Aalborg Universitet

Admittance-type RC-mode Droop Control to Introduce Virtual Inertia in DC Microgrids

Jin, Zheming; Meng, Lexuan; Han, Renke; Guerrero, Josep M.; Vasquez, Juan C.

Admittance-type RC-mode Droop Control to Introduce Virtual Inertia in DC Microgrids

Zheming Jin, Lexuan Meng, Renke Han, Josep M. Guerrero, Juan C. Vasquez
Department of Energy Technology
Aalborg University
Aalborg, Denmark
zhe@et.aau.dk

Abstract— **One of the major feature of DC microgrids is its high penetration of power electronic converters, as a result, the system inertia becomes a problem. In this paper, an admittance-type droop control with additional capability of introducing virtual inertia to the system. With the proposed method, each energy source will also contribute virtual inertia to the system, thus improving transient response and stability of the entire DC microgrid. The inertia issue of droop control is firstly analyzed. A comparative study is carried out between conventional method (i.e. impedance-type droop control method) and the new proposal in terms of their different control principles, characteristics of equivalent output admittance/impedance, and effectiveness in achieving desired virtual inertia introduction. Ultimately, simulations and experiments are carried out to verify proposed control methods. The results show improved system inertia and enhanced performance.**

Keywords—*DC microgrids, droop control, virtual inertia, stability, transient response.*

I. INTRODUCTION

DC microgrids (MGs) are drawing great attention due to their convenience and high efficiency in integrating renewable energy sources, energy storage systems and modern electronic loads, especially in off-grid or islanded applications [1]-[2]. Power electronic converters are the key components, as well as the enabling technology, in the DC MGs, providing necessary interface between energy sources and the common DC buses. However, the high penetration of PECs will also result in a low-inertia system, the stability and the dynamic performance of which can be easily affected [3]. Therefore, virtual inertia is a promising and effective way to solve the problem without introducing additional cost or loss. Heretofore, virtual inertia control of PECs mainly focus on the active power support to the utility grid or AC MG in transient response. A representative virtual inertia control method is to operate inverters as virtual synchronous generators [4]. However, the research of virtual inertia control in the field of DC MG is barely reported.

Droop control is the common control method in both AC and DC MGs to regulate the frequency/voltage at the common buses (i.e. point of common coupling) and to share the loads properly among all the power sources [5]. In case of DC MGs, the most frequently used droop method is the V-I droop, also namely virtual resistance control, the control diagram of which

is illustrated in Fig. 1(a) (using Buck converter as example). In several recent studies [6], the I-V droop, as known as reverse droop, is introduced to achieve the similar control effect, the control diagram of which is shown in Fig. 1(b). It can be seen from the control diagrams that a virtual resistance is used in the feedback loop of V-I droop method, meanwhile, its reciprocal (physically the conductance) is used in the I-V droop method. For this reason, these two methods and their derivatives can be categorized into impedance-type and admittance-type methods to realize droop control. However, with conventional droop design (i.e. using only virtual resistance/conductance), neither V-I droop method nor I-V droop method will introduce additional inertia to the DC MGs.

(a) Control diagram of *V-I* droop method

(b) Control diagram of *I-V* droop method

(c) Generalized diagram of impedance-type droop method

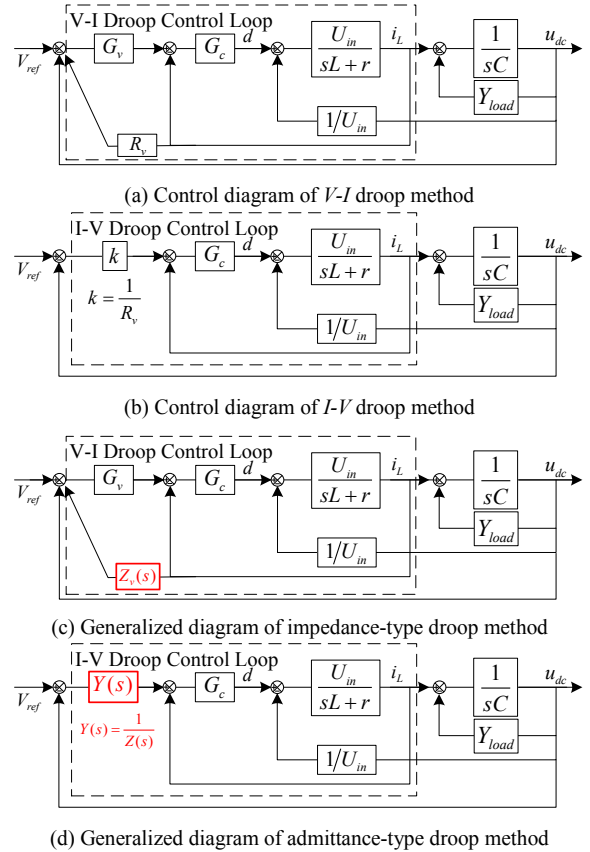(d) Generalized diagram of admittance-type droop method

