Voltage containment and current sharing in multi-bus DC microgrids: Both leader and non-leader impulse-like control scheme

Rui Wang,[1,*] Xu Tian,[1] Qiuye Sun,[1] and Peng Wang[2]
[1]The College of Information Science and Engineering, Northeastern University, Shenyang 110819, China
[2]School of Electrical and Electronic Engineering, Nanyang Technological University, 50 Nanyang Ave 639798, Singapore
*Correspondence: wangrui@ise.neu.edu.cn
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Dear Editor,

The objective of 'carbon peaking and carbon neutrality' has promoted the development of new power systems.[1] As an important part of new power systems, the multi-bus DC microgrid has been widely used to integrate distributed renewable energy. For this system, the current should be shared based on the capacity, and the voltage should be contained within the maximum allowable range to meet the demand on voltage quality.[2] However, voltage containment belongs to the formation containment control problem in leader multi-agent systems. The current sharing belongs to the consensus control problem in non-leader multi-agent systems. The current sharing and voltage containment in multi-bus DC microgrids are rarely realized at the same time. Thus, an impulse-like control scheme is first proposed to realize current sharing and voltage containment in multi-bus DC microgrids, simultaneously. Then experimental results are provided to verify the performance of this impulse-like control scheme.

VOLTAGE CONTAINMENT AND CURRENT SHARING: SIGNIFICANCE AND CHALLENGES IN MULTI-BUS DC MICROGRIDS

The multi-level control mode has been widely used to realize power management in multi-bus DC microgrids.[3] The droop control as a common primary control scheme is proposed to realize current sharing and voltage regulation in DC microgrids. However, it causes bus voltage deviation and inaccurate current sharing since the unbalanced impedance is ignored.[4] Thus, numerous secondary control schemes including centralized and distributed control schemes are proposed to solve the problem.[5] Therein, the centralized control scheme easily results in high-bandwidth communication and single-point failure, which is not applicable to DC microgrids.

To solve the problem, secondary distributed control schemes based on sparse communication are proposed. Numerous control schemes including voltage shifting, slop adjusting and hybrid voltage/sloping-adjusting schemes are proposed to realize voltage restoration and accurate current sharing in DC microgrids.[6] Note that realizing the voltage restoration control in multi-bus DC microgrids means that the average bus voltage is maintained at the rated voltage. However, the bus voltage is not contained within the allowable range of the power system due to the increasing unbalanced impedance. The voltage restoration control in multi-bus DC microgrids is shown in Figure 1B. Meanwhile, a voltage deviation among different buses is necessary to ensure that current sharing is realized. Thus, realizing both current sharing control and voltage containment control is essential for multi-bus DC microgrids.

Inspired by these, an impulse-like control scheme is first proposed to realize current sharing and voltage containment in multi-bus DC microgrids, simultaneously. Therein, the voltage containment is realized at impulse instants, and the current sharing is realized at non-impulse instants. This control scheme can improve the bus voltage quality and the reliability of DC microgrids.

