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The influence of internal current loop on transient response performance of I-V droop controlled paralleled DC-DC converters

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The Influence of Internal Current Loop on Transient Response Performance of I-V Droop Controlled Paralleled DC-DC Converters

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Abstract—The external droop control loop of *I-V* droop control is designed as a voltage loop with embedded virtual impedance, so the internal current loop plays a major role in the system bandwidth. Thus, in this paper, the influence of internal current loop on transient response performance of *I-V* droop controlled paralleled dc-dc converters is analyzed, which is guided and significant for its industry application. The model which is used for dynamic analysis is built, and the root locus method is used based on the model to analyze the dynamic response of the system by shifting different control parameters. Analysis results show that any converter's inner current loop can influence all converters' dynamic responses in the system and the one with larger Virtual Resistance (VR) has greater effect. Increasing the proportional terms can decrease the fluctuations of current and voltage, and key parts of errors can be reduced more rapidly during dynamical process, but adverse effect on completely eliminating errors can be caused; increasing integral terms can enlarge current fluctuations during dynamical process, but the errors can be eliminated more rapidly. The experiments are performed to verify the analysis.

Keywords—Paralleled dc-dc converters; I-V droop control; transient response performance; internal current loop

I. INTRODUCTION

With the development of dc distributed generation and energy storage, increasing proportion of DC load and higher requirement of power quality for sensitive load, dc microgrid will become an important part of power system in the future [1]-[3]. Paralleled operation of dc-dc converters have been widely used in various applications in DC Microgrids (MGs), such as connecting multi batteries to the common bus or connecting multiple busses with different voltages [4-8]. A typical structure of a dc MG consisted of paralleled dc-dc converters with multiple energy storage systems (ESS) is shown in Fig. 1.

Since droop control method is a decentralized strategy by imposing virtual resistance which does not require communication links and offers higher reliability and flexibility, it is often used in the primary control level to make the system stable and guarantee load sharing between each converter. However, when using droop control methods, the major concerns of previous works are focused on the *V-I* droop control which is achieved by linearly reducing the voltage reference when the output current increases, so a slow voltage loop and a separate extra virtual impedance loop is included, which may limit the system bandwidth. However, the *I-V* control method, whose external droop control loop is designed as a voltage loop with embedded virtual impedance, has not been studied so much in previous works [9]. The internal current loop of *I-V* droop control, thanks to the external control loop simplification, plays a major role in the system bandwidth, so that the influence of the internal current loop on the transient response performance of dc-dc converters is analyzed in this paper, which is guided and significant for its industry application.

As a typical method, average-value modeling for converters has been studied in many publications [10], [11]. Average-value modeling method, whose objective is to replace the discontinuous switching cells with continuous blocks that represent the averaged behavior of the switching cell within a prototypical switching interval, can be derived using state-space averaging or circuit averaging methods [12-14]. Based on the average-value modeling theory, the state-space modeling method which is used for the analysis of the dynamic characteristics of paralleled dc-dc converters is proposed. The load current change is set to the input of the model, and the state variables of the model include the variations of converter's output currents and bus voltage caused by load changes, so that the model can be used to analyze the dynamic response performance of the system.

This paper is structured as follows. In Section II, the state-space modeling method is proposed for *I-V* controlled paralleled dc-dc converters to analyze its transient response performance. In Section III, the influence of internal current loop on the dynamic response performances is analyzed. In Section IV, experiments are performed to verify the analysis. Section V concludes this paper.

II. MODELING FOR PARALLELED CONERTERS

A. I-V Droop Control Diagram

The *I-V* droop control can be obtained as shown in Fig. 2(b), which is achieved by linearly increasing the current reference when the bus voltage decreases. The current reference can be computed as
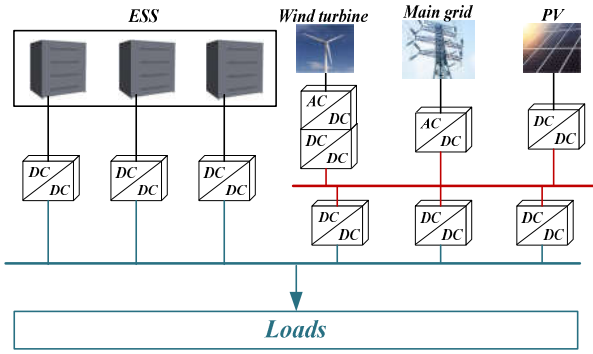
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Fig. 1. A typical structure of dc MG.

