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Wireless Input-Voltage-Sharing Control Strategy for Input-Series Output-Parallel (ISOP) System Based on Positive Output-Voltage Gradient Method

Wu Chen, Member, IEEE, Guangjiang Wang, Xinbo Ruan, Senior Member, IEEE, Wei Jiang, and Wei Gu

Abstract—An input-series output-parallel (ISOP) system, in which multiple converter modules are connected in series at the input sides and parallel at the output side, is very suitable for high input-voltage, low output-voltage, and high output-current applications. Input-voltage sharing (IVS) and output-current sharing of the constituent modules among the ISOP system must be ensured. The existing IVS control strategies have drawbacks of lower reliability and lower modularity. In this paper, we propose a wireless IVS control strategy for ISOP systems based on positive output-voltage gradient method, which can effectively improve the reliability and modularity of ISOP systems. First, the operation principle of the proposed control strategy is introduced, and the IVS performance and output-voltage regulation characteristics of ISOP systems are analyzed. The stability of the proposed control strategy is also explored. A three-module ISOP system prototype is fabricated and tested in the laboratory, and the experimental results verify the effectiveness of the proposed control strategy.

Index Terms—Input-series output-parallel (ISOP), input-voltage sharing (IVS), positive output-voltage gradient method, stability, wireless.

I. INTRODUCTION

WIT THE rapid development of power electronics technology, the development orientations of switching-mode power supply are high frequency, modularity, and integration. The series-parallel power conversion system, in which multiple standardized high-frequency converter modules are connected in series or parallel at the input and output sides to meet various applications, has become a hot topic of power electronics system integration. The major advantage of the series-parallel power conversion system is that the voltage and current stresses on the power devices of the constituent modules can be reduced. As one of the series-parallel configurations, the input-series output-parallel (ISOP) dc–dc conversion system is suitable for high-input-voltage and high-output-current applications, such as in converters fed from the dc voltage supply in an electric railway system or dc voltage supply after a power factor correction (PFC) preregulator [1].

In order to ensure the proper operation of ISOP systems, the basic objective is to ensure input-voltage sharing (IVS) and output-current sharing (OCS) among the constituent modules. Control strategies to achieve IVS and OCS for the ISOP system have been studied extensively [1]–[20], and generally speaking, these control strategies can be classified into two categories, one is the natural voltage/current sharing method in which IVS and OCS are achieved without special control approach, and the other is the method with special IVS control approach. Common-duty-cycle control is usually employed for the natural voltage/current sharing method [2]–[7], which relies on the inherent self-correcting characteristic of the ISOP system when the duty cycles of all the constituent modules are the same. In [8], a control strategy based on sensorless current mode is proposed for the ISOP system with improved input disturbance rejection performance, which has a similar IVS mechanism with that of the common-duty-cycle control. The most significant advantage of the natural voltage/current sharing method is that no special input-voltage or OCS controllers are required and the control strategy is very simple. However, from the point of view of modularity, the ISOP system with the natural voltage/current sharing method has the shortages of low modularity and poor reliability due to the fact that all the constituent modules share the same central controller [2]–[8] and sometimes need to share the transformer [6] or inductor [7]. Moreover, excellent IVS and OCS cannot be achieved due to parameter mismatches among the modules.

The exact sharing of the input voltage and output current can be achieved by means of the control method with special IVS control approach. In [9], a charge control with input-voltage feedforward is proposed for the ISOP system for the high-speed-train power system application, and for the inner-current loop, both average-current control [10] and peak-current control [11] can also be used. In [12] and [13], the inner-current loop is removed and only voltage mode control with input-voltage feedforward for ISOP systems is implemented. In [14] and [15], Sha et al. proposed a cross-feedback output-current-sharing control strategy for ISOP systems without input-voltage feedforward term, which can eliminate the input-voltage...
sensing and ensure even sharing of the input voltage and output current. Compared with the natural voltage/current sharing method, ISOP systems with special IVS control can realize excellent IVS and OCS; however, the constituent modules of ISOP systems still share the same central controllers [9]–[15] and the ISOP system cannot be separated into standardized modules, which limits the series-parallel system benefits such as modularity, reliability, and expansibility.