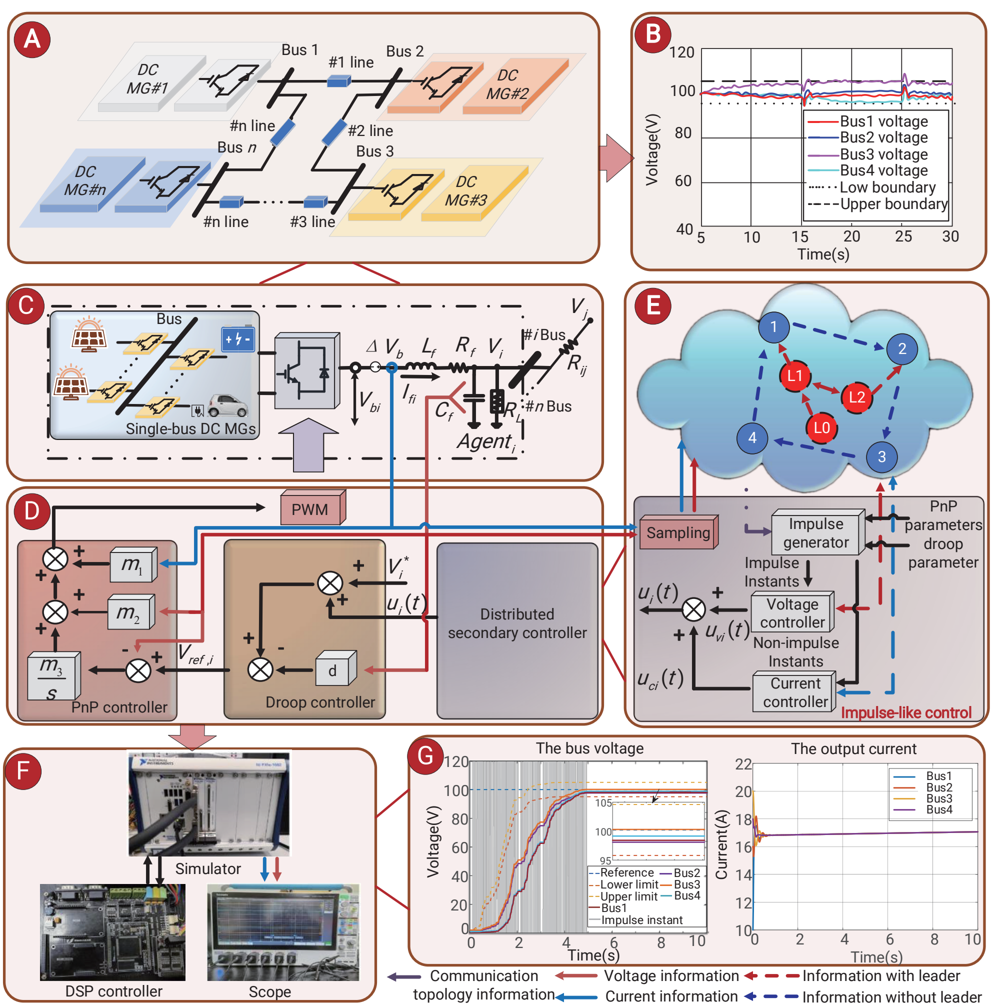

Figure 1. The impulse-like control scheme in multi-bus DC microgrids (A) The structure regarding multi-bus DC microgrids. (B) The bus voltage restoration for DC microgrids under traditional distributed control schemes. (C) The hardware topology of multi-bus DC microgrids. (D)The adopted control framework. (E) The impulse-like control scheme in multi-bus DC microgrids. (F) The HIL experiment topology. (G) The output voltage and current.

THE MODEL OF MULTI-BUS DC MICROGRIDS

The hardware topology of multi-bus DC microgrids is shown in Figure 1C. Then the PnP controller is embedded to provide the PnP capacity and stable voltage in primary control. The V-I droop control scheme is adopted to realize voltage regulation and preliminary current sharing in primary control, and the control framework is shown in Figure 1D.

By applying the concept of the block model, the multi-bus DC microgrid can be regarded as a multi-agent system. And one agent includes one single-bus microgrid, one conversion device, one RLC filter and loads. To simplify the model, it can be assumed that each RLC filter has the same parameters. Thus, the state-space equation of multi-bus DC microgrids can be built as:[7]

$$\begin{cases} \dot{x}_i(t) = Ax_i(t) + Bu_i(t) + f_i(t) \\ y_i(t) = Cx_i(t) \end{cases} \tag{1}$$

where $A = [-R_L/C_f, 1/C_f, 0; (m_1-1)/L_f, (m_2-R_f)/L_f, m_3/L_f; -1, d, 0]$, $x_i(t) = [V_i, I_{fi}, z_i]^T$, $y_i(t) = [V_i, I_{fi}]^T$, $B = [m_1, m_2, m_3]^T$, $f_i(t)$ represents the disturbance, and d is the droop gain in the droop controller. V_i represents the bus voltage of agent i, and I_{fi} represents the current of agent i. m_1, m_2, m_3 are parameters of PnP controllers.

PROBLEM CONVERSION

Based on this, it can be defined $x_i(t) = M_1x_{vi}(t) + M_2x_{ci}(t)$, $u_i(t) = u_{vi}(t) + u_{ci}(t)$, $y_i(t) = y_{vi}(t) + y_{ci}(t)$ where $u_{ci}(t)$ is the current controller, $u_{vi}(t)$ is the voltage controller, $y_{vi}(t) = [V_i, 0]^T$ and $y_{ci}(t) = [0, I_{fi}]^T$. Meanwhile, set $x_{vi}(t) = M_1x_i(t)$ and $x_{ci}(t) = M_2x_i(t)$ where $M_1 = M_1^2$ and $M_2 = M_2^2$. Since the state-space equation (1) represents a linear system, the system model can be decomposed into two independent parts by applying the superposition theorem. Thus, the state-space equation (1) is rebuilt as:

$$\begin{cases} \dot{x}_{vi}(t) = A_vx_{vi}(t) + Bu_{vi}(t) \\ y_{vi}(t) = C_vx_{vi}(t) \end{cases} \tag{2}$$

$$\begin{cases} \dot{x}_{ci}(t) = A_cx_{ci}(t) + Bu_{ci}(t) + f_i(t) \\ y_{ci}(t) = C_cx_{ci}(t) \end{cases} \tag{3}$$

where $A_v = AM_1$, $C_v = CM_1$, $A_c = AM_2$ and $C_c = CM_2$.