$$i_{ref} = \frac{1}{r}(U_{rate} - u) \quad (1)$$

where U_{rate} is the no load voltage of the source, r is the virtual resistance (VR), i_{ref} is the current reference and u is the bus voltage. For n paralleled dc-dc converters the total load current can be shared in proportion to their reciprocals of VRs at steady-state:

$$i_1 r_1 = i_2 r_2 = \cdots = i_n r_n \quad (2)$$

where i_k ($k=1, 2, \ldots, n$) is the output current, r_k ($k=1, 2, \ldots, n$) is the VR, and n is the number of parallel-connected converters.

B. Modeling for V-I Droop Control

According to the average-value modeling method, the follow can be obtained as [15]

$$\Delta i_{cycle} = \int_0^T \frac{dU_{in} - u_{dc}}{L} dt \quad (3)$$

where Δi_{cycle} is the increment of the average inductor current in an arbitrary switching cycle, L is the inductance value, T is the switching cycle, U_{in} is the input voltage, d is the duty ratio of the upper bridge arm and u_{dc} is the dc bus voltage.

In steady-state, suppose that i_{ld0} and u_{dc0} is the load current and bus voltage respectively, $\boldsymbol{I_{ref0}}$, $\boldsymbol{I_0}$ and $\boldsymbol{D_0}$ are the average inductor current, the current reference and the duty ratio of n converters respectively, where

$$\boldsymbol{I_{ref0}} = \begin{bmatrix} i_{ref10} & i_{ref20} & \cdots & i_{refn0} \end{bmatrix}$$

$$\boldsymbol{I_0} = \begin{bmatrix} i_{10} & i_{20} & \cdots & i_{n0} \end{bmatrix}$$

$$\boldsymbol{D_0} = \begin{bmatrix} d_{10} & d_{20} & \cdots & d_{n0} \end{bmatrix}$$

Setting zero-time as the instant of load changing, let $i_{ldv}(t)$ and $u_{ddc}(t)$ represent the variation of load current and DC bus voltage, $\boldsymbol{I_{dref}}(t)$, $\boldsymbol{I_d}(t)$ and $\boldsymbol{D_d}(t)$ represent the variation of n converter's current reference, inductor current and duty ratio respectively, where
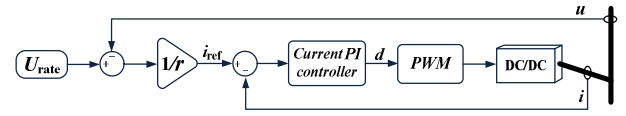

Fig. 2. *I-V droop control implementations.*

$$\boldsymbol{I_{dref}} = \begin{bmatrix} i_{dref1} & i_{dref2} & \cdots & i_{drefn} \end{bmatrix}$$

$$\boldsymbol{I_d} = \begin{bmatrix} i_{d1} & i_{d2} & \cdots & i_{dn} \end{bmatrix}$$

$$\boldsymbol{D_d} = \begin{bmatrix} d_{d1} & d_{d2} & \cdots & d_{dn} \end{bmatrix}$$

Let $\boldsymbol{I}$ represent the n-order vector, according to (3), the following matrix identity can be obtained as

$$\boldsymbol{I_d}(t)^T = \boldsymbol{L^{-1}} \cdot \int_0^t \{ \boldsymbol{U_{in}} \cdot [\boldsymbol{D_0}^T + \boldsymbol{D_d}(t)^T] - \boldsymbol{I}^T \cdot [u_{dc0} + u_{ddc}(t)] \} dt \quad (4)$$

where

$$\boldsymbol{U_{in}} = \begin{bmatrix} U_1 & 0 & \cdots & 0 \\ 0 & U_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & U_n \end{bmatrix} \quad \boldsymbol{L} = \begin{bmatrix} L_1 & 0 & \cdots & 0 \\ 0 & L_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & L_n \end{bmatrix}$$

According to (3), the following equation can also be obtained as

$$\boldsymbol{I}^T \cdot u_{dc0} = \boldsymbol{U_{in}} \cdot \boldsymbol{D_0}^T \quad (5)$$

