Input-Voltage Balancing of Series-Connected Converters

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***Abstract*—A method of input-voltage balancing of converters that have inputs connected in series and outputs in parallel is described. The proposed method maintains balance of input voltages by using the voltage-control loop of one converter to regulate the output voltage and by using the voltage-control loop in the remaining converters to regulate their respective input voltages. In addition, to improve the output-voltage transient response during load changes, a simple high-pass filter is employed to couple output voltage changes into the input-voltage regulation loops. Because the converters have the same input and output voltages, they deliver the same amount of power and, therefore, carry the same amount of current without a need for a current sharing circuit. The performance of the proposed method was evaluated on a 1.2-kW prototype circuit that was designed to operate from an 800-V dc input and deliver a 12-V output.**

I. INTRODUCTION

In many applications, instead of a single power converter, a number of power converters with a lower power rating are employed to bring about performance improvements and/or reduce the cost. For example, paralleling of power converters is a widely used approach in today's high-efficiency, high-power density applications since it makes possible to implement redundancy, as well as to improve partial-load efficiency by employing power management. Similarly, in applications with a relatively high input voltage, instead of a single converter, a number of converters are used by connecting their inputs in series and their outputs in parallel. Series connection of converters' inputs makes possible to use converters designed with lower-voltage-rated components, which are typically more efficient and less expensive than their high-voltage-rated counterparts.

For example, in applications where a front end provides high-voltage to downstream dc/dc converters, it is a common practice to use series connection of lower-voltage-rated energy-storage capacitors at the output of the front end and connect dc/dc converters directly across them, as illustrated in Fig. 1. In the connection of the converters in Fig. 1, the balance of the input voltages, i.e., the balance of the capacitor voltages, can only be maintained if the converters are identical and capacitors C_1 and C_2 have same characteristics. Otherwise, the input voltages of the two converters will be different depending on the mismatching of the two converters and capacitors. To prevent the input-voltage imbalance from exceeding a permissible range, a voltage-balancing control must be implemented.

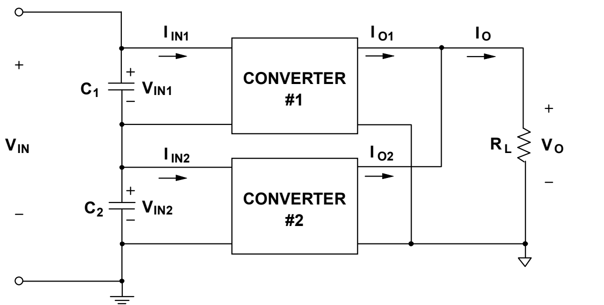


Fig. 1. Two converters with inputs connected in series and outputs in parallel.

A number of input-voltage balancing approaches have been proposed [1]-[13]. A simple and effective active input-voltage method is shown in Fig. 2. This method is implemented with the totem-pole switches operating with the 50% duty cycle and an inductor connected between the mid points of the switches and capacitors. Since for the 50% duty cycle, the mid voltage of switches is exactly one-half of input voltage V_{IN}, the capacitor mid-point voltage is also equal to $V_{IN}/2$ since average inductor voltage is zero. As a result, the voltage balancing circuit ensures excellent balancing and can handle a relatively large mismatching of converters' input currents effectively. The major drawback of the circuit is that it requires additional power components

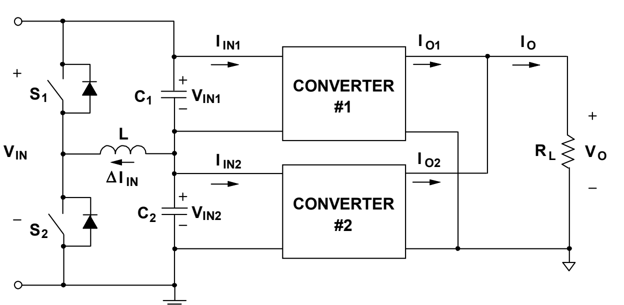


Fig. 2. Active input-voltage balancing circuit that consists of a totem-pole switch and an inductor [4].

which decreases the efficiency and power density and increases the cost [1]-[6].

Figure 3 shows another input-voltage balancing method introduced in [9]. In this method, voltage balancing is implemented solely at the control level, i.e., without addition of any components in the power circuit. As a result, this method offers voltage balancing without adversely affecting, the efficiency, power density, or cost. The approach in Fig. 3 achieves input-voltage balancing by directly regulating the input voltage of the converters. Specifically, in this method a controller is used to regulate the input and output voltage of each converter. As illustrated in Fig. 3, for each converter the input and output voltage are sensed and the sensed voltages are processed by the controller. Because in each converter a single control variable (duty cycle) has to simultaneously regulate the input and the output voltage, a simultaneous tight regulation of both is not possible. Since in a majority of applications the output has to be tightly regulated, the input voltage balancing of this method is relatively poor.

Figure 4 shows a master/slave control of input-voltage balancing method introduced in [13]. In this method, the output and the input voltages are independently regulated. As a result, both a tight regulation of the output voltage and

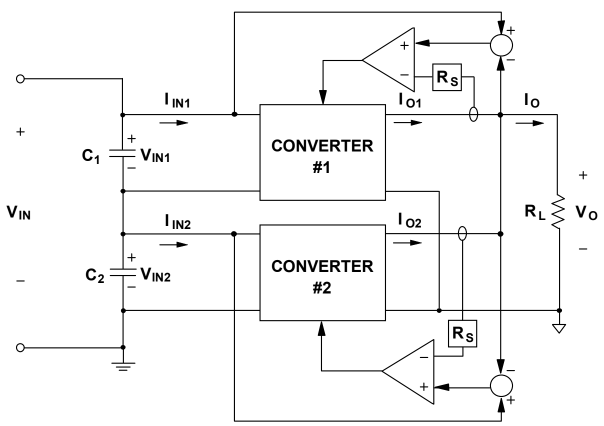


Fig. 3. Active input-voltage balancing method that employs closed-loop control of the input voltages [9].

