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# Power Oscillations Damping in DC Microgrids

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**Abstract**—This paper proposes a new control strategy for damping of power oscillations in a multi-source dc microgrid. A parallel combination of a fuel cell (FC), a photovoltaic (PV) system and a supercapacitor (SC) are used as a hybrid power conversion system (HPCS). The SC compensates for the slow transient response of the FC stack. The HPCS controller comprises a multi-loop voltage controller and a virtual impedance loop for power management. The virtual impedance loop uses a dynamic droop gain to actively damp the low-frequency oscillations of the power sharing control unit. The gain of virtual impedance loop is determined using small signal analysis and pole placement method. The Mesh analysis is employed to further study the stability of low-frequency modes of the overall dc microgrid. Moreover, based on the guardian map theorem, a robust stability analysis is carried out to determine a robustness margin for the closed-loop system. The main advantage of the proposed method is its robustness against uncertainties imposed by microgrid parameters. This feature provides DG units with plug-and-play capability without needing the exact values of microgrid parameters. The performance of the proposed control scheme is verified using hardware-in-the-loop (HIL) simulations carried out in OPAL-RT technologies.

**Index Terms**—DC microgrid, droop control, dynamic response, small signal analysis, virtual impedance loop.

## I. INTRODUCTION

Existing passive electrical distribution systems are experiencing a compelling transition to active distribution networks with the ability of bidirectional electricity power exchange between the distribution systems and the main utility. This transition has been basically initiated by the employment of small scale distribution generation (DG) units and is being further facilitated by the advent of microgrids. Microgrids are the entities involving a number of DGs, energy storage systems (ESS) and loads that are electrically interconnected. This architecture has the capability to operate either as a grid-connected or as an islanded system, and offers a promising solution for coordinated control of an aggregation of DG units. A microgrid also helps with the efficient and reliable operation of the electrical networks, while improving the quality of service [1]–[3].

Generally, microgrids are categorized as ac, dc and hybrid ac-dc microgrids each providing particular benefits to the loads and the electrical network. AC microgrids have drawn an extensive attention on various aspects including interfacing converters, power sharing among parallel sources and power

quality issues [4]–[6]. Despite their complex control topologies, ac microgrids are still popular since the existing power system is ac in nature.

The considerable amount of dc power generated by renewable energy sources, e.g., photovoltaic systems, fuel cells, and wind turbine systems, along with the rapid growth of dc loads are among the main driving factors for the development of dc microgrids. Moreover, dc microgrids require structurally simple power electronic interfaces and provide more efficient energy conversion systems as compared to the ac microgrids. The dc microgrids are also easier to control as they do not need any frequency and reactive power regulations. The dc converters can efficiently operate in parallel connection mode. Thus, the dc microgrids offer more modular and scalable system, and are more flexible to expand [7]–[10].

Despite their advantages, there are several technical challenges associated with the use of both ac and dc microgrids. Robust stability and dynamic performance of microgrid systems in both grid-connected and islanded mode of operation are among main technical challenges [11]–[13]. In the islanded mode, the control strategy has a more complicated structure as it must cope with voltage stability and power management among the DGs. Nevertheless, the DGs and ESSs must guarantee robust stability of the microgrid. The stability margin and the dynamic behavior of converter-based DG units in a dc system basically differ from those of conventional ac systems. Thus, further researches are required to overcome the challenges of dc microgrids [14], [15]. It should be noted that an appropriate coordinated power management among the hybrid energy resources in dc microgrids will maximize the microgrid robust stability margin.

Constant-power loads reduce voltage stability margin of dc microgrids, introduce significant oscillations, and even result in instability [16]. To overcome the instability issues caused by constant-power loads in dc distribution systems, various techniques have been proposed in the literature [17]–[19]. In particular, load shedding [20], filtering [21], direct connection of energy storage to the main bus [22], and control approaches [18] are among the well-known methods. The existing methods, however, do not investigate low-frequency instabilities (i.e., low-frequency power oscillations) in dc microgrids, imposed by power sharing control loops.

Virtual impedance loops are augmented to the control systems of inverters (mainly used in ac microgrids and UPS systems) for soft-starting of voltage source inverters [23], increasing the accuracy of real and reactive power sharing in microgrids [24], compensating voltage imbalance in islanded ac microgrids [25], and sharing harmonic and oscillatory currents in islanded microgrids [5], [26].

This paper presents a detailed modeling and control design

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as well as an accurate robust stability analysis for HPCSs used by residential dc microgrids. The proposed control strategy employs an inductive virtual impedance loop to effectively damp the low-frequency power/current oscillations. The frequencies of the oscillations are usually lower than 300 rad/s (50 Hz) depending on the parameters of dc microgrid. The damping factor and frequency of oscillations are obtained using Mesh analysis approach. The overall dc microgrid is controlled based on a decentralized control strategy, i.e., each HPCS is individually controlled by a multi-functional control scheme. The SC energy storage systems are used to improve the transient response of the fuel cell (FC) stack and the PV modules. The proposed HPCS controller consists of a multi-loop voltage controller for regulating the microgrid voltage, and a virtual impedance loop for power management. The virtual inductive impedance loop (dynamic droop gain) improves the dynamic performance of the power sharing control unit. In this paper, using the guardian map theorem [27], a robust stability analysis is also performed to determine a robustness margin for the uncertain parameters due to the loads and lines. Finally, the performance of the dc microgrid is evaluated using hardware-in-the-loop (HIL) simulations carried out in OPAL-RT technologies. The HIL results confirm that the proposed control strategy effectively damps the low-frequency power oscillations, and properly performs power management among the energy sources and the storage units.