Proof: According to $x_i(t) = M_1x_{vi}(t) + M_2x_{ci}(t)$ and the equation (1), there is:

$$\begin{cases} M_1\dot{x}_{vi}(t) = A_vx_{vi}(t) + Bu_{vi}(t) \\ y_{vi}(t) = C_vx_{vi}(t) \\ M_2\dot{x}_{ci}(t) = A_cx_{ci}(t) + Bu_{ci}(t) + f_i(t) \\ y_{ci}(t) = C_cx_{ci}(t) \end{cases} \tag{4}$$

Based on $x_{vi}(t) = M_1x_i(t)$, $x_{ci}(t) = M_2x_i(t)$, $M_1 = M_1^2$ and $M_2 = M_2^2$, there is $M_1\dot{x}_{vi}(t) = M_1^2\dot{x}_i(t) = M_1\dot{x}_i(t) = \dot{x}_{vi}(t)$. Similarly, there is $M_2\dot{x}_{ci}(t) = \dot{x}_{ci}(t)$. Thus, the equation (4) can be rebuilt as equation (2) and (3).

To realize voltage containment, the virtual leader L_0 is introduced to represent the reference voltage in this letter. Meanwhile, leaders L_1 and L_2 are introduced to represent the upper and lower limits of outputs, respectively. The agent set N_i is divided into two sets, i.e., 2 leaders with $i \in \mathcal{J}_L = \{L_1, L_2\}$ and N followers with $i \in \mathcal{J}_F = \{1, \ldots, N\}$. Then the system model (2) is rebuilt as follows:

$$\begin{cases} \dot{x}_{vi}(t) = A_vx_{vi}(t) + Bu_{vi}(t) \\ y_{vi}(t) = C_vx_{vi}(t) \\ \dot{x}_{v0}(t) = A_vx_{v0}(t) + Bu_{v0}(t) \\ y_{v0}(t) = C_vx_{v0}(t) \end{cases} \tag{5}$$

where $x_{v0}(t) = (V_{ref}, 0, 0)^T$ and $y_{v0}(t) = (V_{ref}, 0)^T$. Then $h_L(t) = (h_{L_1}(t), \ldots, h_l(t))$ is defined as the formation information where $h_i(t)$ represents the relative position between the leader i and the virtual leader L_0 for $i \in \mathcal{J}_L$. It can be said that the output formation-containment control is realized for the system (5) if there are $\lim\limits_{t\to\infty} \inf\limits_{y_{vl} \in Co(y_L)} \|y_{vi}(t) - y_{vl}(t)\| = 0$ for $i \in \mathcal{J}_F$ and $l \in \mathcal{J}_L$, i.e., $\lim\limits_{t\to\infty} y_{vi}(t) \in [y_{vL_1}(t), y_{vL_2}(t)]$, and $\lim\limits_{t\to\infty} \|y_{vi}(t) - y_{v0}(t) - C_vh_i(t)\| = 0$ for $i \in \mathcal{J}_L$, where $Co(y_L)$ is the defined output convex hull consisting of leaders.

From the above analysis, it can be found that the accurate current sharing control is realized if and only if the system (3) realizes $y_{c1}(t) =, \ldots, = y_{ci}(t)$ by designing $u_{ci}(t)$ for $i = 1, \ldots, N$. The voltage containment is realized if and only if the system (5) realizes $\lim\limits_{t\to\infty} \|y_{vi}(t) - y_{v0}(t) - C_vh_i(t)\| = 0$ for the leader i where $i \in \mathcal{J}_L$ and $\lim\limits_{t\to\infty} y_{vi}(t) \in [y_{vL_1}(t), y_{vL_2}(t)]$ for $i \in \mathcal{J}_F$ where $\lim\limits_{t\to\infty} y_{vL_1}(t) = (V_{min}, 0)^T$ and $\lim\limits_{t\to\infty} y_{vL_2}(t) = (V_{max}, 0)^T$ by designing $u_{vi}(t)$ for $i = L_0, L_1, L_2, 1, \ldots, N$. Therein, V_{min} is the lower limit of the bus voltage, and V_{max} is the upper limit of the bus voltage.

CONTROLLER DESIGN AND VERIFICATION

The voltage containment and current sharing problems in multi-bus DC microgrids are divided into formation containment control in the system (5) and output consensus control in the system (3).