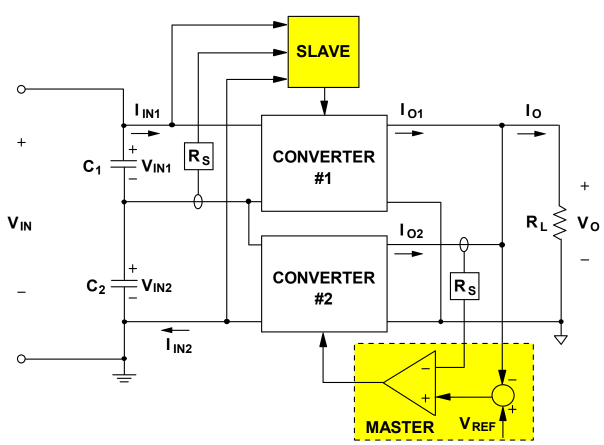


Fig. 4. Active input-voltage balancing method that employs closed-loop control of the input voltages [13].

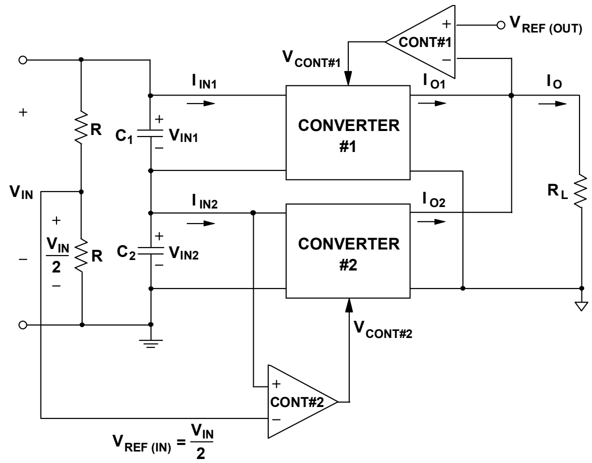


Fig. 5. Proposed input-voltage balancing method.

good input-voltage balancing can be simultaneously achieved. Since in this method the input voltage balancing is achieved by balancing converters' input currents, a bi-directional dc current sensing circuit is required to sense the current difference between the two converters. The complexity of the sensing circuit increases as the number of converters increases.

In this paper, a method of input-voltage balancing that employs a direct control of the input and output voltages is proposed. However, different from the known methods, the proposed method independently controls the input and output voltages without a need for input current sensing. Specifically in the proposed method, input-voltage balancing is achieved by using the voltage control loop of one converter to regulate the output voltage and by using the voltage control loop in the remaining converters to regulate their respective input voltages. Therefore, in this method, a tight regulation of both the input voltages and the output voltage can be achieved. Moreover, because of tight regulation of both the input and output voltages, in the proposed method, the current sharing of the load current is maintained automatically, i.e., without a need for a current share control of any kind. The current sharing performance is solely dependent on the mismatching of the converters characteristics which is relatively very small. Finally, the proposed method does not affect the efficiency, power density and cost since it does not require any additional power components. To improve the input-voltage balancing during load transients, the control signals that regulate the input voltages are also made responsive to output voltage changes by coupling a signal representative of output voltage changes into the input-voltage regulation loop.

II. Input Voltage Balancing of Series Connected Converters

A block diagram of the proposed method that balances input-voltages of two converters with their inputs connected in series and outputs in parallel is shown in Fig. 5. As shown in Fig. 5, one converter is controlled to regulate the output voltage, whereas the other converter is controlled to regulate its input voltage. Specifically, voltage controller CONT#1 of CONVERTER#1 regulates the output voltage, whereas voltage controller CONT#2 of CONVERTER#2 regulates the input voltage of CONVERTER#2. The output voltage regulation is achieved by comparing output voltage V_O with desired reference voltage $V_{REF(OUT)}$ and by processing the error with controller CONT#1 to adjust the control variable (duty cycle) of CONVERTER#1 so that the converter's output voltage assumes the desired value. Similarly, the input voltage control of CONVERTER#2 is regulated by comparing its input voltage V_{IN2} with desired reference voltage $V_{REF(IN)}$ derived from the input-voltage sensing and scaling network and by processing the error with controller CONT#2 so that the control variable of CONVERTER#2 is adjusted to a value necessary to produce the desired input voltage. By making reference voltage $V_{REF(IN)}=V_{IN}/2$, i.e., by using two identical resistors to split the input voltage, the two converters will have a perfectly balanced input voltages.

Moreover, because two converters with the proposed voltage-balancing circuit have identical input voltages and the same output voltage, the load current sharing between the converters is automatically achieved, i.e., no additional current sharing circuit/control is necessary. If the characteristics of both converters are identical, the current sharing is perfect. Otherwise, it depends on the mismatching of the converters' characteristics. Typically, this mismatching, which is primarily caused by component tolerances, is small.

