Input Series-Output Parallel Connected Converter Configuration for High Voltage Power Conversion Applications

Jung-Won Kim, J.S. You and B.H. Cho
School of Electrical Engineering Seoul National University
San 56-1 ShinLim-Dong KwanAk-Ku Seoul Korea
Phone + 82-2-880-7260, Fax + 82-2-878-1452
e-mail: jwk@plaza1.snu.ac.kr

ABSTRACT - In this paper, the charge control with the input voltage feed forward is proposed for the input series-output parallel connected converter configuration for high voltage power conversion applications. This control scheme accomplishes the output current sharing for the output-parallel connected modules as well as the input voltage sharing for the input-series connected modules for all operating conditions including the transients. It also offers the robustness for the component value mismatches among the modules.

I. INTRODUCTION

In the field of high voltage power conversion the circuit designer is often confronted with a serious problem that there are no semiconductors capable of sustaining the required voltage and suitable for the desired switching speed. For this reason, several series connection methods and converter topologies are proposed. But the arising problem with series connection is the voltage balancing at the device turn-off. To get the voltage balancing at the device turn-off, a passive or active balancing method is used. The passive method requires a snubber circuit and this causes slow switching speed and introduces additional loss. The active methods require complicated control circuits to get the voltage balancing[1-4]. The control delay of the voltage balancing controller[3,4] increases the device stress and the switching speed is restricted. Moreover, in spite of control efforts the perfect balancing is hard to be accomplished during switching instance.

The problems of device series connection mentioned above can be solved by the input series-output parallel connected converter configuration. In this configuration, the input voltages and the output currents must be balanced for the equal power distribution.

In this paper, the charge control with the input voltage feed forward scheme is proposed, which balances the input voltage sharing as well as the output current sharing for each module. With this scheme, the converter modular approach can easily be implemented for any types of converter topologies.

II. INPUT SERIES-OUTPUT PARALLEL CONNECTED CONVERTER CONFIGURATION

Fig. 1 shows the input series-output parallel connected converter configuration for high voltage power conversion applications.

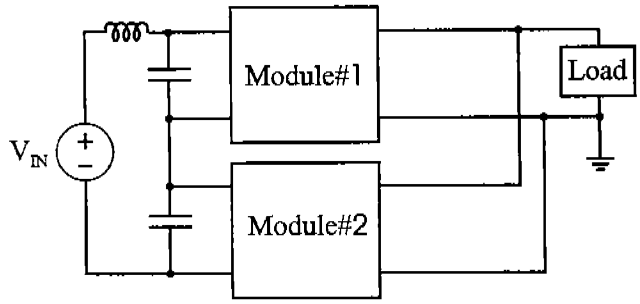

Fig.1 Input series-output parallel connected converter configuration

Two modules are shown in this figure where the input voltage is divided by the series connected input capacitors and the output is paralleled, and according to the input voltage range more modules can be stacked. In this configuration any converter topology can be used if an isolation transformer is used. the input voltage is divided by the series connected input capacitors and the output is paralleled. The series connected converter experiences only divided input voltage so the device rating can be reduced. Since the input capacitors are used to share the voltage, these capacitors can be utilized as part of an input filter as shown in the figure.

In this system, there are two separate requirements for control: First, the load current must be shared equally for each output-paralleled module. Secondly, the input voltage must be shared equally for each input-series module.

For the output current sharing, a current mode control can be used. However if the output current is controlled to be the same between the two modules for example, then even a slight mismatch in the transformer causes the input current imbalance and this fails the input voltage sharing. The input capacitor voltage of a module which draws more input current than the other module, falls down. Thus, the average input current must be controlled to prevent the input voltage mismatch. For the forward type converter shown in Fig.2, the charge control can directly controls the average input current.

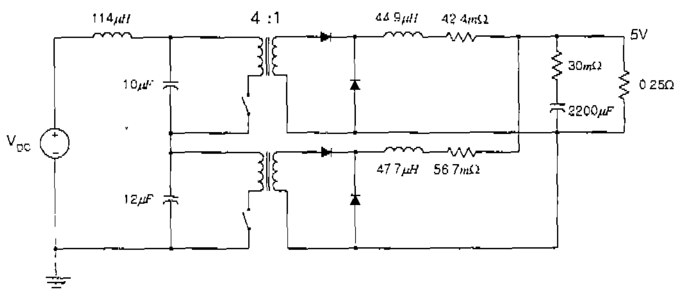

Fig.2 Schematic of the input series-output parallel connected forward converter

However, the conventional charge control scheme has the following problems : If the component value mismatches in the switch current sensing circuit and the charge capacitor, the average input current can be mismatched, which eventually causes the voltage imbalance. Fig.3 simulates this case with the two module forward converter system shown in Fig.2.

