Single-Wire Current-Share Paralleling of Current-Mode-Controlled DC Power Supplies

Chang-Shiarn Lin and Chern-Lin Chen, *Senior Member, IEEE*

Abstract—This paper presents a new single-wire autonomous current-share paralleling of current-mode-controlled dc power supplies. The proposed control scheme makes use of the nature of fast response of the inner current loop and the share bus injected signal to improve the response of the power supplies. It reduces the unbalance of current distribution during the transient state and avoids the fault alarm for the current limit. Through the theoretical derivation, the proposed control circuit can be designed by the three-loop control method. A design example of two 400-V/48-V 20-A parallel modules is set up and experimental recordings verify the performance of current sharing.

Index Terms—Current-mode control, current sharing, single wire.

I. INTRODUCTION

IN RECENT years, due to the rapid advance of computer and communication, the power supplies must provide high current up to hundreds of amperes, and still have high efficiency and reliability. Under such requirements, multimodule paralleling is usually used and the load current is equally shared. In this way, the current stress of the switching devices is reduced and the efficiency and reliability [1] are improved. About the current-sharing control, a variety of schemes have been presented [2]–[10] over the years. The single-wire current-share method [7] is comparatively simple and, hence, favorable. The configuration is shown in Fig. 1. The share bus carries the average current signal reference for every module. No central control unit is required and only a few operational amplifiers or comparators [10] are added in the modules.

In practical applications, some unnecessary minor alarms occur as the load rapidly changes or one module fails and shuts down. The output currents of the converter modules are not equally distributed during the load transient. The protection circuit limits the output currents when they exceed the rated values and an alarm may be raised. These imbalances usually occur when the circuit components or output cables are not identical for every module [3]. To avoid the unfavorable situation, we try to use the current-mode control instead of the conventional voltage-mode control in the modules. The

Fig. 1. Single-wire current sharing of paralleled converter modules.

simplified circuit of conventional voltage mode is shown in Fig. 2(a). The current-sharing error signal is injected into the voltage loop to adjust the voltage command [2]–[5]. In current-mode control, the inner current loop, which has less phase shift, can have wider bandwidth without instability and, hence, improve transient response. It can be used to alleviate the unbalance problem during the transient. The current sensor is already used to sense the inductor current in current-mode control; it can be also used for current sharing.

The paralleled current-mode control has been investigated [11]–[14]. A simplified circuit of the paralleled current-mode control is shown in Fig. 2(b). Because the output current is proportional to the voltage error signal, the current command of every module is controlled by common voltage feedback. The common feedback circuit cannot be modularized, and the system may be shut down for the failure of the common part. The single-wire current sharing for current-mode control has been studied in the literature [5], [7], [15]. Commercialized control ICs, such as the UC3907, can also be used in current-mode-controlled modules [5], but the share bus carries the maximum current information of paralleled modules. Another method proposed by Small in 1988 [7] is shown in Fig. 2(c). The share bus carries the average current command signal, and the current-sharing error is injected into the reference voltage. The bandwidth of the current-sharing response is limited by the voltage loop. In this paper, a novel current-sharing control scheme is proposed. The simplified circuit is shown in Fig. 2(d). The share bus carries the average inductor current signal and the injected

Manuscript received May 16, 1999; revised April 9, 2000. Abstract published on the Internet April 21, 2000. This paper was presented at the 29th Annual IEEE Power Electronics Specialists Conference, Fukuoka, Japan, May 17–22, 1998.

The authors are with the Department of Electrical Engineering, National Taiwan University, Taipei 10617, Taiwan, R.O.C. (e-mail: clchen@cc.ee.ntu.edu.tw).

Publisher Item Identifier S 0278-0046(00)06827-1.

Fig. 2. Comparison among the current-sharing control schemes. (a) Conventional voltage mode. (b) Current mode with the common voltage feedback, (c) Current mode with the average current command share bus. (d) Proposed control scheme: current mode with the average inductor current-share bus.

point of current-sharing signal is on the inner current loop. Thus, the bandwidth of the current-sharing control is not limited by the voltage loop.

