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# Decoupled Average Current Balancing Method for Interleaved Buck Converters with Dual Closed-Loop Control

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***Abstract*—Dual closed-loop feedback control is commonly used to regulate the output voltage of interleaved buck converters. Meanwhile, current balancing control is used to balance inductor currents between the sub-modules. However, the coupling of dual closed-loop and balancing loop will cause interaction between control loops and complicate the design of controller parameters. In this paper, a decoupled average current balancing method with parallel dual closed-loop control is proposed. Based on the small signal model of interleaved buck converters, the decoupling conditions of dual closed-loop and balancing loops are derived. Then, the decoupled average current balancing control is designed. The small-signal transfer functions show that proposed current balancing loops and dual closed-loop are decoupled. Therefore, the controller parameters of each control loop can be designed independently. Finally, the experimental results are presented to validate the effectiveness of the proposed control method.**

***Keywords—interleaved Buck converter, current balancing control, decoupled***

## I. INTRODUCTION

The interleaved DC-DC converters is widely used in applications where the number of parallel modules is fixed to meet the requirements of high power and high reliability. However, differences in circuit components will cause current imbalance [1], which will reduce converters performance. Therefore, the current balancing control method of the interleaved technology has been studied. The current balancing control method can be roughly divided into multiloop control and parallel loops control [2].

In [3], the voltage regulation loop and the current balancing loop form a multiloop. The output of the voltage regulation loop is used as the reference of the current balancing loop. Therefore, both loops must be coupled. the coupling of both loops will complicate the design of controller parameters and cause interaction between controller. In [4], the voltage regulation loop and the current balancing loop form a parallel loop. The control method is simple, but the regulation of the current balancing loop will contribute to the fluctuation of the output voltage. Therefore, the control loops are still coupled. In [5] and [6], the decoupled current balancing control is proposed, which is able to solve the coupled problem between the voltage regulation loop and the current balancing loops. In [7], the decoupled current balancing control is also proposed, which is able to solve the coupled problem between the output current regulation loop and the current balancing loops. However, in [5]-[7], the decoupled output control loop is a single feedback control loop, which is difficult to apply to high power applications. Therefore, it is necessary to control the output voltage with dual closed-loop for excellent converters transient characteristics.

In this paper, a decoupled average current balancing control with parallel dual closed-loop is proposed. The dual closed-loop with inner current-regulating loop and outer voltage-regulating loop is used to improve converters transient characteristics. Firstly, the small-signal transfer functions of the dual closed-loop and current balancing loops are derived. The results show the decoupling conditions of the dual closed-loop and balancing loops. Then, dual closed-loop feedback controller, current balancing controller and decoupling networks are designed. The small-signal transfer functions show all control loops are decoupled. Finally, the experimental

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results are presented to validate the effectiveness of the proposed control method.

## II. Mechanism Analysis of Decoupling Control

The topology of N-phase interleaved buck converters is shown in Fig. 1. It is constituted of n parallel buck converters, and there is a phase difference 360°/n between the driving signals of each phase SiC MOSFET. $R$ and $C$ are the load resistance and the output capacitance. $L_1 \sim L_n$ and $r_{L1} \sim r_{Ln}$ are the buck inductances and the inductor resistances.

### A. Small-Signal Transfer Functions

If the inductor currents are operating in continuous current mode (CCM), the switching averaging model can be used instead of the converter switch network as shown in Fig. 2 [8]. The small-signal model can be obtained from Fig. 2, as shown in (1) and (2). $u_{in}$ and $u_o$ are the input voltage and the output voltage. $i_{Lk}$ and $i_z$ are the inductor current and load current disturbance.

$$L_k \frac{d\hat{i}_{Lk}}{dt} = -r_{Lk}\hat{i}_{Lk} - \hat{u}_o + D_k \hat{u}_{in} + U_{in}\hat{d}_k \tag{1}$$

$$C\frac{d\hat{u}_o}{dt} = \sum_{k=1}^{n}\hat{i}_{Lk} - \frac{\hat{u}_o}{R} - \hat{i}_z \tag{2}$$

In the average current balancing control method, the output voltage $u_o$, the average inductor current $i_{Lavg}$, and the current imbalance $i_{Lk} - i_{Lavg}$ are regarded as control variables. Besides, the inductances, the inductor resistances and the DC inductor currents are constant and equal, respectively. From (1) and (2), the small-signal transfer function can be obtained as shown in (3)~(5), where $d_{avg} = \frac{1}{n}\sum_{k=1}^{n} d_k$ .

