A Review of Voltage/Current Sharing Techniques for Series-Parallel-Connected Modular Power Conversion Systems

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A Review of Voltage/Current Sharing Techniques for Series–Parallel-Connected Modular Power Conversion Systems

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***Abstract*—Recently, more occasions with high input voltage and/or high output voltage applications are emerging. However, the existing switching devices are limited by the voltage stress, e.g., the available maximum blocking voltage of insulated-gate bipolar transistors is 6.5 kV. Therefore, several methods are provided to solve this issue, including series connection of switches, multilevel converters, and modular series–parallel structures, where the modular series–parallel systems are the most popular choice due to the advantages of low cost, simple design process, high modularity, reliability, and redundancy. The main objective of series–parallel systems is to ensure the sharing of input/output voltage/current. Based on this, a comprehensive review on the available voltage/current sharing methods for series–parallel systems, which include input-series output-parallel, input-parallel output-series, and input-series output-series structures is provided in this article. Moreover, the relationships between the input voltage/current sharing and output voltage/current sharing of series–parallel systems are explained.**

***Index Terms*—Current sharing, input-parallel output-series (IPOS), input-series output-parallel (ISOP), input-series output-series (ISOS), series–parallel systems, voltage sharing.**

I. Introduction

With the advancement of power electronic technology and the emergence of new requirements, the power conversions with high input/output voltage and/or high input/output current are gradually increasing. For instance, as a power electronic interface between medium-voltage system and low-voltage system, solid-state transformer (SST) and dc transformer are the emerging technologies for modern distribution system [1], and the medium-voltage or even high-voltage power converters are required for offshore and subsea electric distribution and collection grids [2]. Power supplies with output currents as high as tens of thousands of amperes are commonly required for the electrolytic process and electroplating process [3]. Due to the limited voltage/current rating of power devices, various approaches have been proposed for the high-voltage and/or high-current applications, such as multilevel technology [4], series-connected power devices [5], parallel-connected power devices [6], and series–parallel connection of modular building-block power converters [7]. For the series–parallel-connected modular power conversion systems (called as *series–parallel systems* hereinafter), in which multiple low-power low-voltage modules can be connected in any combination of series and/or parallel connections at the input and/or output ports, the salient features include: 1) ease of selecting power devices; 2) increased overall system reliability due to reduced thermal and electrical stresses on the power devices and components; 3) shortened design process and lowered cost of system; and 4) ease of capability expansion of power conversion system.

The series–parallel systems can be mainly categorized into four kinds, namely, input-parallel output-parallel (IPOP), input-series output-parallel (ISOP), input-parallel output-series (IPOS), and input-series output-series (ISOS), as shown in Fig. 1. IPOP systems are suitable for the applications requiring large output currents, ISOP systems can be used in the applications where the input voltage is relatively higher and the output voltage is relatively lower, IPOS systems become a desired choice for the applications requiring high output voltages, and ISOS systems are well suited for the applications where both the input voltage and output voltage are high.

For the series–parallel systems, a critical challenge is to ensure the voltage sharing at the series ports and/or current sharing at the parallel ports among the constituent modules. Over the past few decades, a variety of approaches with varying complexity and voltage/current sharing performance have been proposed. The main intention of this review article is to provide a better understanding of the voltage/current sharing approaches of the series–parallel systems. The current sharing of IPOP systems have been studied extensively [8]–[10]. However, the approaches of achieving the voltage/ current sharing for the ISOP, IPOS, and ISOS systems are relatively immature, and significant efforts have been made to address the challenges. Hence, the current sharing approaches for IPOP systems are not included in this review.

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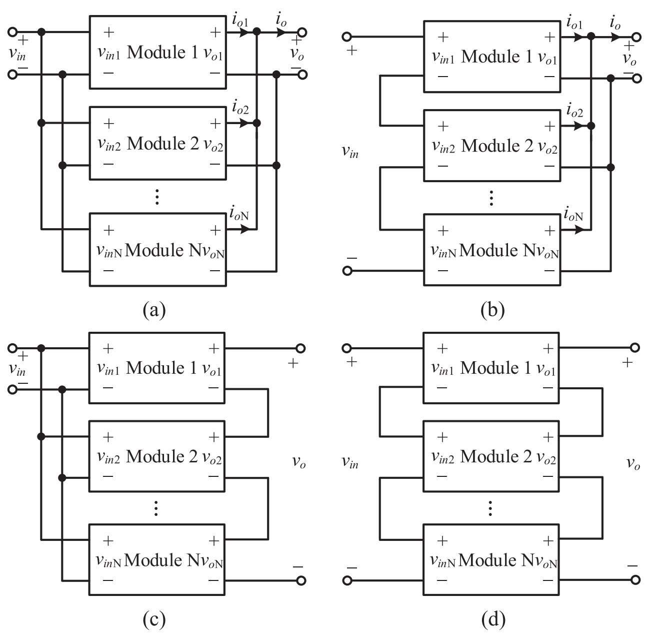

Fig. 1. Four series–parallel connection structures. (a) IPOP. (b) ISOP. (c) IPOS. (d) ISOS.

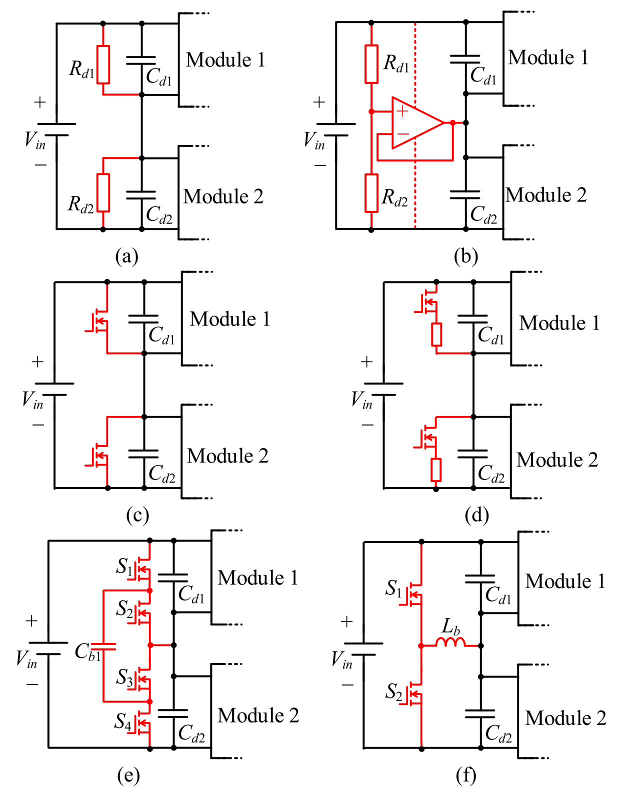

Fig. 2. External voltage balancing circuits. (a) Balancing resistors [11]. (b) High-voltage operational amplifier [12]. (c) MOSFETs operating in linear region [13]. (d) Switched balancing resistors [14], [15]. (e) Switched-capacitor circuit [16], [17]. (f) Buck-boost balancing circuit [18].