## II. OPERATION PRINCIPLES OF PROPOSED CONTROL STRATEGY

The study system of this paper is a residential dc microgrid with the nominal voltage of 48 V, which is a standard value for these types of dc grids. Fig. 1 represents the general structure of a typical hybrid FC/PV/SC unit used to provide an almost constant dc-bus voltage for residential dc microgrids. The FC stack and the SC module are, respectively, connected to the dc microgrid through a unidirectional and a bidirectional dc/dc converter. The SC, as a fast and short term discharge ESS, plays an effective role for proper functionality of its corresponding DG unit in terms of power quality and reliability, particularly for the sensitive loads. The dc/dc converters are used to regulate the output voltage of each DG unit at the desired dc-link value, while providing a smooth output current. In this paper, we have used the exact models of FC and SC sources whose detailed descriptions are given in [28]. A PV system operating under maximum power point tracking (MPPT) conditions helps to minimize the fuel consumption of the FC module.

Fig. 2 shows the overall structure of the residential dc microgrid comprising four DGs, as labeled by DG<sub>1</sub>, DG<sub>2</sub>, DG<sub>3</sub> and DG<sub>4</sub>. The first two units consist of an FC module working in parallel with an SC and a PV system. DG<sub>3</sub> is composed of an FC module equipped with an SC module, while DG<sub>4</sub> is a single PV system. The parameters of dc microgrid including the real powers, the line resistances and the parameters of the DG units are summarized in Table I.

The main objectives of the HPCS control system are as follows; (i) voltage control of the dc microgrid, (ii) power

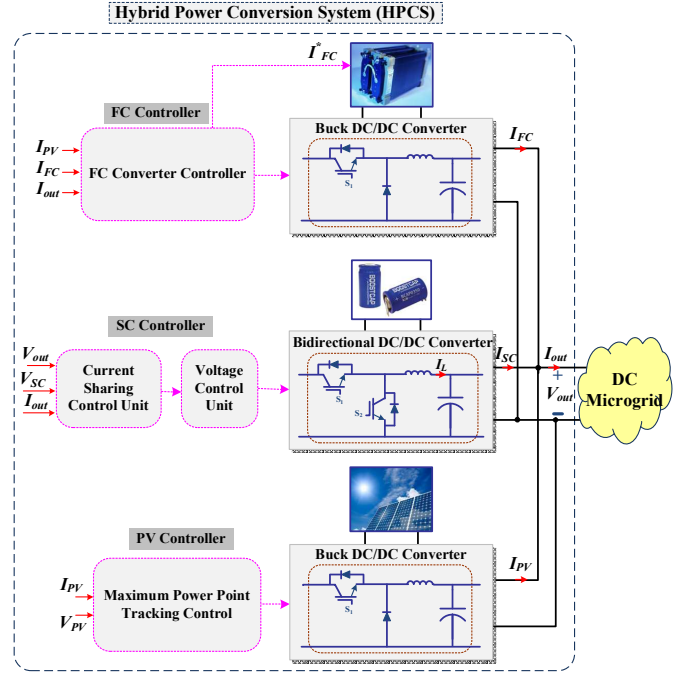


Fig. 1. General structure of an HPCS.

TABLE I  
DC MICROGRID PARAMETERS

Parameter	Representation	Value
$P_{base}$	Base power	10 kW
$P_{IC}$	Interlink converter power	10 kW
$V_{base}$	DC microgrid voltage	48 V
HPCS Parameters		
$P_{FC1}, P_{PV1}, P_{SC1}$	Rated power of DG <sub>1</sub>	2, 0.6, 2.2 kW
$P_{FC2}, P_{PV2}, P_{SC2}$	Rated power of DG <sub>2</sub>	1, 0.8, 1.1 kW
$P_{FC3}, P_{SC3}$	Rated power of DG <sub>3</sub>	0.5, 0.55 kW
$P_{PV4}$	Rated power of DG <sub>4</sub>	0.8 kW
$V_{PV}$	MPPT voltage	70-150 V
$V_{FC}$	FC rated voltage	80 V
$V_{SC}$	SC rated voltage	55-65 V
$f_{sw}$	Switching frequency	25 kHz
$L_f$	SC inductor	2.5 mH
$R_f$	SC inductor resistance	0.01 $\Omega$
$C_f$	SC converter capacitor	47 $\mu$ F
Lines Parameters		
$R_{L1}, R_{L2}, R_{L3}$	Lines resistance	5, 15, 1 (m $\Omega$ )
$R_{L4}, R_{L5}, R_{L6}$	Lines resistance	1, 2, 1 (m $\Omega$ )
$L_{L1}, L_{L2}, L_{L3}$	Lines inductance	1, 3, 0.2 ( $\mu$ H)
$L_{L4}, L_{L5}, L_{L6}$	Lines inductance	0.2, 0.4, 0.4 ( $\mu$ H)

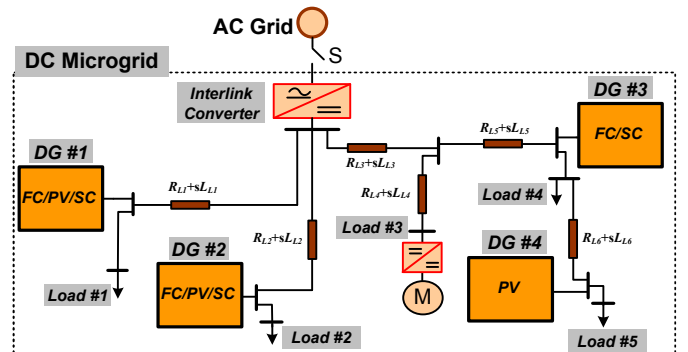


Fig. 2. Schematic diagram of DC microgrid consisting of four DG units.



cutoff frequency ( $f_c$ ) of 5 Hz is incorporated to the current sharing unit, as shown in Fig. 3. In other words, the use of LPF provides the voltage control loop with a ripple-free reference signal ( $V^*$ ), which in turn results in a high quality voltage regulation. The high-frequency oscillations (ripples) imposed to the DG output currents are due to the switching ripples of the converter, power electronic-based loads, or even the oscillatory currents produced by some types of dc loads [26]. The cutoff frequency of the LPF is determined to eliminate the imposed ripples. It will be shown that the value of  $f_c$  has a significant effect on the low-frequency oscillations of DG output power. As shown in Fig. 3, the averaged current is then applied to the current sharing controller whose output is the reference signal of the voltage control loop. To achieve active damping of the low-frequency oscillations of DG output power, the following V-I droop function is proposed:

$$V^*(s) = V_0(s) - (R_D + sL_D)I_{avg}(s), \quad (4)$$

where  $V_0(s)$  is the nominal voltage of the dc microgrid,  $R_D$  and  $L_D$  are the static and dynamic droop gains (i.e., virtual impedance loop gains), respectively, and  $I_{avg}(s)$  is the output of LPF. It should be noted that the conventional droop control strategy does not include any dynamic droop gain, i.e.,  $L_D$  is zero. The static droop gain ( $R_D$ ) is defined such that the output voltage of the converter ( $V_{out}$ ) will not exceed the permissible voltage variations when the maximum power is transferred by the converter.