Substituting (5) into (4), (4) can be rewritten as

$$\boldsymbol{I_d}(t)^T = \boldsymbol{L^{-1}} \cdot \int_0^t [\boldsymbol{U_{in}} \cdot \boldsymbol{D_d}(t)^T - \boldsymbol{I}^T \cdot u_{ddc}(t)] dt \quad (6)$$

Then

$$\frac{d\boldsymbol{I_d}(t)^T}{t} = \boldsymbol{L^{-1}} \cdot [\boldsymbol{U_{in}} \cdot \boldsymbol{D_d}(t)^T - \boldsymbol{I}^T \cdot u_{ddc}(t)] \quad (7)$$

Considering load current as the input of the model, the following matrix equation can be easily obtained as

$$\begin{aligned} \frac{d[u_{dc0} + u_{ddc}(t)]}{dt} &= \frac{du_{ddc}(t)}{dt} \\ &= \frac{1}{C} \{ \boldsymbol{I} \cdot [\boldsymbol{I_0}(t)^T + \boldsymbol{I_d}(t)^T] - i_{ld0} - i_{ldv}(t) \} \\ &= \frac{1}{C} [\boldsymbol{I} \cdot \boldsymbol{I_d}(t)^T - i_{ldv}(t)] \end{aligned} \quad (8)$$

According to (1), the follow can be obtained as

$$\boldsymbol{I_0}^T = \boldsymbol{I_{ref0}}^T = \boldsymbol{R^{-1}} \cdot \boldsymbol{I}^T \cdot (U_{rate} - u_{dc0}) \quad (9)$$

$$\boldsymbol{I_{ref0}}^T + \boldsymbol{I_{dref}}(t)^T = \boldsymbol{R^{-1}} \cdot \boldsymbol{I}^T \cdot \{ U_{rate} - [u_{dc0} + u_{ddc}(t)] \} \quad (10)$$
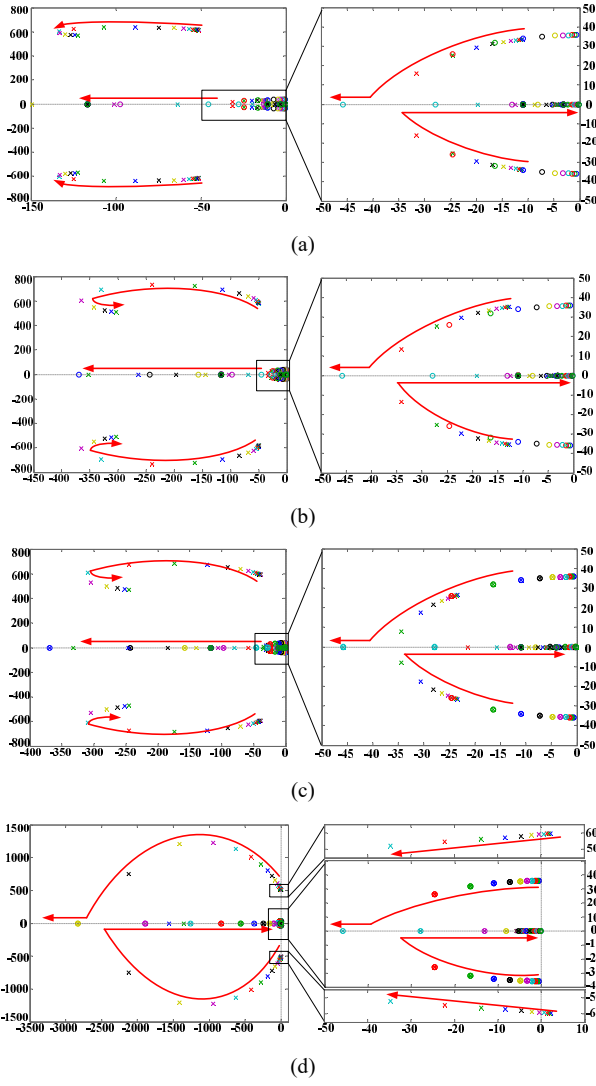
where

(a)

(b)

(c)

(d)