For the four series–parallel connection structures shown in Fig. 1, the power conversion could be dc–dc, ac–dc, dc–ac, and ac–ac. To the authors' knowledge, the number of literature of dc–dc series–parallel systems is maximum [11]–[89], [129]–[135], followed by the ac–dc [90]–[112] and dc–ac [113]–[124] systems, and the least is ac–ac system [125]–[128], which is mainly because the high-voltage dc and ac applications are emerging, such as the high-voltage dc (HVDC), medium-voltage dc grids, and SST. Hence, the voltage/current sharing approaches of dc–dc, ac–dc, and dc–ac series–parallel systems are the main focus of this article.

This article will provide a comprehensive review on the most recent advances on the voltage/current sharing approaches for the ISOP, IPOS, and ISOS systems. The rest of this article is organized as follows. The voltage/current sharing approaches for the ISOP dc–dc systems, IPOS dc–dc systems, and ISOS dc–dc systems are presented in Section II, III, and IV, respectively. Section V introduces the voltage/current sharing approaches for the ISOP ac–dc systems. Furthermore, in Section VI, the voltage/current sharing strategies for the dc–ac series–parallel systems are presented. The summations and discussions on the sharing techniques of ISOP, IPOS, and ISOS systems are presented in Section VII. Some special structures and module topologies of series–parallel systems are briefly introduced in Section VIII. Finally, Section IX concludes this article.

II. Voltage/Current Sharing Approaches for ISOP DC–DC Systems

For an ISOP dc–dc system, once input voltage sharing (IVS) among the constituent modules is achieved, output current sharing (OCS) is nearly achieved automatically and vice versa [47]. That is to say, we need to ensure either IVS or OCS. There is a plurality of IVS and OCS approaches for ISOP dc–dc systems, and these approaches are described and discussed in this section, with an attempt to investigate their principles and applications, highlighting their merits and limitations.

A. External Voltage Balancing Circuits

A simplest method to achieve IVS is using a voltage divider, which consists of two equal balancing resistors $R_{\rm d1}$ and $R_{\rm d2}$, as shown in Fig. 2(a) [11] (only a two-module ISOP system is exemplified for clarity). However, these balancing resistors bring about high dissipative losses. An active balancing circuit with operational amplifier is proposed to reduce the losses of balancing resistors [see Fig. 2(b)]; its shortcoming is that the high-voltage operational amplifier is expensive and itself owns noticeable quiescent power loss [12]. In [13], a MOSFET operating in linear region is connected in parallel with the input side of each constituent module [see Fig. 2(c)], showing good IVS dynamic characteristics. To eliminate quiescent power losses of balancing circuits in [11]–[13], an auxiliary balancing circuit consisting of a switch and a resistor is proposed [14], [15], as shown in Fig. 2(d). The switch is turned OFF when IVS is achieved at steady state; thus, no quiescent power losses occur, and the switch is pulsewidth modulation (PWM) controlled at transient state to achieve IVS. The voltage balancing capability of the aforementioned balancing circuits (Fig. 2(a)–(d)) is relatively limited or at the price of large dissipative losses. In [16],

TABLE I
COMPARISON AMONG VARIOUS VOLTAGE BALANCING CIRCUITS

Balancing Circuits	Balancing Capability	Loss	Complexity	Active Driver
Fig. 2(a)	Low	Large	Simplest	No
Fig. 2(b)	Medium	Medium	Simple	No
Fig. 2(c)	Medium	Medium	Medium	Yes
Fig. 2(d)	Low	Medium	Medium	Yes
Fig. 2(e)	High	Small	Complex	Yes
Fig. 2(f)	High	Small	Medium	Yes

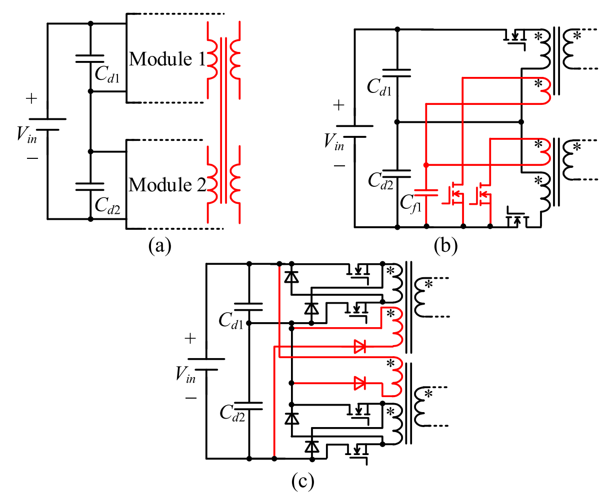

Fig. 3. Unique converter topologies to achieve IVS. (a) Integrated-transformer topology [19]–[23]. (b) Common clamping capacitor [24]. (c) Balancing windings [25].

a switched-capacitor voltage balancing circuit is proposed [see Fig. 2(e)]. If the input voltage of module 1 $V_{\mathrm{in}1}$ is higher than that of module 2 $V_{\mathrm{in}2}$, the charge stored in $C_{\mathrm{d}1}$ is delivered to $C_{\mathrm{b}1}$ when S_1 and S_3 are ON, and $C_{\mathrm{b}1}$ charges $C_{\mathrm{d}2}$ when S_2 and S_4 are ON; in other words, the energy stored in $C_{\mathrm{d}1}$ is transferred to $C_{\mathrm{d}2}$ through $C_{\mathrm{b}1}$. It can be seen that the voltage balancing capability is significantly improved with the switched-capacitor balancing circuit. The four switches S_1–S_4 are provided and shared by two full-bridge converters in [17]. In Fig. 2(f), a buck-boost balancing circuit employing an inductor as the energy transmission is used to balance the two divided capacitor voltages [18]. The ISOP system can be taken as a black box and no more attention needs to be paid to the equilibrium operation of ISOP system itself with the external balancing circuits. However, these balancing circuits inevitably cause additional cost and losses. Table I presents a comparison of the voltage balancing circuits described in this section.

B. Unique Converter Topologies

Some classical converter topologies are generally used for the constituent modules of ISOP dc–dc system, such as the full-bridge, forward, and flyback topologies. However, some converter topologies are purposely modified to achieve equilibrium operation of ISOP dc–dc system. The most common modification is that all constituent converter modules share an integrated transformer [19]–[23], as shown in Fig. 3(a), and IVS is automatically achieved due to Faraday's law. In [24], a dual active-clamp forward topology utilizing two auxiliary windings to share one common capacitor is proposed [see Fig. 3(b)], in which IVS is ensured by the same turns ratios of two transformers and sharing a common capacitor. In [25], an ISOP system with dual two-transistor forward converters is proposed [see Fig. 3(c)], in which a balancing winding is introduced into each transformer and the number of the balancing winding is equal to the number of the primary winding of transformer, and then IVS can be automatically achieved with the two balancing windings. It can be seen that ISOP systems with these unique converter topologies are not separable into multiple standardized modules, although external balancing circuits or voltage/current sharing control strategies are usually not required.