To maintain the input-voltage balancing of converters at all times, all converters should start up simultaneously. Since in practice a perfectly synchronized start up is impossible, the converters regulating their input voltages should be designed to start up a short time prior to the start up of the converter that regulates the output voltage. The start-up delay of the output-voltage regulating converter should be as short as possible to minimize input-voltage imbalances during the start up.

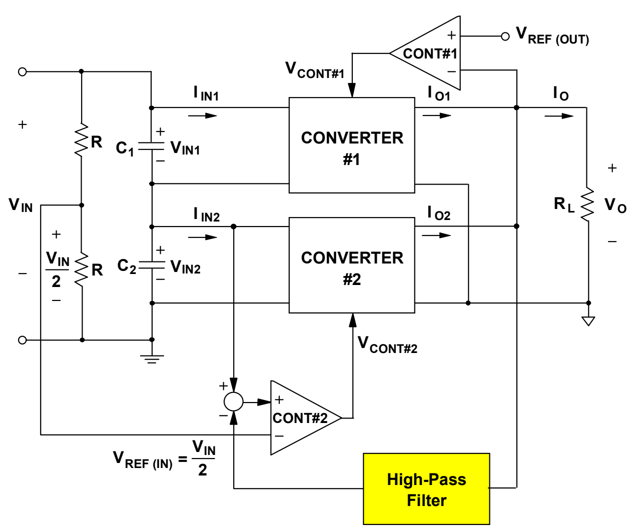


Fig. 6. Proposed input-voltage balancing method with improved output-voltage-transient response.

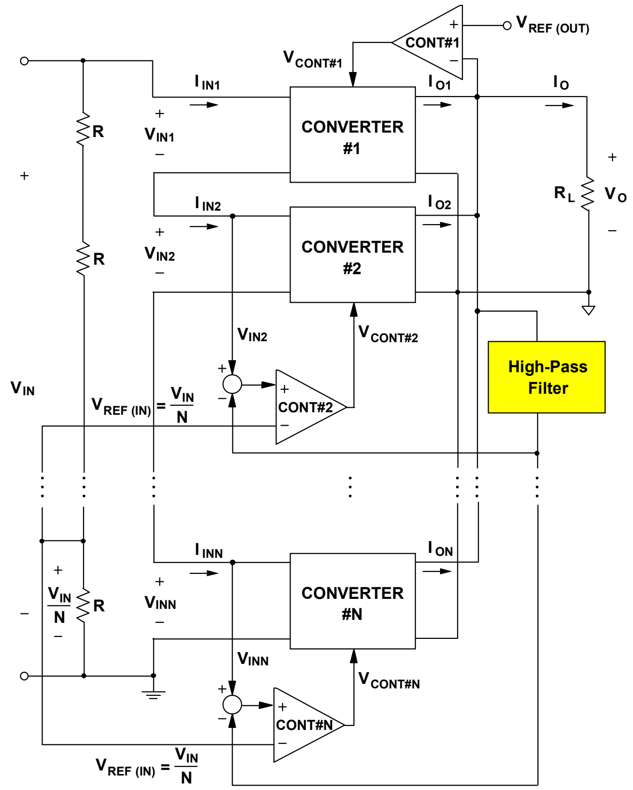


Fig. 7. Proposed input-voltage balancing method for N converters.

To improve the output-voltage transient response of the proposed input-voltage balancing method with respect to step load-current changes, a signal representative of output voltage transients is coupled to the input of the controller that regulates the input voltage through a high-pass filter, as shown in Fig. 6. Generally, the high-pass filter does not noticeably affect the steady-state operation, i.e., in steady state, the output voltage is not coupled to the controller that regulates the input voltage. The coupling exists only when there is a substantial change in the output voltage which produces a change at the high-pass filter output. With the high-pass filter path, both controller CONT#1 that regulates the output voltage and controller CONT#2 that regulates the input voltage are capable of instantaneously responding to output voltage changes. As a result, both controllers can immediately start adjusting the operation of the corresponding converters to the new load current requirement, which minimizes the output voltage transient.

The concept of the proposed method can be extended to any number of converters with their inputs connected in series and outputs in parallel. For N converters that have their inputs connected in series and the outputs in parallel, one converter is employed to regulate the output voltage, whereas the remaining converters are used to regulate their respective input voltages as shown in Fig. 7.

III. Experimental Results

The performance of the proposed method was evaluated on a 1.2-kW prototype circuit that was designed to operate from a 800-V dc input and provide a 12-V output. The prototype circuit consists of two 600-W full-bridge converters operating at 120 kHz with their inputs connected in series. Each full-bridge converter, shown in Fig. 8, is implemented with a SPA11N60CFD MOSFET for each of the bridge switches and two parallel FDP047AN08AD MOSFETs for each of the synchronous rectifier switches. Transformer TR was built using a pair of ferrite cores (PQ 2625-DMR95) with twenty three turns of two triple-insulated magnet wires (0.35 mm diameter) in parallel for the primary winding and two turns of copper foil for the secondary winding. Output filter inductors L_{F1} and L_{F2} were built using a toroidal high flux core (CH203125) and 10 turns of four magnet wires (1.0 mm diameter) in parallel. Three low voltage aluminum capacitors (2200 µF, 16 VDC) were used for the output capacitor. Two parallel STP80NF03L MOSFETs are used as the oring diode which is required for parallel operation of the power supplies in a redundant system. The control was implemented with the UC3895 (peak-current-mode) phase-shift controller. The voltage-loop crossover frequency was designed following the well-establish design procedure in [14] and [15] to achieve the 60° phase margin at the 1 kHz cross-over frequency. Figure 9 shows measured output-voltage feedback loop gain and phase of one of the converters which operates from a 400-V dc input and provides a 12-V output as a stand-alone converter.