Fig. 3. Root locus analysis for all converters with proportional terms changing. (a) k_{pi1} changing from 0.00001 to 0.1, $k_{pi2}=k_{pi3}=k_{pi4}=0.001$. (b) k_{pi4} changing from 0.00001 to 0.1, $k_{pi1}=k_{pi2}=k_{pi3}=0.001$. (a) k_{pi1} and k_{pi2} changing from 0.00001 to 0.1, $k_{pi3}=k_{pi4}=0.001$. (c) k_{pi1}, k_{pi2}, k_{pi3} and k_{pi4} changing from 0.00001 to 0.1

$$R = \begin{bmatrix} r_1 & 0 & \cdots & 0 \\ 0 & r_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & r_n \end{bmatrix}$$

Let K_{pi} and K_{ii} represent the diagonal matrix whose diagonal elements are the proportion parameters and the integral parameters of n converter's inner current loop respectively where

$$K_{pi} = \begin{bmatrix} k_{pi1} & 0 & \cdots & 0 \\ 0 & k_{pi2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & k_{pin} \end{bmatrix}, K_{ii} = \begin{bmatrix} k_{ii1} & 0 & \cdots & 0 \\ 0 & k_{ii2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & k_{iin} \end{bmatrix}$$
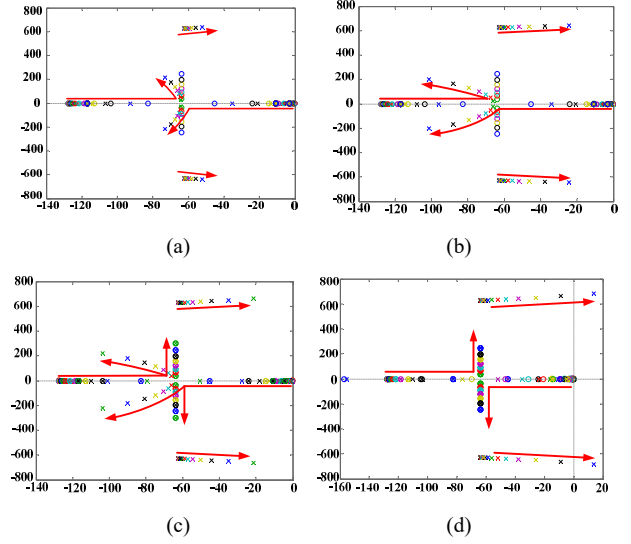

(a)

(b)

(c)

(d)

Fig. 4. Root locus analysis for all converters with integral terms changing (a) k_{ii1} changing from 0.0001 to 1, $k_{ii2}=k_{ii3}=k_{ii4}=0.01$. (b) k_{ii4} changing from 0.0001 to 1, $k_{ii1}=k_{ii2}=k_{ii3}=0.01$. (c) k_{ii1} and k_{ii2} changing from 0.0001to 1, $k_{ii3}=k_{ii4}=0.01$. (d) k_{ii1}, k_{ii}, k_{ii3} and k_{ii4} changing from 0.0001 to 1.

Considering the inner current loop, the difference of the duty ratios compared with D_0 can be given as

$$D_d(t)^T = K_{pi}\{[I_{ref0}{}^T + I_{dref}(t)^T] - [I_0{}^T + I_d(t)^T]\}$$
$$+ K_{ii}\int_0^t \{[I_{ref0}{}^T + I_{dref}(t)^T] - [I_0{}^T + I_d(t)^T]\}dt \tag{11}$$

Calculating the time derivative of (11) and by considering (9) and (10), (12) can be rewritten as

$$\frac{dD_d(t)}{dt} = [-\frac{du_{ddc}(t)}{dt}IR^{-1} - \frac{dI_d(t)}{dt}]K_{pi}$$
$$+ [-u_{ddc}(t)IR^{-1} - I_d(t)]K_{ii} \tag{12}$$

Substituting (7) and (8) into (12), (12) can be rewritten as

$$\frac{dD_d(t)}{dt} = -(\frac{K_{pi}\cdot S\cdot I^T\cdot I}{C} + K_{ii})\cdot I_d(t)^T - K_{pi}\cdot L^{-1}\cdot U_{in}\cdot D_d(t)^T$$
$$+ (K_{pi}L^{-1} - K_{ii}\cdot R^{-1})\cdot I^T\cdot u_{ddc}(t) + \frac{K_{pi}\cdot R^{-1}\cdot I^T}{C}\cdot i_{ldv}(t) \tag{13}$$