Fig. 1. Illustration of different droop control methods

In this paper, an admittance-type RC-mode droop control method is proposed to introduce virtual inertia into DC MGs. The major contributions can be summarized as: (1) analysis of the inertia issue and mechanism of virtual inertia is carried out; (2) a comparison of different realization methods of droop control is carried out to address their different characteristics, especially considering complex virtual impedance/admittance; (3) propose a decentralized virtual inertia control method for inertia enhancement in DC MGs. Simulations and experiments are carried out with the proposed method and the results show enhanced system inertia and improved transient response.

II. System Inertia of DC MG

In general, inertia of a power system behaves as to prevent sudden change in critical variable spontaneously by releasing its stored energy, and thereby allowing the power sources to rebuild equilibrium timely. For AC power systems, the inertia behaves as to prevent sudden change in systemic frequency, and the active power is regulated to rebuild equilibrium, as detailed in rotation equation of synchronous machine [4]:

$$P_{set} - P_o - D_p(\omega - \omega_n) = J\omega\frac{d\omega}{dt} = P_{vi} \tag{1}$$

where P_{set}, P_o, P_{vi}, ω, ω_n, D_p, J are the active power reference, the output power, released power of inertial behavior, the real-time angular frequency, the rated angular frequency, the damping coefficient, and the moment of inertia, respectively.

When setting $J=0$, the equation (1) can be rewritten as:

$$\omega = \omega_{no} - mP_o \quad \text{where} \quad \omega_{no} = \omega_n + P_{set}/D_p; \quad m = 1/D_p; \tag{2}$$

which is the widely-used ω-P droop equation in the field of AC MGs [5]. In other words, the ω-P droop characteristic is actually emulating the behavior of a synchronous machine without inertia.

Similarly, in DC MGs, the inertia behaves as to prevent sudden change in DC bus voltage, and the output power of converters will be regulated to rebuild equilibrium, as detailed in the following power balancing equation:

$$P_{set} - P_o - D_p(u - u_n) = C_v u\frac{du}{dt} = P_{vi} \tag{3}$$

where u, u_n, C_v are the DC bus voltage, the rated DC bus voltage and the inertia coefficient (physically as a capacitance).

When setting $C_v=0$, the equation (3) can be rewritten as:

$$u = u_{no} - mP_o \quad \text{where} \quad u_{no} = u_n + P_{set}/D_p; \quad m = 1/D_p; \tag{4}$$

where i_v represents the desired current injection, u_{no} is the no-load bus voltage of DC droop control, m presents the droop coefficient of the power source.

From (1) and (3), it can be derived that the virtual inertia control is essentially modification to the droop method with additional power injection to support the system in transient-states. In addition to that, when substitute the basic power equation into (3), the desired current injection of virtual inertia control can be derived as:

$$i_{vi} = -\frac{kP_{vi}}{u} = -kC_v\frac{du}{dt} = C_v'\frac{d(u_{no} - u)}{dt} \tag{5}$$

where the injected power of virtual inertia control is k times of the system's original inertial behavior, the negative sign is to present that power is injecting to the system, $C_v'=kC_v$ which is the virtual inertia coefficient introduced to the system.

The equation (5) can be also transformed into:

$$u(s) = u_{no} - \frac{1}{sC_v'}i_{vi}(s) \tag{6}$$

$$i_{vi}(s) = sC_v'(u_{no} - u(s)) \tag{7}$$

The equation (6) and (7) show that the desired virtual inertia control can be achieved using droop control framework by adding capacitive virtual impedance/admittance in addition to the conventional virtual resistance/conductance. It is also noteworthy that the proposed component shall be equivalently parallel connected to the original virtual component. Therefore, the modified droop control function become:

$$u(s) = u_{no} - \left(\frac{1}{sC_v'} \| R_d\right)i_{vi}(s) = u_{no} - Z_d(s)i_o(s) \tag{8}$$

$$i_o(s) = \left(\frac{1}{R_d} + sC_v'\right)(u_{no} - u(s)) = Y_d(s)(u_{no} - u(s)) \tag{9}$$

In this case, each participant of droop based voltage regulation will be able to contribute both power support and virtual inertia support to the DC MG. Meanwhile, the virtual inertia become additional degree of freedom for the system design and management.