$$\hat{u}_o = \frac{R\left(nU_{in}\hat{d}_{avg} + nD\hat{u}_{in} - \left(r_L + Ls\right)\hat{i}_z\right)}{RLCs^2 + \left(Rr_L C + L\right)s + r_L + nR} \tag{3}$$

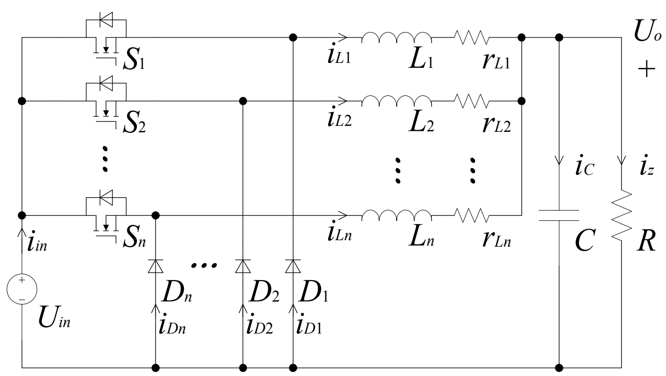

Fig. 1. N-phase interleaved buck converters topology

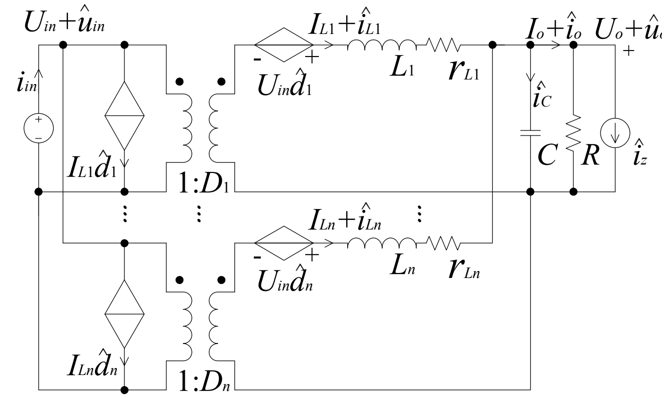

Fig. 2. N-phase interleaved buck equivalent circuit

$$\hat{i}_{Lavg} = \frac{U_{in}\left(RCs+1\right)\hat{d}_{avg} + D\left(RCs+1\right)\hat{u}_{in} + R\hat{i}_z}{RLCs^2 + \left(Rr_L C + L\right)s + r_L + nR} \tag{4}$$

$$\hat{i}_{Lk} - \hat{i}_{Lavg} = \frac{U_{in}}{Ls + r_L}\left(\hat{d}_k - \hat{d}_{avg}\right) \tag{5}$$

### B. The Conditions of Decoupling Control

From (3) and (4),when the input voltage and the output load are constant, the output voltage $\hat{u}_o$ and the average inductor current $\hat{i}_{Lavg}$ are only related to the average duty ratio $\hat{d}_{\text{avg}}$ . Similarly, from (5), the current imbalance $\hat{i}_{Lk} - \hat{i}_{Lavg}$ is only related to the duty ratio imbalance $\hat{d}_k - \hat{d}_{\text{avg}}$ .Therefore, to achieve the decoupling between current balancing loops and the dual closed-loop, the output signal of the dual closed-loop feedback controller should keep $\hat{d}_k - \hat{d}_{\text{avg}}$ constant at zero. Meanwhile, the output signals of current balancing controller should keep $\hat{d}_{\text{avg}}$ constant at zero.

## III. Proposed Current Balancing Control Method

Based on the above analysis of decoupling control conditions, the decoupled average current balancing control method for N-phase interleaved buck converters is shown in Fig. 3, where $G_u$ , $G_i$ and $G_b$ are the output voltage feedback controller, the average current feedback controller and the current balancing controller, respectively. $p_u$ and $p_i$ are the output signals of the output voltage feedback controller and the average current feedback controller. $p_1 \sim p_{n-1}$ are the output signals of the current balancing controller. The duty ratios $d_1 \sim d_n$ composed of the output signals $p_i$ and $p_1 \sim p_{n-1}$ can be expressed as $d_k = p_i + p_k$ (k= 1, 2, …, n-1) and $d_n = p_i - \sum_{k=1}^{n-1} p_k$ .