C. Auto-Balancing Mechanisms

Some ISOP dc–dc systems have the ability of auto-balancing the input voltages or output currents. When the constituent modules are operated in dc transformer mode, IVS is automatically achieved [26]–[29]. For instance, an *LC* series resonant converter is a typical dc transformer when it is operated at the resonant frequency and its voltage ratio is merely determined by the transformer turns ratio [26], [27]. So, IVS is automatically achieved by having uniform turns ratios.

Common duty cycle control is always applied to the ISOP dc–dc systems for achieving inherent auto-balancing ability. When the buck-derived converter is adopted as the basic module, the imbalance of the input voltage or output current mainly depends on the mismatch in the transformers' turns ratios [30]–[38]. When the flyback converter operating in discontinuous conduction mode (DCM) is taken as the basic module, the input voltage imbalance is only contributed by the mismatch in transformers' magnetizing inductances rather than the turns ratios [39], [40]. However, it is worth noting that the common duty cycle control may lead to unstable operation when the converters with current-source characteristic are employed, such as a dual active bridge (DAB) converter [48] and a quasi-Z-source-based isolated dc–dc converter [56].

D. Active Voltage/Current Sharing Control Strategies

1) Positive Output-Voltage Gradient (POVG) Methods: A POVG method is proposed in [41] to make the system output voltage increase with the increase of the system input voltage or load current, as shown in Fig. 4(a), which is realized by programming a positive input impedance, and thus achieving IVS or OCS for the ISOP systems. With this method, each module input voltage is sensed and used to produce a positive gradient in the system output voltage that is proportional to the system input voltage, as shown in Fig. 4(b). The module input voltage feedback can also be replaced by the module output current feedback, in which the system output voltage is proportional to the system output current [42]–[44]. Similar to the droop methods for IPOP dc–dc systems, there is a tradeoff between the IVS (or OCS) and system output voltage regulation performance, that is, the better the IVS or OCS performance, the worse the system output voltage regulation. The advantages

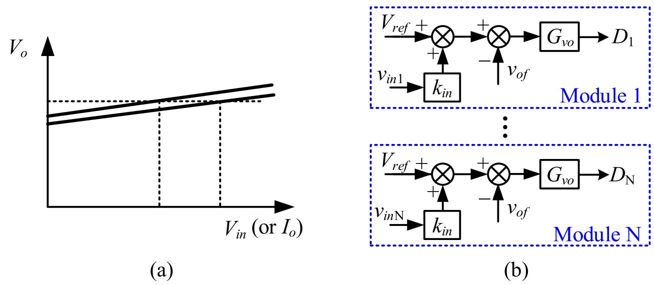

Fig. 4. Positive output-voltage gradient (POVG) methods [41]. (a) POVG regulation characteristic. (b) Control strategy with input voltage feedback.

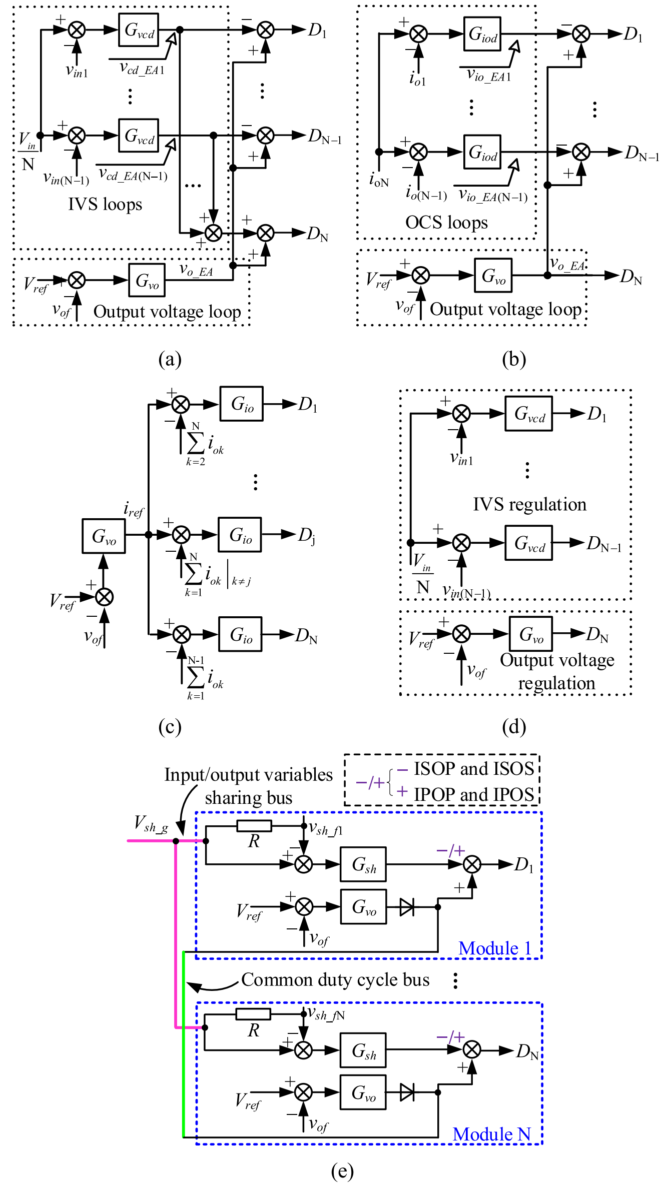

Fig. 5. Voltage/current sharing control methods of ISOP system. (a) IVS-controlled method [45]. (b) Master–slave OCS-controlled method [62]. (c) Cross-feedback OCS-controlled method [63]. (d) Independent control method [52]. (e) Distributed modularization control method [47].

of the POVG include: 1) no wire connection among the control circuits of constituent modules; 2) easy to implement and expand; 3) high reliability and modularity; and 4) degraded output voltage regulation.

2) Voltage/Current Sharing Loop Control Methods: For the voltage/current sharing loop control methods mentioned in this article, the voltage/current sharing closed loops and corresponding voltage/current sharing references are incorporated [45]–[63]. The general control requirements of ISOP dc–dc systems are the output voltage regulation and IVS (or OCS). Hence, the voltage/current sharing loop control methods can be categorized from different aspects, which are: 1) IVS-controlled and OCS-controlled methods from the viewpoint of control object of equilibrium; 2) independent control and coupled control methods from the viewpoint of whether the output voltage regulation and IVS (or OCS) are controlled separately; and 3) centralized control and distributed modularization control methods from the viewpoint of the control structure.

a) IVS-Controlled and OCS-Controlled Methods: Both IVS and OCS are alternatives for ISOP systems. For the IVS-controlled methods, IVS loops are required to maintain balance of input voltages [45]–[61], and a typical IVS-controlled method is shown in Fig. 5(a) [45]. The system average input voltage V_{in}/N is set as the voltage reference of the IVS loops. A common output voltage loop provides a main duty cycle signal v_{o_EA} for each module. For the first N – 1 module, $v_{\mathrm{cd\_EA}j}$ $(j = 1, 2, \ldots, N-1)$, which is derived from each IVS regulator, is subtracted from v_{o_EA} to obtain the corresponding duty cycle signal of module *j*. For the module *N*, the control signal derived from the sum of outputs of the first $N-1$ IVS loops is added to v_{o_EA} to obtain the duty cycle signal. With the IVS control strategy, the duty cycles of the modules with high input voltages will increase and the duty cycles of modules with low input voltages will decrease, and finally to achieve IVS. There is only a system output voltage control loop in Fig. 5(a), and the system dynamic performance can be improved by introducing inner current control loop to form voltage-current double closed loop. The feedback signal of inner current control loop can be the input current or output current of module. In [50], the output filter inductor currents are taken as the feedback signals for the inner current loops with average current control. Charge control method is used for the inner current control loops with input currents of modules as the feedback signals [55]. The input currents of modules are taken as the feedback signals for the inner current loops with peak current control in [54] and [58].

