

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Distributed Cooperative Control of Hybrid AC/DC Microgrid

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Abstract— This paper presents a distributed cooperative control-based power management algorithm for a hybrid AC/DC microgrid. The proposed algorithm for a hybrid microgrid system controls the power flow through the interface converter between the AC and DC microgrids. This algorithm allows power sharing between the distributed generators in the microgrid according to their power ratings. Moreover, it enables the fixed scheduled power delivery through the interface converters in both directions at different operating conditions while maintaining voltage regulation and improving the frequency profile. The effectiveness of the controller is confirmed by simulation.

Keywords—distributed cooperative control, hybrid AC/DC microgrid

I. INTRODUCTION

Pros and cons of using AC and DC microgrids were studied in [1]–[3]. References [4] and [5] presented hybrid AC/DC microgrids that incorporated the benefits of both AC and DC microgrids to provide a better platform for the integration of distributed generation in a power system. Hybrid AC/DC microgrids use interface converters to link the AC and DC subgrids. The power management control strategy of a hybrid AC/DC microgrid focusses on the control of these interface converters. The power management strategy of individual AC and DC microgrids has been studied extensively; however, the power management strategy of a hybrid AC/DC microgrid has not yet received much attention. A droop control-based scheme was presented in [4] to ensure proportional power sharing among the AC and DC sources through the interface converters. A decentralized control algorithm was proposed in [5] for an AC/DC/distributed storage hybrid microgrid that realizes decentralized power control by local power sharing for individual AC or DC networks, global power sharing for the entire microgrid, and storage power sharing for the energy storage system. A two-stage, modified, droop-based method for the control of interface converters in an AC/DC hybrid microgrid was investigated in [6]. The controller takes the frequency information from the AC microgrid and voltage measurement from the DC microgrid to generate the power reference for the interface converters using the droop method. Reference [7] proposed an interlinking control scheme for a hybrid AC/DC microgrid to share the active power proportional to the rating of the sources, not on the placement of the sources. A nonlinear disturbance-observer-based DC-bus voltage control algorithm for a hybrid microgrid was discussed in [8] that eliminated the requirements of remote measurement with communication; however, this method improves only transient performance without any contribution to the power management of the studied AC/DC microgrid system. Most of proposed power management strategies for hybrid AC/DC microgrids are droop-based, and they suffer from the inherent problems of the droop-based control algorithm, such as poor voltage regulation and inaccurate power sharing.

This paper presents a distributed cooperative control algorithm (DCC) for a hybrid AC/DC microgrid system through controlling the interface converters. This work is a continuation of the work done by the authors on the control of an AC microgrid [9] and a DC microgrid [10]. In the previous work, controls of AC and DC microgrids were investigated separately under different conditions; the control of an AC/DC hybrid microgrid is the logical next step to create a hybrid microgrid. A flexible hybrid microgrid architecture is considered where all the distributed generation and loads are placed in either AC or DC subgrids, depending on their AC or DC characteristics. Overall system integration cost can be decreased and efficiency can be increased because this flexible hybrid microgrid architecture reduces the number of various power conversion stages, such as AC-DC or DC-AC.

II. HYBRID MICROGRID ARCHITECTURE AND MODES OF OPERATION

Fig. 1 shows a simple flexible structure of hybrid AC/DC microgrid, which is formed by one AC microgrid and one DC microgrid connected through an IC The subgrids in the hybrid system are serving their local loads. The IC provides bi-directional power flow between the two subgrids, depending on the demand-supply constraints in the individual subgrids. Moreover, the hybrid microgrid can relate to the utility from the AC side by a static transfer switch. The hybrid AC/DC microgrid operates as grid connected and islanded modes. Details of the operation are described in the following section.

A. Grid-Connected Mode of Operation for Hybrid Microgrid

During grid-connected mode, the voltage and frequency of the AC subgrid is controlled by the utility. The voltage of the DC subgrid is controlled by the utility through the interface converter. Distributed generation connected to the AC subgrid