III. Impact of Different Realizations

In the last section, the inertia issue and the control principle of the proposed virtual inertia control method is analyzed. However, in the previous analysis, the dynamic behavior of controllers and the impact of using different control diagrams (i.e. impedance-type or admittance-type droop methods as shown in Fig. 1) is completely neglected. To address this problem, the impact of different realization of the proposed method is analyzed in this section.

To analyze the impact of using different realization, an admittance based analysis is carried out to address and compare the effectiveness of impedance-type and admittance-type droop methods when realizing the proposed virtual inertia control. In Fig. 2 the admittance based analysis is illustrated.
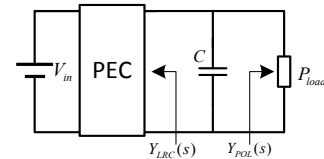

Fig. 2.   Illustration of different droop control methods

In order to analyze the behavior of dual-loop control system, a common method is to assume the inner current loop is well-designed with a control bandwidth of ω_c, and simplified as a first order transfer function [6]. In this paper, the general-case controller (PI based voltage/current control loop) is considered, therefore, the transfer function of voltage controller and close-loop transfer function of current loop are considered as:

$$G_v(s) = k_p + \frac{k_i}{s} = k_p \frac{s+\alpha}{s}; \quad G_{clc}(s) = \frac{\omega_c}{s+\omega_c}; \quad (10)$$

In [7], the detailed state-space model of the two basic droop control methods has been established. From which, the detailed close-loop transfer function of current loop and simplified case are shown in Fig. 3, it shows that the approximation is still accurate enough for further analysis.
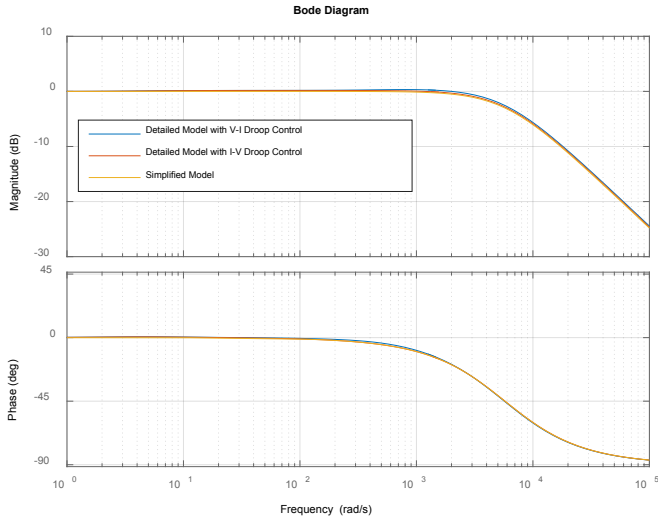

Fig. 3.   Frequency response of detailed close-loop current control

In equation (8) and (9), the ideal droop control principle has been shown. However, when considering the non-ideal control behavior of the practical controllers, the variables shown in (8) and (9) are actually the reference of inner-loop controllers. By analyzing the control diagrams shown in Fig. 1, the behaviors of impedance-type and admittance-type droop controller can be described as following equations:

$$I_o^{V-I}(s) = \frac{G_v(s)G_{clc}(s)}{1 + Z_d(s)G_v(s)G_{clc}(s)}(u_{no} - u(s)) \quad (11)$$

$$I_o^{I-V}(s) = Y_d(s)G_{clc}(s)(u_{no} - u(s)) \quad (12)$$

In this case, the output admittance/impedance of droop-controlled converters can be derived by:

$$\begin{cases} Y_o^{V-I}(s) = \dfrac{I_o^{V-I}(s)}{u_{no} - u(s)} = \dfrac{G_v(s)G_{clc}(s)}{1 + Z_d(s)G_v(s)G_{clc}(s)} \\[3mm] Z_o^{V-I}(s) = \dfrac{1}{Y_o^{V-I}(s)} = Z_d(s) + \dfrac{1}{G_v(s)G_{clc}(s)} \end{cases} \quad (13)$$

$$\begin{cases} Y_o^{I-V}(s) = \dfrac{I_o^{I-V}(s)}{u_{no} - u(s)} = Y_d(s)G_{clc}(s) \\[3mm] Z_o^{I-V}(s) = \dfrac{1}{Y_o^{I-V}(s)} = \dfrac{Z_d(s)}{G_{clc}(s)} = Z_d(s) + \dfrac{s}{\omega_c}Z_d(s) \end{cases} \quad (14)$$

From these equations, several very important remarks can be derived:

- The output admittance/impedance of impedance-type realization is performed by desired virtual impedance and an irrelevant component connected in series. The additional component is determined by the parameters of the dual-loop controller, which can be treat as the intrinsic impedance of the controller.