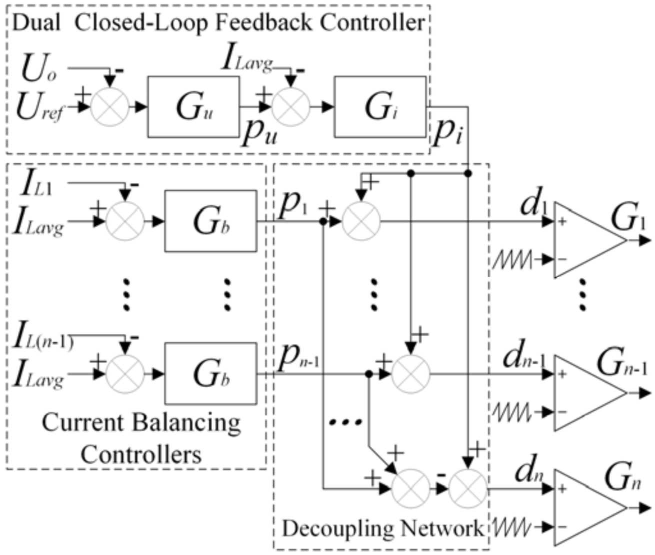


Fig. 3. Proposed decoupled average current balancing control

From Fig. 3, the average duty ratio $d_{\text{avg}}$ and the duty ratio imbalance $d_k - d_{\text{avg}}$ can be expressed as

$$d_{avg} = p_i \tag{6}$$

$$d_k - d_{avg} = p_k \tag{7}$$

The small-signal transfer functions from the output signal of the dual closed-loop feedback controller $\hat{p}_i$ to the average inductor current $\hat{i}_{Lavg}$ and the output voltage $\hat{u}_o$ are obtained as

$$G_{iavg\_pi} = \frac{\hat{i}_{Lavg}}{\hat{p}_i} = \frac{U_{in}\left(RCs+1\right)}{RLCs^2 + \left(Rr_L C + L\right)s + r_L + nR} \tag{8}$$

$$G_{u\_pi} = \frac{\hat{u}_o}{\hat{p}_i} = \frac{nRU_{in}}{RLCs^2 + \left(Rr_L C + L\right)s + r_L + nR} \tag{9}$$

The small-signal transfer functions between output signals of the current balancing controller $\hat{p}_k$ and the current imbalance $\hat{i}_{Lk} - \hat{i}_{Lavg}$ have the same equation.

$$G_{ik-iavg\_pk} = \frac{\hat{i}_{Lk} - \hat{i}_{Lavg}}{\hat{p}_k} = \frac{U_{in}}{Ls + r_L} \tag{10}$$

The other transfer functions $\hat{u}_o / \hat{p}_k$, $\hat{i}_{Lavg} / \hat{p}_k$ and $\left(\hat{i}_{Lk} - \hat{i}_{Lavg}\right) / \hat{p}_i$ are zero. That is, the dual closed-loop and current balancing loops are decoupled. Furthermore, the transfer function $\left(\hat{i}_{Lk} - \hat{i}_{Lavg}\right) / \hat{p}_{j(j\neq k)}$ is also zero, which meaning that current balancing loops are also decoupled to each other.

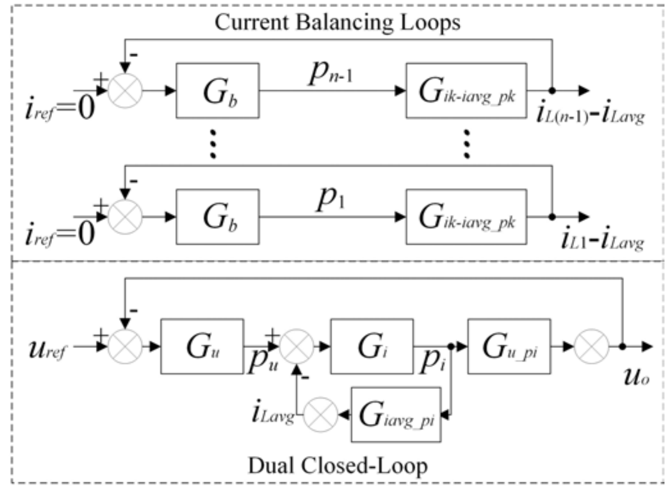


Fig. 4. Block diagram of the dual closed-loop and current balancing loops

The small-signal transfer functions show that current balancing loops and the dual closed-loop are decoupled. The block diagram of the dual closed-loop and current balancing loops are shown in Fig. 4. Therefore, the proportional-integral (PI) controller parameters of each control loop can be designed independently.