In [17]–[19], a modularization architecture for the ISOP system is proposed, which has the following features: 1) All the constituent modules are identical and the individual module has its own power stage and control stage with output-voltage loop and can operate in stand-alone mode; 2) no external controller is needed to achieve IVS and OCS; and 3) a sharing bus or duty-cycle bus is needed to connect up the modules to form the ISOP system and voltage/current signals are delivered through the sharing bus to achieve IVS and OCS. In [20], the controllers are also distributed into individual module, and one module is controlled to regulate the output voltage, whereas the other modules connected through a sharing bus are controlled to regulate their own input voltages. The modularization architecture realizes the modularity design of the ISOP system and increases system reliability and expansibility. It can be seen that the sharing bus or duty-cycle bus is a key interconnection channel to keep the operation of the ISOP system stable. When the bus is disrupted or failed, the operation of the ISOP system will be affected or even lead to paralysis, which reduces the system reliability to some extent. Therefore, eliminating the interconnection among the modules is a desired choice.

Inspired by the idea that the parallel operation of dc–dc converters or dc–ac inverters with droop method can realize wireless load current sharing without interconnection among the modules [21]–[24], we propose a wireless IVS control strategy for ISOP systems based on positive output-voltage gradient method in this paper. The constituent modules of the ISOP system with the proposed control strategy merely need to sense their own input/output voltage, and there is no control interconnection among these modules, leading to a truly modular design for ISOP systems and high system reliability.

This paper is organized as follows. The operation principle of the proposed control strategy is analyzed in Section II and its characteristics of IVS and output-voltage regulation are also presented. The detailed block diagram of the control strategy is illustrated in Section III, and its stability is explored in Section IV. Section V shows the experimental results for an ISOP system consisting of three modules, and a brief conclusion is given in Section VI.

II. OPERATION PRINCIPLE OF THE PROPOSED CONTROL STRATEGY

To simplify the analysis, the ISOP system consisting of two modules is taken as an example to explain the operation principle of the control strategy based on the positive output-voltage gradient method, as shown in Fig. 1. It is assumed that the two modules have the same output-voltage regulation characteristic, which means that the output voltage of the module increases as the module input voltage increases, as shown in Fig. 2.

At steady state, the two modules share the input voltage and both work at point O. Assuming a perturbation occurs on the input filter capacitor voltages, \( V_{\text{in1}} \) decreases and \( V_{\text{in2}} \) increases, i.e., \( V_{\text{in1}} < V_{\text{in}/2} < V_{\text{in2}} \), while the input voltage \( V_{\text{in}} \) is unchanged. According to the positive output-voltage gradient regulation characteristic (Fig. 2), the output voltages of modules #1 and #2 should be \( V_{O1} \) and \( V_{O2} \), respectively. For the ISOP system, the output sides of the two modules are connected in parallel and the two modules have the same output voltage \( V_{O1} \), and we can obtain \( V_{O1} < V_{O2} < V_{O3} \). Therefore, for the controller of module #1, the output voltage is considered to be higher than its corresponding reference voltage, and the duty cycle will be regulated to reduce the input power of module #1, \( I_{\text{in1}} \) will decrease, and \( I_{\text{in2}} \) will increase. Then, the input voltage of module #1 increases and the working point moves up from point A. Meanwhile, for the controller of module #2, the output voltage is considered to be lower than its corresponding reference voltage, and its duty cycle will be regulated to increase the input power of module #2, \( I_{\text{in2}} \) will increase, and \( I_{\text{in1}} \) will decrease. Then, the input voltage of module #2 decreases and the working point moves down from point A. Finally, the operating points of the two modules return to the steady-state point O.

In practice, it is difficult to make the positive output-voltage gradient regulation characteristics of the two modules exactly the same as shown in Fig. 2. The output voltage of each module increases as the input voltage increases by

\[
V_{O1} = V_{O1\text{ min}} + k_1 \cdot (V_{\text{in1}} - V_{\text{in\text{ min}}}) \tag{1}
\]

\[
V_{O2} = V_{O2\text{ min}} + k_2 \cdot (V_{\text{in2}} - V_{\text{in\text{ min}}}) \tag{2}
\]

where \( V_{O1\text{ min}} \) and \( V_{O2\text{ min}} \) are the minimum output voltages of modules #1 and #2 under lowest input-voltage condition, respectively, \( k_1 \) and \( k_2 \) are the gradient gains of modules #1
The output voltage of each module is $V_{o1}$ and $V_{o2}$, respectively, and $V_{in_{\text{min}}}$ is the minimum input voltage for each module.