A thorough experimental performance evaluation of the proposed input-voltage-balancing method was performed in a series of measurements designed to compare various control strategies. First, the prototype circuit without any active input-voltage balancing circuit was evaluated, i.e., the measurements were done with each converter regulating the output voltage with its own independent feedback control. To prevent any accidental damage to the circuit in case of severely unbalanced input voltages, the input voltage was set to 400 V and output to 6 V, which is one half of the specified input and output voltages, respectively. Figure 10 shows measured voltages V_{IN1} and V_{IN2} of capacitors C_1 and C_2, their difference V_{IN1}-V_{IN2}, output voltage V_O, and output currents I_{O1} and I_{O2} during the start up. The imbalance of the initial voltages across capacitors C_1 and C_2 was deliberately introduced. The measurements were performed at approximately 60-W load. As seen in Fig. 10(b), the two converters continuously deliver unbalanced output currents I_{O1} and I_{O2} which produces continuously increasing voltage difference between their input voltages.

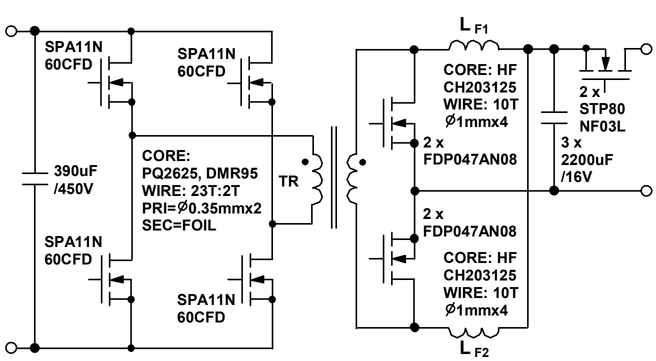


Fig. 8. Experimental full-bridge dc-dc converter prototype.

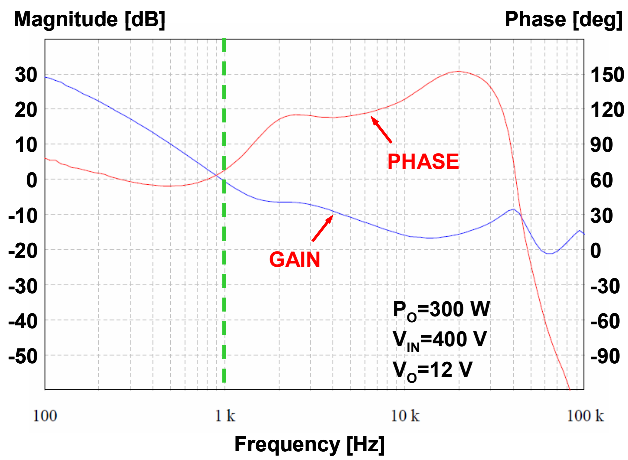
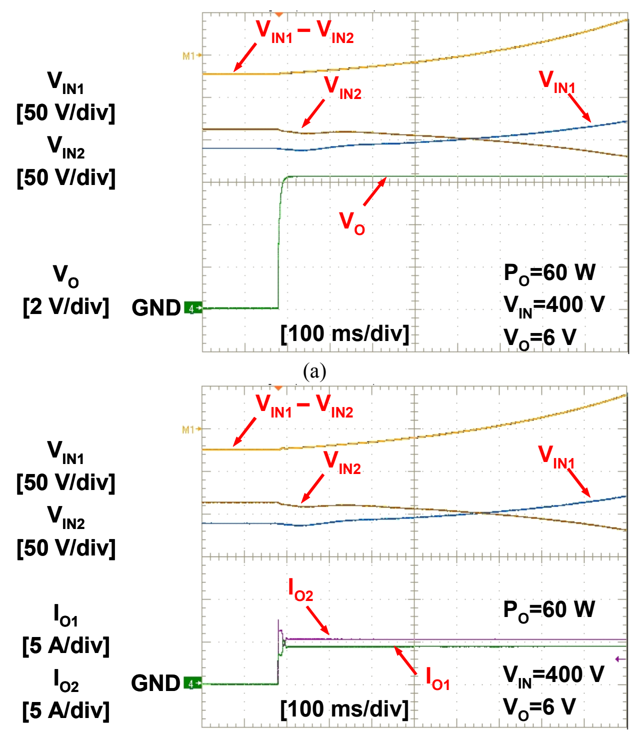


Fig. 9. Measured output voltage feedback loop gain of experimental full-bridge dc-dc converter.



(a)

(b)

Fig. 10. Measured start-up waveforms for two converters without input-voltage-balancing circuit: (a) capacitor voltages V_{IN1} and V_{IN2}, their difference V_{IN1}-V_{IN2}, and output voltage V_O; (b) capacitor voltages V_{IN1} and V_{IN2}, their difference V_{IN1}-V_{IN2}, and output currents I_{O1} and I_{O2}.

