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Published in:
IEEE Transactions on Power Electronics

Link to article, DOI:
10.1109/TPEL.2020.3024716

Publication date:
2020

Document Version
Peer reviewed version

Link back to DTU Orbit

Citation (APA):

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Design of Passivity-based Damping Controller for Suppressing Power Oscillations in DC Microgrids

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Abstract—In this paper, a novel damping control scheme for V/I droop-controlled DC microgrids is proposed to attenuate the oscillatory components in the power and current. At first, the model of the DC microgrid is introduced providing stability analysis. Then, the damping controller is designed using the interconnection and damping assignment – passivity-based control (IDA-PBC) methodology. In addition, the gain selection technique for the IDA-PBC is developed. The proposed control scheme ensures that the oscillations of the output power and current are effectively attenuated. The validity of the proposed control algorithm has been verified by the results from both hardware-in-the-loop simulation (HILS) and prototype experiments.

Index Terms—DC microgrids, damping control, IDA-PBC, V/I droop.

I. INTRODUCTION

In recent years, the direct current (DC) power systems have attracted a lot of attention in the areas of power transmission and distribution including ships, aircrafts, buildings, data centers and so on since they have advantages of no reactive power, fewer power conversion steps, and higher power density [1]–[4].

The DC microgrid can operate in a grid-connected mode or a stand-alone mode. The power sources are comprised of diesel engines, gas turbines, photovoltaic, and wind power generation systems, fuel cells, and so on. Its power rating covers several kW or less to several hundreds of MW depending on the type of microgrids such as residential, educational, industrial, and commercial applications [5]. A structure of the typical DC microgrid is shown in Fig. 1.

In spite of these advantages, the DC power system has some issues to solve technically, such as stability, accurate sharing of the output power and current, etc. In the past, various research has been conducted [2]. Among them, the suppression of power and current oscillations due to the droop control of voltage-source converters (VSCs) has been studied a lot [6]–[12].

To attenuate the power and current oscillations, several damping control methods applied to the DC source side have been proposed [6]–[12]. At first, a low-pass filter (LPF) has been added in the droop control loop to achieve damping enhancement [6], [7]. In this method, the cut-off frequency of the LPF should be very low if the bandwidth (BW) of the voltage control loop is low. Also, the cut-off frequency of the LPF should be found appropriately for stable operation of the DC microgrid. In [8], a feed-forward control technique for the input voltage error has been proposed, which can be applied to the applications that include the variable DC sources. Furthermore, virtual impedance scheme has been proposed in [9], where the oscillatory components below the cut-off frequency of the feedback filter can be suppressed. In [10] and [11], the output current feedback scheme with an observer has been proposed, where the controller is relatively complex compared with other methods. Also, there are many controller gains which should be tuned at the different operating points. Meanwhile, in [12], a simple output current feedback control to compensate for the output of the voltage controller has been suggested with a proportional gain, which can suppress the oscillatory components effectively. However, there is a possibility that the behavior of the output of the DC source sensitively responds to the load disturbance since the output current is directly affected by the reference of the current controller where it usually requires the appropriate LPF.

Fig. 1. Typical DC microgrid.
conventional techniques aforementioned can suppress the oscillatory components effectively. However, the controller gains should be carefully tuned in order to achieve stable operation.

An energy-based controller design techniques have been utilized for the feedback control system to ensure asymptotic stability [13], [14]. The passivity-based control (PBC) is a type of energy-based control schemes. The passivity means that energy is only dissipated during the operation of the system. If a certain system is passive, it is known that it is always stable. The PBC design approach has been widely applied to the power system stabilization and power electronic converter control [15], [16]. Moreover, a passivity realization technique for DC microgrids with a voltage feed-forward control term has been introduced, which makes the overall system passive [14]. However, the conventional PBC design approach is very sensitive to load variations [17]. To overcome this issue, the interconnection and damping assignment PBC (IDA-PBC) has been proposed in [18], which is based on the mathematical model called a port-controlled Hamiltonian system (PCHS). In DC microgrids, the IDA-PBC has been applied to control buck [19], buck–boost [20], boost converters [21] and solid state transformers (SSTs) [22] to mitigate the effect of the constant power load (CPL). However, the information of power in the CPL is required in the control loop. In [23], the IDA-PBC has been applied to the controller design for the source-side dual active bridge (DAB) DC/DC converters in MVDC microgrids, where the controller is designed based on the mathematical model of the DAB converter. Recently, a DC-bus voltage and inner current control scheme for the ESS in DC microgrids is proposed, using the IDA-PBC theory. The controller is designed based on the mathematical model of the DAB converter. The DC source part is modelled as DC/DC boost converters with ideal DC sources, of which the output terminal is connected to the DC bus through the line impedance.