In the following, the new current-sharing circuit of current-mode controlled converters is described and analyzed. The design guidelines are listed and a design example of the average current-mode-controlled modules is implemented. Finally, the experimental results verify the performance of the circuit.

II. CIRCUIT DESCRIPTION

The circuit of a single module in the proposed control is depicted in Fig. 3. Three operational amplifiers form the control circuit. The functions of each portion are as follows.

- 1) *Share Bus*: It carries the instantaneous average current signal for the reference of the module current when paralleling. A share resistor R_s of high accuracy is connected between the share bus and the output of the current sensor H . When the values of R_s for every module are all the same, the output currents of the modules are the same. If they are proportional, the output currents are also proportional.
- 2) *Voltage Error Amplifier U_v* : The output voltage error signal is amplified as part of the current command. The current command is composed of the voltage error and the current-sharing error.
- 3) *Current-Sharing Amplifier U_s* : It amplifies the error signal between the share bus and the inductor current, and injects its signal into the current command.
- 4) *Current Amplifier U_c* : It amplifies the error signal between the inductor current and the current command, and sends the error to the modulator.
- 5) *Pulsewidth Modulator*: The analog control signal is converted into discrete control pulses.

Fig. 3. Proposed control circuit for one current-mode-controlled module.

- 6) *Power Stage*: The power switches, switch drivers, and output filter components L_f and C_o are included.
- 7) *Current Sensor H* : Hall-effect sensors or other current-sensing devices may be used to sense the inductor current.

III. CIRCUIT OPERATIONS

In this section, the circuit operations of a single module and multimodule paralleling are presented.

A. Single Module

The current signal of the module is equal to the share bus because the input impedance of the share amplifier is high enough and no current passes through R_s . Thus, the sharing error signal is zero and the control is the same as a standard two-loop control.

Fig. 4. Circuit between share bus and the share resistors.

B. Multimodule Paralleling

For the same value of the share resistors R_s , the share bus carries average current signal reference. The share error signal is the difference between the share bus and the individual output current. This error is injected into the current command. By the pulsewidth modulation (PWM) control and power circuit, the average inductor current is adjusted. When the output current is lower than the share bus signal, the injected error tends to increase the inductor current to reduce the error. This negative feedback mechanism will reduce the error within the tolerance. At the steady state, the output current of every module is the same as the share bus indicated, and the purpose of the current sharing is achieved.

IV. ANALYSIS

There are three control loops in the presented circuit—the voltage loop, the sharing loop, and the current loop. A simplified circuit model for paralleled modules is set up and the control loop analysis is performed to derive the design rules of the proposed current-sharing controller.

The circuit between share resistors and the share bus is shown in Fig. 4. For n paralleled modules, $v_{I1} \dots v_{In}$ are the instantaneous voltage signals derived by the current sensors from the inductor currents and v_{Ibus} is the instantaneous voltage signal on the share bus. If the share resistors $R_{S1} \dots R_{Sn}$ are equal, then

$$v_{Ibus} = \frac{1}{n} (v_{I1} + v_{I2} + \dots + v_{In}). \quad (1)$$

In small-signal analysis,

$$\hat{v}_{Ibus} = \frac{1}{n} (\hat{v}_{I1} + \hat{v}_{I2} + \dots + \hat{v}_{In}). \quad (2)$$

If the transfer function of the current sensor is H , then

$$\hat{v}_{Ibus} = \frac{H}{n} (\hat{i}_{L1} + \hat{i}_{L2} + \dots + \hat{i}_{Ln}) \quad (3)$$

where $\hat{i}_{L1}, \hat{i}_{L2}, \dots, \hat{i}_{Ln}$ are the small-signal representations of the output inductor currents.

Fig. 5. Block diagram of the control circuits.