- The output admittance/impedance of admittance-type realization is performed by desired virtual admittance and a higher-order term of the virtual admittance. The additional component is determined by both the virtual admittance design and control bandwidth of the system.

By substitute (10) into (13), the intrinsic impedance can be described as:

$$\begin{aligned} Z_{con}^{V-I}(s) &= \frac{1}{G_v(s)G_{clc}(s)} = \frac{1}{k_p\omega_c}\frac{s(s+\omega_c)}{s+\alpha} \\[2mm] &= s\frac{1}{k_p\omega_c} + s\frac{\omega_c - \alpha}{k_p\omega_c\alpha} \parallel \frac{\omega_c - \alpha}{k_p\omega_c} \\[2mm] &= sL_1 + sL_2 \parallel R_1 \end{aligned} \quad (15)$$

In Fig. 4, the derived output admittance/impedance are presented by equivalent circuits. It is important to notice that the intrinsic impedance of the dual-loop controlled converter (including both voltage mode control and impedance-type droop control) is mainly inductive. The presence of inductive intrinsic impedance will make impedance-type method less effective when achieving proposed virtual inertia control.
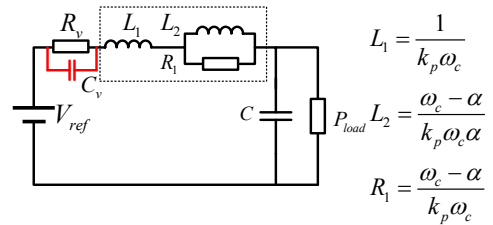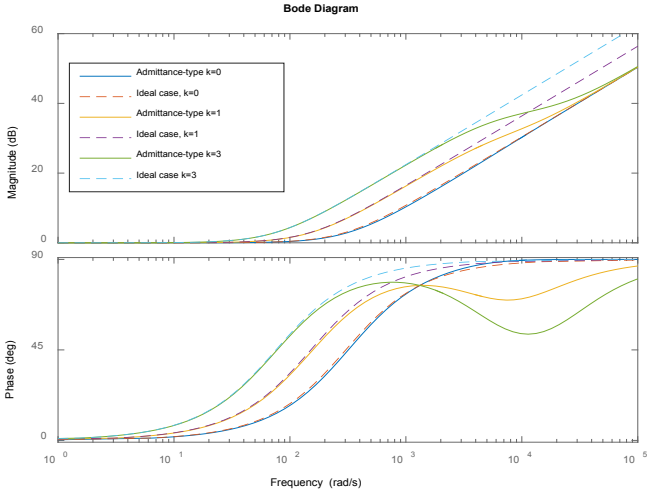

(a)   Derived equivalent circuit of impedance-type droop method
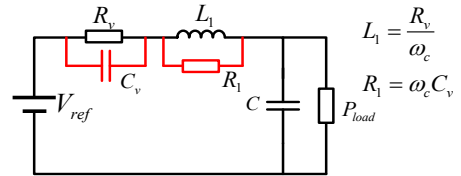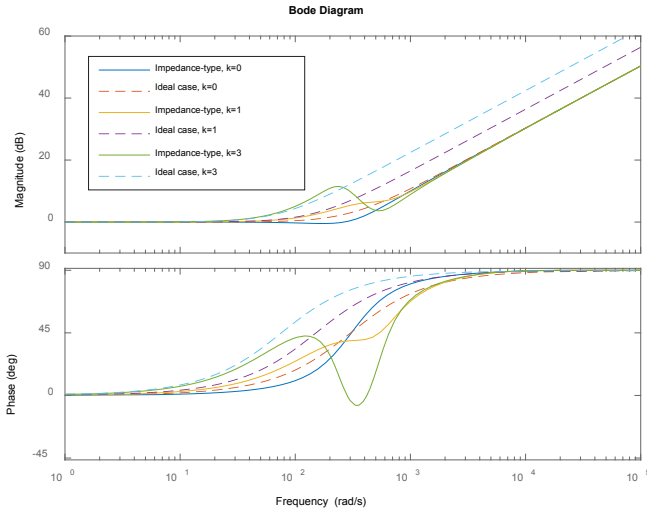

(b)   Derived equivalent circuit of admittance-type droop method

Fig. 4. Equivalent circuits of different droop approaches with proposed virtual inertia control. (virtual components introduced by proposed virtual inertia method is marked red)

(a) Source-side admittance of the system using admittance-type droop method with different settings of virtual inertia

(b) Source-side admittance of the system using impedance-type droop method with different settings of virtual inertia

Fig. 5. Derived source-side admittance of the system using different droop approaches together with different settings of virtual inertia.