In this paper, a novel damping control scheme for V/I droop-controlled microgrids is proposed, using the IDA-PBC theory. At first, the model of the DC microgrid is built, where the DC voltage source converter (VSC), CPL and resistive loads are included. Then, the effects of the system parameter change such as droop gains and control loop bandwidths on the bus impedance are investigated by using the passivity-based stability analysis. Next, the PCHS form of DC VSCs with new control inputs for damping is developed. Then, the proposed damping controller is designed with the IDA-PBC theory, for which a gain selection technique is developed. Finally, the validity of the proposed damping control scheme is verified by hardware-in-the-loop (HIL) simulation and experimental results.

II. MODELING OF DC MICROGRIDS

A. DC microgrid

Fig. 2. illustrates the circuit representation of a simplified DC microgrid. The DC source parts are modelled as DC/DC boost converters with ideal DC sources, of which the output terminal is connected to the DC bus through the line impedance. The

![Fig. 2. Circuit representation of a simplified DC microgrid.](image)

![Fig. 3. Different types of DC output voltage converters. (a) AC/DC converter. (b) Rectifier and back-end DC/DC converter. (c) DC/DC converter.](image)
LPF is used for the droop control [6], [7]. The block diagram of the V/I droop-controlled DC VSC, where the capacitor. Therefore, the output of the AC/DC PWM converter the rectifier is regarded as constant due to its large output converters, can be employed, as shown in Fig. 3. In this work, the CPL and a resistive load which is a type of CIL  are involved, which are shown in Fig. 2.

**B. DC voltage-source converters**

To supply the power to the DC microgrid, different structures of the DC VSC, such as AC/DC PWM converters, rectifiers with back-end DC/DC converters, and DC/DC converters, can be employed, as shown in Fig. 3. In this work, it is assumed that the diode rectifier with a back-end DC/DC converter supplies the DC power, where the output voltage of the rectifier is regarded as constant due to its large output capacitor. Therefore, the output of the AC/DC PWM converter is regarded as a voltage source as shown in Fig. 2.

To provide the stable DC voltage, the output voltage of the DC VSC is controlled with an inner current control loop and an outer voltage control loop. During the parallel operation of multiple DC VSCs, the droop control is usually employed for sharing of the power and current. Fig. 4(a) shows the control block diagram of the V/I droop-controlled DC VSC, where the LPF is used for the droop control [6], [7]. The $v_{dcn}$ and $v_{dc}$ are the nominal DC-bus voltage and the output voltage of the VSC, respectively, $i_c$ is the input current of the VSC, $i_{dc}$ is the output current of the source side flowing through the line impedance and $r_d$ is the droop controller gain.

In Fig. 4(a), the behavior of the current control loop can be simplified as an LPF since the BW of the current control loop is sufficiently higher than that of the voltage control loop [26]–[29]. Then, the DC VSC can be modelled as a current source with a parallel capacitor, which is shown in Fig. 4(b), where the droop controller and voltage controller are not included and $r_c$ means the small equivalent series resistance (ESR) of the capacitor [27], [29]. Fig. 5 shows the equivalent circuit of one source converter and one load with a line impedance and a droop control gain, from which electrical equations of the system can be expressed as

$$L_{Lz} \frac{di_c}{dt} = v_c + r_c i_c + (-r_c - r_d - R_{Lz}) i_{dc} - v_{dc \_bus},$$

$$C \frac{dv_c}{dt} = i_c - i_{dc},$$

where $L_{Lz}$ and $R_{Lz}$ are the line inductance and resistance, respectively.

**C. Loads**

The different types of loads are connected to the DC bus, which can be classified into constant power load (CPL), constant impedance load (CIL) and constant current load (CCL) [30], [31]. In DC power systems, the CPL affects the voltage stability dominantly since its input impedance is negative which varies according to the operating condition [31], [32]. The input impedance of the CPL at an operating point can be expressed as

$$R_{CPL} = -V_L^2 / P_L,$$

where the $P_L$ and $V_L$ are the power and voltage at the input terminal of the load at operating point, respectively. In this work, a CPL and a resistive load which is a type of CIL are involved, which are shown in Fig. 2.

**D. DC bus capacitor**

In Fig. 5, if the ESR of input capacitor on the load side, $r_L$, is neglected, the voltage across the DC-bus capacitor can be expressed as

$$C_L \frac{dv_{cl}}{dt} = i_{dc} - (v_{dc \_bus} / R_{Load}),$$

where $C_L$ and $R_{Load}$ are the capacitance and resistance on the load side, respectively.

### III. STABILITY ANALYSIS OF DC MICROGRIDS

#### A. Passivity-based stability analysis

To guarantee the reliability or quality of the bus voltage of the distributed DC power system, stability analysis should be
carried out. Conventionally, the stability analysis is performed with the forbidden-region-based method using Nyquist contour of the impedance ratio between the source and load such as Middlebrook Criterion, Gain and Phase Margin Criterion, Energy Source Analysis Consortium (ESAC) Criterion and so on [33]. On the other hand, a passivity-based stability analysis method was proposed in [34], which is effective for the applications that a bi-directional power flow exists due to the change of operating mode or system reconfiguration.