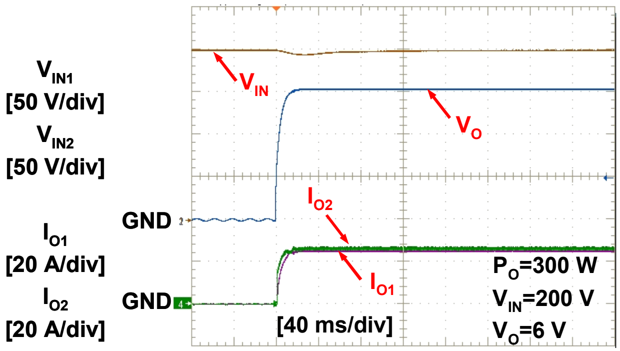


Fig. 11. Measured input voltage V_{IN2}, output voltage V_O, and output currents I_{O1} and I_{O2} during start-up of two paralleled converters with current-sharing circuit.

To evaluate the effect of a current-sharing loop on the input-voltage balancing of converters without any input-balancing control, an active current-sharing control loop is added to the converters. First, the performance of the active current sharing circuit itself was evaluated with a 200-V input by connecting the inputs and outputs of the two full-bridge converters in parallel. Figure 11 shows that the output currents of the converters are very well balanced, i.e., that the accuracy of the current-sharing circuit is good. Knowing that the current sharing circuit exhibits good

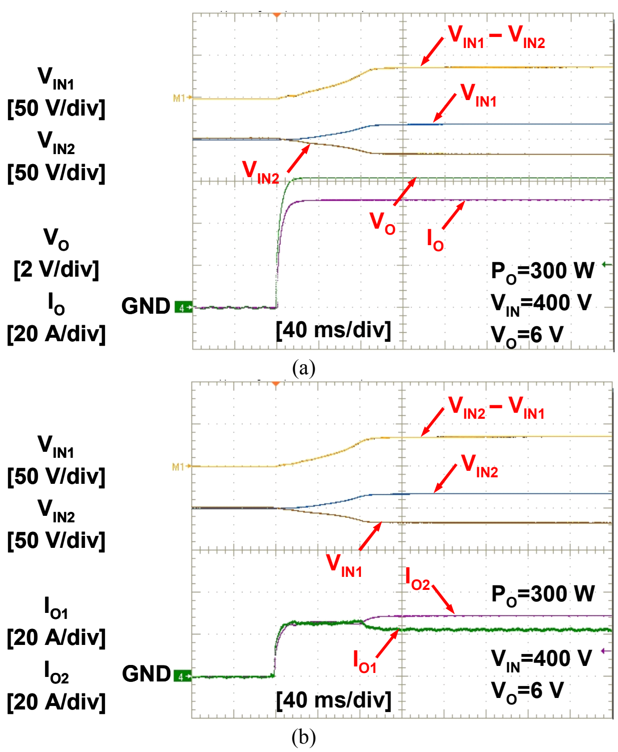


Fig. 12. Measured start-up waveforms for two converters without input-voltage-balancing circuit, but with active current-sharing circuit added: (a) capacitor voltages V_{IN1} and V_{IN2}, their difference V_{IN1}-V_{IN2}, output voltage V_O, and load current I_O; (b) capacitor voltages V_{IN1} and V_{IN2}, their difference V_{IN1}-V_{IN2}, and output currents I_{O1} and I_{O2}.

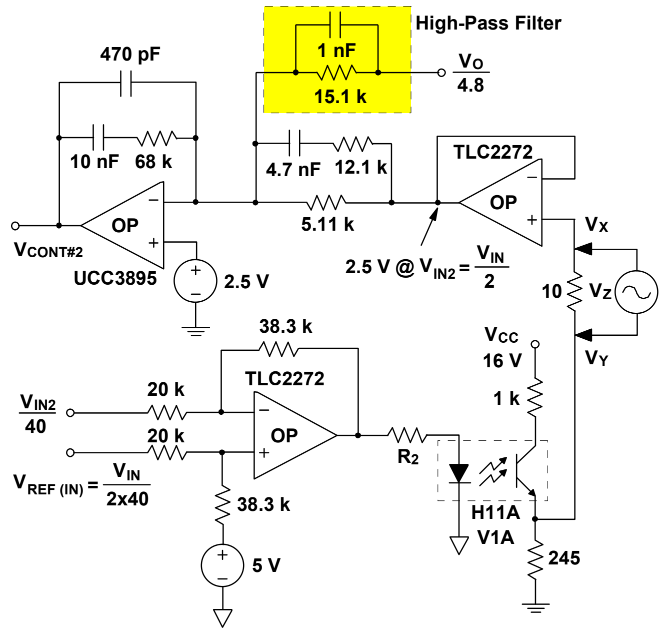


Fig. 13. Schematic diagram of input-voltage feedback control circuit with the high-pass filter that couples sensed output voltage to input of the controller.

accuracy, the inputs of the converters are connected in series and a 400-V input is applied. As shown in Fig. 12, not only does the imbalance of the capacitor voltage occur but also the output current sharing accuracy decreases. It seems as if the current sharing control is altered to allow the voltages across capacitors C_1 and C_2 to reach their steady states.