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is responsible for generating fixed active/reactive power or varying its value by a small amount around some fixed points to provide voltage support and other ancillary services. Distributed generation connected to the DC subgrid will generate active power following maximum power point tracking (MPPT) in case of renewable energy or can be placed on standby mode for later use in case of dispatchable distributed generation. Considering these constraints, the grid-connected hybrid AC/DC microgrid can be described by the following power balance equations:

$$P_{IC} = \sum_{i \in N_{DG,DC}} P_{DC,i}^{Gen} - \sum_{i \in M_{Load,DC}} P_{DC,i}^{Load} \tag{1}$$

$$P_{grid} = \sum_{j \in L_{DG,AC}} P_{AC,j}^{Gen} + P_{IC} - \sum_{i \in M_{Load,DC}} P_{DC,i}^{Load} \tag{2}$$

where P_{IC} is the active power flow through the interface converter; P_{grid} is the power flow between the grid and the microgrid; $P_{DC,i}^{Gen}$ and $P_{DC,i}^{Load}$ are the power generation and load at the *i*-th node in the DC subgrid, respectively; $P_{AC,j}^{Gen}$ is the power generation at the *j*-th node in the AC subgrid; $N_{DG,DC}$ and $L_{DG,AC}$ are the total number of distributed generation units in the DC and AC subgrids, respectively; and $M_{Load,DC}$ is the total number of loads in the DC subgrid.

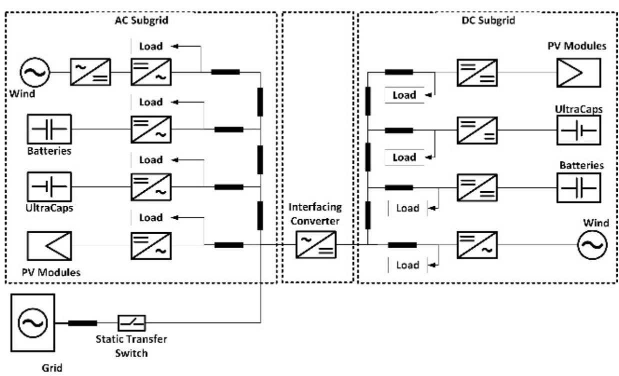

Fig. 1. Structure of the AC/DC hybrid microgrid

B. Islanded Mode of Operation for Hybrid Microgrid

Controlling a hybrid microgrid in islanded mode is more critical because the entire load of the hybrid microgrid system is shared by distributed generation on both sides of the subgrid autonomously while keeping the voltage and frequency within acceptable limits. A DCC-based control strategy for the interface converter used to control the power management of the hybrid microgrid shown in Fig. 1 is presented here. To fully comprehend the operating conditions that can occur in a hybrid microgrid in islanded mode of operation, the following states in terms of the interface converter power flow management are identified:

1. *Fixed Scheduled Power through Interface Converter*

During light load conditions, the power demand in each subgrid is less than the generation capacity of individual subgrids. Distributed generation in the AC subgrid will regulate its own voltage and frequency and will supply its own load, whereas distributed generation in the DC subgrid will supply the DC loads and maintain an acceptable voltage level in the DC subgrid. Under this circumstance, the power flow through the interface converter will be a fixed scheduled power, P_{IC}^{sch}; the value of P_{IC}^{sch} may be determined by the operators of the subgrids to reduce operational costs. This scenario can be described by (3)–(5):

$$P_{IC} = P_{IC}^{sch}, P_{grid} = 0 \tag{3}$$

$$\sum_{j \in N_{DG,DC}} P_{DC,j}^{Gen} \geq \sum_{i \in M_{Load,DC}} P_{DC,i}^{Load} \tag{4}$$

$$\sum_{j \in L_{DG,AC}} P_{AC,i}^{Gen} \geq \sum_{i \in K_{Load,AC}} P_{AC,j}^{Load} \tag{5}$$

where $P_{AC,j}^{Load}$ is the load at the *j*-th node in the AC subgrid, and $K_{Load,AC}$ is the total number of loads in the AC subgrid.

2. *Power Balance in the Subgrids through the Interface Converter*

This situation will occur when there is a power surplus in one subgrid and the other subgrid has a power deficit. To serve all the loads without power interruption, the subgrid with the power surplus should export power to the power deficit subgrid through the interface converter. The interface converter will play a crucial role in maintaining the stability of the subgrid that is receiving power. There are number of ways to share power in this situation, but if the total load in the hybrid microgrid is divided among all distributed generation units according to their power ratings on both sides of the subgrid, none will be overstressed. Therefore, the power flow management algorithm for the interface converter will try to match the normalized power of all the distributed generation in both subgrids to the same per-unit power. This situation is mathematically presented by (6)–(9):