In Fig. 5, the frequency-response of source-side admittance with different settings of virtual inertia ($k=0,1,3$). In order to compare the effectiveness (or suitableness) of different droop approaches, the ideal cases which is derived by assuming the output admittance of droop-controlled converters are exactly as desired design (i.e. $Y_o=1/R_d+sC_v'=1/R_d+ksC_v$).

From Fig. 5(a), it can be found that the system behavior within the control bandwidth of current loop is following the ideal case very well when using admittance-type realization of proposed virtual inertia control. Beyond the control bandwidth limitation, the virtual inertia will gradually degrade.

As for impedance-type realization, the output admittance of the system does not follow the ideal case very well, which means the system behavior will not meet the expectation. In addition to that, the interaction between the intrinsic impedance and desired virtual capacitance is significant. The interaction

shows resonant behavior and it will further reduce the effective range of the impedance-type realization.

Based on these analytical results, the admittance-type droop method is chosen as the realization method for proposed virtual inertia control.

IV. SIMULATION VALIDATION OF PROPOSED METHOD

In order to validate the proposed virtual inertia control method, simulations are carried out using PLECS. The study case DC MG used in the simulation has the same parameters of experimental setup. In the simulation, two droop-controlled converters are connected in parallel, feeding a resistive load. The system parameters are listed in Table I.

In Fig. 6 the simulation results are shown. In Fig. 6(a), the simulation results of basic admittance-type realization without virtual inertia control (i.e. $k=0$). In Fig. 6(b), the simulation results of using proposed virtual inertia control are shown.
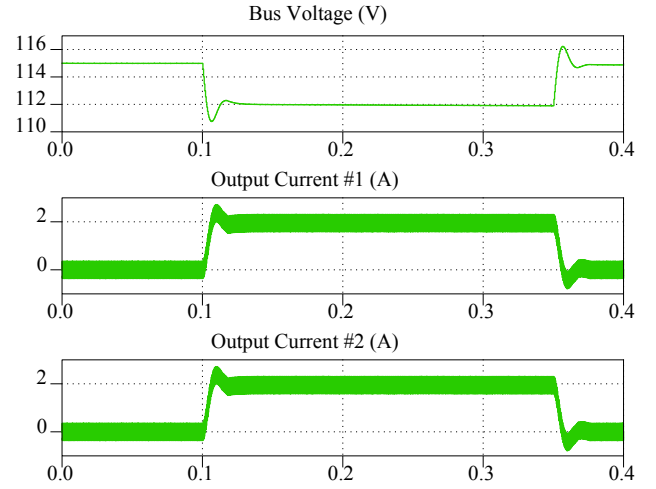
(a) Simulation results of load changing without proposed virtual inertia control
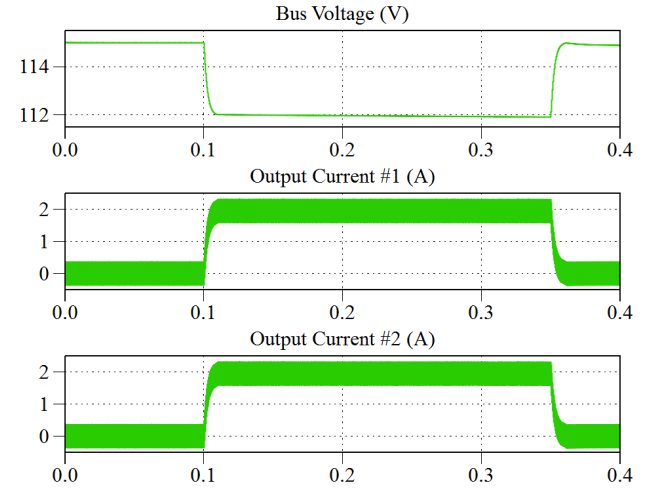
(b) Simulation results of load changing with proposed virtual inertia control

Fig. 6. Simulation results of load changing with and without proposed virtual inertia control.