## IV. Controller Parameters Design

To verify the performance of proposed current balancing control scheme, the controller parameters of two-phase interleaved buck converters are designed. $G_u = K_{Iu}/s + K_{Pu}$ is the output voltage feedback PI controller. $G_i = K_{Ii}/s + K_{Pi}$ is the average current feedback PI controller. $G_b = K_{Ib}/s + K_{Pb}$ is the current balancing PI controller. According to the rules of controller design [6], the phase margin should be greater than 45 degree and the gain margin should be positive. In addition, digital control delay $e^{-1.5T_s s}$ should be considered in the controller parameters design. the nominal parameters of two-phase interleaved buck converters are presented in TABLE I.

In the inner current-regulating loop, the controller parameters are selected as $K_{Pi} = 0.02$ and $K_{Ii} = 120$, respectively. The bode diagram of the current-regulating open-loop is shown in Fig. 5, where the gain margin is 11.0 dB and the phase margin is 51.1 degree. Moreover, the crossover frequency is at 2.79 kHz.

TABLE I. Nominal Parameters of Two-Phase Interleaved Buck

| ***Parameters*** | ***Value*** |
|---|---|
| Inductances $L_1$ $L_2$ | 840μH |
| Inductor resistances $r_{L1}$ $r_{L2}$ | 26mΩ |
| Output capacitance $C$ | 15μF |
| Load resistance $R$ | 10Ω |
| Input voltage $U_{in}$ | 400V |
| Switching frequency $f_s$ | 40kHz |

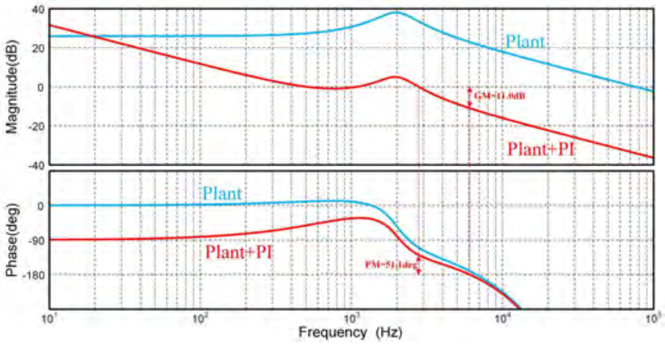


Fig. 5. Bode plots of the inner current-regulating loop

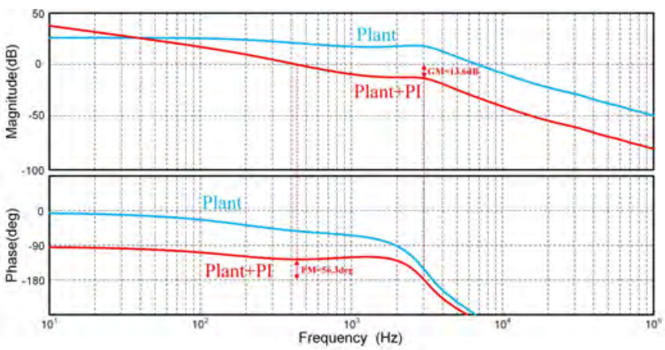


Fig. 6. Bode plots of the outer voltage-regulating loop

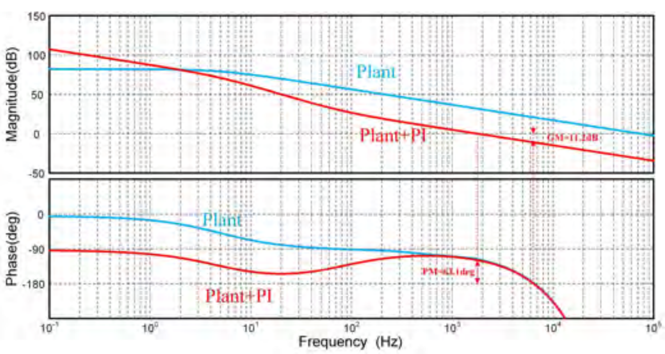


Fig. 7. Bode plots of the current balancing loop

The crossover frequency of the outer voltage-regulating loop can be designed to be 1/5 of the crossover frequency of the inner current-regulating loop. In the outer voltage-regulating loop, the crossover frequency is designed at 433 Hz, and the controller parameters are selected as $K_{Pu} = 0.024$ and $K_{Iu} = 240$. The bode diagram of the voltage-regulating open-loop is shown in Fig. 6, where the gain margin is 13.6 dB and the phase margin is 56.3 degree.