For the passivity-based stability analysis, the impedance of the one-port system is needed, which can be expressed as [34]

\[ Z_{bus}(s) = \frac{V_{bus}(s)}{I_{bus}(s)} = \frac{Z_1}{Z_2} / \ldots Z_n / \ldots Z_{n+m}, \]  

(5)

where \( Z_{bus} \) is the total bus impedance and \( Z_1 \) to \( Z_n \) are the input and output impedances of the subsystems (\( n \) source converters and \( m \) load converters), \( V_{bus} \) and \( I_{bus} \) are bus voltage and bus current, respectively.

If a system can only absorb energy, it is considered as passive, for which the necessary and sufficient conditions of the one-port system with \( Z_{bus} \) can be expressed as

\[ \int_{-\infty}^{\infty} v_{bus}(\tau) i_{bus}(\tau) d\tau \geq 0 , \text{ for all } \tau . \]  

(6)

For the linear time-invariant (LTI) system, the system is stable if and only if the following conditions are satisfied as [34]

\[ \cdot Z_{bus}(s) \text{ includes no right half-plane poles.} \]

\[ \cdot \text{Re}\{ Z_{bus}(j\omega) \} \geq 0 \text{ or } -90^\circ \leq \angle Z_{bus}(j\omega) \leq 90^\circ, \forall \omega. \]

**B. Bus impedance**

To derive the bus impedance, the output impedance of the source and the input impedance of the load are required. Fig. 5 shows the equivalent circuit of one source and one load with a line impedance and droop control gain, where the voltage control loop is excluded.

From Fig. 4 and Fig. 5, the output impedance of the DC VSC with a droop controller (\( Z_{c\_out} \)) can be expressed by applying the Mason's gain formula as [35],

\[ Z_{c\_out} = \frac{V_{dc}}{I_{dc}} = \frac{H_d(s)H_c(s)G_v(s) + G_i(s)}{1 + (H_v(s)H_c(s)G_v(s))}, \]  

(7)

where

\[ H_d(s) = \frac{\omega_{dl}}{s + \omega_{df}}, \]  

(8)

\[ H_v(s) = \frac{k_v s + k_i}{s + \omega_{vi}}, \]  

(9)

\[ H_c(s) = \frac{\omega_c}{s + \omega_c}, \]  

(10)

**C. Effects of system parameters**

![Graph showing the influence of the low pass filter used for droop control on bus impedance (fd: 10 Hz→100 Hz).](image)

(a) Bode plot, (b) Pole-zero map.

\[ G_v(s) = \frac{1}{Cs}, \]  

(11)

where \( \omega_{dl} \) and \( \omega_{df} \) are the cut-off frequencies of the LPF, \( k_v \) and \( k_i \) are the PI gains of voltage controller, \( \omega_c \) is the BW of the current control loop, \( r_c \) is the ESR of the capacitor. In addition, the output impedance of the source side including the line impedance, \( Z_{S\_out} \), can be expressed as

\[ Z_{S\_out} = Z_{c\_out} + sL_{Lz} + R_{Lz}. \]  

(12)

For a resistive load, the input impedance of the load side can be expressed as

\[ Z_{L\_in} = \frac{V_{dc\_bus}}{I_{dc}} = \frac{R_{load}}{sC_LR_{load} + 1}. \]  

(13)

In addition, \( R_{load} \) can be substituted by \( R_{CPL} \) from (3) in term of CPL.

By substituting (12) and (13) into (5), the impedance of the bus with one source and one load is obtained as

\[ Z_{bus}(s) = Z_{S\_out} / Z_{L\_in}. \]  

(14)
A. Introduction of IDA-PBC theory

The network representation of a non-resistive system with independent storage elements that interact with its environment leads to the mathematical model of a port-controlled Hamiltonian system (PCHS). The PCHS form can be expressed as [18], [39]

$$\dot{x} = [J(x) - R(x)] \frac{\partial H(x)}{\partial x} + g(x)u + \varepsilon, \quad (15)$$

$$y = g^T(x) \frac{\partial H(x)}{\partial x}, \quad (16)$$

where $J(x)$ and $R(x)$ are the interconnection and the dissipation matrices ($J(x)=J^T(x)$, $R(x)=R^T(x)$), respectively, $H(x)$ is the Hamiltonian function, $\varepsilon$ is the disturbance matrix, $g$ is the external-port connection matrix, $u$ is the control input, and $y$ is the output of the system. The superscript $T$ means the transpose of the matrix.