The summation of the input voltages of the two modules is the ISOP system input voltage, i.e., $V_{in} = V_{in1} + V_{in2}$. The two modules have the same output voltages, i.e., $V_{o1} = V_{o2} = V_{o}$.

According to (1) and (2), we have

$$V_{in1} = \frac{k_2 V_{in} + V_{o2_{\text{min}}} - V_{o1_{\text{min}}} + (k_1 - k_2)V_{in_{\text{min}}}}{k_1 + k_2} \quad (3)$$

$$V_{in2} = \frac{k_1 V_{in} + V_{o1_{\text{min}}} - V_{o2_{\text{min}}} + (k_2 - k_1)V_{in_{\text{min}}}}{k_1 + k_2} \quad (4)$$

The IVS error is expressed as

$$\Delta V_{in12} = \frac{V_{in1} - V_{in2}}{V_{in}} = \frac{(k_2 - k_1)V_{in} + 2(V_{o2_{\text{min}}} - V_{o1_{\text{min}}}) + 2(k_1 - k_2)V_{in_{\text{min}}}}{(k_1 + k_2)V_{in}}. \quad (5)$$

It can be seen that the input sharing error is determined by the gradient gains and minimum input and output voltages of the two modules.

Based on (5), the gradient gain of the ISOP system is

$$\frac{\Delta V_o}{\Delta V_{in}} = \frac{V_{o_{\text{a}}} - V_{o_{\text{b}}}}{V_{in_{\text{a}}} - V_{in_{\text{b}}}} = \frac{k_1 k_2 (V_{ina} - V_{inb})}{(k_1 + k_2)(V_{ina} - V_{inb})} = \frac{1}{k_1 + \frac{1}{k_2}}. \quad (6)$$

For an ISOP system consisting of $N$ modules where the output voltage of each module is $V_{oj} = V_{o_{j_{\text{min}}} + k_j(V_{inj} - V_{in_{\text{min}}})}$ ($j = 1, 2, \ldots, N$), the gradient gain of the ISOP system is

$$\frac{\Delta V_o}{\Delta V_{in}} = \frac{1}{k_1 + \frac{1}{k_2} + \ldots + \frac{1}{k_N}}. \quad (8)$$

It can be seen that the gradient gain of the ISOP system is only determined by the module gradient gains and the larger the $N$, the smaller the gradient gain of the ISOP system, which means that the system has better output-voltage regulation performance. In particular, when $k_1 = k_2 = \ldots = k_N = k$, the gradient gain of the ISOP system is equal to $1/k$.

Fig. 3 shows the dependence of the IVS accuracy on the mismatch of the output-voltage set point for a two-module ISOP system, and Fig. 4 shows the IVS accuracy dependence on the output-voltage gradient gain.

As seen from Fig. 3, the IVS accuracy improves as the output-voltage set-point mismatching decreases, and when the output-voltage gradient gains are perfectly matched, as shown in Fig. 3(c), the two modules share the input voltage evenly. From Fig. 4, it can be seen that a larger output-voltage gradient gain results in better IVS.

Combining (6), (7), and Figs. 3 and 4, we can obtain the following conclusion: The larger the module gradient gain, the better the IVS characteristic, but the system output-voltage regulation performance is deteriorated. On the contrary, the smaller the module gradient gain, the worse the IVS characteristic, but the system output-voltage regulation performance is improved. Therefore, a tradeoff must be made between the IVS and the output-voltage regulation performance when designing the control circuit. Hence, the proposed control strategy is more suitable for the application narrow input-voltage range. For instance, eight 48 V–48 V modules are used to construct a 384 V–48 V ISOP system for the server power supply, where the input voltage of the ISOP system is tightly regulated by a PFC converter [25].
III. BLOCK DIAGRAM OF THE PROPOSED WIRELESS IVS CONTROL STRATEGY

The concrete block diagram of the proposed wireless IVS control strategy based on positive output-voltage gradient method is shown in Fig. 5. \( V_{\text{ref}} \) represents the given reference voltage for the ISOP system, \( k_i \) (\( i = 1, 2, \ldots, N \)) represents the sensing factor of the input voltage of each module, and \( k_{vo} \) represents the sensing factor of the output voltage. In order to ensure proper sharing of input voltages, the input-voltage sensing signal is added to \( V_{\text{ref}} \) for each module. Then, when the module input voltage increases, the reference voltage of each module \( v_{\text{refi}} \) (\( i = 1, 2, \ldots, N \)) will increase and the positive output-voltage gradient regulation characteristic (Fig. 2) is obtained.