Using the small signal analysis, the value of  $L_D$  in (4) for each DG unit is determined such that an appropriate damping factor for low-frequency power sharing modes is achieved. The proposed dynamic term behaves as an inductive impedance which is implemented by a virtual impedance loop. To obtain  $L_D$ , first the characteristic equation of the current sharing unit will be derived. According to (1) and (4), the output voltage of the DG units can be calculated as:

$$V_{out}(s) = H(s)V_0(s) - Z_{s0}(s)I_{sc}(s) - [Z_{RD}(s) + Z_{LD}(s)]I_{out}(s), \quad (5)$$

where  $Z_{RD}(s)$  and  $Z_{LD}(s)$  denote the output impedances of the HCPS units and are obtained in terms of the static and dynamic droop gains as follows:

$$Z_{RD}(s) = \frac{\omega_c R_D}{s + \omega_c} H(s), \text{ and } Z_{LD}(s) = \frac{s\omega_c L_D}{s + \omega_c} H(s). \quad (6)$$

According to Fig. 1,  $I_{out}(s)$  in (5) is

$$I_{out}(s) = I_{sc}(s) + I_{pv}(s) + I_{FC}(s). \quad (7)$$

From (5) and (7), the model of the closed-loop hybrid DG unit is derived as shown in Fig. 5. In Fig. 5,  $H(s)V_0(s)$  and  $Z_{s0}(s)$  are the voltage source and the output impedance of the SC converter, respectively, and the FC and PV systems have been modeled by two parallel current sources characterized by low transient responses. Moreover, the local load of each DG is modeled by a parallel resistance  $R_{load}$ , Fig. 5. The line resistance and inductance are respectively denoted by  $R_{Line}$  and  $L_{Line}$  which are unknown parameters, i.e., they may vary about their nominal values.  $V_g(s)$  represents the Thevenin voltage of the rest parts of dc microgrid and its

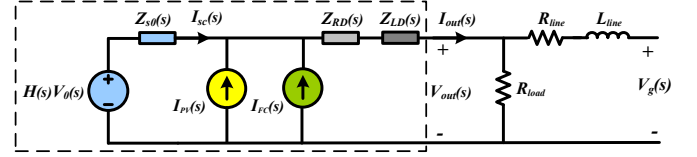


Fig. 5. Model of the closed-loop HPCS.

dynamic significantly depends on the dynamic behavior of the other DG units and line impedances. This will be detailed in the next subsection.

Based on Fig. 5, it can be concluded that

$$V_{out}(s) - V_g(s) = Z_{Line}(s)(I_{out}(s) - \frac{V_{out}(s)}{R_{load}}), \quad (8)$$

where  $Z_{Line}(s) = R_{Line} + sL_{Line}$ . The impact of the load resistance and line impedance on the low-frequency modes of the DG unit can be studied based on (5) and (8). Substituting (5) in (8) yields the output current of the DG as

$$I_{out}(s) = \frac{(R_{load} + Z_{Line}(s))[H(s)V_0(s) + Z_{s0}(s)(I_{PV}(s) + I_{FC}(s))] - R_{load}V_g(s)}{R_{load}(Z_{Line}(s) + Z_{out}(s)) + Z_{out}(s)Z_{Line}(s)}, \quad (9)$$

where  $Z_{out}(s) = Z_{s0}(s) + Z_{RD}(s) + Z_{LD}(s)$ . The denominator of (9) is the characteristic equation of the DG closed-loop system. Further, substituting (6) in (9) yields

$$(R_{load} + Z_{Line}(s))[(s + \omega_c)Z_{s0}(s) + \omega_c H(s)(R_D + sL_D)] + R_{load}(s + \omega_c)Z_{Line}(s) = 0. \quad (10)$$

From (10), it can be concluded that the eigen-participation analysis of the DG system depends on the parameters of converters and controllers, line impedance, and load. In the first step of the analysis, DG<sub>1</sub> with  $R_{D1} = 0.057 \Omega$  and  $L_{D1} = 0$  is considered. Fig. 6 shows the loci of the dominant low-frequency modes of DG<sub>1</sub> when the line resistance ( $R_{Line}$ ) increases from 0 to 0.1 pu,  $L_{Line} = 0$ , and  $R_{load} = 1.15 \Omega$ . As it is observed, DG<sub>1</sub> system is unstable for  $R_{Line} < 0.012$  pu. Moreover, the frequency of dominant low-frequency modes of DG<sub>1</sub> is between 110 to 150 rad/s (18 to 24 Hz) when the line resistance increases and, accordingly, the stability margin of the system improves. Theoretically, we can increase the line resistance to obtain an appropriate damping factor required for the stable operation of the microgrid. However, the increase of the line resistance is not always a practical solution as it increases the line losses and degrades the voltage profile. Moreover, it has a negative impact on the accuracy of the current sharing unit [7], [14]. Fig. 7 shows the impact of line inductance on the dynamic performance of dc microgrid for a specific line resistance (e.g.,  $R_{Line} = 0.0125$  pu). As observed, the system with a higher line inductance presents a better damping factor.