$$P_{grid} = 0 \tag{6}$$

$$P_{IC} = \sum_{i \in N_{DG,DC}} P_{DC,i}^{Gen} - \sum_{i \in L_{DG,AC}} P_{AC,i}^{Gen} - \sum_{i \in M_{Load,DC}} P_{DC,i}^{Load} + \sum_{i \in K_{Load,AC}} P_{AC,i}^{Load} \tag{7}$$

$$P_{DC,1}^{Gen,p.u} = P_{DC,2}^{Gen,p.u} = \cdots = P_{DC,N_{DG,DC}}^{Gen,p.u} = P_{AC,1}^{Gen,p.u} = P_{AC,2}^{Gen,p.u} = \cdots = P_{AC,L_{DG,AC}}^{Gen,p.u} \tag{8}$$

$$P_n^{Gen,p.u} = \frac{P_n^{Gen}}{P_n^{Gen,rated}} \tag{9}$$

where $P_n^{Gen,p.u}$ and P_n^{Gen} are the power generation at the n-th node in any of the AC or DC subgrids in per unit and in watt, respectively; and $P_n^{Gen,rated}$ is the power rating of the distributed generation at the n-th node in watt.

3. *Load Shedding*

In islanded mode of operation, when the total load demand in the hybrid microgrid is greater than the combined capacity of the distributed generation in both subgrids, there is no way to serve all the loads. In this scenario, there must be some load-shedding scheme to serve the critical loads by curtailing less

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important loads in the microgrid. Equation (10) describes this situation:

$$\sum_{i\in N_{DG,DC}} P_{DC,i}^{Gen} + \sum_{i\in L_{DG,AC}} P_{AC,i}^{Gen} < \sum_{i\in M_{Load,DC}} P_{DC,i}^{Load} + \sum_{i\in K_{Load,AC}} P_{AC,i}^{Load} \tag{10}$$

III. PROPOSED DCC FOR HYBRID AC/DC MICROGRID

Controlling the individual AC and DC microgrids using the DCC is presented in [11], [12]. Making the operation of the hybrid microgrid smooth requires not only a power control strategy inside each subgrid but also the power management strategy through the interface converter. The power management of the interface converter is different than the power control strategy of the individual microgrids because the interface converter is required to provide bidirectional power flow between the AC and DC subgrids. This situation can be addressed by a communications graph for the interface converter, transferring adequate information to the DCC controller of the interface converter. The DCC should be able to handle the scenarios that arise in the operation of the hybrid microgrid, as discussed in the previous section. Keeping these conditions in mind, the following communications graph and DCC for interface converter power management is proposed. The communications graph developed for the DCC of a hybrid AC/DC microgrid is presented in Fig. 2. This graph contains all the characteristics that were required for the DCC of individual AC and DC microgrids. For the case of a hybrid AC/DC microgrid, in addition to the communications graphs for individual subgrids, the interface converter gets information from the AC and DC subgrids to implement the DCC for power management. Information shared by the AC and DC subgrids with the interface converter is depicted in Fig. 2. The interface converter does not exchange information about the reactive power because the AC and DC subgrids do not share any reactive power.

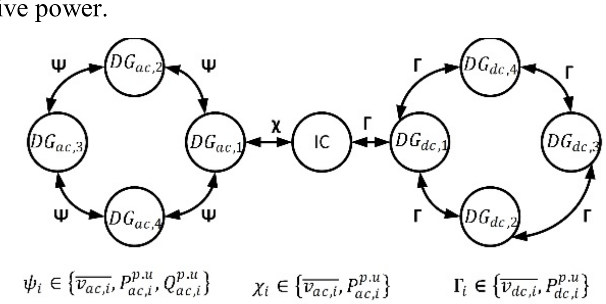

Fig. 2. Communication graph for DCC of hybrid AC/DC microgrid

The first two cases in islanded mode of operation (fixed scheduled power through the interface converter and power balance in the subgrids through the interface converter) require power management control for the interface converter, but the third case (load shedding) does not require any power management for the interface converter because there is not enough generation in either subgrid to meet the load of the hybrid microgrid. For the first two cases, power could flow either to the DC subgrid or to the AC subgrid through the interface converter. When power Is flowing to the DC subgrid, the DCC controls the DC-side voltage of the interface converter to achieve the objectives of power sharing and voltage regulation. The reference output voltage of the interface converter, v_{DC}^{IC*}, is calculated by (11):