From Fig. 5, it can be seen that only input/output voltages are sensed for each module and there is no control interconnection among the constituent modules, which implies that a wireless controller is obtained and the system reliability can be significantly enhanced. Moreover, all the modules are identical and can operate in stand-alone mode, which means that the loop connection among the constituent modules, which implies that a truly modular design can be realized for the ISOP system. A truly modular design can be realized for the ISOP system with the proposed control strategy.

IV. SYSTEM STABILITY WITH THE PROPOSED WIRELESS IVS CONTROL STRATEGY

The purpose of this section is to study the stability of the ISOP system with the proposed wireless IVS control strategy. With no loss of generality and for ease of analysis, the ISOP system under study consists of two two-transistor forward converter modules, as shown in Fig. 6. The corresponding small-signal circuit model is shown in Fig. 7, where \( \hat{d}_1 \) and \( \hat{d}_2 \) are the perturbations of the duty cycles, \( \hat{v}_{in1} \) and \( \hat{v}_{in2} \) are the perturbations of individual input voltages, \( \hat{i}_{o1} \) and \( \hat{i}_{o2} \) are the perturbations of individual output currents, \( N_1 \) and \( N_2 \) are turns ratios of the transformers, and \( D_1, D_2, I_{o1}, \) and \( I_{o2} \) are steady-state duty cycles and output currents, respectively.

From Fig. 7, the following relations are readily obtained:

\[
\hat{i}_{o1} = \frac{N_1}{D_1} \left( \hat{v}_{in} - sC_{d1}\hat{v}_{in1} - \frac{I_{o1}}{N_1}\hat{d}_1 \right) \tag{9}
\]

\[
\hat{i}_{o2} = \frac{N_2}{D_2} \left( \hat{v}_{in} - sC_{d2}\hat{v}_{in2} - \frac{I_{o2}}{N_2}\hat{d}_2 \right) \tag{10}
\]

\[
\hat{v}_o = (\hat{i}_{o1} + \hat{i}_{o2}) \frac{R_L}{sC_fR_L + 1}. \tag{11}
\]

Assuming the turns ratios of the transformers are the same, i.e., \( N_1 = N_2 = N \) and the steady-state duty cycles of the two modules are the same, i.e., \( D_1 = D_2 = D \), we have

\[
I_{o1} = I_{o2} = \frac{V_o}{2R_L} \tag{12}
\]

\[
V_{in1} = V_{in2} = \frac{V_{in}}{2}. \tag{13}
\]

From Fig. 5, we obtain the expressions of \( \hat{d}_1 \) and \( \hat{d}_2 \) as

\[
\hat{d}_1 = G_{vo}F_m(\hat{v}_{in1}k_1 - \hat{v}_o) \tag{14}
\]

\[
\hat{d}_2 = G_{vo}F_m(\hat{v}_{in2}k_2 - \hat{v}_o) \tag{15}
\]

where \( F_m \) is the gain of the ramp and \( G_{vo} \) is the gain of the output-voltage loop compensator.

Assuming a fast output-voltage controller and \( k_1 = k_2 = k \), then according to (7), the expression of output-voltage perturbation is

\[
\hat{v}_o = \frac{k}{2}\hat{v}_{in}. \tag{16}
\]
Putting (9), (10), (14)–(16) into (11) yields
\[ \hat{v}_{in} \left( \frac{kD(sC_f R_L + 1)}{2NR_L} + \frac{I_v G_{vo} F_m k(1 - k_{vo})}{N} \right) = 2 \hat{i}_{in} - sC_{d1} \hat{i}_{in1} - sC_{d2} \hat{i}_{in2}. \] (17)

From Fig. 7, the ISOP system input and output power can be expressed as
\[ P_{in} + \hat{P}_{in} = (V_{in} + \hat{v}_{in})(I_{in} + \hat{i}_{in}) = V_{in}I_{in} + \hat{V}_{in} \hat{I}_{in} \]
\[ P_o + \hat{P}_o = \left( \frac{V_o + \hat{v}_o}{R_L} \right)^2 = \frac{V_o^2}{R_L} + \frac{2V_o \hat{v}_o}{R_L} + \frac{\hat{v}_o^2}{R_L} \] (18)  (19)

where \( \hat{P}_{in} \) and \( \hat{P}_o \) are input and output power perturbations, respectively.