The goal of the interconnection and damping assignment passivity-based control (IDA – PBC) is to find a state feedback control law, $u = \beta(x)$, such that the closed-loop dynamics is a PCHS with a dissipation [18].

B. Design of proposed damping control based on IDA-PBC

To damp the oscillatory components of power and current, the imaginary voltage source ($u_s - r_c u_c$) and current sources ($u_c$) are newly added to the equivalent circuit of Fig. 5, which results in Fig. 8. By adding these imaginary voltage and current sources, the power and current oscillations can be compensated effectively without a modification of the basic structure of voltage and current control loops.

From Fig. 8, the dynamic equations of the current and voltage oscillatory components can be expressed as

$$L_z \frac{d\tilde{i}_d}{dt} = (-r_c - R_{L_z})\tilde{i}_d + v_c + u_s - \tilde{v}_{dc_{-bus}} + r_c\tilde{i}_c, \quad (17)$$

$$C \frac{d\tilde{v}_c}{dt} = -\tilde{i}_d + u_s + \tilde{i}_c, \quad (18)$$

where the superscript ‘~’ denotes the oscillatory components.

From (17) and (18), the state variables for the PCHS can be set as
where \( D = \begin{bmatrix} L_{Lz} & 0 \\ 0 & C \end{bmatrix} \). (20)

The control inputs are selected as
\[
u = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix},
\]
and the output variables are expressed as
\[
y = \begin{bmatrix} i_{dc} \\ v_e \end{bmatrix}.
\]

Then, the Hamiltonian function can be set as
\[
H(x) = \frac{1}{2} x^T D^{-1} x = \frac{1}{2 L_{Lz}} \ddot{i}_{dc}^2 + \frac{1}{2 C} \ddot{v}_e^2. (23)
\]

From (15) to (23), the PCHS form of the oscillatory components in the DC VSC is derived as
\[
\dot{x} = \left[ J(x) - R(x) \right] \frac{\partial H(x)}{\partial x} + g(x) \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} + \varepsilon, (24)
\]

\[
y = g^T(x) \frac{\partial H(x)}{\partial x} = \begin{bmatrix} i_{dc} \\ v_e \end{bmatrix}, (25)
\]

where
\[
\left[ J(x) - R(x) \right] = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} - \begin{bmatrix} r_a + r_{dc} + r_c & 0 \\ 0 & 0 \end{bmatrix}, (26)
\]

\[
\frac{\partial H(x)}{\partial x} = D^{-1} x, (27)
\]

\[
g = g^T = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 1 \end{bmatrix}, (28)
\]

\[
\varepsilon = \begin{bmatrix} r_c \\ i_{dc} \\ -1 \\ 0 \end{bmatrix} \ddot{v}_{dc_{bus}}. (29)
\]

To achieve the asymptotical stability at the equilibrium point, \( x^* \), the desired dynamics of the closed-loop system, \( H_d(x) \), can be set as
\[
H_d(x) = \frac{1}{2 L_{Lz}} \left( x_1 - x_1^* \right)^2 + \frac{1}{2 C} \left( x_2 - x_2^* \right)^2, (30)
\]

where \( H_d(x) \) is minimized at \( x^* \). With the control law, \( u = \beta(x) \), the PCHS form with a dissipation can be expressed with \( J_d(x) \) and \( R_d(x) \) as
\[
\dot{x} = \left[ J_d(x) - R_d(x) \right] \frac{\partial H_d(x)}{\partial x}. (31)
\]

To obtain the control law based on the desired Hamiltonian function, the \( J_d(x) \) and \( R_d(x) \) should be selected to satisfy the following conditions as
\[
\left[ J(x) + J_d(x) \right] = - \left[ J(x) + J_d(x) \right]^T, (32)
\]
\[
\left[ R(x) + R_d(x) \right] = \begin{bmatrix} r_a + r_{dc} + r_c \\ 0 \end{bmatrix} \geq 0, (33)
\]

where
\[
J_d(x) = J(x) + J_d(x), (34)
\]
\[
R_d(x) = R(x) + R_d(x). (35)
\]

If it is assumed that \( \beta(x), J_d(x), R_d(x) \) and the vector function \( K(x) \) can be found for the PCHS, the PDE (partial differential equation) for the desired energy function is given as [18]
\[
\left[ J(x) + J_d(x) - (R(x) + R_d(x)) \right] K(x) = -\left[ J(x) - R(x) \right] \frac{\partial H(x)}{\partial x} + g^T \beta(x) + \varepsilon, (36)
\]

where a vector function \( K(x) \) should satisfy the following conditions as
\[
\frac{\partial K}{\partial x}(x^*) = \begin{bmatrix} \frac{\partial K}{\partial x}(x^*) \end{bmatrix}^T: \text{Integrality}, (37)
\]

\[
K(x^*) = \frac{\partial H}{\partial x}(x^*): \text{Equilibrium assignment}, (38)
\]

\[
\frac{\partial K}{\partial x}(x^*) > \frac{\partial^2 H}{\partial x^2}(x^*): \text{Lyapunov stability.} (39)
\]