The current balancing loop and the dual closed-loop are decoupled, so the PI controller parameters of the current balancing loop can be designed independently. In the current balancing loop, the controller parameters are selected as $K_{Pb} = 0.024$ and $K_{Ib} = 12$, respectively. The bode diagram of the current balancing open-loop is shown in Fig. 7, where the gain margin is 11.2 dB, the phase margin is 63.1 degree and the crossover frequency is at 1.82 kHz.

From Fig. 5 - Fig. 7, the system phase margins are greater than 45 degree and the gain margins are positive, indicating that the system is stable.

## V. Experimental Results

To verify the performance of proposed current balancing control scheme, a prototype of two-phase interleaved buck converter is setup as shown in Fig. 8. The experimental parameters of the prototype are presented in TABLE II. The experimental verification of the decoupled average current balancing control method proposed in this paper includes three parts: enabling the current balancing loop, changing the output voltage command, and changing the load resistance.

In Fig. 9, the inductor currents $i_{L1}$ and $i_{L2}$ are imbalanced until the current balancing loop is enabled. Notably, the output voltage $u_o$ maintains constant during current balancing. The experimental results show that the current balancing loop has almost no effect on the output voltage.

In Fig. 10, the output voltage command is suddenly changed from 180V to 190V. The output voltage $u_o$ can smoothly track the change in the output voltage command within 3ms. In the transient response, both inductor currents are consistently balanced. It shows that the dual closed-loop has no effect on the current balancing.

In Fig. 11, the load resistance is suddenly changed from 11.4Ω to 10Ω. The output voltage $u_o$ can also track the output voltage command within 3ms, while both inductor currents are consistently balanced.

From the experimental transient waveform Fig. 9 - Fig. 11, the average current balancing control method proposed in this paper achieves the decoupling between current balancing loops and the dual closed-loop.

TABLE II. Experimental Parameters of Two-Phase Interleaved Buck

| ***Parameters*** | | ***Value*** |
|---|---|---|
| Inductances | $L_1$ | 840μH |
| | $L_2$ | 820μH |
| Inductor resistances | $r_{L1}$ | 26mΩ |
| | $r_{L2}$ | 24mΩ |
| Input voltage | | 400V DC |
| Output voltage | | 180V DC |
| Input capacitance | | 3mF |
| Output capacitance | | 15μF |
| Switching frequency | | 40kHz |
| Load resistance | | 10Ω |