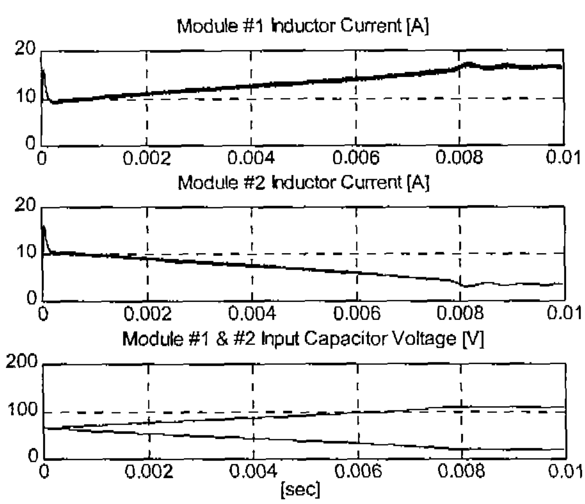

Fig.3 Simulation result of the charge capacitor mismatch

In this simulation, there is 20% mismatch in the charge capacitor and this causes the input voltage mismatch. The excessive voltage mismatch can cause the input voltage to exceed the voltage rating of components.

Also, if the value of the input voltage sharing capacitors are not perfectly matched, then the input capacitor voltage can be different during the transient. If the average input current of each module is the same, the voltage imbalance can never be fixed after the input voltage mismatch occurs. Fig.4 simulates this case with the two module forward converter system shown in Fig.2. The initial input voltage is 130V and steps up to 150V at 2ms and the initial load current is 20A and steps down to 10A at 7ms. The 20% imbalance of the input capacitors causes the imbalance of the input capacitor voltage and the input capacitor voltage remains unbalanced because input currents are balanced by charge control.

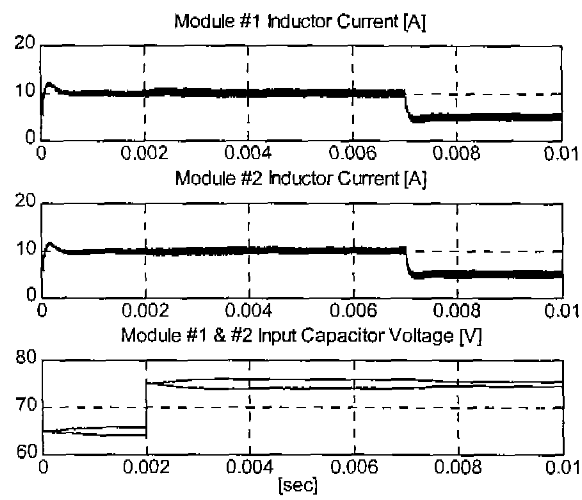

Fig.4 Simulation result of the input capacitor mismatch case

III.CHARGE CONTROL WITH THE INPUT VOLTAGE FEED FORWARD

In order to solve the problems discussed above, the charge control employing the input voltage feed forward scheme is proposed. The proposed charge control scheme is shown in Fig.5. In this figure, Vc is the output of the output voltage compensator. There is only one output voltage compensator in this scheme.

The input current of each module can be adjusted according to the input capacitor voltage to achieve the voltage balance between the modules for all operating conditions. In this scheme, the input voltage difference is multiplied by a gain, k and this controls the offset voltage in the duty ratio modulator. If the input capacitor voltage of one module, v1 is higher than that of the other module, v2, the offset voltage k*(v2-v1) becomes lower in the modulator to increase the input average current. At the same time, the offset voltage for the other module k*(v1-v2) becomes higher in the modulator to reduce the input average current.