$$v_{DC}^{IC*} = V_{rated} + \Delta v_1^{IC} + \Delta v_2^{IC} \tag{11}$$

where V_{rated} is the rated voltage of the DC side of the interface converter. Two correction factors (Δv_1^{IC} and Δv_2^{IC}) are added to the rated voltage level for the interface converter. The first correction factor regulates the DC-side voltage of the interface converter by estimating the average voltage of all nodes of the DC subgrid. It calculates the average voltage by taking the estimated average DC subgrid voltage from the distributed generation in the DC subgrid that are connected to the interface converter by the communications graph [11]. The average voltage is then estimated by (12):

$$\overline{V_{IC}} = V_{IC} + \sum_{j\in N_{DC}} a_j\left(\overline{V_j} - \overline{V_{IC}}\right) \tag{12}$$

where a_j is the edge of the communications graph connecting the interface converter with other distributed generation; V_{IC} is the output voltage of the interface converter; and $\overline{V_{IC}}$, $\overline{V_j}$ are the estimated average voltage at the IC and the neighboring distributed generations in the DC subgrid, respectively. The difference between $\overline{V_{IC}}$ and V_{rated} is then passed through a PI controller to get the first correction factor (Δv_1^{IC}) of (11).

The second correction factor (Δv_2^{IC}) in (11) is responsible for maintaining the scheduled power through the interface converter or maintaining the same per-unit power sharing by all distributed generation in the hybrid microgrid. When the interface converter is maintaining a fixed scheduled power, the difference between the actual delivered power and scheduled power is passed through a PI controller to obtain the second correction factor. The DCC in each individual subgrid ensures that the distributed generation is sharing the same per-unit power in their respective subgrids [12]. This realization is exploited when the interface converter is maintaining the same per-unit power for all distributed generation in the hybrid microgrid. The difference between the per-unit power in DC subgrid and the AC subgrid is processed by a PI controller to obtain the second correction factor. Because of this correction factor, a small deviation in the interface converter output voltage from the rated value is observed, but this deviation is necessary to achieve the stated objectives. The update protocol for the second correction factor is illustrated in Fig. 3.

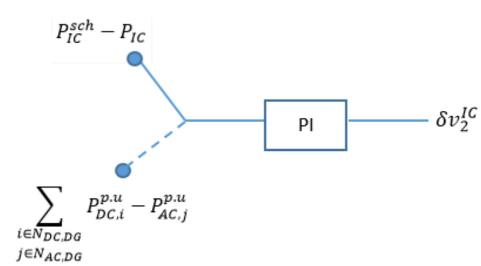

Fig. 3. Calculation of second correction factor

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When the IC is injecting power from the DC subgrid to the AC subgrid, the reference frequency, ω^*, is updated according to (13) to achieve the objectives for power management through the interface converter:

$$\omega^* = \omega_{rated} + \delta\omega_1^{IC} + \delta\omega_2^{IC} \quad (13)$$

where ω_{rated} is the rated frequency of the AC subgrid. Similar to the previous case, two correction factors ($\Delta\omega_1^{IC}$ and $\Delta\omega_2^{IC}$) are added to the rated frequency. The first correction factor, $\Delta\omega_1^{IC}$, regulates the frequency of the AC subgrid, and the second correction factor regulates the power flow through the interface converter. The correction factors in (13) can be calculated similarly to those in (11).

IV. Simulation Results

To validate the proposed method, an AC/DC hybrid microgrid like the microgrid system depicted in Fig. 1 was simulated in MATLAB/Simulink. The pictured hybrid microgrid system has one AC subgrid and one DC subgrid, and the subgrids are connected to each other through an interface converter. Each subgrid contains four distributed generation units and local loads. The subgrids are controlled by distributed control [11], [12], whereas the power management through the interface converter was done by the proposed DCC method. The following two case studies were considered to validate the proposed method:

Case 1

The hybrid AC/DC microgrid is assumed to be operating with the condition that a fixed scheduled power should flow through the interface converter. Fig. 4 shows the performance of the proposed method. Initially, the AC/DC hybrid microgrid was running with DCC controlling the power flow through the interface converter. At t = 1.5 s, the DCC for the IC was employed. A fixed 80 W of power was scheduled to flow through the interface converter from the AC subgrid to the DC subgrid. Fig. 4 (a) shows that the power through the interface converter changes to a fixed 80 W at t = 1.5 s without any severe transient. The power delivered by the distributed generation in the DC subgrid changes, Fig. 4 (b), because the DC subgrid is receiving extra power from the AC subgrid. The voltage profile of the DC subgrid remains at an acceptable limit, which is evident from Fig. 4 (b). The power delivered by the distributed generation at the AC subgrid also changes to generate this extra 80 W of power. At t = 4.1 s, an extra 200-W load was added in the DC subgrid to evaluate the dynamic performance of the controller. From the curves in Fig. 4 (a) and Fig. 4 (c), it is clear that although there is an increase in the DC load, the power flow through the interface converter does not change and the AC subgrid does not have any impact from the DC subgrid load change. The high transient response in the AC side distributed generator outputs, at t = 1.5 s, is caused by the change of control method of interfacing controller from non-DCC to DCC. Once the DCC control is active, the transient response does not show high magnitude of over-shoot when the operating condition of the AC/DC microgrid changes due to load or generation change.

