Classification of Parallel DC/DC Converters Part II: Comparisons and Experimental Verifications

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***Abstract*— This paper describes the current sharing and voltage regulation performance of three types of paralleling configurations, i.e., paralleling Thévenin sources, paralleling one Thévenin source with many Norton sources and paralleling Norton sources. The corresponding control methods with and without current-sharing loop for the three types to obtain both current sharing and voltage regulation are detailed. Using small-signal analysis, the inherent characteristics of the basic schemes are expounded. Comparisons are made for all the schemes in terms of current sharing and voltage regulation. Finally, an experiment prototype is built to validate the analysis. Experimental results verify the analysis.**

I. Introduction

In parallel connected converter systems, mandatory control is needed to ensure proper current sharing, and many effective control methods have been proposed in the past two decades [1]–[4]. In Part I of this work [2], a circuit theoretic classification of the paralleling schemes that permits a clear exposure of the structures, behaviors and limitations of all possible schemes has been proposed. In this classification, converters are recognized as either dependant voltage sources or dependent current sources. Then, applying the two Kirchhoff's laws for connecting ideal sources, three configurations for paralleling dc/dc converters are identified, i.e., (i) connecting Thévenin sources in parallel, (ii) connecting one Thévenin source with many Norton sources in parallel, and (iii) connecting Norton sources in parallel, as shown in Fig. 1. Moreover, various control methods, with or without a current-sharing loop, are needed to achieve the functions of output regulation and current sharing.[1]

In the Part I paper [2], some qualitative comparisons are made in terms of current sharing accuracy, dynamic performance and voltage regulation based on intuitive analysis and computer simulations. In this paper, we will continue to discuss the performance of various types of paralleling schemes based on the small-signal analysis and practical execution. Small-signal analysis provides information about the inherent characteristics of all the paralleling schemes. We will highlight the roles and effects of current-sharing loops, and the origins of current-sharing error. An experimental prototype of two parallel connected buck converters is constructed, with six different controllers to validate the behavior of above mentioned schemes. Finally, the steady-state performances of various schemes are compared experimentally.

[1]The presence of a current-sharing loop is characterized by the use of a current-sharing control signal which is derived from the output currents of one or more constituent converters.

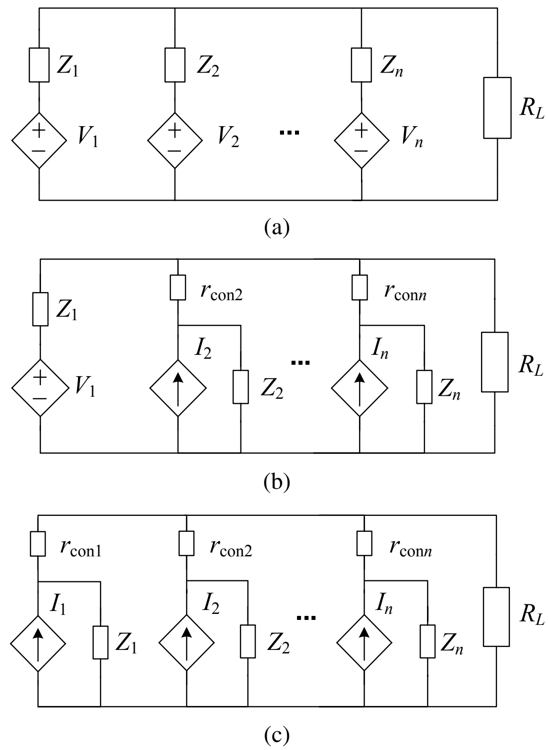


Fig. 1. Three configurations for paralleling converters. (a) Connecting Thévenin sources in parallel; (b) connecting one Thévenin source with many Norton sources in parallel; (c) connecting Norton sources in parallel.

II. Small-Signal Analysis

A. Thévenin Sources in Parallel

One type of paralleling configurations is to parallel imperfect voltage sources, each being modeled as a dependent voltage source behind an impedance, as shown in Fig. 1 (a). In this type of connection, each constituent converter has its own voltage loop to regulate the output voltage, which makes it behave as an independent voltage converter.