As already discussed, the dynamic droop gain ( $L_D$ ) is included to the current sharing controller to overcome the stability problem and to efficiently damp the low-frequency modes of the dc microgrid. The loci of the dominant low-frequency modes of DG<sub>1</sub>, DG<sub>2</sub> and DG<sub>3</sub> for different values of  $L_D$  are shown in Fig. 8 ( $R_{Line}$  is assumed to be zero for all DG units). The dynamic droop gain  $L_D$  associated with



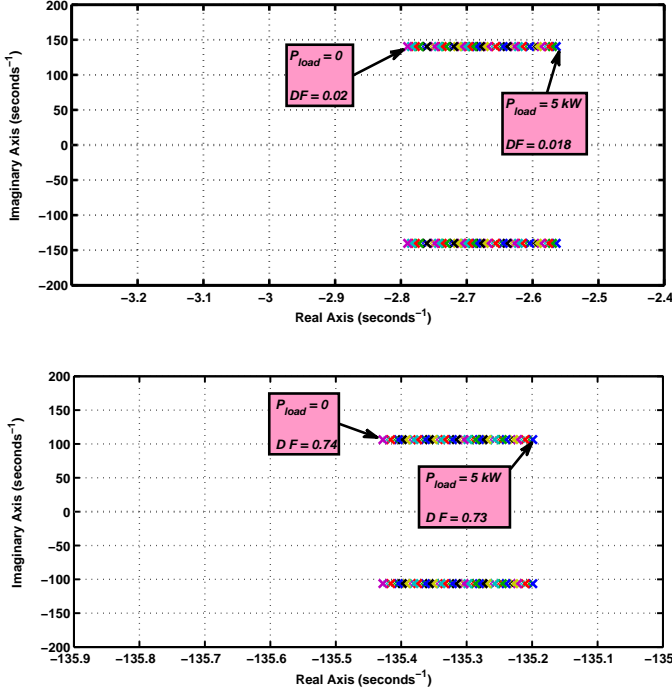


Fig. 10. Dominant low-frequency modes of DG<sub>1</sub> when the local load power increases from 0 to 5 kW, and  $R_{Line}=0.0125$  pu. (Top) conventional droop is in service. (Bottom) proposed control system is in service.

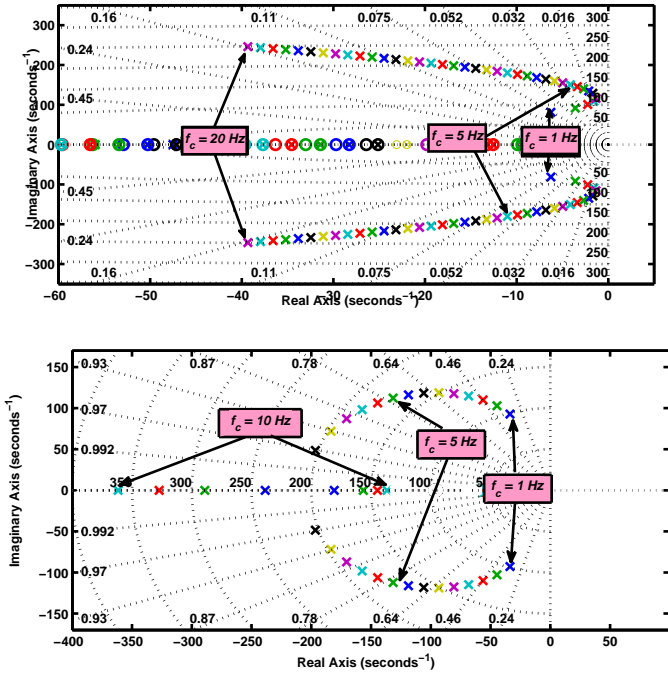


Fig. 11. Dominant low-frequency modes of DG<sub>1</sub> when  $f_c$  increases from 1 to 20 Hz, and  $R_{Line}=0.0125$  pu,  $P_{Load}=2$  kW. (Top) conventional droop is in service. (Bottom) proposed control system is in service.

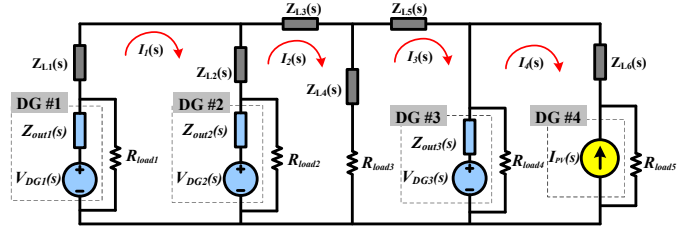


Fig. 12. The circuit model of the overall dc microgrid for mesh analysis.

The characteristic equation of a circuit is the determinant of its mesh impedance matrix. The mesh impedance matrix of Fig. 12 is denoted by  $Z_{MG}(s)$  and can be expressed as:

$$Z_{MG}(s) = \begin{bmatrix} Z_{MG11}(s) & Z_{MG12}(s) & Z_{MG13}(s) & Z_{MG14}(s) \\ Z_{MG21}(s) & Z_{MG22}(s) & Z_{MG23}(s) & Z_{MG24}(s) \\ Z_{MG31}(s) & Z_{MG32}(s) & Z_{MG33}(s) & Z_{MG34}(s) \\ Z_{MG41}(s) & Z_{MG42}(s) & Z_{MG43}(s) & Z_{MG44}(s) \end{bmatrix}, \quad (11)$$

where

$$\begin{aligned} Z_{MG11}(s) &= Z_{out1}(s) \parallel R_{load1} + Z_{out2}(s) \parallel R_{load2} \\ &+ Z_{L1}(s) + Z_{L2}(s), \\ Z_{MG12}(s) &= Z_{MG21}(s) = -[Z_{out2}(s) \parallel R_{load2} + Z_{L2}(s)], \\ Z_{MG13}(s) &= Z_{MG31}(s) = Z_{MG14}(s) = Z_{MG41}(s) = 0, \\ Z_{MG22}(s) &= Z_{out2}(s) \parallel R_{load2} + Z_{L2}(s) + Z_{L3}(s) \\ &+ Z_{L4}(s) + R_{load3}, \\ Z_{MG23}(s) &= Z_{MG32}(s) = -[Z_{L4}(s) + R_{load3}], \\ Z_{MG24}(s) &= Z_{MG42}(s) = 0, \\ Z_{MG33}(s) &= Z_{out3}(s) \parallel R_{load4} + Z_{L4}(s) + Z_{L5}(s) + R_{load3}, \\ Z_{MG34}(s) &= Z_{MG43}(s) = -[Z_{out3}(s) \parallel R_{load4}], \text{ and} \\ Z_{MG44}(s) &= Z_{out3}(s) \parallel R_{load4} + Z_{L6}(s) + R_{load5}. \end{aligned} \quad (12)$$