Neglecting the input voltage disturbance, the control block diagram for one of the paralleled module is shown in Fig. 5 where

- F_v voltage feedback transfer function;
- H current to voltage signal transfer function;
- F_m PWM modulator transfer function;
- G_v duty cycle to output voltage transfer function;
- G_i duty cycle to inductor current transfer function;
- G_s transfer function of the current-sharing amplifier;
- G_{cc} current amplifier transfer function for current loop;
- G_{cs} current amplifier transfer function for sharing loop;
- G_{cv} current amplifier transfer function for voltage loop.

$\hat{v}_o$, $\hat{i}_L$, and $\hat{d}$ are the disturbances of output voltage, inductor current, and duty cycle, respectively. The reference voltage V_r is constant and the small signal $\hat{v}_r = 0$.

In Fig. 5, if the module n has a current-sharing disturbance, the injected current-sharing error signal into the controller $\hat{v}_S$ is

$$\hat{v}_S = G_S (\hat{v}_{Ibus} - H \hat{i}_L). \quad (4)$$

Substitute (3) into (4) and $\hat{i}_L \equiv \hat{i}_{Ln}$,

$$\hat{v}_S = -\frac{n-1}{n} G_S H \hat{i}_{Ln} + G_S \frac{H}{n} (\hat{i}_{L1} + \hat{i}_{L2} + \dots + \hat{i}_{Ln-1}). \quad (5)$$

The disturbances of the inductor currents of other modules do not form a local feedback loop in module n . The second term of (5) can be considered as an external disturbance to take into account the interactions among the modules. If the interactions could be neglected, the current-sharing error is

$$\hat{v}_S \cong -\frac{n-1}{n} G_S H \hat{i}_L. \quad (6)$$

The open-loop gains—the voltage loop T_V , the sharing loop T_S , and the current loop T_I can be derived from Fig. 5

$$T_I = F_m G_{cc} H G_i \quad (7)$$

$$T_V = F_m G_{cv} F_v G_v \quad (8)$$

$$T_S = \frac{n-1}{n} F_m G_{cs} G_s H G_i. \quad (9)$$

When only one module is used, the loop gain of current sharing, $T_S = 0$. For an arbitrarily large number of modules paralleled,

center-tapped connection. It can improve the efficiency of the converter. The complete circuit of a single module is shown in Fig. 6, where Q_a , Q_b , Q_c , and Q_d are the main switches of full-bridge converter controlled by commercial phase-shifted PWM IC UC3875N. The inductor L_{lk} is designed for ZVS of the main switches. C_r blocks the dc voltage to prevent the main transformer T_x from saturation. The diodes D_1 and D_2 rectify the ac output. The bulk capacitor C_o and two inductors, L_{f1} and L_{f2} , are the output filter. A current sensor H is put in the loop path of the two output inductors for feedback control of current mode and current sharing. The proposed control circuit is designed to sense the output voltage, inductor current, and share-bus voltage, and inject the control signal into the phase-shifted PWM controller UC3875N.

The circuit parameters are listed as follows:

switching frequency	f_s 100 kHz;
turn ratio of the main transformer	18 : 6;
power MOSFET Q_a – Q_d	500 V/30 A;
output inductor filter	
L_{f1} , L_{f2}	200 μ H;
fast-recovery diodes D_1 , D_2	600 V/60A;
primary inductor L_{lk}	4 μ H;
output capacitor C_o	6900 μ F;
transfer ratio of the current sensor H	4 V/100A.

The output voltage of the current doubler is half of the transformer voltage output and the equivalent filter inductance is half as much as one of the two inductor filters. The turns ratio m of the main transformer is $0.5 * (1/3) = 1/6$, and the output filter inductor $L_f = L_{f1}/L_{f2} = 100 \mu$ H. The equivalent circuit is illustrated in Fig. 7. After the power stage parameters are determined, the controller and current-sharing network can then be designed.