For the OCS-controlled methods, the OCS loops are required to ensure balance of output currents [62], [63], and a master-slave OCS-controlled method is shown in Fig. 5(b) [62]. A master module (module *N*) regulates the system output voltage through a common output voltage loop and provides the current references to slave modules (first N – 1 modules). For the slave modules, $v_{\mathrm{cd\_EA}j}$ $(j = 1, 2, \ldots, N-1)$, which is derived from each OCS regulator, is subtracted from v_{o_EA} to obtain the duty cycle signal of the corresponding module *j*. With the control strategy, the duty cycles of modules with larger output currents will increase and the duty cycles of modules with smaller output currents will decrease, and finally to achieve OCS. We can see that the duty cycle of module with high input voltage, which is equivalent to high output current, increases for both IVS-controlled and master–slave OCS-controlled methods; in other words, the two control methods have the same operating mechanism although with different control object of equilibrium. An interesting cross-feedback OCS-controlled method is proposed in [63], as shown in Fig. 5(c). An output-voltage loop provides a common reference for all individual current loops in which the current feedback for an individual converter is not its own but the sum of all other remaining output currents. However, when the number of modules increases, the control strategy will become complex due to mutual cross-feedback among the current signals and lower the degrees of system modularity.

For the IVS-controlled methods, high-voltage isolation voltage sensors are required to sense the module input voltages. While the output side of ISOP system is low-voltage side which means that the output current sampling is easier than the input voltage sampling and if the control loops are all on the output side, there is no isolation issue for the output current sampling of OCS-controlled methods.

b) Coupled Control and Independent Control Methods: As seen from Fig. 5(a)–(c), the duty cycle of each module regulates both the system output voltage and corresponding module input voltage (or output current) except for the module N in Fig. 5(b), and these are regarded as *coupled control methods* [45]–[50], [55]–[63]. And if the regulation object of each module is separated, that is, the system output voltage and module input voltages (or output currents) are independently regulated, then they are called *independent control methods* [51]–[54], and a typical independent control method is shown in Fig. 5(d) [52]. For the first $N - 1$ modules, the duty cycles are used to regulate the input voltage of each module to be V_{in}/N, and, obviously, the input voltage of module N is also V_{in}/N. The system output voltage is only regulated by the module N. In [51], the independent control method is referred to as a minimal control structure. In [53] and [54], the independent control method is also referred to as a master/slave control, in which the master module regulates the system output voltage and the slave modules ensure IVS.

It can be seen that there is almost no connection among the module controllers for the independent control methods, and it has the advantages of a simple design process and better degree of modularity than coupled control methods. However, because the system output voltage is merely regulated by the master module and the slave modules regulate the module input voltages which only respond to input voltage change, then the performance of output voltage transient response during load step is degraded. When the master module starts adjusting operation to the new load condition, the slave modules continue to deliver the same power as that before the load step until the difference in the delivered power of the master and slave modules causes input voltage imbalance and then the slave modules start responding [52]. The output voltage transient response is degraded due to the delayed response of the slave modules. While for the coupled control methods, all the modules respond to the load step immediately and better output voltage transient response is achieved.

TABLE II
SUMMARY OF DIFFERENT VOLTAGE/CURRENT SHARING APPROACHES FOR ISOP DC–DC SYSTEMS

Voltage/Current Sharing Approaches	Features
External Voltage Balancing Circuits [11]–[18]	•Take ISOP system as a black-box. •Require additional power components. •Reduce efficiency and increase cost.
Unique Converter Topologies [19]–[25]	• External balancing circuits or sharing control strategies are not required. • Low degree of modularity.
Auto-Balancing Mechanisms [26]–[40]	• Very simple. • Voltage/current unbalance due to mismatch of module parameters.
Positive Output Voltage Gradient [41]–[44]	• Fully modular, high reliability. • Tradeoff between IVS/OCS and output voltage regulation performance. • Degraded output voltage regulation.
IVS-controlled [45]–[61]	• IVS-controlled: require high-voltage isolation voltage sensor. • OCS-controlled: easier output current sampling and voltage-current dual-loop.
OCS-controlled [62], [63]	
Independent Control [51]–[54]	• Independent control: better degree of modularity than coupled control methods, degraded output voltage transient response during load step. • Coupled control: good output voltage transient response during load step.
Coupled Control [45]–[50], [55]–[63]	
Centralized Control [45], [46], [50]–[63],	• Centralized control: lower modularity and redundancy. • Distributed control: all modules are self-contained and standardized, high modularity and redundancy.
Distributed Control [47]–[49]	

c) Centralized Control and Distributed Modularization Control Methods: As seen from Fig. 5(a)–(d), although the power circuit of each constituent module is uniform, the control circuits of the constituent modules are centralized (Fig. 5(a)–(c)) or different (Fig. 5(d)), which inevitably restricts modularity and flexibility of the ISOP system to a certain extent. Moreover, the ISOP system will collapse if the common output voltage loop or master controller goes wrong. Hence, a fully modular ISOP system is desired, including not only uniform power circuits but also uniform control circuits of constituent modules, which is defined as *distributed modularization control methods* [47]–[49], and a typical one is shown in Fig. 5(e). As seen, all the modules are the same including the power circuits and control circuits, and each module can operate in standalone mode. Only two buses, namely, an IVS bus and a common duty cycle bus, are needed and no external controller is required when multiple modules are connected to form the ISOP systems. Thus, the distributed modularization control methods have the following advantages: 1) all modules are self-contained and standardized; 2) no extra control is needed to achieve IVS or OCS; 3) easy to expand system capacity; and 4) high modularity and redundancy.

As a conclusion to this section, a summary of main characteristics of the reviewed voltage/current sharing approaches is given in Table II.

III. VOLTAGE/CURRENT SHARING APPROACHES FOR IPOS DC–DC SYSTEMS

According to [47], for an IPOS dc–dc system, once input current sharing (ICS) among constituent modules is achieved, output voltage sharing (OVS) is nearly achieved automatically and vice versa. That is to say, we need to ensure either ICS or OVS.

A. Auto-Balancing Mechanisms

Similar to ISOP systems, IPOS systems also have auto-balancing mechanism if the common duty cycle control strategy is applied and the output voltage mismatch depends on the difference among turns ratios [64], [65]. OVS is also automatically achieved when the constituent modules operate in dc transformer mode [66].