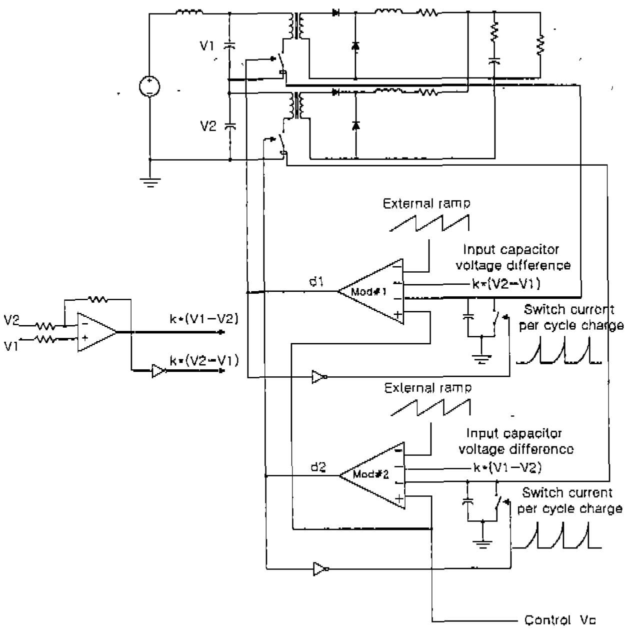

Fig. 5 Proposed charge control scheme with the input voltage feed forward

Increasing the average input current, however, to reduce the input capacitor voltage may cause an excessive unbalance of the input average current. Therefore the current limiting function must be included. The amount of the difference in the input average current to balance the input voltage during the transient can be estimated by (1).

$$\Delta I_{in\max} = k \cdot C_T \frac{\Delta V_{in\max}}{\Delta t_{on}} \quad (1)$$

where, $\Delta V_{in\max}$ is the maximum of the input capacitor voltage difference, C_T is the charge control capacitor, Δt_{on} is the on-time of the switch and k is the gain of the differential amplifier of the input voltages. The higher the gain k, the larger the $\Delta I_{in\max}$ becomes, and lower the gain k makes $\Delta I_{in\max}$ small but it takes longer time to reach the balanced steady state of the input capacitor voltages. Therefore, there must be a design trade-off for the gain, k between the current rating of the converter and the settling time.

Fig. 6 shows the simulation result of the proposed scheme. There is 20% mismatch in the charge capacitor and in the input capacitor. The initial input voltage is 130V and steps up to 150V at 2ms and the initial load current is 20A and steps down to 10A at 7ms. The imbalance of the input capacitor voltage is controlled to be balanced by the proposed scheme in spite of mismatches in the charge capacitor and the input capacitor in the steady and transient state. To achieve the balance of the input capacitor voltage the input average currents are controlled to be somewhat different at the transient.

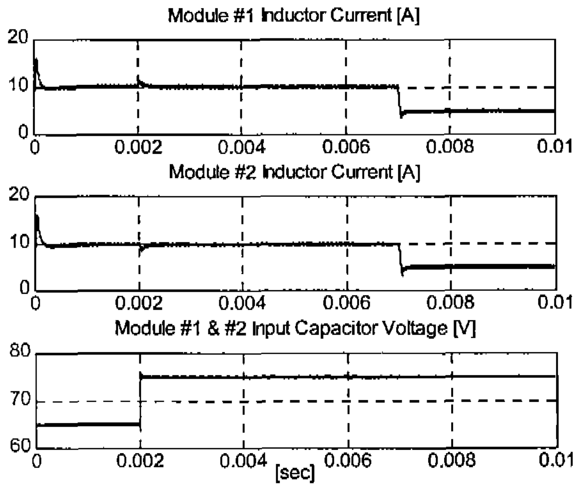

Fig. 6 Simulation result of the proposed charge control scheme with the input voltage feed forward

IV. EXPERIMENTAL RESULT

To verify the effectiveness of the proposed control scheme experiments are performed. The experimental setup is the same as that of the previous simulations. Fig. 7 shows an experimental result employing the conventional charge control scheme.

The input voltage steps up at 1.5s from 130V to 150V, steps down at 2.5s to 120V and steps up at 3.5s to 130V. The input capacitor of module #2 is 20% greater than that of module #1. The input voltage variation of module #1 in the transients, is greater than that of module #2 because of the smaller input capacitor. In the figure input voltage mismatch is observed not only in the steady state but also in the transients because of module mismatches. Employing charge control, the input average currents are controlled to be the same therefore the voltage imbalance is not fixed after the input voltage mismatch occurs. So the supplying power of two modules are unbalanced and one module suffers more stress than the other and this worsens the system reliability.

Fig. 8 shows an experimental result employing the proposed charge control scheme with the input voltage feed forward. The experimental condition is the same as that of fig. 7.