The parameters and the transfer functions are listed as follows:

n	number of modules be paralleled, $n = 1$ to infinity;
R_o	load resistance for a module. If $n = 2$ and the output voltage and current is 48 V/40 A, then the load current for every module is 20 A, and the load resistance $R_o = 2.4 \Omega$;
V_{in}	input voltage, $V_{in} = 400$ V;
F_V	$= R_{Vf}/R_{V1} \cong 1$;
G_s	$= 10$;
F_m	$= 0.25$;
L_{lk}	$= 4 \mu$ H;
m	equivalent transformer turns ratio $m = 1/6$;
L_f	equivalent output filter inductor 100 μ H;
C_o	output filter capacitor 6900 μ H;
R_i	transfer ratio of the Hall sensor, $R_i = 0.04$ V/A.

For modeling the current-mode control, the sampling gain of Ridley's model is inserted in the current-sensing network [18], so the transfer function of the current sensor is

$$H = R_i H_e(s) = R_i \left(1 + \frac{s}{\omega_s Q} + \frac{s^2}{\omega_s^2} \right). \quad (12)$$

Fig. 7. The equivalent circuit of the current doubler. (a) Current doubler. (b) Equivalent circuit.

$H_e(s)$ is the sampling gain of the current-mode control, $Q = -2/\pi$, $\omega_s = 2\pi f_s$. The models of the phase-shifted PWM converter are [22]

$$G_V = \frac{mV_{in}Z_f}{Z_f + R_d} \left(\frac{1}{\Delta f} \right) \quad (13)$$

$$G_I = \frac{mV_{in}}{Z_f + R_d} \quad (14)$$

where

$$R_d = 4m^2L_{lk}f_s \quad (15)$$

$$Z_f = \frac{R_o\Delta f}{1 + sR_oC_o} \quad (16)$$

$$\Delta f = s^2L_fC_o + s\frac{L_f}{R_o} + 1. \quad (17)$$

The transfer functions of the current amplifier are

$$G_{CC} = \omega_t \frac{(s + \omega_z)}{s(s + \omega_p)} \quad (18)$$

$$G_{CS} = \frac{R_{iv}}{R_{is} + R_{iv}} \left[1 + \omega_t \frac{(s + \omega_z)}{s(s + \omega_p)} \right] \quad (19)$$

$$G_{CV} = \frac{R_{is}}{R_{is} + R_{iv}} \left[1 + \omega_t \frac{(s + \omega_z)}{s(s + \omega_p)} \right] \quad (20)$$

where

$$\omega_z = \frac{1}{R_fC_{f1}} \quad (21)$$

$$\omega_p = \frac{C_{f1} + C_{f2}}{R_fC_{f1}C_{f2}} \quad (22)$$

$$\omega_t = \frac{1}{R_{ii}C_{f2}}. \quad (23)$$

Half of the switching frequency is 50 kHz. The second pole of the error amplifier is placed at 160 kHz and the zero is placed at 500 Hz. The gain of the error amplifier is set to make the bandwidth of the current loop high enough and the system stable. The gain of the current loop can be adjusted by changing the value of R_{ii} in (23).

The following equation can help to find the approximate value of R_{ii} [17]:

$$R_{ii} = \frac{\left(\frac{1}{2} + \frac{1}{\pi} \right) F_m V_{in} R_i}{(C_{f1} + C_{f2})L_f f_s \omega_z}. \quad (24)$$

Fig. 8. Simulated closed-loop gains T_1 and T_2 for light load ($R_o = 480 \Omega$) case. (T_1 —, T_2 - - -).

Fig. 9. Simulated closed-loop gains T_1 and T_2 for full load ($R_o = 2.4 \Omega$) case. (T_1 —, T_2 - - -).

The voltage loop gain can be adjusted by R_{is} , R_{iv} , and G_s . For the circuit of Fig. 6, the small-signal models are built and simulated using MATLAB. The simulated closed-loop gains of light load ($R_o = 480 \Omega$) condition are shown in Fig. 8. The simulated closed-loop gains for full load ($R_o = 2.4 \Omega$) condition are shown in Fig. 9. All the closed-loop gains show that the power supply system is stable.