In order to analyze a general multi module system consisting of n converters, (7), (8) and (13) can be rewritten in a more compact state space model defined as

$$\dot{x} = A\cdot x + B\cdot y \tag{14}$$

where

$$A = \begin{bmatrix} 0 & L^{-1}U_{in} & -L^{-1}I^T \\ \dfrac{K_{pi}R^{-1}I^TI}{C} - K_{ii} & -K_{pi}L^{-1}U_{in} & K_{pi}L^{-1}I^T - K_{ii}R^{-1}I^T \\ \dfrac{1}{C}\cdot I & 0 & 0 \end{bmatrix} \tag{15}$$

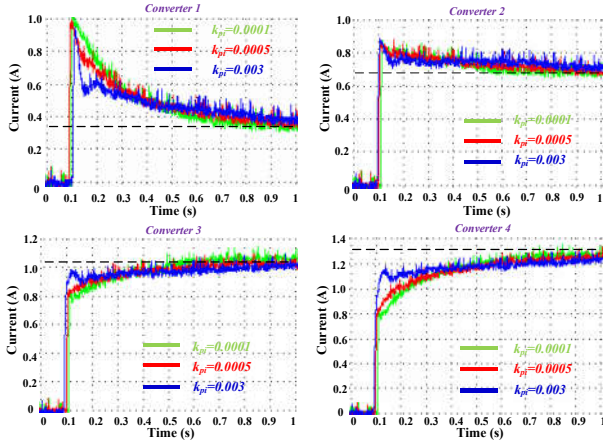Fig. 6. Dynamic process of four converters with different proportional term values when integral term values are 0.01.

Fig. 5. Dynamic process of four converters with different proportional term values when integral term values are 0.1.

$$x = [I_{\mathrm{d}}(t) \quad D_{\mathrm{d}}(t) \quad u_{\mathrm{ddc}}(t)]^{\mathrm{T}} \tag{16}$$

$$B = [0 \quad \frac{IK_{\mathrm{pi}}R^{-1}}{C} \quad -\frac{1}{C}]^{\mathrm{T}} \tag{17}$$

$$y = i_{\mathrm{ldv}}(t) \tag{18}$$

III. Dynamic Analysis for *I-V* Droop Control

Taking four paralleled converters as an example, the root locus method is used based on the model shown in (14) to analyze the dynamic response of the system by shifting different control parameters. The electrical setup and droop parameters which are kept constant are shown in Table I.

TABLE I.   PARAMETERS

Parameters		Value
Symbol	**Description**	
E	Input Voltage Voltage	230 V
L	Converter Inductance	1.8 mH
C	DC Bus Capacitance	8800μF
r_1	VR of Converter 1	1Ω
r_2	VR of Converter 2	1/2Ω
r_3	VRe of Converter 3	1/3Ω
r_4	VR of Converter 4	1/4 Ω
U_{rate}	Rated Bus Voltage	100V

A. Influence of Proportional Term

The proportional and integral term values for four converters are initialized as 0.001 and 0.01, respectively. Then respectively changing the proportional term values of different converters from 0.00001 to 0.1, the pole shifting trajectories of all converters' average inductor currents are shown in Fig. 3 (a)-(d).
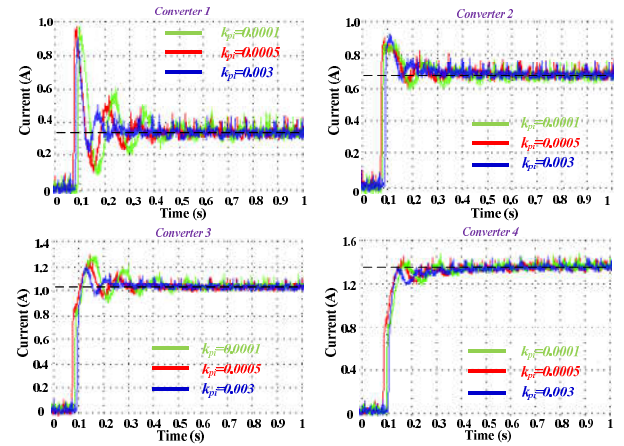
Fig. 3 (a) and (b) indicate that one converter's proportional term influences all converters' dynamic responses in the system and the one with larger VR has greater effect. According to Fig. 3 (a), (c) and (d) it can be seen that the proportional term shifting of more converters has more influence on the all converters' dynamic response performances.