Neglecting the second-order terms of (18) and (19) and noting that the dc terms on both sides of the equations are equal, by the law of conservation of energy, we obtain
\[ \hat{v}_{in} = \frac{kV_{in} V_o - V_o^2}{R_L V_{in}^2} \hat{v}_{in}. \] (20)

Putting (20) into (17) yields
\[ \hat{v}_{in1} = \frac{kD(sC_f R_L + 1)}{2NR_L} + \frac{G_{vo} B - E + sC_{d2}}{sC_{d2} - sC_{d1}} \]
\[ \hat{v}_{in2} = \frac{kD(sC_f R_L + 1)}{2NR_L} + \frac{G_{vo} B - E + sC_{d1}}{sC_{d2} - sC_{d1}} \]
(21)  (22)

where \( B = (I_o F_m k(1 - k_{vo})) / N \) and \( E = 2((kV_{in} V_o - V_o^2) / (R_L V_{in}^2)) \).

From (21) and (22), the transfer function of the input-voltage difference of the two modules to the total input voltage can be derived as
\[ \Delta \hat{v}_{in12} = \frac{\hat{v}_{in1} - \hat{v}_{in2}}{sC_{d2}} + \frac{kD(sC_f R_L + 1) + 2(G_{vo} B - E) + sC_{d2} + sC_{d1}}{sC_{d2} - sC_{d1}} \] (23)

For the output-voltage loop, a classical proportional–integral (PI)-type regulator is used and the \( G_{vo} \) can be expressed as
\[ G_{vo} = k_p + \frac{k_i}{s}. \] (24)

Substituting (24) into (23) yields (25), as shown at the bottom of the page.

In practice, \( C_{d1} \) is impossible equal to \( C_{d2} \) precisely; hence, there are two roots at the origin in the characteristic equation of the transfer function \( \Delta \hat{v}_{in12} / \hat{v}_{in} \), which means that the system is critically stable, i.e., if the input-voltage difference exists between the two modules when there is a system input-voltage perturbation, the difference will neither converge nor diverge. However, the actual system is surely damped by the parasitic resistance of the switches or inductors, so the perturbation will eventually converge and the ISOP system with the proposed control strategy will be stable in practice.

V. EXPERIMENTAL RESULTS

In order to verify the theoretical analysis in the previous sections, we have constructed an ISOP system including three two-transistor forward converter modules in the laboratory, as shown in Fig. 8, and the specifications of each module are as follows:
1) input voltage \( V_{in} : 100 \sim 150 \text{Vdc} (V_{in\min} = 100 \text{Vdc}) \);
2) minimum output voltage \( V_{o\min} : 50 \text{Vdc} \);
3) maximum output current \( I_o : 5 \text{A} \);
4) gradient gain \( k: 0.0568 \);
5) switching frequency \( f_s: 100 \text{kHz} \).

The power stage consists of the following devices and components:
1) switching devices: IRFP460;
2) clamping diodes: 1N5404;
3) rectifier diodes: DSEP 30-03A;
4) transformer: E42, primary winding is 15 turns and secondary winding is 18 turns;
5) output filter inductor: 180 \( \mu \text{H} \) (E55, 22 turns);
6) output filter capacitor: 4400 \( \mu \text{F} \) (2200 \( \mu \text{F} \times 2 \)).

Fig. 9 shows the calculated and measured curves of the output-voltage regulation of each module when the ISOP system input voltage varies from 300 to 450 Vdc. It can be seen that the slopes of the output-voltage regulation characteristic of each module are nearly parallel and the measured curves are very close to the calculated one. Due to small mismatches in the controller parameters among the three prototypes, such as reference voltages, voltage sensors, and operational amplifiers, the measured maximum input-voltage difference among the three modules is 4 Vdc. It should be noted that even though the control strategies proposed in [9]–[20] are employed for ISOP

\[ \frac{\Delta \hat{v}_{in12}}{\hat{v}_{in}} = \frac{s^2 \left[ (C_{d2} + C_{d1}) NR_L + kDC_f R_L \right] + s \left[ kD + 2NR_L (k_p \cdot B - E) \right] + 2k_i BNR_L}{s^2 NR_L (C_{d2} - C_{d1})} \] (25)
systems, the input-voltage differences among the constituent modules still exist due to the controller parameter mismatches; however, the detailed precise measured results like those in Fig. 9 are not listed in these papers. The input-voltage difference of 4 Vdc is less than 3% of the maximum module input voltage and is perfectly acceptable when we take into account the voltage margin of the prototype. Like the droop method, where the main shortage of the proposed wireless IVS control strategy is the deteriorated output-voltage regulation, the output-voltage regulation is 5.6% in the whole system input-voltage range from 300 to 450 Vdc.