VII. EXPERIMENTAL RESULTS

Two 400-V/48-V 20-A output current dc/dc converter modules are implemented as shown in Fig. 6. To test the performance of the current-sharing circuit, an experiment of the total load changing from 0 to 20 A has been conducted. The transient response of the output currents and inductor currents for disconnected and connected share-bus conditions are shown in Fig. 10. In Fig. 10(a), without the current-sharing bus, the output current is not equally distributed because the inductor currents do not charge the output capacitors at the same time during the

(a)

(b)

(c)

Fig. 10. Transient responses of the output and inductor currents. (a) Share bus disconnected. (b) Share bus connected.

TABLE I
CURRENT-SHARING TEST RECORDINGS

nominal output current (A)	module 1 current (A)	module 2 current (A)	total current (A)	average current (A)	error current (A)	error rate (%)
5	2.54	2.61	5.15	2.58	0.07	2.72
10	5.04	4.95	9.99	5.00	0.09	1.80
15	7.48	7.25	14.73	7.37	0.23	3.12
20	9.94	9.70	19.64	9.82	0.24	2.44
25	12.53	12.05	24.58	12.29	0.48	3.91
30	14.86	14.29	29.15	14.58	0.57	3.91
35	17.76	17.11	34.87	17.44	0.65	3.73
40	19.87	19.45	39.32	19.66	0.42	2.14

load transient. This imbalance is usually measured when the output inductors or capacitors or cable resistances are not exactly identical. In Fig. 10(b), the share bus forces the output inductor currents to charge the output capacitors almost simultaneously. The output currents of the two modules are very close. The overcurrent condition is, thus, avoided. At the steady state, the output current is equal to the inductor current. The current sharing is always controlled by the proposed circuit in transient or steady state. The steady-state test for current-sharing accuracy is recorded in Table I.

VIII. CONCLUSIONS

The proposed single-wire current sharing of current-mode-controlled power supplies has the high-speed response to reduce the unbalance of the current distribution during the transient state and avoids the minor alarm of the current limit. The current sensor is used for feedback control and current sharing so that the cost is not higher than the voltage-mode control. It can be used in all modularized converters and the design of the modules can follow the multiloop control method. Compared with the conventional voltage-mode-control current sharing, the performance of the proposed current-mode power supply system is much improved.

REFERENCES

- [1] L. Thorsell and P. Lindman, "Reliability analysis of a direct parallel connected $n + 1$ redundant power system based on high reliable DC/DC modules," in *Proc. IEEE Int. Telecommunications Energy Conf.*, 1988, pp. 511–516.
- [2] H. Tanaka, K. Kobayashi, F. Ihara, K. Asahi, and M. Motoyama, "Method for centralized voltage control and current balancing for parallel operation of power supply equipment," in *Proc. IEEE Int. Telecommunications Energy Conf.*, 1988, pp. 434–440.
- [3] I. Batarseh, K. Siri, and H. Lee, "Investigation of the output droop characteristics of parallel-connected DC–DC converters," in *Proc. IEEE APEC'94*, 1994, pp. 1342–1351.
- [4] F. Petruzzello, P. D. Ziogas, and G. Joos, "A novel approach to paralleling of power converter units with ture redundancy," in *Proc. IEEE PESC'90*, 1990, pp. 808–813.
- [5] M. Jordan, "UC3907 Load Share IC Simplifies Parallel Power Supply Design," Unitrode Corp., Merrimack, NH, Unitrode Application Note U-129, 1993–1994.
- [6] R. B. Ridley, "Small-signal analysis of parallel power converters," M.S. thesis, Virginia Polytechnic Inst. and State Univ., Blacksburg, VA, Mar. 1986.