TABLE II.   PARAMETERS OF SIMULATED STUDY CASE

Description of the Parameter	Symbol	Value
Global No-load Voltage Reference	V_{ref}	115 V
Source Voltage	E_1, E_2	230 V, 230 V
Inductance of Buck Converters	L_1, L_2	8 mH, 8 mH
Stary Resistance of inductors,	r_1, r_2	0.1 Ω, 0.1 Ω
Switching Frequency	f_{sw}	10 kHz
Virtual Resistances for Droop Control	R_{v1}, R_{v2}	1.5 Ω, 1.5 Ω
Total Capacitance in DC Bus	C	3.3 mF
Proportion Term of Current Controller	K_{pc1}, K_{pc2}	0.02, 0.02
Integral Term of Current Controller	K_{ic1}, K_{ic2}	0.1, 0.1
Resistive Load	R_{Load}	28.75 Ω

TABLE I.   PARAMETERS OF EXPERIMENTAL TESTBED

Description of the Parameter	Symbol	Value
Global No-load Voltage Reference	V_{ref}	120 V
Source Voltage	E_i	240 V, 240 V
Inductance of Buck Converters	L_i	8.6 mH, 8.6 mH
Stary Resistance of inductors,	r_i	0.1 Ω, 0.1 Ω
Switching Frequency	f_{sw}	10 kHz
Virtual Resistances for Droop Control	R_{vi}	4 Ω, 4 Ω
Virtual Capacitance for Virtual Inertia	C_{vi}	2mF
Total Capacitance in DC Bus	C	3.3 mF
Proportion Term of Current Controller	K_{pci}	0.02, 0.02
Integral Term of Current Controller	K_{ici}	0.1, 0.1
Resistive Load	R_{Load}	17 Ω

The simulation results show that with proposed virtual inertia control, the dynamic response of DC bus voltage will have reduced overshoot and smoother transient when load changing occurs in the system.

V.   EXPERIMENTAL VALIDATION OF PROPOSED METHOD

In order to verify the proposed virtual inertia control methods, especially its performance under noised real-world DC MGs, experiments are also carried out using a LVDC MG setup with four DC/DC converters. The parameters of the

LVDC MG setup are shown in Table II. The real-time control and data acquisition are done by dSpace RTI 1006 platform. The experimental results are shown in Fig. 7 and Fig. 8.

By comparing the experimental results shown in Fig. 7 and Fig. 8, it can be found that the inertial behavior of the system is strengthened after adopting proposed virtual inertia control method. It is performed by the improved bus voltage transient,
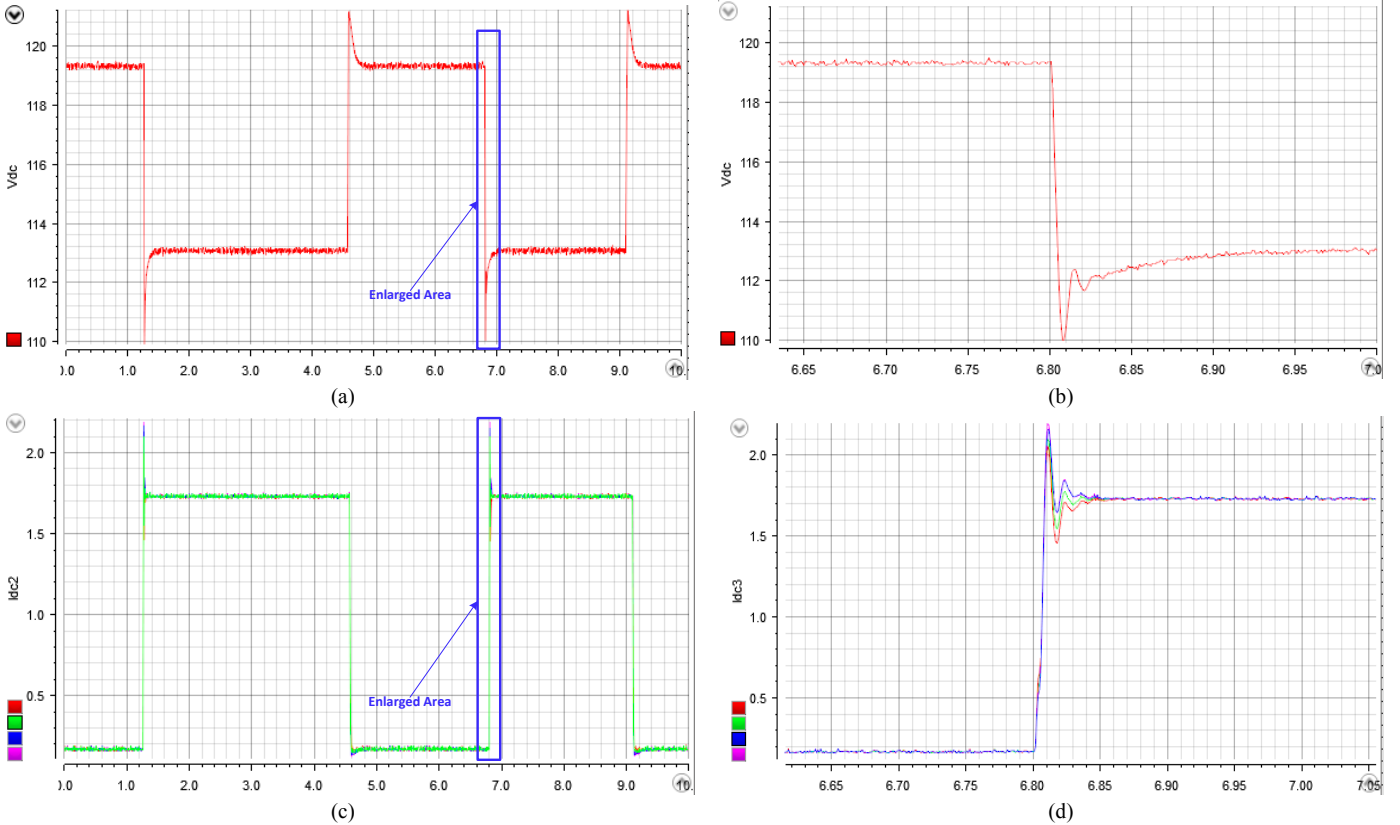