If these conditions are satisfied, the closed-loop system becomes a PCH form with a dissipation, where
\[
H_d(x) = H(x) + H_d(x). (40)
\]

To satisfy the conditions of (37) to (39), the \( K(x) \) can be set as [40]
\[
K(x) = \frac{\delta H_d(x)}{\delta x} = \frac{\delta H_d(x)}{\delta x} - \frac{\delta H(x)}{\delta x} = -D^{-1} x. (41)
\]

Also, let’s choose the \( J_d(x) \) and \( R_d(x) \) as
\[
J_d(x) = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}, \quad R_d(x) = \begin{bmatrix} k_1 \\ 0 \end{bmatrix}, (42)
\]

where \( k_1 \) and \( k_2 \) are the damping controller gains.

Meanwhile, in Fig. 8, the oscillatory components in the capacitor voltage and output voltage of the DC VSC are regarded as equal due to the low value of \( r_c \). Then, from (36), the control law, \( \beta(x) = \begin{bmatrix} u_1, u_2 \end{bmatrix}^T \), for damping of power and current oscillations is derived as
\[
u_1 = -k_1 \ddot{i}_{dc} - \ddot{v}_{dc} - r_{dc} \dot{i}_{dc} + \ddot{v}_{dc_{bus}}, (43)
\]

\[
u_2 = \ddot{i}_{dc} - k_2 \ddot{v}_{dc} - \ddot{v}_{dc_{bus}}, (44)
\]

where \( \ddot{i}_{dc}, \ddot{v}_{dc}, \ddot{v}_{dc_{bus}} \) are the high-pass filtered quantities of each signal.
frequencies of filters are listed in Table I.

From (27), (30) and (41), if

\[
\frac{\partial H_d}{\partial x}(x) = D^{-1}(x - x^*) = 0, \quad (48)
\]

Then, the condition of (39) is satisfied, so that the system is asymptotically stable.

D. Gain selection technique

As can be seen in (43) and (44), there are two gains \((k_1, k_2)\) for the proposed controller. The basic conditions for determining these gains are given in (32) and (33). However, it is necessary to perform repetitive time-domain simulations in order to obtain satisfactory performances. To avoid this trouble, a gain selection technique is developed as follows.

By substituting (43) and (44) into (24), the system dynamic equation for damping control is obtained as

\[
\dot{x} = \begin{bmatrix}
  -r_x - R_{L2} - r_c - k_1 \\
  L_{L2}
\end{bmatrix} \begin{bmatrix}
  x \\
  L_{L2} C
\end{bmatrix} + \begin{bmatrix}
  r_x + R_{L2} + r_c + k_1 \\
  L_{L2} C
\end{bmatrix} k_2 = 0, \quad (50)
\]

From (50), then, the characteristic equation can be expressed as

\[
s^2 - \left(\frac{-r_x - R_{L2} - r_c - k_1}{L_{L2} C}\right)s + \left(\frac{r_x + R_{L2} + r_c + k_1}{L_{L2} C}\right)k_2 = 0. \quad (51)
\]

When (51) is compared with the standard second-order form as
\[ s^2 + 2\zeta \omega_n + \omega_n^2 = 0, \]  
(52)

the damping ratio \( \zeta \) and natural frequency \( \omega_n \) for the PCHS are expressed, respectively, as

\[
\omega_n = \sqrt{-\frac{r_d - R_{LZ} - r_c - k_1}{L_{LZ}} \cdot -\frac{k_2}{C}},
\]
(53)

\[
\zeta = \left( \frac{r_o + R_{LZ} + r_c + k_1}{2L_{LZ}} \right) \cdot \frac{k_2}{2C} \sqrt{-\frac{r_d - R_{LZ} - r_c - k_1}{L_{LZ}} \cdot -\frac{k_2}{C}},
\]
(54)

From (51) and (52), then, the resultant controller gains are given by

\[
k_1 = \frac{L_{LZ} C \omega_n^2}{k_2} - (r_d + R_{LZ} + r_c),
\]
(55)

\[
k_2 = \omega_n C \zeta \pm \sqrt{(\omega_n C \zeta)^2 - C^2 \omega_n^2}.
\]
(56)

In (55) and (56), the natural frequency, \( \omega_n \), needs to be equal to or lower than the BW of the voltage control loop. In addition, the damping ratio can be set as unity in order to avoid overshoots.

**E. Bus impedance analysis with proposed control method**

In this subsection, the effects of the proposed active damping control method are investigated, where \( f_1 \) to \( f_4 \) are set as 3 Hz,

the natural frequency \( \omega_n \) of the controller is set equal to the BW of the voltage control loop and the damping ratio \( \zeta \) is set as 1.