- [7] K. T. Small, "Single-wire current-share paralleling of power supplies," U.S. Patent 4 734 844, Mar. 1988.
- [8] T. Ninomiya, R. H. Wu, Y. Kodera, T. Kohama, and F. Ihara, "Novel control strategy for parallel operation of power supply modules," in *Proc. IEEE PCC-Yokohama Conf.*, 1993, pp. 159–164.
- [9] C. Jamerson, T. Long, and C. Mullett, "Seven ways to parallel a Magamp," in *Proc. IEEE APEC'93*, 1993, pp. 469–474.
- [10] M. M. Jovanovic, D. E. Crow, and L. Fang-Yi, "A novel, low-cost implementation of democratic load-current sharing of paralleled converter modules," *IEEE Trans. Power Electron.*, vol. 11, pp. 604–611, July 1996.
- [11] B. Choi, B. H. Cho, R. B. Ridley, and F. C. Lee, "Control strategy for multi-module parallel converter system," in *Proc. IEEE PESC'90*, 1990, pp. 225–234.
- [12] S. Schulz, B. H. Cho, and F. C. Lee, "Design considerations for a distributed power system," in *Proc. IEEE PESC'90*, 1990, pp. 611–617.
- [13] B. H. Cho and B. Choi, "Analysis and design of multi-stage distributed power systems," in *Proc. IEEE Int. Telecommunications Energy Conf.*, 1991, pp. 220–226.
- [14] L. R. Lewis, B. H. Cho, F. C. Lee, and B. A. Carpenter, "Modeling, analysis and design of distributed power systems," in *Proc. IEEE PESC'89*, 1989, pp. 152–159.
- [15] V. J. Thottuvellil and G. C. Verghese, "Analysis and control design of paralleled DC/DC converters with current sharing," *IEEE Trans. Power Electron.*, vol. 13, pp. 635–644, July 1998.
- [16] B. Choi, B. H. Cho, and F. C. Lee, "Three-loop control for multi-module converter systems," *IEEE Trans. Power Electron.*, vol. 8, pp. 466–474, Oct. 1993.
- [17] W. Tang, F. C. Lee, and R. B. Ridley, "Small-signal modeling of average current-mode control," *IEEE Trans. Power Electron.*, vol. 8, pp. 112–119, Apr. 1993.
- [18] R. B. Ridley, "A new, continuous-time model for current-mode control," *IEEE Trans. Power Electron.*, vol. 6, pp. 271–280, Apr. 1991.
- [19] R. B. Ridley, B. H. Cho, and F. C. Lee, "Analysis and interpretation of loop gains of multiloop-controlled switching regulators," *IEEE Trans. Power Electron.*, vol. 3, pp. 489–498, Oct. 1988.
- [20] N. H. Kutkut, "A full bridge soft switched telecom power supply with a current doubler rectifier," in *Proc. IEEE Int. Telecommunications Energy Conf.*, 1997, pp. 344–351.
- [21] A. Pietkiewicz and D. Tollik, "Coupled-inductor current-doubler topology in phase-shifted full-bridge Dc–Dc converter," in *Proc. IEEE Int. Telecommunications Energy Conf.*, 1998, pp. 41–48.
- [22] V. Vlatkovic, J. A. Sabate, R. B. Ridley, F. C. Lee, and B. H. Cho, "Small-signal analysis of the phase-shifted PWM converter," *IEEE Trans. Power Electron.*, vol. 7, pp. 128–135, Jan. 1992.

Chang-Shiarn Lin received the B.S. degree from National Cheng Kung University, Tainan, Taiwan, R.O.C., and the Ph.D. degree from National Taiwan University, Taipei, Taiwan, R.O.C., in 1993 and 2000, respectively, both in electrical engineering.

He is currently a Postdoctoral Fellow at National Taiwan University. His research interests include switching-mode power supplies and electronic ballasts.

Chern-Lin Chen (S'86–M'90–SM'99) was born in Taipei, Taiwan, R.O.C., in 1962. He received the B.S. and Ph.D. degrees in electrical engineering from National Taiwan University, Taipei, Taiwan, R.O.C., in 1984 and 1987, respectively.

Since 1987, he has been with the Department of Electrical Engineering, National Taiwan University, where he is presently a Professor. His current research interests lie in the areas of analysis, design, and application of power electronics converters and the control circuitry for plasma display panels.