Fig. 7. Experimental results of load changing with basic admittance-type droop (without proposed virtual inertia control design) : (a) DC bus voltage response; (b) Transient response of DC bus voltage; (c) Output currents of converters; (d) transient response of output currrent.

Fig. 8. Experimental results with proposed virtual inertia control realized by admittance-type droop method ($R_v=4\Omega$, C_v=2mF): (a) DC bus voltage response; (b) Transient response of DC bus voltage; (c) Output currents of converters; (d) transient response of output currents.
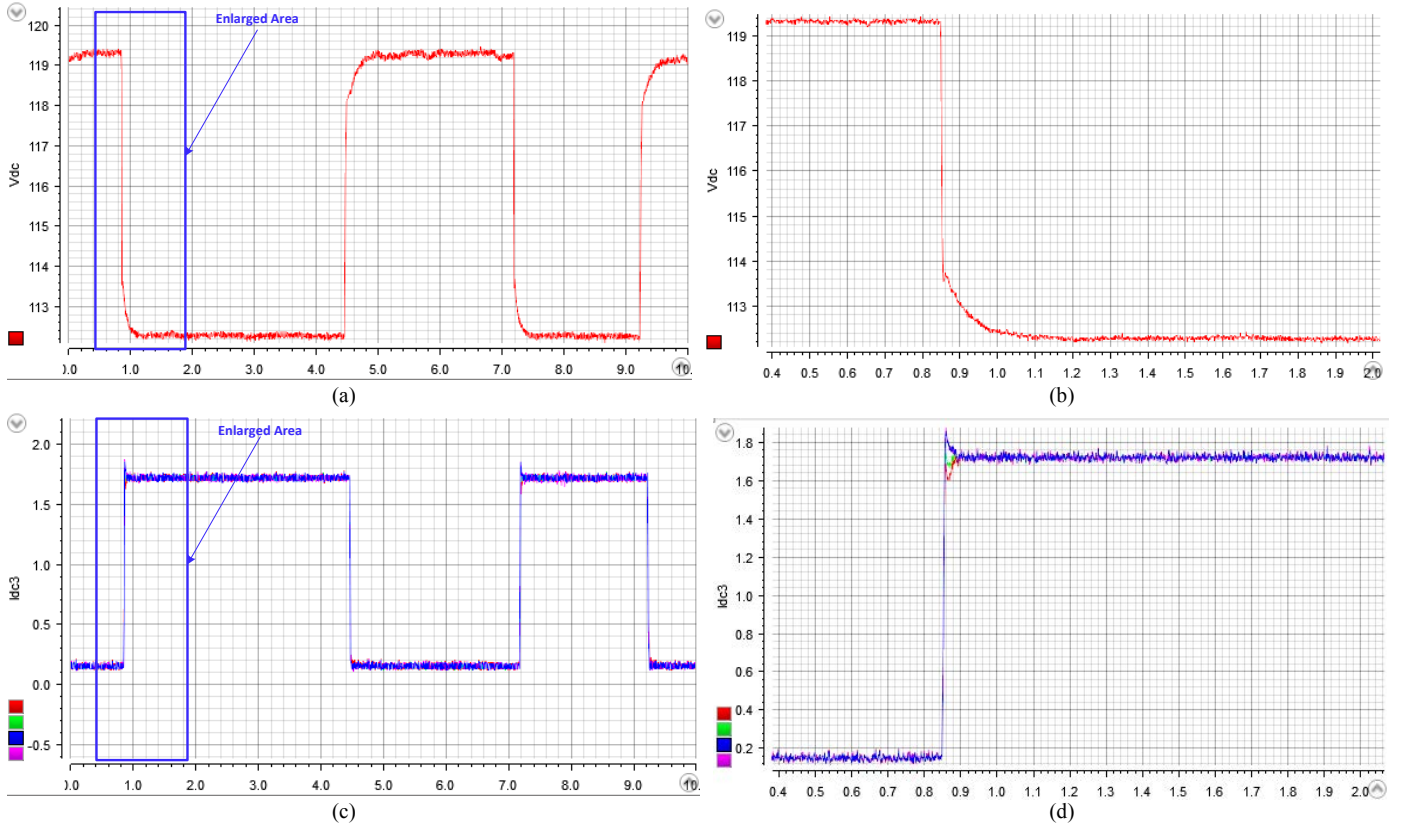
significantly reduced overshoots, faster response of output voltage, and the increased time constant of the system when load increases. It is also noteworthy that the proper power sharing effect of droop control is not affected by the proposed virtual inertia control.