Fig. 10(a) and (b) show the Bode plot and pole-zero map of the bus impedance of the conventional and proposed methods when \( f_d \) is 50 Hz. For the conventional method, the passivity condition of the bus impedance is not satisfied, whereas it is satisfied for the proposed control due to the phase compensation near 400 Hz. In addition, it is shown that there are no right half-plane poles. In the proposed method, it can be seen that the poles located closely to the right half-plane move to the left half-plane far away, as shown in Fig 11(b).

Fig. 11 shows the effects of the BWs of the voltage control loop when they are set as 200 Hz, 400 Hz, 600 Hz and 800 Hz. As known from Fig. 7, when the BW of the voltage control loop is high, the passivity condition is not satisfied. However, even when the control BW is high for the proposed method, the passivity condition is satisfied due to the phase compensation, as shown in Fig. 11(a). Also, the poles move to the left half-plane further from the imaginary axis, as shown in Fig. 11(b).

Fig. 12 shows the Bode plot of the bus impedance as the number of sources (\( N_s \)) is increased, where the line impedances for each source side are assumed to be the same. It can be seen that the magnitude (dB) is increased as \( N_s \) is increased, but the phase is unchanged. So, it is confirmed that the proposed controller satisfies the passivity condition even when more sources are connected.
The microgrid model (Fig. 2) was realized with the boost converters. The load consists of a buck implemented by the Labview [41]. The DC VSCs were (XILINX-XC3S400-PQ208), analog-to-digital converter 7821R, PXI-6723), and laboratory control boards. The control of NI-PXIe-1078 chassis with modules (PXIe-1078, 8840, 3200F28335), FPGA (XILINX-XC3S400-PQ208), analog-to-digital converter (MAX11056) and etc. The microgrid model (Fig. 2) was implemented by the Labview 2016 [41]. The DC VSCs were realized with the boost converters. The load consists of a buck converter (CPL load) and a resistor. The system parameters are listed in Table I. The PI gains of the voltage and current controller are 23 and 1162. The damping controller gains are determined from (55) and (56) as 

\[
k_1 = -2.1 \quad \text{and} \quad k_2 = 2.5.
\]

Firstly, the dynamic responses of the DC microgrid without and with the proposed damping controller are illustrated in Fig. 15 and Fig. 16, respectively. The load is changed from 0.2 p.u. to 0.8 p.u. and back to 0.2 p.u. in the steady state, control performances of DC microgrid without and with the proposed damping controller are almost similar, which provides a sufficient power to the CPL and resistive load. The deviation in the DC-bus voltage is kept within 10% of the nominal value of 380 V, as shown in Fig. 15(b) and 16(b). When the load power is increased, the output current is increased \((i_{dc1} \) and \(i_{dc2})\) but the output voltage is decreased by the droop control. In the transient state, the settling time of the \(V_{dc-bus}\) is longer than that of in Fig. 15 due to the influence of the damping control [31], which is shown in Fig. 16. However, it has no negative effect on the transient response of output currents as shown in Fig. 16(c) and (d). So, the transient responses in the supplied power \((p_{out1} \) and \(p_{out2})\) are not different between two methods.

Secondly, superiority of the proposed controller is demonstrated for parameter variations. Four cases of parameter change are investigated: the cut-off frequency of the LPF for droop control \((f_d)\), the BW of the voltage control loop \((f_{vc})\), the output capacitance of the DC VSCs \((C_1, C_2)\), and the DC-bus capacitance \((C_b=C_{L1}+C_{L2})\). The change in the load power is made by varying the load resistance \((R_{CPL})\).

Fig. 17 illustrates the transient responses of the DC microgrid in the case that the LPF of the droop controller is only used without any special damping control strategy. The load condition is changed from 0.2 p.u. to 0.8 p.u. and back to 0.2 p.u. Fig. 17(i) shows the results when \(f_d=50\) Hz. The deviation of the DC-bus voltage stays within ±10% of the nominal
Dynamic responses of DC microgrid with LPF for droop control.

(i) $f_d$: 50 Hz, $f_{ic}$: 400 Hz, $C$: 1000 μF, $C_b$: 2000 μF

(ii) $f_d$: 40 Hz, $f_{ic}$: 200 Hz, $C$: 1000 μF, $C_b$: 2000 μF

(iii) $f_d$: 40 Hz, $f_{ic}$: 400 Hz, $C$: 2000 μF, $C_b$: 2000 μF

(iv) $f_d$: 40 Hz, $f_{ic}$: 400 Hz, $C$: 1000 μF, $C_b$: 1000 μF

Operating performance of DC microgrid with the proposed damping control.