B. Active Voltage/Current Sharing Control Strategies

1) POVG Methods: An IPOS modular dc grid-connected renewable power system is presented in [67], in which a distributed autonomous voltage balancing control strategy with positive output-voltage gradient (POVG) is used to realize power balancing without information exchange or central controller among constituent modules.

2) OVS Control Strategies: Fig. 6(a) shows an OVS control strategy [68], in which the output voltage loop regulates the system output voltage, v_{of}/N is taken as reference for all OVS loops and compared with each module output voltage, and the control signal derived from each OVS regulator is summed with the output signal of output voltage regulator to regulate its respective module to accomplish uniform module output voltage and desired system output voltage. The control strategy with v_{of}/N as voltage reference for all OVS loops is not fault-tolerant, and the OVS loops will lose regulation if one module fails to produce its output voltage because in this case, the voltage reference should be changed to $v_{of}/(N-1)$. To realize fault tolerance, the highest module output voltage is taken as the common voltage reference for all OVS loops, and then, if a module fails, the common voltage reference is automatically increased to compensate for the loss of a failed module [57], [68], as shown in Fig. 6(b). In [69], a "non-dedicated master" control scheme is proposed with the similar operation principle to achieve a fault-tolerant performance.

3) ICS Control Strategies: A master–slave ICS control strategy is proposed for the IPOS system [70], as shown in Fig. 6(c), in which the system output voltage is sensed and compared with the reference voltage and the output of system output voltage regulator is fed to the input of peak current mode PWM comparator of each constituent module, where the current is sampled at the primary winding of transformer, leading to all the modules having the same input currents. In [71], an average current control is employed to ensure ICS.

An IPOS system is proposed for large-scale photovoltaic (PV) generation connected to HVDC grid and its control strategy is shown in Fig. 6(d) [72]. The output voltage of IPOS system is maintained to be constant by a modular multilevel converter and

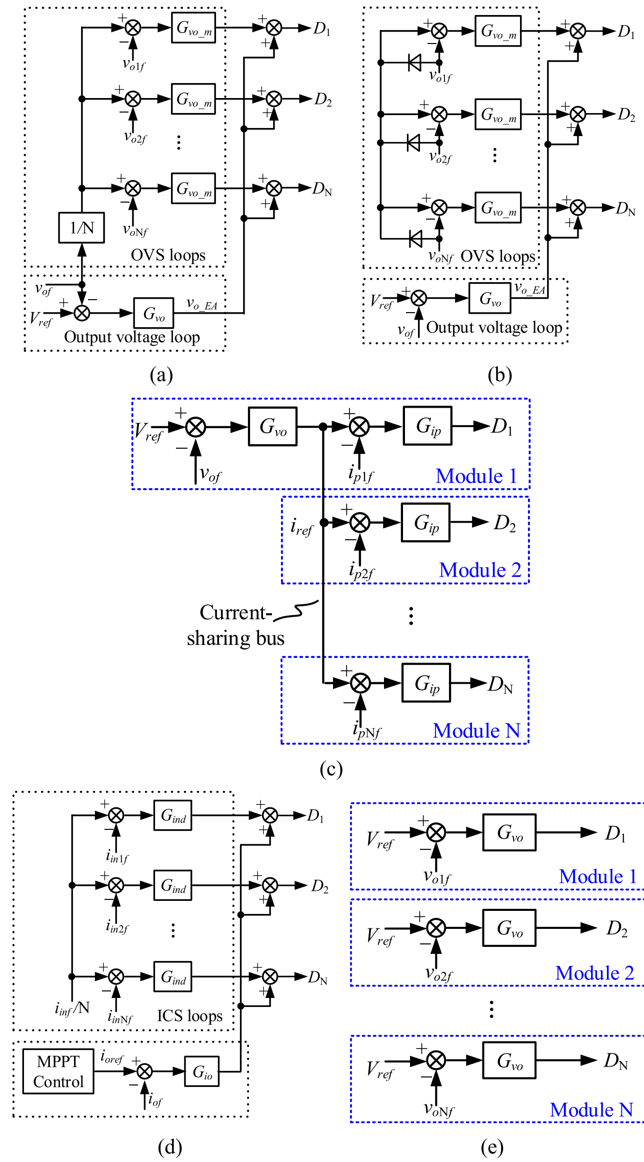

Fig. 6. Voltage/current sharing control methods of IPOS system. (a) OVS control strategy [68]. (b) Fault-tolerant OVS control strategy [68]. (c) Master–slave ICS control strategy [70]. (d) ICS control strategy [72]. (e) Independent module output voltage control strategy [73].

so an output current loop is used to control the output current to realize maximum power point tracking. Each module input current is compared with the average value of system input current and its output is added to the output of the output current loop regulator to realize ICS. A similar ICS control strategy is proposed in [18]. Using the input currents instead of the output voltages as the control variable for IPOS system enables to avoid the measurement of high output voltage so that no high-voltage isolated measurement equipment is needed.

4) Regulating Each Module Output Voltage Independently: Besides the above-mentioned OVS and ICS control strategies to ensure equilibrium among the constituent modules for IPOS system, the desired system output voltage and voltage/current sharing can also be obtained if an individual module manages to regulate its own output voltage, and its control strategy is shown

TABLE III
SUMMARY OF DIFFERENT VOLTAGE/CURRENT SHARING APPROACHES OF IPOS DC–DC SYSTEMS

Voltage/Current Sharing Approaches	Features
Auto-Balancing Mechanisms [64]–[66]	• Very simple. • Voltage/current unbalance due to mismatch of module parameters.
Positive Output Voltage Gradient [67]	• Fully modular, high reliability. • Degraded output voltage regulation.
OVS-controlled [57], [68], [69]	• Require high-voltage isolation voltage sensor. • Fault-tolerant control.
ICS-controlled [18], [70]–[72]	• Easier input current sampling and voltage-current dual-loop.
Independent Control [47], [73], [74]	• All the modules are completely uniform and operate in stand-alone mode, high modularity and flexibility. • Poor fault-tolerant performance.

in Fig. 6(e) [47], [73]. In [74], an inner current loop is contained in each module to improve the performance. It can be seen that all the modules are completely uniform and each can operate in a stand-alone mode, leading to high modularity and flexibility. However, if one module fails, the system output voltage will reduce to the summation of output voltages of $N - 1$ remaining modules and cannot return to the normal desired level because there is no control interconnection.

As a conclusion to this section, a summary of main characteristics of the reviewed voltage/current sharing approaches of IPOS systems is given in Table III.

IV. Voltage/Current Sharing Approaches for ISOS DC–DC Systems

For an ISOS dc–dc system, once IVS among the constituent modules is achieved, OVS is nearly achieved automatically and vice versa [47]. That is to say, we need to ensure either IVS or OVS.