Fig. 10 shows the voltages across the primary winds of individual transformers under normal input voltage (400 Vdc) and full load. Fig. 11 shows the input currents of each module under steady state. It can be seen that all the voltages have almost the same positive amplitudes, which means that the module input voltages are equal and the module OCS occurs naturally. It also should be noted that the switching signals of the three modules are not interleaved or synchronized to realize the goal of no control interconnection; hence, the switching frequencies of the three modules are slightly different due to the tolerance of $RC$ parameters, which determine the switching frequency.

Figs. 12 and 13 show the experimental waveforms of the ISOP system corresponding to stepped input voltage and stepped load, respectively. Fig. 12 shows the input voltages of the three modules and the system’s output voltage corresponding to an input-voltage stepping between 300 and 450 Vdc. Fig. 13 shows the input voltages of the three modules corresponding to a load stepping between full load (15 A) and half load (7.5 A). It can be seen that input voltages are well shared both at steady state and during transient and sharing of the output current is achieved automatically.

Fig. 14 shows the output currents and output filter inductor currents of the three modules corresponding to a load stepping between full load and half load. It can be seen that the load sharing is achieved both at steady state and during transient.

In order to verify the redundancy of the ISOP system with the proposed control strategy, a fault is imitated in the three-module ISOP system by shorting the input capacitor of one of the modules with a switch in series with a 0.5-Ω resistor which limits the discharging current of the capacitor. Fig. 15 shows the system response to a fault of module #1. Fig. 15(a) shows the input voltages of the three modules and the system’s output voltage corresponding to a short fault of module #1 under system input voltage $V_{in} = 310$ Vdc and full load condition. It can be seen that the system input voltage is evenly shared by the remaining two modules when the short switch is closed. The system output voltage increases slightly because the input voltage changes from about 100 to 150 Vdc for modules #2 and #3, and the output voltage increases according to the positive output-voltage regulation. Fig. 15(b) shows the system response when module #1 is inserted into the system by opening the short switch under system input voltage $V_{in} = 310$ Vdc and full load condition. After opening the short switch, the input capacitor of module #1 is charged by the system input current and the input voltage increases; meanwhile, the input voltages of modules #2 and #3 decrease. After a certain amount of regulation time, the three modules share the system input voltage and the output voltage is restored to be stable. The system output voltage decreases slightly because the input voltage changes from about 150 to 110 Vdc for modules #2 and #3 and the output voltage decreases according to the positive output-voltage regulation. It can be seen that without any control interconnection among the modules, redundancy in combination with the hot-swap capability of modules can be easily achieved.

VI. CONCLUSION

It is critical to ensure IVS and OCS among the constituent modules for the ISOP system. In this paper, a novel wireless IVS control strategy for the ISOP system based on positive output-voltage gradient method is proposed, focusing on the
Fig. 12. Response in individual input voltages and output voltage to stepped system input voltage. (a) Step up. (b) Step down.

Fig. 13. Response in individual input voltages to stepped load. (a) Step up. (b) Step down.

Fig. 14. Response in individual output currents and output filter inductor currents to stepped load. (a) Output currents of each module. (b) Output filter inductor currents of each module.

Fig. 15. Response of individual input voltages and output voltage when one module is isolated and inserted, respectively. (a) Module #1 is isolated. (b) Module #1 is inserted.
issues of system modularity, reliability, and maintainability. A truly modular ISOP system can be achieved with the proposed control strategy, where all the modules are totally identical for both power and control stages. Each module is self-contained, and no extra supervisory controller is needed to achieve IVS among the modules. Moreover, there is no control interconnection among the modules, which considerably increases the redundancy with the improved system reliability and maintainability. Experimental results of a three-module ISOP system verify the validity of the proposed control strategy.

REFERENCES
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