Fig. 13 shows the dominant low-frequency modes of the dc microgrid for both cases of the conventional droop and the proposed control system. As it is observed, the damping factor of the dominant low-frequency modes is 0.015 when the conventional droop method is in service, whereas it is 0.774 ( $DF=0.774$ ) when the proposed control system is used. It can be simply verified that the damping factor of the overall dc microgrid will be higher than 0.7 when the dynamic droop gain of each individual DG unit is adjusted such that its damping factor becomes 0.7. Fig. 13 also shows that the frequency of the dominant low-frequency modes is about 226 rad/s (36 Hz) when the DG units use the conventional droop controller. It is to be noted that the dominant low-frequency modes of the overall dc microgrid can not be determined by separately analyzing each single DG system.

### III. ROBUST STABILITY ANALYSIS

In this section, based on the guardian map theorem presented in [27], a robust stability analysis is carried out to

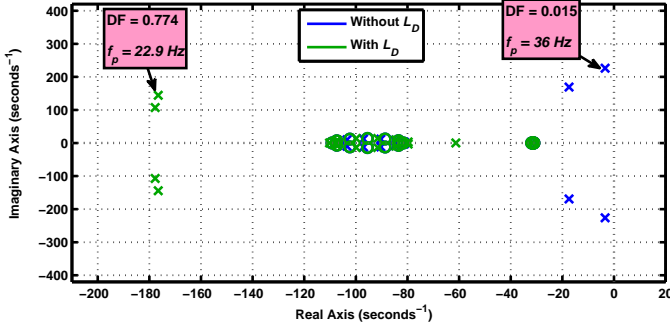


Fig. 13. Dominant low-frequency modes of dc microgrid with and without proposed control system.

obtain a robustness margin for the uncertain parameters of dc microgrid. The characteristic equation of the closed-loop DG system, i.e., (10), includes the load and line parameters which are uncertain. In particular, the line and the load resistances ( $R_{line}$  and  $R_{load}$ ) significantly vary about their nominal values, and thus affect robust stability and the dominant low-frequency modes of each closed-loop DG unit. On the other hand, the parameters of voltage controller, static droop gains, capacitor of buck converter,  $K_{PWM}$ , and LPF parameters are almost fixed or have very small variations. Therefore, we can assume that the parameters with small variations have no impact on the robust stability.

As discussed above, the two parameters  $R_{line}$  and  $R_{load}$  are the main sources of uncertainties in DG model. The robustness margin is a region in the space of parameters in which the closed-loop system remains stable. The guardian map is a powerful tool which accurately determines the robustness margin of an uncertain system. The main advantage of the guardian map is that it can be applied to any uncertain system irrespective of its structural complexity. A summary of guardian map is given in the following theorem and proposition [27].

**Theorem 1.** Let  $\mathcal{X}$  be the set of all polynomials with degree at most  $n$ , and let  $\mathcal{S}$  be an open subset of  $\mathcal{X}$ . Moreover, assume that  $\nu$  is a scalar valued function which maps  $\mathcal{X}$  into complex numbers  $\mathbb{C}$ . Then,  $\nu$  guards  $\mathcal{S}$  if

$$x \in \delta\mathcal{S} \Leftrightarrow \nu(x) = 0, \quad (13)$$

holds. In (13),  $\delta\mathcal{S}$  denotes the boundary of region  $\mathcal{S}$ .

This theorem and its subsequent statement can be used to tackle the robust stability problem of parameterized family of polynomials [27].

**Proposition 1.** Let  $\mathcal{S}$  be guarded by the map  $\nu$  and  $r = (r_1, r_2, \dots, r_k) \in U$  be the set of uncertain parameters. Moreover, assume that  $x(r^0) \in \mathcal{S}$  for some  $r^0 \in U$ . Then:

$$x(r) \in \mathcal{S} \forall r \in U \Leftrightarrow \nu(x(r)) \neq 0 \forall r \in U \quad (14)$$

The above statement shows that for an arbitrary set in the  $s$ -plane, there exists a function which guards that given set. For example, the determinant function  $\nu: A \rightarrow \det(A)$  guards the set of nonsingular matrices  $A_{n \times n}$ .

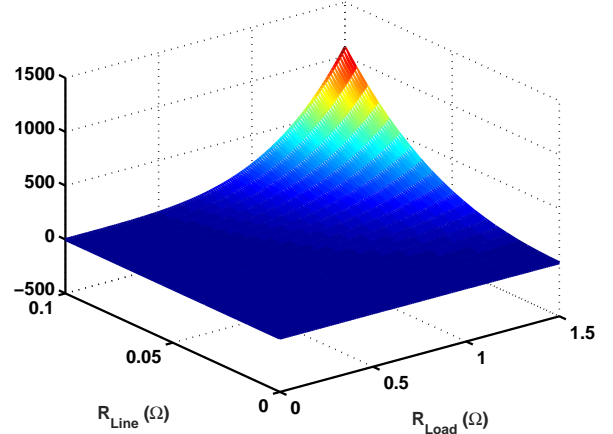


Fig. 14. Guardian map analysis for the closed-loop polynomial with respect to parameters  $R_{line}$  and  $R_{load}$  in 3D space.