Some IVS approaches proposed for the ISOP systems are also effective to the ISOS systems, which will be briefly descripted here. In [75], additional MOSFETs working in linear region are employed to achieve IVS of ISOS system [see Fig. 2(c)]. The POVG method [see Fig. 4(b)] also can be used for ISOS system to ensure IVS [76]. The IVS-controlled method [see Fig. 5(a)] is also effective to ISOS system [77], in which additional inner current loops are introduced to improve the system dynamic response. A duty cycle-based model predictive control scheme is proposed to achieve IVS for an ISOS system [78], which directly calculates the optimal duty cycles of constituent modules according to the sampled modules' input voltages, leading to a faster dynamic performance.

A. *Auto-Balancing Mechanisms*

It has been stated in [33] that the common duty cycle control is suitable for IPOS and ISOP systems rather than ISOS systems, which results in an unstable operation. The conclusion is correct for most of the converter topologies and if converter losses are not taken into account. By taking into account the converter losses [79], [80] or selecting a proper topology and operating mode [81]–[85], the ISOS systems with common duty cycle control will be stable.

In [79], two factors affecting auto-balancing mechanism of ISOS systems are studied, i.e., interleaving of switching information of different modules and voltage-dependent losses. It is concluded that a weak auto-balancing mechanism exists depending on the interleaving of different modules. Another auto-balancing mechanism is the voltage-dependent losses of module, such as switching losses and transformer magnetic losses. The module with higher voltage will have higher switching and transformer losses. In [80], an ISOS system consisting of two DAB modules is also proved to be auto-balancing when the circuit losses are taken into account.

Regardless of losses, some special converter topologies and operating modes with auto-balancing mechanism are investigated in [81]–[85]. In [81], an ISOS system in which a full-bridge PWM converter with output capacitive filter as the constituent module is studied, and due to an output voltage drop characteristic of the special topology, the input and output voltages of individual modules are naturally balanced. For a flyback converter operating in DCM, it also has an output voltage drop characteristic, and the ISOS system presents auto-balance of the input and output voltages [82]. For a flyback converter operating in continuous conduction mode (CCM), its dc voltage ratio is constant and only related to duty cycle and turns ratio of transformer; however, it also shows an output voltage drop characteristic when the leakage inductance is taken into account, and an intrinsic voltage balance can be achieved for the ISOS system [83]. In [84], an ISOS system with a hybrid combination of flyback modules operating in different modes is proposed, in which only one flyback module is operated in CCM and the others are operated in DCM. In [85], the voltage sharing of an ISOS system consisting of phase-shift full-bridge modules with common duty cycle control is researched, and it is pointed out that the inherent characteristic of duty cycle loss of full-bridge converter is conducive to realize the voltage sharing. For a full-bridge converter, its duty cycle loss is directly proportional to its output current; hence, the larger the output current is, the smaller the effective duty cycle is and consequently the lower output voltage. In other words, the full-bridge converter presents an inherent output voltage drop characteristic due to the duty cycle loss. It can be seen that all the constituent modules present a similar output voltage drop characteristics in [81]–[85].

For [79] and [80], the auto-balancing mechanism is caused by converter losses, and for a converter with given constant duty cycle, it also presents an output voltage drop characteristic with the increase of output current in practical circuits when the losses are taken into account. It can be seen that for ISOS systems with auto-balancing mechanisms, all the constituent modules present output voltage drop characteristics caused by circuit losses [79], [80] or special converter topologies and operating modes [81]–[85], and the reason why the output voltage drop characteristic can lead to auto-balancing of ISOS systems is analyzed in detail in [86].

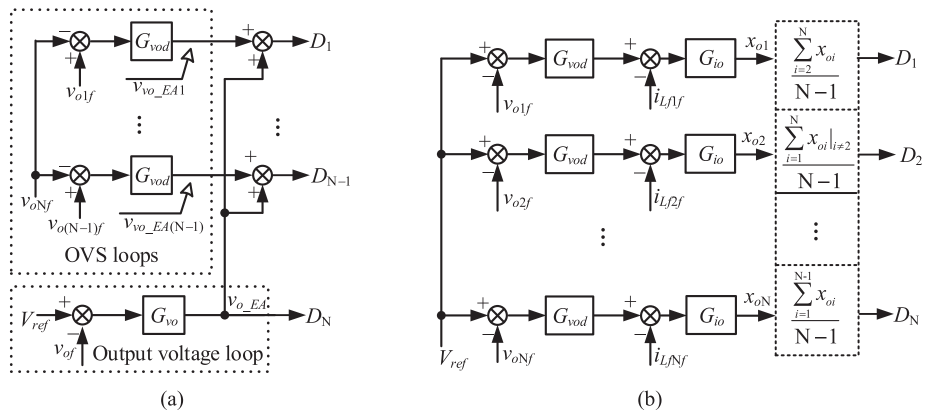

Fig. 7. OVS control strategies. (a) Master–slave OVS control strategy [87]. (b) Duty cycle exchanging OVS control strategy [89].

B. OVS Control Strategies

In [87], a master–slave OVS control strategy is proposed, which has a common output voltage loop in the master module and $N - 1$ OVS loops in the slave modules, as shown in Fig. 7(a). An output voltage loop regulates the system output voltage, which is common to all modules, and the drive signal of the master module is directly derived from v_{o_EA}. The voltage reference for all OVS loops is the output voltage of the master module. The output signal of each OVS regulator is added to v_{o_EA} to slightly adjust the respective module drive signal to ensure OVS. It should be noted that the OVS loops are in positive feedback operation for system stability. In [88] and [89], a duty cycle exchanging OVS control strategy is proposed, as shown in Fig. 7(b). As seen, there is no common system output voltage loop. Each constituent module has respective inner current loop and module output voltage loop, which provides the reference for its own inner current loop. The OVS is achieved by exchanging the duty cycle, in which one module's duty cycle is obtained by comparing the average value of all the other inner current loop outputs with a carrier signal, as shown in the dashed block diagram of Fig. 7(b).

V. Voltage/Current Sharing Approaches for ISOP AC–DC Systems

For ac–dc series–parallel systems, almost all the literature are related to the ISOP systems, and the power distribution system [1] and railway traction system [90] are the major applications where the voltage transformation with the traditional line frequency power transformer is replaced by medium-to-high frequency transformer to reduce the volume and weight. It is well known that the 12 kV/60 Hz and 10 kV/50 Hz are the most widely used power distribution system and the 15 kV/16.7 Hz and 25 kV/50 Hz are the most widely used railway catenary system. Hence, the ISOP ac–dc system is a promising alternative due to the lack of commercially available power semiconductor switches.

Considering the conversion stages and whether a dc link exists in medium-voltage ac (MVAC) side, the ISOP ac–dc systems are briefly classified into two different categories: single-stage approach (ac–dc) and two-stage approach (ac–dc/dc–dc). For the single-stage approach, cycloconverters [91], [92] and current source inverter (CSI) topologies [93]–[95] are usually used without a dc link in the MVAC side, and equal ac voltage sharing (ACVS) among the constituent modules is required. The two-stage approach is usually composed of a cascaded H-bridge (CHB) rectifier in the first ac–dc rectifier stage and modular parallel dc–dc converters in the second stage [97]–[112], and a DAB converter is widely employed as the second stage. For the two-stage approach, both the dc-link voltage balance (DLVB) and power balance among the constituent modules are required. Fig. 8 shows the categorization of voltage/power balancing methods of ISOP ac–dc systems.