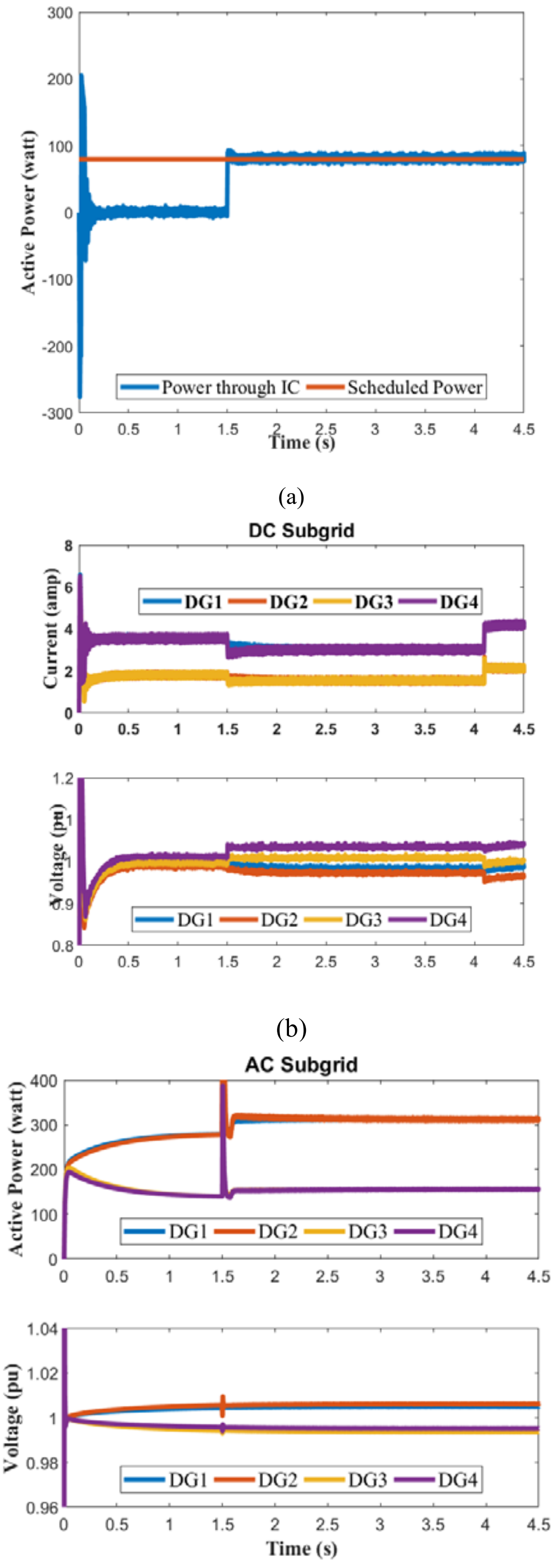

Fig. 4. Performance of the controller under the condition of fixed scheduled power through the interface converter: a) power flow through interface converter, b) power generation by distributed generation in the DC microgrid and their node voltages, C) power generation by distributed generation in the AC microgrid