The set of polynomials given by (15) is stable in sense of Hurwitz if it is guarded by the function  $\nu$  defined in (16), where  $H(p)$  is the Hurwitz matrix associated with the polynomial  $P(s)$  [30].

$$P(s) = a_n s^n + a_{n-1} s^{n-1} + \dots + a_0 \quad (15)$$

$$\nu: P \rightarrow \det(H(p)) \quad (16)$$

$$H(p) = \begin{pmatrix} a_{n-1} & a_{n-3} & a_{n-5} & \cdot & \cdot & \cdot & 0 \\ a_n & a_{n-2} & a_{n-4} & \cdot & \cdot & \cdot & \cdot \\ 0 & a_{n-1} & a_{n-3} & \cdot & \cdot & \cdot & \cdot \\ \cdot & a_n & a_{n-2} & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & 0 \\ \cdot & \cdot & \cdot & \cdot & a_3 & a_1 & 0 \\ 0 & 0 & \cdot & \cdot & \cdot & a_2 & a_0 \end{pmatrix}$$

To apply the guardian map theorem to the closed-loop DG system, its characteristic polynomial is computed using (10) and Fig. 3. The Hurwitz matrix associated with the characteristic polynomial is then obtained. The guardian map is calculated and graphically depicted in three dimensional space, as shown in Fig. 14.

In order to determine the robustness margin, intersection of the guardian map surface depicted in Fig.14 with  $\nu = 0$  ( $xy$ -plane) is obtained, as shown in Fig. 15. According to Fig. 15, the closed-loop DG system is robustly stable if the uncertain parameters  $R_{line}$  and  $R_{load}$  lie in the green region. Our simulation studies also confirm that the closed-loop DG system is robustly stable when the uncertain parameters are outside the red region.

#### IV. HARDWARE-IN-THE-LOOP SIMULATIONS

To demonstrate the effectiveness of the proposed control strategy, the microgrid system of Fig. 2 is simulated using HIL RT-Lab of OPAL-RT technology. The HIL simulations are advantageous since they tackle the time inefficiency of the off-line simulations, and provide us with the possibility to



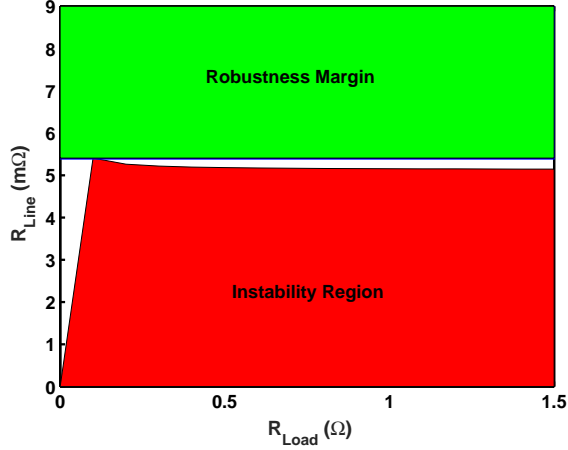


Fig. 15. Robustness margin (green region) of the closed-loop DG in  $R_{Load}$ - $R_{Line}$  plane.

make a sensitivity analysis on the system parameters. The dc microgrid is connected to the ac grid through an interlinking converter (IC). The power flow of the IC is zero indicating that the microgrid is in an islanded mode of operation. As discussed earlier, the dc microgrid contains four DG units whose building modules are described in Section II. DG<sub>1</sub>, DG<sub>2</sub> and DG<sub>3</sub> are considered as dispatchable DG units having the capability to contribute to the power management of the microgrid. DG<sub>4</sub> is a single PV system and is considered as a non-dispatchable source. In this study, the loads are considered as a constant-impedance load. Load #3 is a dc motor which is connected to the dc microgrid via a boost dc/dc converter.

All DG units are equipped with the proposed PI controllers to regulate their buses voltages, while the proposed current sharing control method is employed to improve the transient response of the microgrid. The microgrid parameters are given in Tables I and II. Several load switchings are considered to verify the dynamic performance of the proposed control strategy. More specifically, the high-impedance line refers to the case in which the resistance of the microgrid lines are ten times higher than those of the low-impedance lines listed in Table I. To further accentuate the efficiency of the proposed method, the real-time simulations are repeated for the conventional droop strategy, i.e., only with static droop gains ( $V^* = V_0 - R_D I_{avg}$ ).

Initially, it is assumed that the current through the dc loads #1, #2, #3, #4 and #5 are 11, 12, 1, 16 and 9 A, respectively. At  $t=12$  s, the load of dc motor (load #3) is suddenly increased such that its current becomes 58 A. Subsequent to this load change, at  $t=25$  s, loads #1 and #4 are disconnected from the dc microgrid. The instantaneous currents of the dc loads are shown in Fig. 16.

Figs. 17 (a) and (b) show the dynamic responses of the DG units to the first load change, i.e., stepwise load increase, when the conventional droop is used for both cases of low- and high-impedance lines, respectively. To compare the results of the small signal analysis with those of real-time simulation, the dominant low-frequency modes of the dc microgrid employing

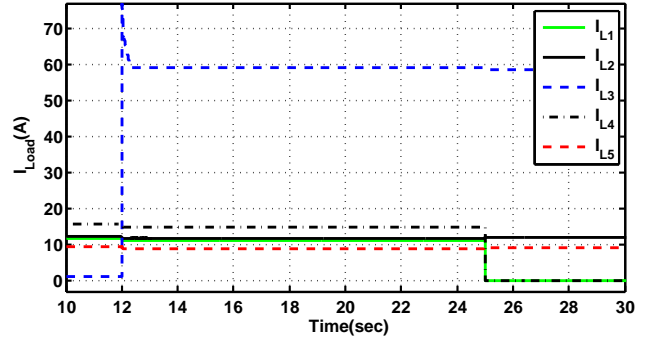


Fig. 16. Instantaneous currents of DC microgrid loads.