For the control without current-sharing loop, the dependent voltage source V_i is the regulated output voltage by the local voltage feedback of each converter. The output impedance of the ith converter is

$$Z_i = Z_{\mathrm{CL}i} + r_{\mathrm{con}i} \tag{1}$$

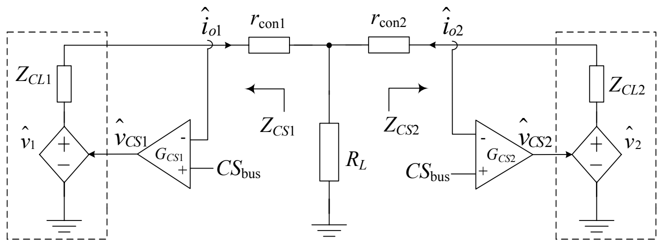


Fig. 2. Small-signal circuit diagram representing current sharing for paralleling Thévenin sources. The two dashed boxes denote the independent converters before connection.

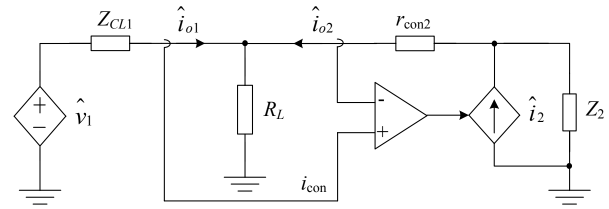


Fig. 3. Small-signal circuit diagram representing current sharing for paralleling one Thévenin source with many Norton sources.

where $Z_{\text{CL}i}$ is the output impedance of the ith converter and $r_{\text{con}i}$ is the connection resistor between the output of the ith converter and the load. Consider two converters connected in parallel. Obviously, the steady-state current-sharing error is expressed as

$$\Delta I = I_{o1} - I_{o2} = \frac{Z_2 V_1 - Z_1 V_2 + 2(V_1 - V_2) R_L}{Z_x} \qquad (2)$$

where $Z_x = Z_1 Z_2 + Z_1 R_L + Z_2 R_L$. Practically, it is very hard to make the parameters of two converters exactly identical. In order to shrink the current difference, large impedance Z_i has to be used, which results in large output voltage droop at heavy load.[2] The larger the droop is, the smaller the current difference is. This droop characteristic limits the performance improvement of such a configuration.

To improve current sharing and voltage regulation of the paralleled Thévenin sources, we may append a current-sharing loop in the converters. The small-signal circuit diagram of an average method to achieve current sharing is shown in Fig. 2, where CS_{bus} is the current sharing control signal derived from the two converters, and Z_{CS1}, Z_{CS2} are the equivalent output impedances after closing the loop. Also, it should be obvious that the function of the current-sharing loop attempts to change the difference between $Z_{CL1} + r_{\text{con1}}$ and $Z_{CL2} + r_{\text{con2}}$ in the direction of their convergence [4].

Mathematically, the steady-state current error between the two converters is

$$\begin{aligned} \Delta I &= I_{o1} - I_{o2} \\ &= \frac{A_1 V_{\text{ref1}} Z_{CS2} - A_2 V_{\text{ref2}} Z_{CS1} + V_o (Z_{CS1} - Z_{CS2})}{Z_{CS1} Z_{CS2} + \frac{A_1 G_{CS1} Z_{CS2}}{2} + \frac{A_2 G_{CS2} Z_{CS1}}{2}} \end{aligned} \qquad (3)$$

where A_i is the gain from the voltage control signal to the output voltage, and G_{CSi} is the current sharing gain. Equation (3) clearly shows the relationship of ΔI with V_{ref1}, V_{ref2}, V_o, Z_{CS1} and Z_{CS2}. Note that even when $Z_{CS1} = Z_{CS2}$, we cannot get zero current-sharing error if $A_1 V_{\text{ref1}} \neq A_2 V_{\text{ref2}}$. Also, the current error is constant in the whole load range if other parameters are fixed. When $A_1 V_{\text{ref1}} = A_2 V_{\text{ref2}}$, the current-sharing error is related to the difference between Z_{CS1} and Z_{CS2}, which may vary with the load.

[2]By "large" impedance and "small" impedance, we actually refer to the modulus of the impedance.