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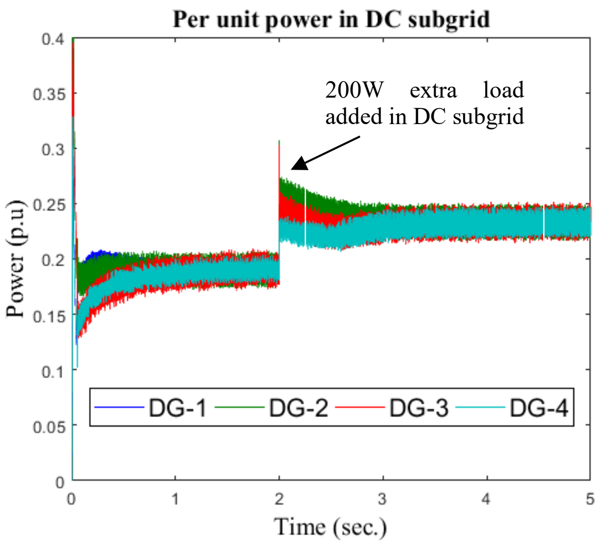
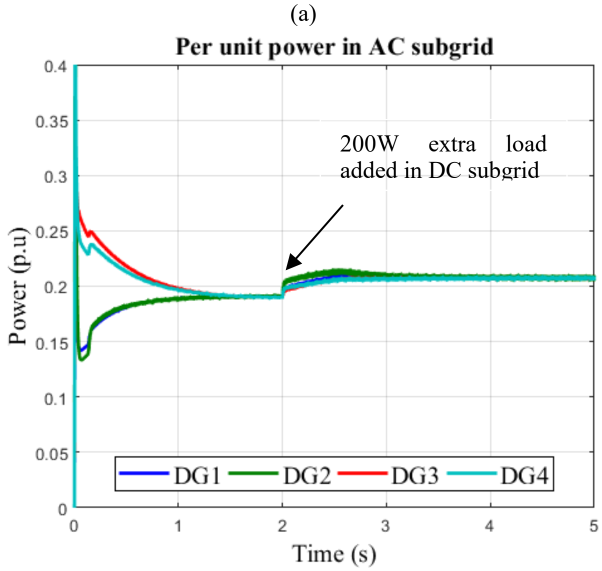
Case 2

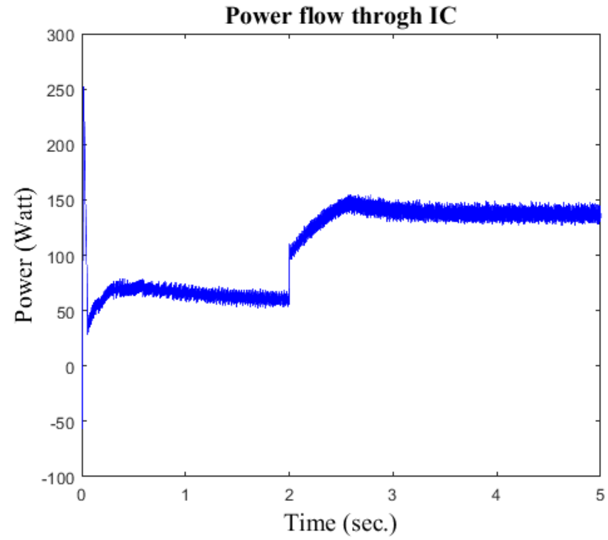
This case simulates the scenario where all the distributed generation units in the hybrid AC/DC microgrid share power according to their ratings. The distributed generation in the AC subgrid and DC subgrid have different ratings, and the subgrids were loaded with different local loads. Fig. 5 (a) shows the per-unit power delivered by the distributed generation connected at the DC subgrid, and Fig. 5 (b) shows the per-unit power delivered by the distributed generation connected to the AC subgrid. From these figures, it is clear that the distributed generation units are sharing the same per-unit power irrespective of their location. At t = 2 s, an extra 200 W of load was added in the DC subgrid to verify the performance of the controller. The curves show that the increased load was equally shared by all the distributed generation. Fig. 5 (c) shows the power flow through the interface converter under a varying load when the distributed generation units were sharing power proportional to their ratings.



(a)



(b)



(c)

Fig. 5. Performance of the controller to share the load among the distributed generation units in a hybrid microgrid according to the power rating: a) per-unit power of the distributed generation in the DC subgrid, b) per-unit power of the distributed generation in the AC subgrid, and c) power flow through the interface converter.

V. Conclusion

This paper presented a distributed cooperative control scheme for an AC/DC hybrid microgrid. The proposed algorithm for a hybrid AC/DC microgrid controls the power flow through the interfacing converter between the AC and DC subgrids. The control algorithm uses limited information exchanged with some of the distributed generation in both the AC and DC subgrids to achieve the control objectives, i.e., scheduled power flow through the interface converter or load sharing by the distributed generation units accruing to their ratings. The simulation results show that the proposed DCC enables control of the power flow through the interface converter in different modes of operation at different operating conditions while maintaining good voltage regulation in both subgrids and an improved frequency profile in the AC subgrid.

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