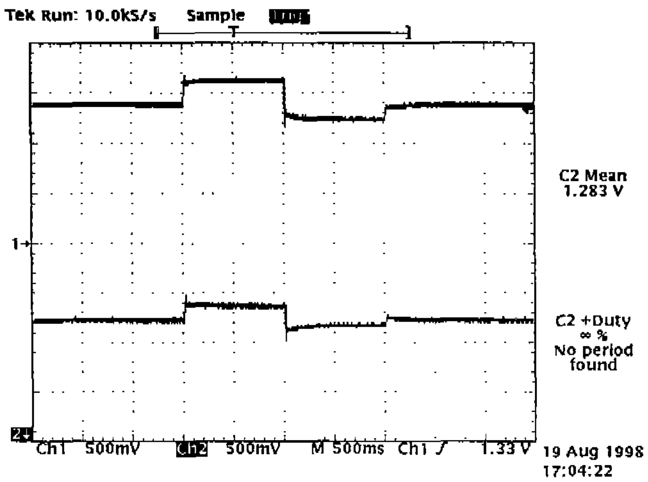

Fig.7 Experimental wave forms with conventional charge control scheme, [25V/div], [0.5s/div]
Ch1, Ch2: input capacitor voltage of module #1, #2

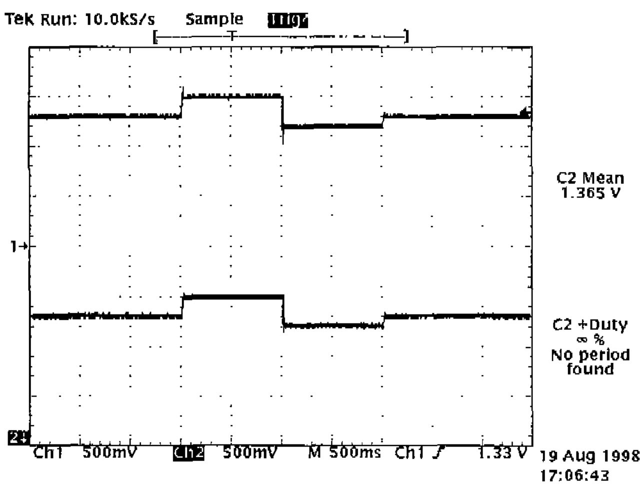

Fig.8 Experimental wave forms with proposed charge control scheme, [25V/div], [0.5s/div]
Ch1, Ch2: input capacitor voltages of module #1, #2

In both the steady and transient states the perfect balance of the input capacitor voltages is achieved by the proposed control scheme. So the power balance between two modules is accomplished by the proposed control scheme and the voltage stress is equally divided between two modules.

Fig.9 shows the input capacitor voltages and the inductor currents of two modules during input voltage step change . The input voltage steps up from 130V to 150V at 10ms. Because the input capacitor of module #1 is smaller, the input capacitor voltage of module #1 goes higher than that of module #2. To balance the input capacitor voltage the proposed charge controller increases the input average current of module #1 and decreases the input average current of module #2. In the figure the inductor currents are plotted instead of input average currents for the displaying convenience. There is about 2A difference between the inductor currents of two modules to balance the input capacitor voltages.

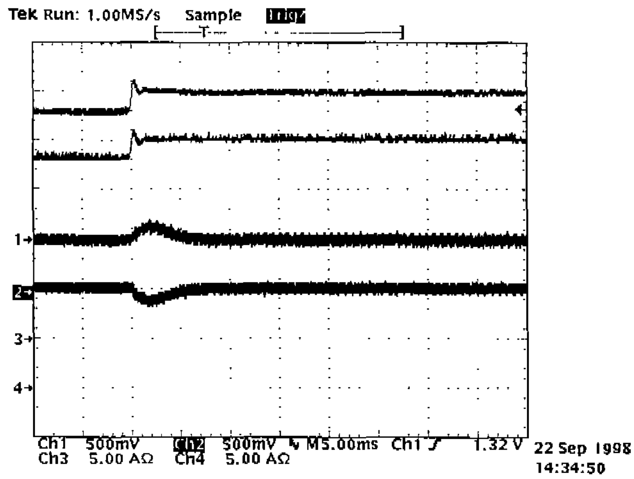

Fig.9 Experimental wave forms with proposed charge control scheme, [25V/div], [5A/div], [5ms/div]
Ch1, Ch2: input capacitor voltages of module #1, #2
Ch3, Ch4: inductor currents of module #1, #2

V. CONCLUSION

In this paper, the charge control with the input voltage feed forward is proposed for the input series-output parallel connected converter configuration for high voltage power conversion applications. This control scheme accomplishes the output current sharing for the output-parallel connected modules as well as the input voltage sharing for the input-series connected modules for all operating conditions including the transients. It also offers the robustness for the component value mismatches among the modules. By this approach the device series connection is unnecessary for high voltage power conversion applications.

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