A. ACVS Methods of Single-Stage ISOP AC–DC Approach

A single-stage ISOP buck-type modular ac–dc system is studied in [91], in which each module is composed of an input cycloconverter, a high-frequency transformer, a diode rectifier, and a low-pass *LC* filter. Due to its buck-type characteristics, a similar cross-feedback OCS-controlled method [see Fig. 5(c)] is used to achieve ACVS through OCS. In [92], a Swiss SST (S^3T) topology is proposed, in which multiple half-bridge series resonant cycloconverters are connected in ISOP system to realize isolated ac–|ac| voltage conversion. Similar to a series resonant dc–dc converter taken as a dc transformer [26], [27], a half-bridge series resonant cycloconverter also has the property of dc transformer; hence, ACVS is automatically achieved.

In [93], an ISOP single-phase buck rectifier (BR; CSI topology) with medium-to-high frequency isolation is proposed, as shown in Fig. 9. The current-fed dc–dc converter, which follows the BR module, aims to provide galvanic isolation with 50% duty cycle in open-loop operation. The output signal of the output voltage loop regulator is multiplied with the fundamental voltage waveform obtained through a phase-locked loop and then taken as a common current reference for each module. Errors in the individual module input ac voltages are used to synthesize a correction term, which is added into the common current reference to achieve ACVS. In [94] and [95], a multilevel current source SST is proposed for the railway traction system, in which each module is made from a current source ac–ac cycloconverter and a voltage source dc–ac converter connected

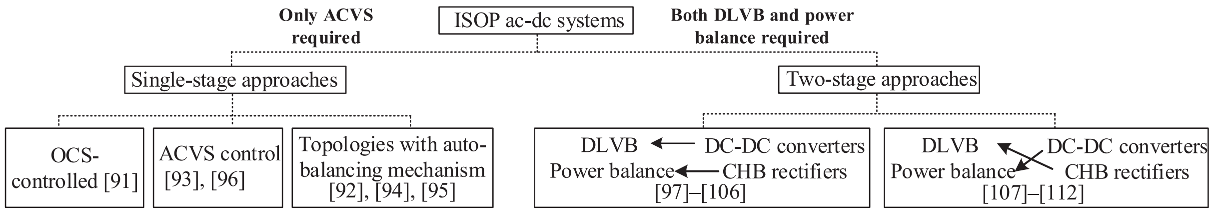

Fig. 8. Categorization of voltage/power balancing methods of ISOP ac–dc systems.

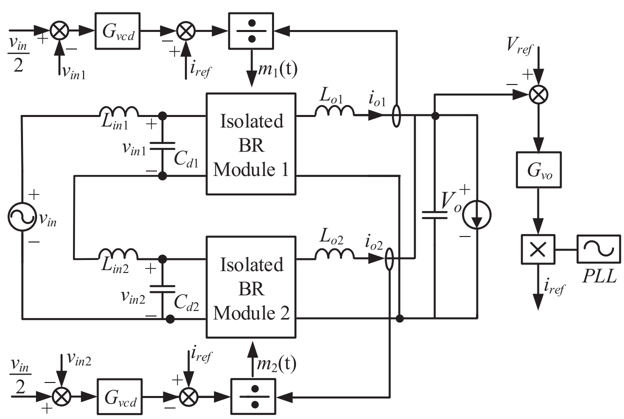

Fig. 9. ACVS control strategy for ISOP BR modules [93].

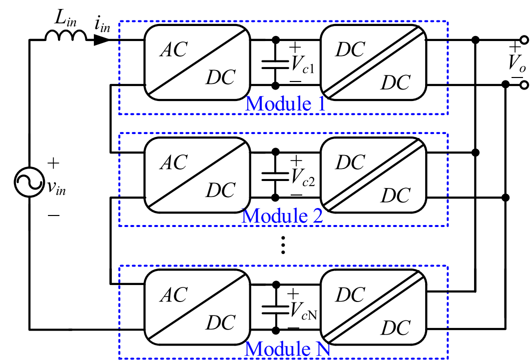

Fig. 10. A two-stage ISOP ac–dc system.

by a medium-frequency transformer. The voltage across each cycloconverter is clamped at the reflected output voltage by the transformer; hence, with the identical reference value for each module, ACVS is achieved automatically in both line-frequency and medium-frequency levels.

In [96], an isolated DAB converter-based single-stage ISOP ac–dc system is proposed for fast charging station. The front-end H-Bridge can be ignored from the control point of view since it operates as a 60-Hz full-bridge rectifier to produce a unipolar ac voltage for the DAB converter, in other words, realizing ac–|ac| conversion in line-frequency open-loop operation. An independent control method (similar to Fig. 5(d)) is proposed. For the first $N-1$ modules, the duty cycles are used to regulate the input voltage of each module to be v_{in}/N, and, obviously, the input voltage of module N is also v_{in}/N and then ACVS is achieved, and the system input current is regulated by the module N.

For the single-stage ISOP ac–dc systems [91]–[96], each module has the same input ac voltage when ACVS is achieved and the same input current, then the module power is balanced automatically.

B. DLVB and Power Balance Methods of Two-Stage ISOP AC–DC Approach

A typical two-stage ISOP ac–dc system structure is shown in Fig. 10. To ensure proper operation, the following objectives should be met: 1) high power factor and low total harmonic distortion (THD) in the input ac current i_{in}; 2) stable output dc voltage V_o; 3) balancing of the dc-link voltages $V_{c1}, \ldots, V_{cN}$; and 4) power balance among the individual modules. High power factor and low THD input ac current are implemented by the H-bridge rectifiers and the stable output dc voltage is controlled by the isolated dc–dc converters. The balancing of the dc-link voltages can be controlled by either the H-bridge rectifiers or isolated dc–dc converters, while the power balance among individual modules can be directly controlled by the dc–dc converters or indirectly ensured when DLVB is achieved and the CHB rectifiers employ the common duty cycle control. One may find that only ACVS is enough for the single-stage ISOP ac–dc system, while both DLVB and power balance are required for the two-stage ISOP ac–dc system. The reason is that when ACVS is achieved, the power balance among individual modules is automatically realized because all the modules have the same input ac current for single-stage ISOP ac–dc system. However, for two-stage ISOP ac–dc system, power balance among individual modules may not be ensured because the output currents of H-bridge rectifiers are not necessarily the same when DLVB is achieved by regulating the duty cycles of H-bridge rectifiers, and, hence, additional controller is required to ensure power balance.