(i) $f_d$: 50 Hz, $f_{ic}$: 400 Hz, $C$: 1000 μF, $C_b$: 2000 μF

(ii) $f_d$: 40 Hz, $f_{ic}$: 200 Hz, $C$: 1000 μF, $C_b$: 2000 μF

(iii) $f_d$: 40 Hz, $f_{ic}$: 400 Hz, $C$: 2000 μF, $C_b$: 2000 μF

(iv) $f_d$: 40 Hz, $f_{ic}$: 400 Hz, $C$: 1000 μF, $C_b$: 1000 μF
Fig. 17(iv) illustrates the performance when the DC-bus voltage and the oscillatory components are much increased at 0.8 p.u. load. Therefore, the instability may happen if the operating point is changed. It is noticed that the passivity condition is not satisfied when the capacitance is increased. It is seen in (a) and (b) of Fig. 17(iii) that the oscillatory components in the load power and the DC-bus voltage are 3 kW and 20 V, respectively, at the 0.8 p.u load conditions. Fig. 17(ii) illustrates the results when the BW of the voltage control loop \( f_{vc} \) as 200 Hz and the low BW of the voltage control loop \( f_{vc} \) is kept at 40 Hz. In this case, the passivity condition is satisfied as shown in Fig. 7. Therefore, the oscillatory components of the load power and DC-bus voltage are relatively low. On the other hand, when the load is increased to 0.8 p.u, the oscillatory components appear in the output current and voltage, as shown in (c) to (f) due to the low BW of the voltage control loop. Fig. 17(iii) shows the transient responses when the output capacitance of the DC VSC is set as 2000 \( \mu F \). In general, the parameter variation such as an increase of the output capacitance makes the PI controller detuned. Therefore, the instability may happen if the operating point is changed. It is noticed that the passivity condition is not satisfied when the capacitance is increased. It is seen in (a) and (b) of Fig. 17(iii) that the oscillatory components in the load power and DC-bus voltage appear at 0.2 p.u. load. Furthermore, the oscillatory components are much increased at 0.8 p.u. load. Fig. 17(iv) illustrates the performance when the DC-bus capacitance is set as 1000 \( \mu F \). It is seen that there are no oscillatory components at 0.2 p.u. load. However, when the load is increased to 0.8 p.u., large oscillations in the bus voltage appear as shown in (b), of which the peak-to-peak value is 80 V.

Fig. 18 shows the operating performance of the DC microgrid, where it is initially operated without the damping control and after a while with the damping control. The load condition is 0.8 p.u. The parameter values used in the four cases of Fig. 18(i) to (iv) are set the same as those of in Fig. 17(i) to (iv), respectively. During the initial operation, the power, voltage, and current oscillations are high. However, after the proposed damping control is applied, all the oscillatory components are significantly reduced in some transient interval. In addition, it is observed that the current and power sharing between two DC VSCs are well done as shown in Fig. 18 (c) and (d), and (g) and (h). In four cases of parameter change, the controller gains \( k_1 \) and \( k_2 \) have not been updated, which shows the robustness of the proposed scheme to parameter variations.

![Fig. 19. Experimental setup.](image)

**TABLE II**

**PARAMETERS OF SMALL-SCALED DC MICROGRID**

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>400 W</td>
</tr>
<tr>
<td>Input voltage</td>
<td>60 V</td>
</tr>
<tr>
<td>Output capacitor ( (C_L, C_T) )</td>
<td>250 ( \mu F )</td>
</tr>
<tr>
<td>Switching / sampling freq.</td>
<td>20 kHz / 40 kHz</td>
</tr>
<tr>
<td>Voltage control-loop BW ( f_{vc} )</td>
<td>130 Hz</td>
</tr>
<tr>
<td>Current control-loop BW ( f_{cc} )</td>
<td>2 kHz</td>
</tr>
<tr>
<td>Droop controller gain ( r_d )</td>
<td>2.5</td>
</tr>
<tr>
<td>Cut-off freq. of LPF for droop control ( (f_b) )</td>
<td>130 Hz</td>
</tr>
<tr>
<td>DC-bus voltage ( v_{dc-bus} )</td>
<td>100 V</td>
</tr>
<tr>
<td>Line impedance ( Z_L1/R_Lz1, L_Lz1 )</td>
<td>16 m( \Omega ), 200 ( \mu H )</td>
</tr>
<tr>
<td>Line impedance ( Z_L2/R_Lz2, L_Lz2 )</td>
<td>30 m( \Omega ), 290 ( \mu H )</td>
</tr>
<tr>
<td>Rated load power ( (CPL + resistive load) )</td>
<td>800 W</td>
</tr>
<tr>
<td>Load capacitor ( (C_L, C_T) )</td>
<td>250 ( \mu F )</td>
</tr>
</tbody>
</table>