The experimental results show that with proposed virtual inertia control method, the inertia of the entire DC MG can be improved, and thus being able to mitigate the low-inertia issue of DC MG.

VI. CONCLUSION

In this paper, an admittance-type RC-mode droop control method is proposed to introduce virtual inertia into DC MGs. The inertia issue and the mechanism of virtual inertia in DC MGs are analyzed. A comparative study is carried out to address the impact of using different realization methods of droop control, especially considering complex design of the virtual impedance/admittance. The analytical results indicate that admittance-type realization method has advantages when achieving proposed virtual inertia control. Based on the analytical results, simulations and experiments are carried out to validate the proposed control methods. The results show effective improvement in the system-level inertial behavior and transient response. Meanwhile, the desired proportional power sharing effect of droop control is not affected. To the author's knowledge, with enhanced system inertia, DC MG will have (1) improved stability margin when feeding constant power loads; (2) enhanced 'Plug & Play' capability and better scalability.

REFERENCES

[1] B. T. Patterson, "DC, Come Home: DC Microgrids and the Birth of the "Enernet"," in *IEEE Power and Energy Magazine*, vol. 10, no. 6, pp. 60-69, Nov.-Dec. 2012.

[2] M. Liserre, T. Sauter, and, Y. Hung John, "Future energy systems Integrating renewable energy sources into the smart power grid through industrial electronics," *IEEE Ind. Electron. Mag.*, vol. 4, no. 1, pp. 18-37, Mar. 2010.

[3] X. Lu, K. Sun, J. M. Guerrero, J. C. Vasquez, L. Huang, and J. Wang, "Stability Enhancement Based on Virtual Impedance for DC Microgrids With Constant Power Loads," *IEEE Trans. Smart Grid*, vol. 6, no. 6, pp. 2770-2783, Aug. 2015.

[4] H. P. Beck and R. Hesse, "Virtual synchronous machine," *2007 9th International Conference on Electrical Power Quality and Utilisation*, Barcelona, 2007, pp. 1-6.

[5] J. M. Guerrero, J. C. Vasquez, J. Matas, L. G. De Vicuña, and M. Castilla, "Hierarchical control of droop-controlled AC and DC microgrids - A general approach toward standardization," *IEEE Trans. Ind. Electron.*, vol. 58, no. 1, pp. 158–172, 2011.

[6] F. Gao *et al.*, "Comparative Stability Analysis of Droop Control Approaches in Voltage-Source-Converter-Based DC Microgrids," in *IEEE Transactions on Power Electronics*, vol. 32, no. 3, pp. 2395-2415, March 2017.

[7] Z. Jin, L. Meng, J. M. Guerrero. "Comparative Admittance-based Analysis for Different Droop Control Approaches in DC Microgrids," *Proceedings of 2nd International Conference on DC Microgrids, IEEE, 2017,* pp1-6.