The performance of current sharing and voltage regulation of the paralleled Thévenin sources controlled with a current-sharing loop is much better than that of the one without current-sharing loop. However, the system can become unstable since the high gain voltage regulator for the individual converter will amplify any small current difference. As a solution, the bandwidth of the current-sharing loop should be much smaller than the voltage feedback loop to avoid severe interaction between the voltage regulation and current sharing loops that affects the stability of the system.

B. One Thévenin Source with Many Norton Sources in Parallel

For the case of paralleling one Thévenin source with many Norton sources, as shown in Fig. 1 (b), one converter serves as the voltage (Thévenin) source and others as current (Norton) sources. The voltage source has a tight voltage feedback loop to control the output voltage of the paralleled converters. All current sources only need to follow a common current control signal to achieve current sharing automatically.

In the case where the current-sharing loop is absent, the voltage (Thévenin) source provides the regulation of the output voltage. While for the current sources, their control signal comes from the division of the load current. This current control signal is then compared with the individual output current of the current source converters to achieve current sharing. Thus, the current in the voltage source branch is controlled indirectly (automatically) in the equilibrium state. For simplicity we consider only one Norton source paralleling a Thévenin source. The current error is

$$\Delta I = I_{o1} - I_{o2} = I_{o1} - I_o F_2/2 = I_o(1 - F_2) \qquad (4)$$

where subscripts 1 and 2 denote the Thévenin and Norton sources respectively, F_2 is the DC gain from the current control signal to the output current of the Norton source.

For the connection controlled with current-sharing loop, the analysis is similar to that of the one without current-sharing loop, except that the control signals of the current source branches are derived from the voltage source branch. The small-signal circuit diagram of current sharing is shown in Fig. 3. This control method is commonly known as *master-slave current-sharing method*. The voltage source is the master and the current sources are the slaves whose currents are programmed to follow the master's. Various current control methods can be used for the slaves. The average-current-mode control, in the ideal case, should ensure equal average

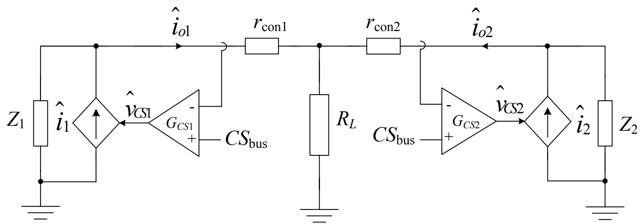


Fig. 4. Small-signal circuit diagram of current sharing for paralleling Norton sources.

output currents, i.e. $I_{o1} = I_{o2}$. While for the peak-current-mode control, the peak currents of slave converters are equal to that of the master's.

Obviously, the control for this type of configuration is much easier than that of paralleling Thévenin sources. Good voltage regulation is easily achieved for tight load voltage regulation. Moreover, the accuracy of current sharing can be improved with a proper design of the current source controllers.

C. Norton Sources in Parallel

For the case of paralleling Norton sources, all converters are under current-mode control so that they behave as good current sources. The output voltage is controlled only at the load side. The structure of this case is shown in Fig. 4.

In the absence of a current-sharing loop, all converters have to follow a current control signal which is derived from the output of voltage compensator. The feedback loop aims to achieve voltage regulation as well as current sharing. Since all current sources follow the same control signal, we can write the current error as

$$\Delta I = I_{o1} - I_{o2} = (F_1 - F_2) I_{con} \quad (5)$$

where F_1, F_2 are the DC gains for the individual controllers, and I_{con} is the common current control signal. If $F_1 = F_2$, we get zero current error even without the presence of a current-sharing loop, as expected. Practically, the error is related to the parameters of the current loops for the individual branches.

To ensure the current sharing accuracy of this type of connection, the current-sharing loop has to be used. The controller is similar to that of the one without a current-sharing loop. The constituent converter is recognized as a current source locally. Figure 4 shows the equivalent circuit diagram for this scheme, where the signal CS_{bus} is the common current sharing control signal. The compensated current-sharing control signals, v_{CS1} and v_{CS2} are used in each converter so as to achieve current sharing as well as voltage regulation. Current-programming methods, such as master-slave method or average method, can be used to generate the common current-sharing control signal. Obviously, the role of current-sharing loop is to adjust the current control signal directly to ensure equal current distribution among the converters. Again, ideally, the current error among the converters can be made zero.