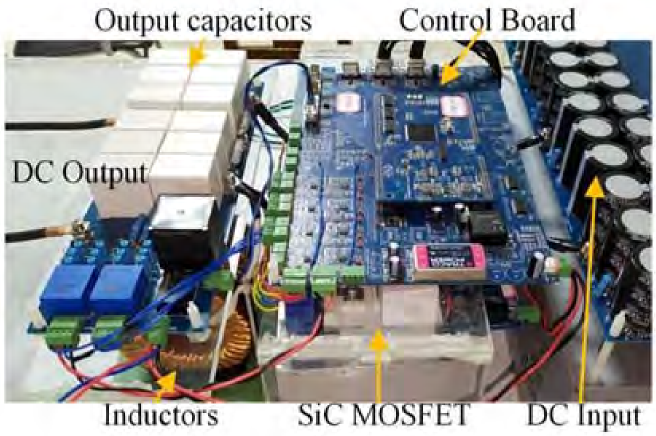


Fig. 8. Experimental circuit of two-phase interleaved buck

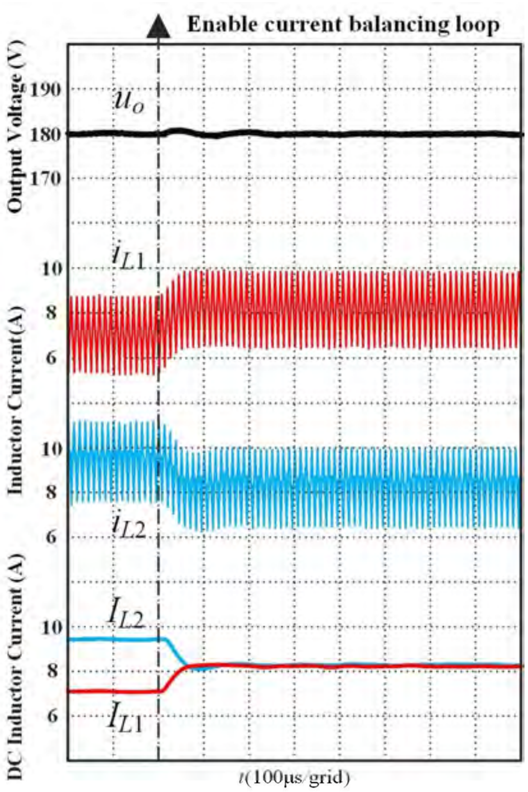


Fig. 9. Experimental transient waveform when the current balancing loop is enabled

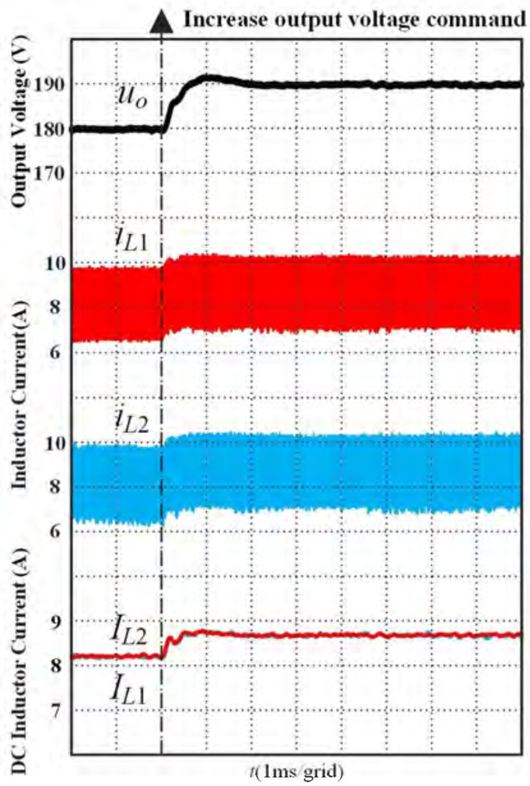


Fig. 10. Experimental transient waveform the output voltage command is changed

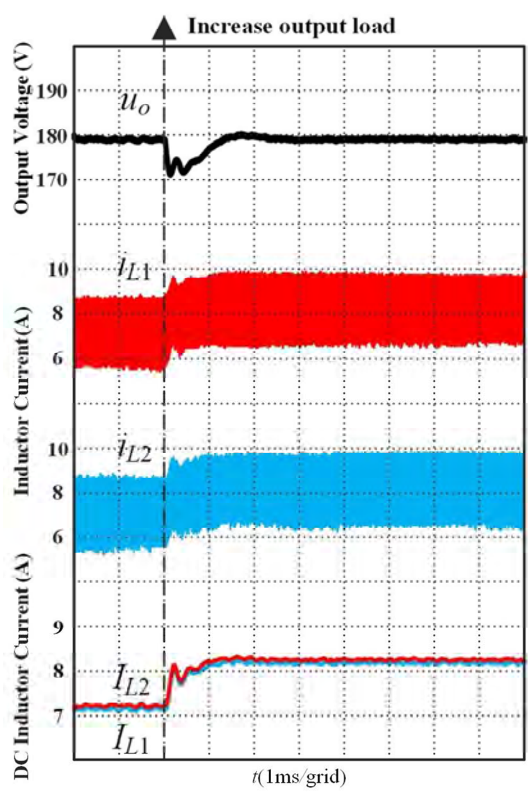


Fig. 11. Experimental transient waveform when the load resistance is changed

## VI. CONCLUSIONS

To solve the coupling problem of dual closed-loop and current balancing loop, a decoupled average current balancing control with the dual closed-loop is proposed in this paper. The proposed control method can make the dual closed-loop and current balancing loops regulate the output voltage and balance the inductor currents independently. The control bandwidths of current balancing loops are not limited by the control bandwidths of the dual closed-loop. Therefore, the proposed control method has the advantages of simplified controller parameters design and excellent transient characteristics. The experimental results demonstrate the effectiveness of the proposed method.

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