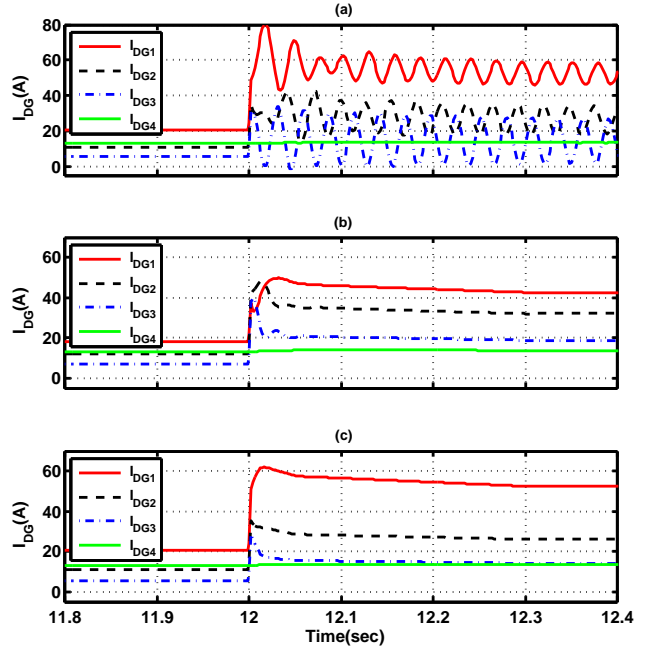


Fig. 17. Dynamic responses of DG units to the stepwise load increase at  $t=12$  s: DG units output currents in (a) microgrid with low-impedance line when the conventional droop is used, (b) microgrid with high-impedance line when the conventional droop is used, and (c) microgrid with low-impedance line when the proposed control system is used.

the conventional droop method, i.e.,  $L_D=0$ , for both low- and high-impedance lines are depicted in Fig. 18. As it is observed, the damping factor is 0.015 for the line with lower impedance, while it is 0.612 for dc microgrid with higher line impedance. Fig. 17 (a) shows that, for the case of low-impedance line with damping factor of 0.015, when the conventional droop strategy is adopted, the output currents of the dispatchable DG units experience significant oscillations with frequency of 36 Hz. This is due to the small damping factor of the dominant poles of the system with low-impedance lines. Fig. 18 also shows that the frequency of the oscillations of the dominant low-frequency modes for the microgrid with low-impedance line is about 36 Hz which matches with the simulation results, Fig. 17 (a).

For the same stepwise load increase, for the case of high-impedance lines, the current oscillations are considerably reduced which indicate the presence of a high damping factor,

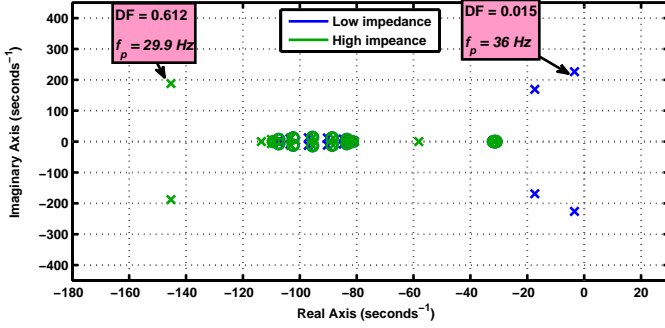


Fig. 18. Dominant low-frequency modes of dc microgrid employing conventional droop method, for both low- and high-impedance lines.

i.e., 0.612, as shown in Fig. 17 (b). Nevertheless, in the latter case, the current is not proportionally shared to the droop coefficients specified for each DG units, and the total loss is significantly increased. To overcome this problem, we resort to the proposed inductive virtual impedance loop that is expected to damp the low-frequency oscillations of the output current of the dispatchable DG units. This is confirmed for the case of the dc microgrid with low-impedance lines experiencing the same stepwise load increase (Fig. 17 (c)). As expected from the small signal analysis results of Fig. 13, the simulation results show that the proposed control strategy effectively damps ( $DF=0.774$ ) the low frequency power oscillations due to the changes in the load. It should be noted that DG<sub>4</sub> is nondispatchable and cannot contribute to the microgrid power sharing.

Similarly, for the second load change (stepwise load decrease), the dynamic response of the DG units when the conventional droop is used for microgrid characterized by both low and high-impedance lines are respectively shown in Figs. 19 (a) and (b). As observed, for the case of low-impedance line, when the conventional droop strategy is used, the output currents of the dispatchable DG units are oscillatory due to the small damping factor (0.015) of the dominant low-frequency modes of the system. However, for the same load step-down and for the case of high-impedance lines, the current oscillations are significantly damped due to the high damping factor characteristics of the lines ( $DF=0.612$ ). Nevertheless, the high damping factor does not merely guarantee the appropriate current sharing among the units as shown Fig. 19 (b). Moreover, the use of inductive virtual impedance loop can effectively damp the unwanted oscillations in the HPCS units' output currents, while providing an appropriate current sharing among the dispatchable units. To achieve this goal, each unit decreases its current by drifting its reference voltage according to its V-I droop curve. A comparison between Figs. 19 (a) and (c) reveals the acceptable steady-state performance for both control strategies.

To further evaluate the performance of the proposed control strategy, similar load step-up, for the case of low-impedance lines with and without proposed virtual inductive loop, are applied at  $t=12$  s. Fig. 20 shows the terminal voltage of DG<sub>1</sub>. The microgrid voltage is changed according to the droop characteristics of the DG units. A comparison between

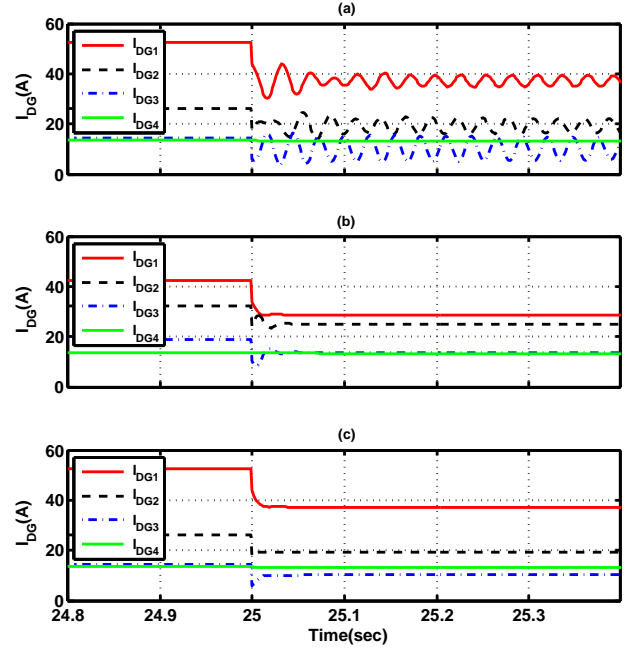


Fig. 19. Dynamic responses of DG units to the stepwise load decrease at  $t=25$  s: DG units output currents in ((a) microgrid with low-impedance line when the conventional droop is used, (b) microgrid with high-impedance line when the conventional droop is used, and (c) microgrid with low-impedance line when the proposed control system is used.