Fig. 3 (a)-(d) show that appropriately increasing the proportional terms can decrease the fluctuations of converters' output currents, and part of errors can be reduced more rapidly during dynamical process. However, adverse effect on completely eliminating errors can be caused by increasing proportional terms. To be mentioned, Fig. 3 (d) shows that the system can be unstable when all the proportional terms are too small.

B. Influence of Integral Term

When the four converters' proportional and integral term values are initialized as 0.001 and 0.01, changing the integral term values of different converters from 0.0001 to 1, respectively, the pole shifting trajectories of four converters' output currents can be observed as show in Fig. 4 (a)-(d).

Fig. 4 (a) and (b) indicate that one converter's integral term influences all converters' dynamic responses in the system and the one with larger VR has more influence. According to Fig. 4 (a), (c) and (d) it can be seen that the integral term shifting of more converters has more influence on the all converters' dynamic response performances. In Fig. 4 (a)-(d), the result can be obtained that increasing integral terms can enlarge current fluctuations during dynamical process, but the errors can be eliminated more rapidly. Specifically, Fig. 4 (d) shows that the system can be unstable when all the integral terms are too large.

IV. Experiment Verification

The islanded experimental platform, which consists of four 0.7 kW dc-dc converters, a battery, a real-time dSPACE1006 platform and resistance loads, has been built. The switching
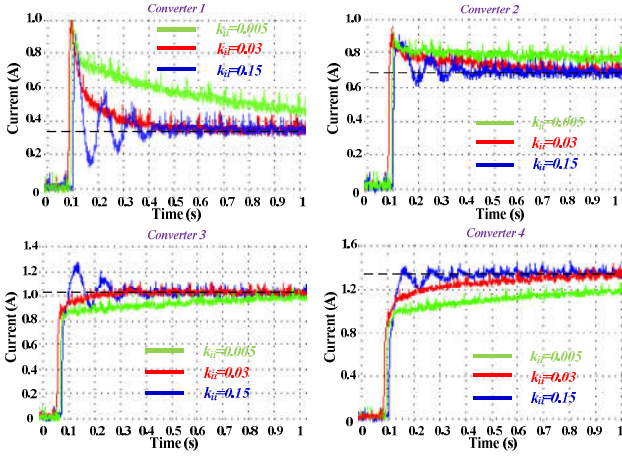
Fig. 7. Dynamic process of four converters with different integral terms.

frequency is set to 10 kHz. The parameters of electrical setup and VR are listed in Table I as well.

A. Changing Proportional Term

The dynamic response experiments have been performed when the proportional term values of four converters are 0.0001, 0.0005 and 0.003, respectively, and the four integral term values equal to 0.01. Setting 350W load into dc bus, the current waveforms under three proportional term values are shown in Fig. 5 which indicate that increasing the proportional terms can reduce errors more rapidly, but adverse effect on completely eliminating errors can be caused.

When the proportional term values of four converters are 0.0001, 0.0005 and 0.003, respectively, and the four integral term values equal to 0.1, setting 350W load into dc bus, the current waveforms under three proportional term values are shown in Fig. 6 which indicates that with the proportional terms increasing, the fluctuations can be decreased more rapidly during dynamical process. The above experiments are in good agreement with root locus analysis.

B. Changing Integral Term

The dynamic response experiments have been performed when the integral term values of four converters are 0.005, 0.03 and 0.15, respectively, and the four proportional term values equal to 0.001. Putting 350W load into dc bus, the output current waveforms are shown in Fig. 7. The experimental results show that increasing integral term values results in more current fluctuations during dynamical process, but the errors of four currents can be eliminated more rapidly, which are in good agreement with the root locus analysis.

V. CONCLUSION

The modeling method of *I-V* droop controlled paralleled dc-dc converters, which is suitable for the analysis of transient response performance, is proposed in this paper. Based on this model, the influence of the inner current loop on the dynamic performance is analyzed by using the root locus method. Analysis results show that any converter's inner current loop

can influence all converters' dynamic responses in the system and the one with larger VR has greater effect. Increasing the proportional terms can decrease the fluctuations of converters' output currents, and key parts of errors can be reduced more rapidly during dynamical process, but adverse effect on completely eliminating errors can be caused; increasing integral terms can enlarge current fluctuations during dynamical process, but the errors can be eliminated more rapidly. Experiments have been performed to verify the aforementioned analysis.

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