The configuration of paralleling Norton sources achieves excellent output voltage regulation and current sharing by controlling all the constituent converters as current sources locally. Good current sharing can be obtained even without the presence of a current-sharing loop.

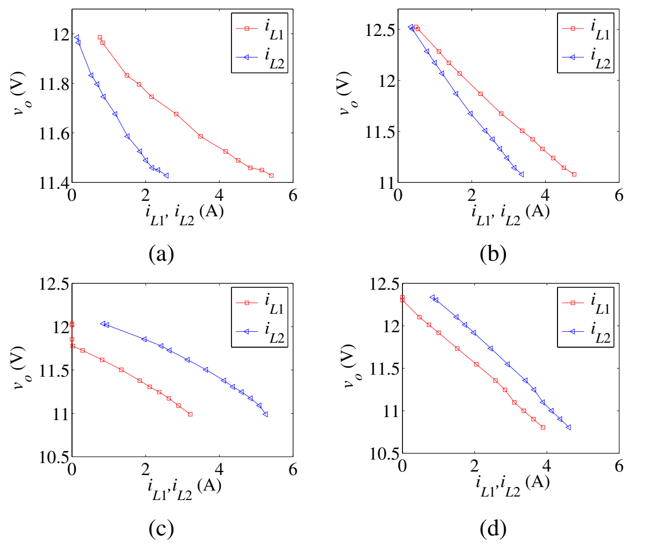


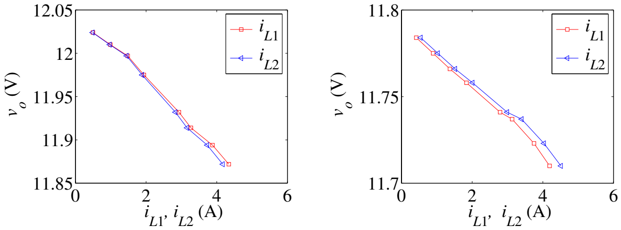
Fig. 5. Output voltage versus inductor current for parallel-connected Thévenin sources without a current-sharing loop. (a) $V_{ref1} = V_{ref2} = 12$ V, $r_{con1} = 0.001\ \Omega$, $r_{con2} = 0.05\ \Omega$, with small output impedance; (b) $V_{ref1} = V_{ref2} = 12$ V, $r_{con1} = 0.001\ \Omega$, $r_{con2} = 0.05\Omega$, with large output impedance; (c) $V_{ref1} = 11.5$ V, $V_{ref2} = 12$ V, $r_{con1} = r_{con2} = 0.025\ \Omega$, with small output impedance; (d) $V_{ref1} = V_{ref2} = 12$ V, $r_{con1} = r_{con2} = 0.025\ \Omega$, with large output impedance.

III. Experimental Results

In the foregoing section, we have discussed the performance of current sharing and voltage regulation for parallel dc/dc converters under different configurations. To verify the analysis, a prototype of two buck converters (24/12 V, 10 A) connected in parallel has been constructed. Six different controllers are designed to compare the performance of all the schemes.

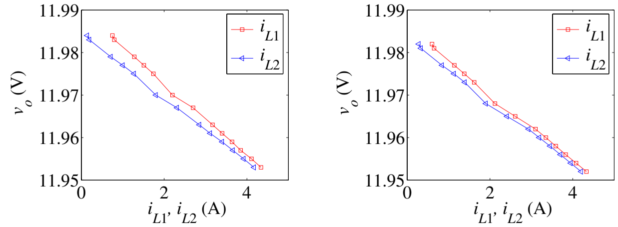
For the configuration of paralleling Thévenin sources, we fix both converters' bandwidth at 10 kHz to ensure the same capability of voltage regulation. For the control without a current-sharing loop, we introduce the current feedback to adjust the value of output impedance. Figure 5 shows the output droop characteristic. Figure 5 (a) shows the results of the two converters with the same reference output voltage, but different connecting resistors. Figure 5 (c) corresponds to the case of two converters with the same connection resistor, but different reference output voltages. Similarly, Figs. 5 (b) and (d) are the corresponding results when larger output impedances are used. Here, we clearly see that the configuration without current-sharing loop does not perform very satisfactorily. Normally, with large output impedances, we may achieve good current sharing but poor output regulation. However, with smaller output impedances, the current sharing becomes worse and output regulation becomes better.