Next, the performance of the proposed method that is implemented exactly as in Fig. 5 was evaluated. Specifically, in the evaluated implementation, one converter regulates the output voltage and the other its own input voltage. Figure 13 shows the implemented input-voltage feedback control circuit. It should be noted that the high-pass filter in the

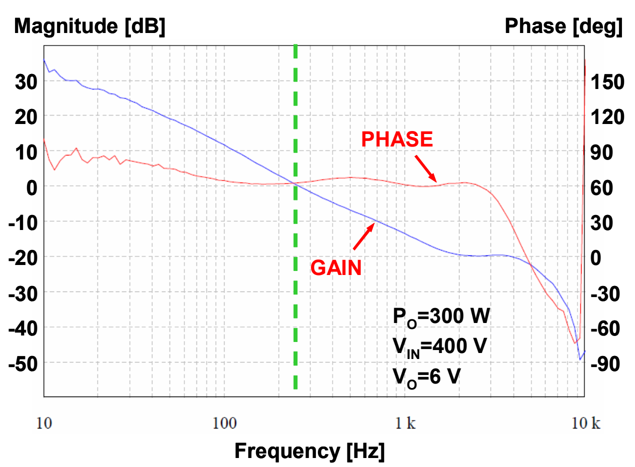


Fig. 14. Measured loop gain of input-voltage feedback with controller shown in Fig. 13 (without high-pass filter).

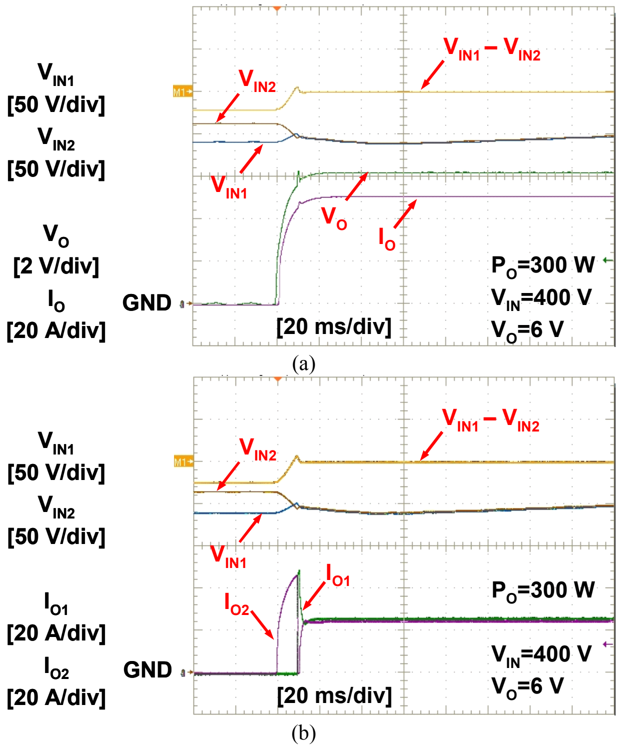


Fig. 15. Measured start-up waveforms for two converters with proposed input-voltage-balancing circuit shown in Fig. 5: (a) capacitor voltages V_{IN1} and V_{IN2}, their difference V_{IN1}-V_{IN2}, output voltage V_O, and load current I_O; (b) capacitor voltages V_{IN1} and V_{IN2}, their difference V_{IN1}-V_{IN2}, and output currents I_{O1} and I_{O2}.

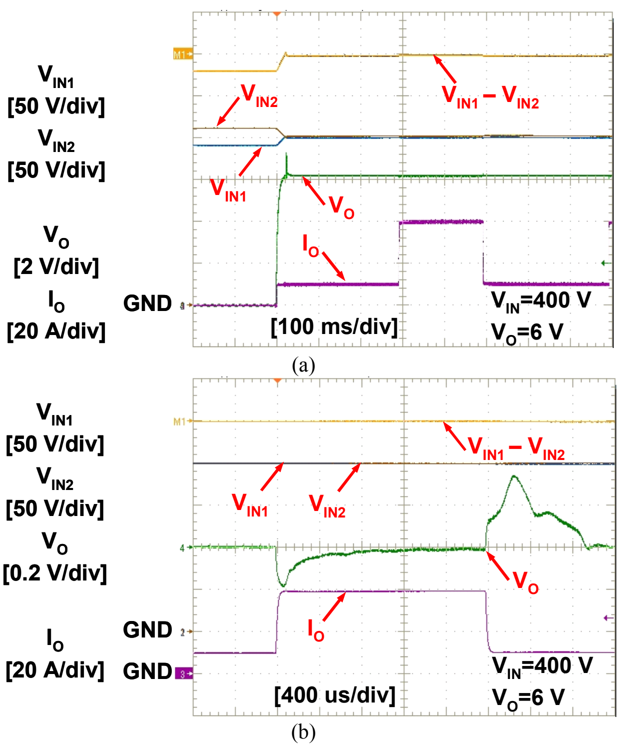


Fig. 16. Measured voltage-transient response waveforms for two converters with proposed input-voltage-balancing circuit shown in Fig. 5: (a) capacitor voltages V_{IN1} and V_{IN2}, their difference V_{IN1}-V_{IN2}, output voltage V_O, and load current I_O; (b) zoom-in waveforms in (a).

dashed line, which couples the output voltage signal to the input-voltage feedback controller, is not connected in this experiment to verify the control scheme in Fig. 5. Figure 14 shows measured input-voltage feedback loop gain and phase, which exhibit the 60° phase margin at the 230 Hz cross-over frequency. The location of the signal-injection point for measuring the input voltage feedback loop gain is depicted in Fig. 13, where voltage V_Z is the injected signal, voltages V_X and V_Y are the input and output signals to obtain the loop gain. The measurements, shown in Figs. 15 and 16, were performed at approximately 300-W load with initially imbalanced capacitor voltages. As shown in Fig. 15(a), the imbalance of the capacitor voltages disappears immediately after the start of the converters. While the circuit exhibits good input-voltage balance and the output voltage regulation during steady state, its performance is not acceptable during large load transients. As shown in Figs. 16(a) and (b), during a load step-change (0.6 A/µSec) from 10 A to 40 A and back to 10 A, the output voltage undershoot and overshoot exceed a typically specified limit of ±3% of the steady-state output voltage. This unacceptable output-voltage transient response is the result of the complete decoupling of the output- and input-voltage control loops which makes it impossible for the input-voltage control loop to immediately respond to an output-voltage change. Finally, it should be noted that if the converters start with the unbalanced voltages across capacitors C_1 and C_2, the converter connected to the higher input voltage delivers most of the output current until voltages V_{IN1} and V_{IN2} become balanced as shown in Fig. 15 (b). It should also be noted that the two converters automatically share their output currents equally in steady state without any active output current sharing circuit.