![Fig. 20. Responses of DC microgrid without damping control at load changes.](image)

(a) Load power \( (p_{load}) \),
(b) DC-bus voltage \( (v_{dc-bus}) \),
(c) Output current #1 \( (i_{dc1}) \),
(d) Output current #2 \( (i_{dc2}) \),
(e) Output voltage #1 \( (v_{dc1}) \),
(f) Output voltage #2 \( (v_{dc2}) \),
(g) Output power #1 \( (p_{out1}) \),
(h) Output power #2 \( (p_{out2}) \).
VI. EXPERIMENTAL RESULTS

Experiments have been carried out to investigate the damping performance of the proposed control scheme. The hardware setup of a small-scaled 100 V DC power system has been built as shown in Fig. 19, which is comprised of a three-phase diode rectifier, two boost converters, a buck-converter load, and a resistive load. The system parameters are listed in Table II. The execution time of the proposed damping control algorithm in DSP is 34 μs. The experimental test has been performed under unstable condition due to incorrect setting of \( f_d \), \( f_d \leq 130 \) Hz without the proposed damping controller.

Fig. 20 shows the responses of the DC microgrid without the proposed active damping control when the load power is changed from 200 W to 450 W and back to 200 W, where the \( f_d \) is set as 200 Hz. As it can be seen in Fig. 20(a) and (b), the oscillatory components in load power and DC bus voltage are not increased much at load power of 250 W. However, at 450 W, the oscillatory components in the output currents, voltages and powers of the DC-VSCs are increased remarkably since the passivity condition of the bus impedance is not satisfied.

Fig. 21 shows the operating performance of DC microgrid without/with proposed damping control method. The load power (\( P_{\text{Load}} \) ), DC-bus voltage (\( V_{\text{dc-bus}} \) ), output current #1 (\( i_{\text{dc1}} \) ), output current #2 (\( i_{\text{dc2}} \) ), output voltage #1 (\( v_{\text{dc1}} \) ), output voltage #2 (\( v_{\text{dc2}} \) ), output power #1 (\( P_{\text{out1}} \) ), and output power #2 (\( P_{\text{out2}} \) ) are shown.

Fig. 22 illustrates the responses of the DC microgrid with proposed damping control at load changes. The load power (\( P_{\text{Load}} \) ), DC-bus voltage (\( V_{\text{dc-bus}} \) ), output current #1 (\( i_{\text{dc1}} \) ), output current #2 (\( i_{\text{dc2}} \) ), output voltage #1 (\( v_{\text{dc1}} \) ), output voltage #2 (\( v_{\text{dc2}} \) ), output power #1 (\( P_{\text{out1}} \) ), and output power #2 (\( P_{\text{out2}} \) ) are shown.

Fig. 21. Operating performance of DC microgrid without/with proposed damping control method.
(a) Load power (\( P_{\text{Load}} \)), (b) DC-bus voltage (\( V_{\text{dc-bus}} \)), (c) Output current #1 (\( i_{\text{dc1}} \)), (d) Output current #2 (\( i_{\text{dc2}} \)), (e) Output voltage #1 (\( v_{\text{dc1}} \)), (f) Output voltage #2 (\( v_{\text{dc2}} \)), (g) Output power #1 (\( P_{\text{out1}} \)), (h) Output power #2 (\( P_{\text{out2}} \)).

Fig. 22. Responses of DC microgrid with proposed damping control at load changes.
(a) Load power (\( P_{\text{Load}} \)), (b) DC-bus voltage (\( V_{\text{dc-bus}} \)), (c) Output current #1 (\( i_{\text{dc1}} \)), (d) Output current #2 (\( i_{\text{dc2}} \)), (e) Output voltage #1 (\( v_{\text{dc1}} \)), (f) Output voltage #2 (\( v_{\text{dc2}} \)), (g) Output power #1 (\( P_{\text{out1}} \)), (h) Output power #2 (\( P_{\text{out2}} \)).
VII. CONCLUSIONS

In this paper, a novel active damping control scheme based on the IDA-PBC has been proposed and implemented to attenuate the power and current oscillatory components of V/I droop-controlled DC microgrids. At first, the model of the DC microgrid with the DC VSC, CPL and resistive load has been built. Next, the effects of the system parameters on the passivity-based stability have been analyzed. After that, using the IDA-PBC theory, the damping controller has been designed where asymptotic stability is guaranteed. Besides, a gain selection technique has been developed to complete the controller design. The validity of the proposed control method has been verified by the HILS results in the four cases of the parameter change: the cut-off frequency of the LPF for droop control, the BW of the DC-voltage control loop, the output capacitance of the DC VSC, and the DC-bus capacitance. Furthermore, experimental tests have been performed for a small-scaled hardware system. It has been shown that the proposed method can effectively attenuate the oscillatory components of the power/current in the DC microgrids.

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