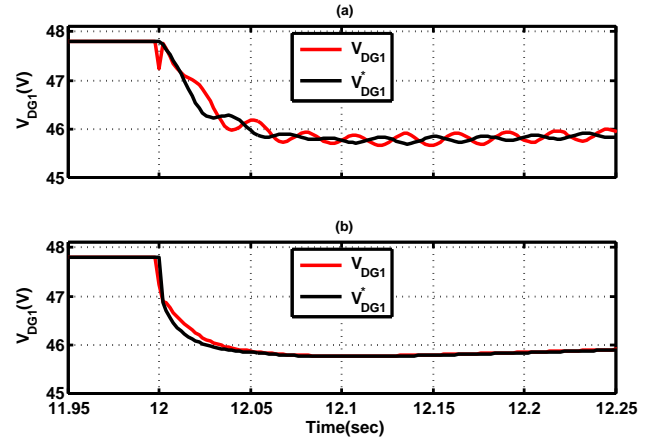


Fig. 20. Terminal voltage of DG<sub>1</sub> due to the stepwise load increase at  $t=12$  s for microgrid with low-impedance lines, (a) conventional droop strategy, (b) proposed strategy.

the voltage profiles at the terminals of DG<sub>1</sub> obtained for the conventional and the proposed control strategies reveals that the proposed strategy succeeds to considerably reduce the low-frequency oscillations of the voltage during transient conditions.

In the final set of real-time simulations, for the microgrid with low-impedance line, subsequent to the same stepwise load change, the dynamic response of the FC/PV/SC modules of the DG units is shown in Fig. 21. As it is observed, the output currents of the PV modules remain constant. In fact, the PV system of each individual DG unit only contributes to provide a portion of the base demanded load, while each

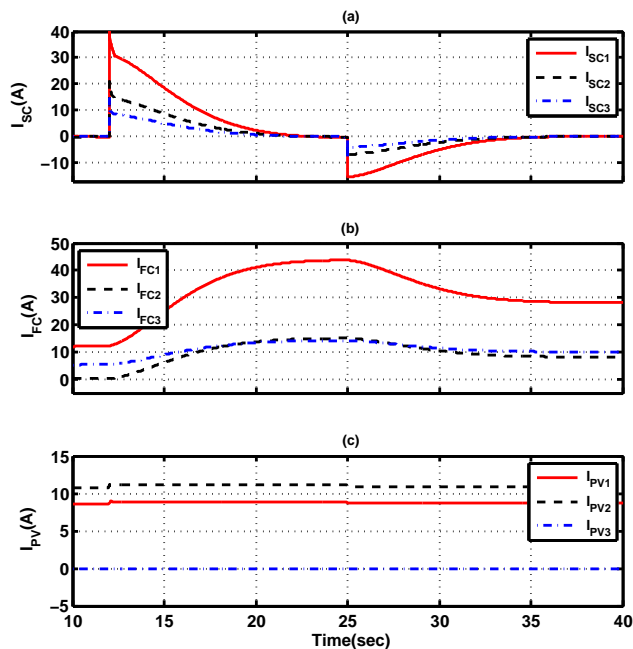


Fig. 21. Dynamic response of DG units to load changes: output current of (a) SC converters, (b) FC converters, and (c) PV converters of DG units.

DG unit participates in the power sharing according to the proposed current sharing strategy. To achieve this goal, at  $t=12$  s, the FC module of each DG unit increases its output power to follow the reference current produced by the FC current controller, while the SC module of each DG unit compensates the shortage between the power of the FC system and the demanded load power. The FC system increases its output power at a limited response rate. It is to be noted that the SC modules will be in standby state when the FC modules successfully provide the demanded load power. Alternatively, at  $t=25$  s when the microgrid is subjected to a load step down, the output current of the FC module converter is decreased to meet the new demanded load power. In this case, the surplus of the power generated by the FC modules is used to charge the SCs.

## V. CONCLUSION

This paper presents a new control strategy for an HPCS to improve the dynamic response of a dc microgrid. The proposed control system employs a multi-loop voltage control system to regulate the microgrid voltage, and a virtual impedance loop to carry out efficient power management. Moreover, a supercapacitor (SC) energy storage is used to compensate the slow transient response of the fuel cell (FC) stack. It is shown that the low-frequency modes of microgrid are mainly dictated by the power management controllers. To actively damp the low-frequency current sharing modes, a virtual inductive impedance loop is proposed. The inductive gain of the dc source is determined using small signal analysis and pole placement methods. The proposed control strategy can simply be applied to other types of dc/dc converters with different topologies (e.g., isolated and non-isolated). In this paper, based on the guardian map theorem, a robust stability

analysis is also carried out to determine the robustness margin for the uncertain parameters of microgrid. The performance of the proposed control strategy is evaluated against both stepwise load increase/decrease using HIL RT-Lab simulator of OPAL-RT technologies. The HIL simulation results reveal that the proposed strategy:

- enhances the dynamic response of the dc microgrid during fast transients,
- effectively eliminates the low-frequency power oscillations,
- robustly regulates the microgrid voltage, and
- provides an appropriate power management among the energy sources and the storage unit of an individual HPCS.

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