To evaluate the effectiveness of the proposed high-pass-filter approach in Fig. 6 to improve the output-voltage transient response, the control of the experimental circuit was modified as shown in Fig. 13. Specifically, a high-pass

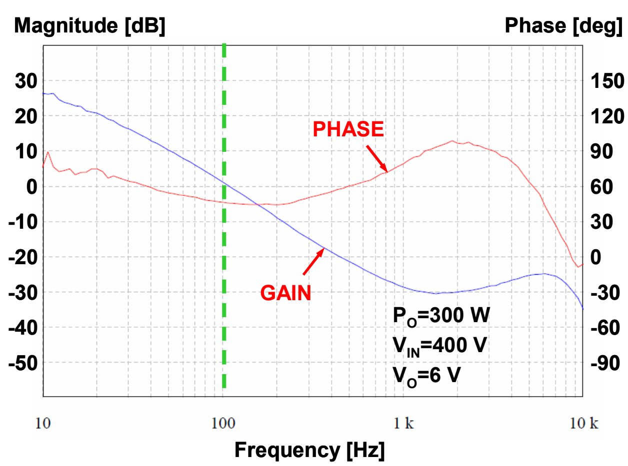


Fig. 17. Measured loop gain of input-voltage feedback with high-pass filter.

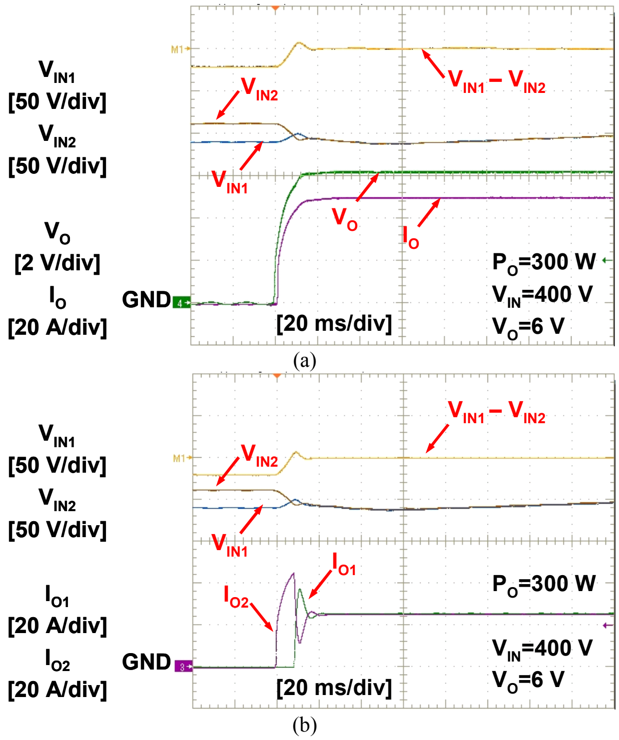


Fig. 18. Measured start-up waveforms for two converters with control that includes high-pass filter: (a) capacitor voltages V_{IN1} and V_{IN2}, their difference V_{IN1}-V_{IN2}, output voltage V_O, and load current I_O; (b) capacitor voltages V_{IN1} and V_{IN2}, their difference V_{IN1}-V_{IN2}, and output currents I_{O1} and I_{O2}.

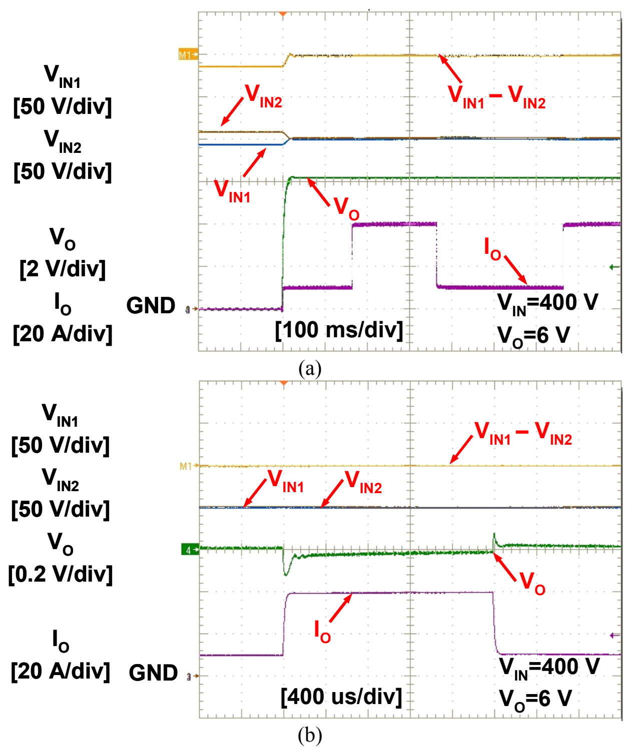


Fig. 19. Measured voltage-transient response waveforms for two converters with control that includes high-pass filter: (a) capacitor voltages V_{IN1} and V_{IN2}, their difference V_{IN1}-V_{IN2}, output voltage V_O, and load current I_O; (b) zoom-in waveforms in (a).

filter consisting of a 1-nF capacitor and a 15-kΩ resistor connected in parallel was added to couple the sensed output voltage to the input of the input-voltage controller. Since the high-pass filter has minor effect on the behavior of the control loops at low frequencies, in steady state the control performance is effectively the same as that without the high-pass filter. Figure 17 shows measured loop gain and phase of the input voltage feedback controller with the high-pass filter. It shows the 45° phase margin at the 100 Hz cross-over frequency.