For parallel-connected Thévenin sources controlled with current-sharing loop, the bandwidth of the current-sharing loop is one tenth of the voltage loop. The results are much better than the one without current-sharing loop, as demonstrated in



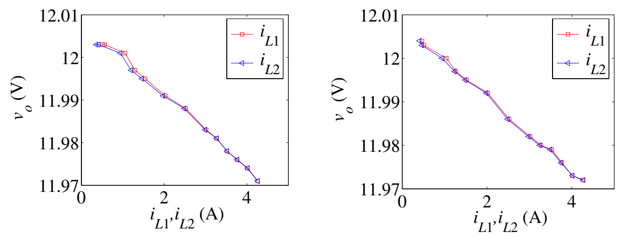
(a) (b)

Fig. 6. Output voltage versus inductor current for paralleling Thévenin sources with a current-sharing loop. (a) $V_{\mathrm{ref1}} = V_{\mathrm{ref2}} = 12$ V, $r_{\mathrm{con1}} = 0.001\ \Omega$, $r_{\mathrm{con2}} = 0.05\ \Omega$; (b) $V_{\mathrm{ref1}} = 11.5$ V, $V_{\mathrm{ref2}} = 12$ V, $r_{\mathrm{con1}} = r_{\mathrm{con2}} = 0.001\ \Omega$.



(a) (b)

Fig. 7. Output voltage versus inductor current for paralleling one Thévenin source with many Norton sources. (a) without current-sharing loop; (b) with current-sharing loop.



(a) (b)

Fig. 8. Output voltage versus inductor current for paralleling Norton sources. (a) without current-sharing loop; (b) with current-sharing loop.

Fig 6. The current error is very small and so is the voltage droop. Figure 6 (a) shows the results of the two converters under the same reference output voltage, but different connecting resistors. Figure 6 (b) shows the results of the two converters with the same connecting resistor, but different reference output voltages. Here, we observe that current sharing is good when the converters have the same reference output voltage. However, there is a constant current error if the reference output voltages are different, as shown in Fig. 6 (b). This is because the current-sharing loop can regulate the equivalent output impedance Z_{CS1} and Z_{CS2}, but it cannot remove the inherent output voltage difference between the converters.

Shown in Fig. 7 are the experiment results for paralleling one Thévenin source with many Norton sources. As shown in Figs. 7 (a) and (b), better current sharing performance can be achieved with the presence of a current-sharing loop. We also notice that the voltage droop is much smaller than that of paralleling Thévenin sources because of the tight regulation of the load voltage. Also, the output voltage will not be affected by the connecting resistor. In Fig. 7 (b), we observe almost constant current difference in the whole load range. The reason is that peak-current-mode control is used in the experiment, and the current control signal of the slave is derived from the average current of the master. As a result, there is constant current difference between the converters, which equals half of the current ripple. A bias voltage should be introduced to decrease such error.

For paralleling Norton sources, only one voltage loop is applied at the load side. For the control with current-sharing loop, again, the bandwidth of the current-sharing loop is one tenth of the voltage loop. From Fig. 8, we observe perfect load voltage regulation and current sharing for both cases with and without current-sharing loop. The current error is much smaller compared to the other schemes. Even for the control without current-sharing loop, the current sharing is very good since all the converters are under current-mode control and follow the same control signal.

IV. Conclusions

In this paper, the steady-state performances of parallel-connected dc/dc converters under various fundamental paralleling schemes have been analyzed. For paralleling Thévenin sources, each converter has its own voltage loop. Obvious droop characteristic is observed for both schemes with and without current-sharing loop. In the case where current-sharing loop is absent, we have to trade off voltage regulation for current sharing, whereas in the case where a current-sharing loop is present, the role of the current-sharing loop is to regulate the output characteristic of the constituent converters. For paralleling one Thévenin source with many Norton sources, the control method is much simpler than that of paralleling Thévenin sources, and the accuracy of current sharing can be further improved by proper design of the current source controllers. In the case of paralleling Norton sources, voltage regulation is executed at the load side. Each converter only needs to follow a current control signal. Both control methods perform well. The role of the current-sharing loop is to regulate the current control signal directly. Thus, excellent voltage regulation and current sharing can be obtained.

Acknowledgment

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