Firstly, set $u_{v0} = K_{v0}x_{v0}(t)$ and design the K_{v0} such that $y_{v0}(t) = (V_{ref}, 0)$. Thus, there is $\dot{x}_{v0}(t) = A_{v0}x_{v0}(t)$ where $A_{v0} = A_v + BK_{v0}$. Considering the maximum allowable range of the power system, $h_1(t)$ and $h_2(t)$ can be designed as $h_1(t) = (-0.05V_{ref}, 0, 0)$ and $h_2(t) = (0.05V_{ref}, 0, 0)$. According to the analysis in the previous section, there are $V_i \in [V_{min}, V_{max}]$, $V_{min} = 0.95V_{ref}$ and $V_{max} = 1.05V_{ref}$ if the formation-containment is realized.

Based on this, the voltage controllers are designed as:

$$\begin{cases} \dot{z}_i(t) = A_{v0}z_i(t) + \gamma \sum\limits_{k=1}^{+\infty} \delta(t - t_k)\bar{z}_{Fi}(t) \\ u_{vi}(t) = K_{vi}^1x_{vi}(t) + K_{vi}^2z_i(t), i \in \mathcal{J}_F \end{cases} \tag{6}$$

$$\begin{cases} \dot{z}_i(t) = A_{v0}z_i(t) + \gamma \sum\limits_{k=1}^{+\infty} \delta(t - t_k)\bar{z}_{Li}(t) \\ u_{vi}(t) = K_{vi}^1x_{vi}(t) + K_{vi}^2z_i(t), i \in \mathcal{J}_L \end{cases} \tag{7}$$

where $\delta(\cdot)$ is the Dirac function, t_k is the kth impulse instant, $\bar{z}_{Li}(t) = \sum\limits_{j \in N_i} (a_{ij}(z_j(t) - h_j(t) - z_i(t) + h_i(t)) + b_{vi}(x_{vL_0}(t) - z_i(t) + h_i(t)))$, and $\bar{z}_{Fi}(t) = \sum\limits_{j \in N_i} a_{ij}(z_j(t) - z_i(t))$. Therein, $a_{ij} > 0$ if the agent i can receive the information from the agent j, $a_{ij} = 0$ otherwise. $b_{vi} > 0$ if the agent i can receive the information from agent L_0, $b_{vi} = 0$ otherwise. Meanwhile, γ, K_{vi}^1 and K_{vi}^2 are the controller gains where $K_{vi}^2 = K_{v0} - K_{vi}^1$. A similar method for solving these controller gains has been proposed,[8] which can be applied in the system (5). Based on this, the voltage containment can be realized at the impulse instants.

Then set $Bu_{ci}(t) = u_{ci}^*(t)$, and the current controller can be designed as:

$$u_{ci}^*(t) = -\alpha_1z_{ci}(t) - \alpha_2\mathrm{sign}(z_{ci}(t)) - \alpha_3\mathrm{sign}(z_{ci}(t))^2 \tag{8}$$

where $z_{ci}(t) = \sum\limits_{j \in N_i} a_{ij}(x_{ci}(t) - x_{cj}(t))) + b_{ci}(x_{ci}(t) - x_1(t)), i \in \{2, \ldots, N\}$ with $t \in (t_k, t_{k+1})$, and $\mathrm{sign}(\cdot)$ is the symbolic function. Meanwhile, there is $u_{ci}^*(t_k) = 0$. Therein, $b_{ci} > 0$ if the agent i can receive the information from the agent 1, $b_{ci} = 0$ otherwise. α_1, α_2 and α_3 are the controller gains.

Remark: The output consensus problem in linear multi-agent systems has been widely studied.[9] On the time scale, the consensus control at non-impulse instants can be regarded as a kind of intermittent control. Based on this, the method for solving a similar controller has been proposed,[10] which can be applied in the system (3). Thus, the current sharing at non-impulse instants can be realized in the system (3).

To sum up, the controller $u_i(t)$ can be designed as $u_i(t) = u_{ci}(t) + u_{vi}(t)$, where $u_{ci}(t) = B^Lu_i^*(t)$ and $B^LB = 1$. The impulse-like control framework can be described in Figure 1E.

Furthermore, the HIL experiment is provided to verify the proposed control scheme. The structure of multi-bus DC microgrids is loaded in a simulator, and the proposed control scheme is applied to the DSP controller. The experiment topology is shown in Figure 1F. Meanwhile, the output voltage and current are shown in Figure 1G.

CONCLUSION

This letter first proposes an impulse-like control scheme in multi-bus DC microgrids, which can realize voltage containment and current sharing at the same time. The problem of current sharing and voltage containment in multi-bus DC microgrids is transformed into two independent problems about formation-containment and current sharing in different linear multi-agent systems. For the multi-bus DC microgrids under this impulse-like control scheme, the current sharing is realized at non-impulse instants, and the voltage containment is realized at impulse instants, which can improve the quality of bus voltage and the reliability of multi-bus DC microgrids.

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DECLARATION OF INTERESTS

The authors declare no competing interests.