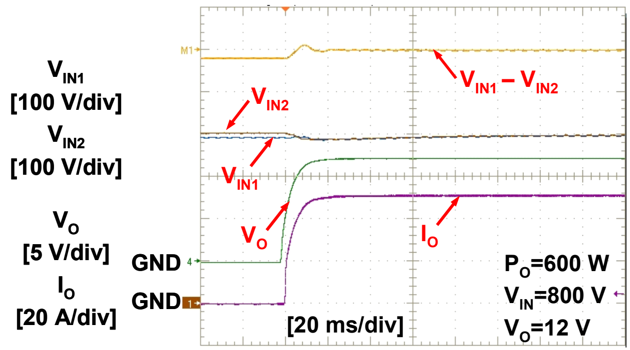


Fig. 20. Measured start-up waveforms for V_{IN} = 800 V for two converters with control that includes high-pass filter: capacitor voltages V_{IN1} and V_{IN2}, their difference V_{IN1}-V_{IN2}, output voltage V_O, and load current I_O.

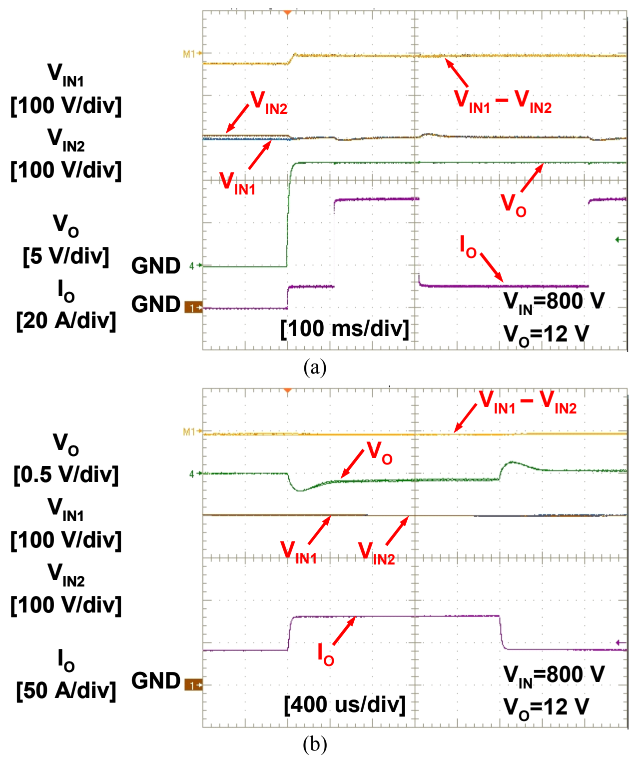


Fig. 21. Measured voltage-transient response waveforms for V_{IN} = 800 V for two converters with control that includes high-pass filter: capacitor voltages V_{IN1} and V_{IN2}, their difference V_{IN1}-V_{IN2}, output voltage V_O, and load current I_O during output-current step change between (a) 10 A and 50 A; (b) 40 A and 80 A.

Figure 18 shows the measured start-up waveforms with control in Fig. 13 for the same test conditions as in Fig. 15. As seen from Fig. 18(a), the imbalance of the capacitor voltages disappears immediately after the start of the converters. In addition, the output-voltage over shoot shown in Fig. 15(a) was eliminated. Figures 19(a) and (b) show the waveforms during the transient test with a step load change (0.6 A/μSec) from 10 A to 40 A and back to 10 A. As shown in Fig. 19(b), the peaks of the voltage undershoot and overshoot are very much reduced compared to that in Fig. 16(b).

Finally, Figs. 20 and 21 show measured start-up and output-voltage transient waveforms, respectively, of the implementation with the high-pass filter when the voltages are increased to 800-V input and 12-V output. Figure 20 shows the measured start-up waveforms with 600 W output power. The imbalance of the capacitor voltages disappears immediately after the start of the converters and over shoot of the output voltage is not observed. Figure 21 (a) shows waveforms during the transient test with a step load change (0.6 A/μSec) from 10 A to 50 A and back to 10 A. Figure 21 (b) shows waveforms measured in the expended time scale during the transient test with step load changes between 40 A and 80 A. As shown in Fig. 21(b), the peaks of the output-voltage undershoot and overshoot meet the requirements. As can be seen from Figs. 20 and 21, the measurements show very good input voltage balancing and transient output-voltage regulation.

IV. SUMMARY

In this paper, a method of maintaining input-voltage balance of the converters that have inputs connected in series and outputs in parallel has been provided. The performance of the proposed method was evaluated on a 1.2-kW prototype circuit that was designed to operate from a 800-V dc input and deliver a 12-V output. The experimental results confirm that with the proposed control method both the input-voltage balancing and output-voltage transient response can be simultaneously maintained within the desired limits.

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