1) DLVB Controlled by Isolated DC–DC Converters: When the balancing of dc-link voltages is controlled by the isolated dc–dc converters, the common duty cycle control is generally adopted for the CHB rectifiers to obtain a constant total/average dc-link voltage (i.e., the sum/average of all dc-link voltages) [97]–[103] or a constant dc-link voltage of a specific H-bridge rectifier [104], [105]. Ignoring the mismatches in gate drivers and switching device characteristics among different H-bridge modules, all the H-bridge modules will have the same output current, i.e., all the isolated dc–dc converters will have the same input current when the CHB rectifier is controlled with common duty cycle method (actually, these modular parallel dc–dc converters in the second dc–dc stage can be equivalent

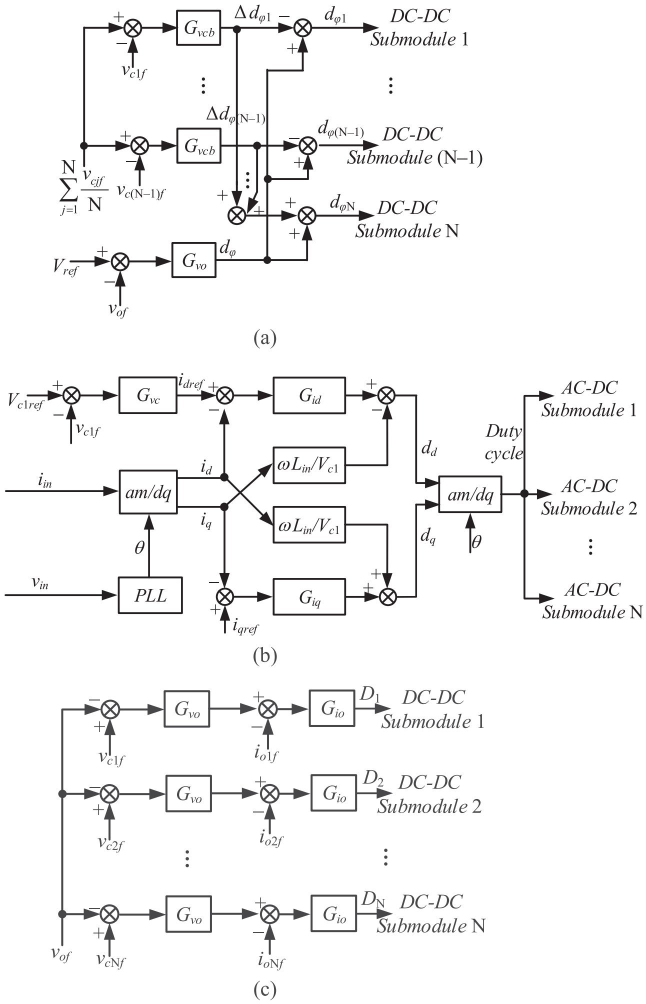

Fig. 11. The overall control strategy of single-phase SST. (a) DLVB control strategy of the DAB converters [97]. (b) *d–q* vector-based common duty cycle control strategy of the CHB rectifiers [104]. (c) Voltage feedforward-feedback control strategy of the DAB converters [104].

to be a real ISOP dc–dc system under this assumption, and, thus, some voltage balance methods for ISOP dc–dc system can also be used in the two-stage ISOP ac–dc system which will be mentioned later). Thus, power balance among different modules is ensured if DLVB is achieved at the moment [97].

In [97], a common duty cycle control is adopted for the CHB rectifiers to obtain a constant total dc-link voltage and its DLVB control strategy of the DAB converters is shown in Fig. 11(a), which is similar to the IVS control strategy [see Fig. 5(a)] for ISOP dc–dc system. The system output voltage is regulated by an output voltage loop, which provides a main common phase-shifted angle d_φ for all DAB converters. For the first N – 1 DAB converters, $\Delta d_{\varphi j}$ (j = 1, 2, ..., N – 1), which is derived from each DLVB regulator, is subtracted from d_φ to obtain the final phase-shifted angle signal of module j. For the Nth DAB converter, the control signal derived from the sum of the outputs of the first N – 1 DLVB loops is added to d_φ to obtain the final phase-shifted angle signal. Besides the DLVB loops and system output voltage loop, an inner current loop can also be added to each DAB converter [98].

Some auto-balancing mechanisms suitable for ISOP dc–dc system are also suitable for ISOP ac–dc system to achieve DLVB when the CHB rectifier adopts the common duty cycle control. Series resonant dc–dc converter [99] and *LLC* resonant dc–dc converters [100], [101] operating as a dc transformer are used in the dc–dc stage, and DLVB is automatically achieved due to the dc transformer characteristics. In [102], the common duty cycle control is used for both the CHB rectifiers and the dc–dc converters. In [103], all the dc–dc converters share an integrated transformer and DLVB is automatically achieved because all windings are linked by the same flux inside the transformer when the CHB rectifiers are controlled by a common duty cycle method.

A *d–q* vector-based common duty cycle control for the CHB rectifiers and a voltage feedforward-feedback control for the DAB converters are proposed in [104] and [105], as shown in Fig. 11(b) and (c), respectively. For the CHB rectifiers, only the dc-link voltage of the first H-bridge rectifier, V_{c1}, is regulated through a voltage loop, which provides the current reference for the inner-current loop to regulate the system input current to obtain the sinusoidal pulsewidth modulation (SPWM) signals of CHB rectifiers, and all the H-bridge rectifiers have the same SPWM signals with shift phase of 360°/N. For each DAB converter, its own input voltage, i.e., the dc-link voltage, is taken as the voltage reference for the system output voltage. It can be seen that all the dc-link voltages are uniform at steady state through the closed-loop regulation, and the module power is balanced as well.

In [106], the voltage feedforward-feedback control strategy is used for the DAB converters to achieve DLVB. However, a hybrid PWM method rather than a common duty cycle control is used for the CHB rectifiers to reduce the switching loss. Although the average power among modules is balanced, a huge power fluctuation exists in each module (see [106, Fig. 8]) because the hybrid PWM method will cause significant difference among the output currents of H-bridge rectifiers in a line frequency cycle, leading to the increase of current ratings of power switches.

2) DLVB Controlled by CHB Rectifiers: When the balancing of the dc-link voltages is controlled by the CHB rectifiers, power balance among the modules is usually controlled by the dc–dc converters.

In [107], a DLVB and power balance control strategy is proposed, as shown in Fig. 12. In Fig. 12(a), a single-phase *d–q* decoupled controller is used to regulate the average dc-link voltage, and original duty cycles of d_d and d_q are obtained for all the H-bridge rectifiers. The errors between the individual dc-link voltages and the dc-link voltage reference are used to generate *d*-axis compensation Δd_{dj} (j = 1, …, N – 1) for the first N – 1 H-bridge rectifiers, and then Δd_{dj} is added to the original d_d to generate the final duty cycles d_{dj} (j = 1, …, N – 1). For the Nth H-bridge rectifier, the sum of Δd_{dj} (j = 1, …, N – 1) is subtracted from d_d to generate the final duty cycle $d_{d\mathrm{N}}$. With the DLVB control strategy, the real power of the H-Bridge rectifier with a lower dc-link voltage is increased, and the real power with a higher dc-link voltage is decreased to eliminate the voltage unbalance. The power balance control

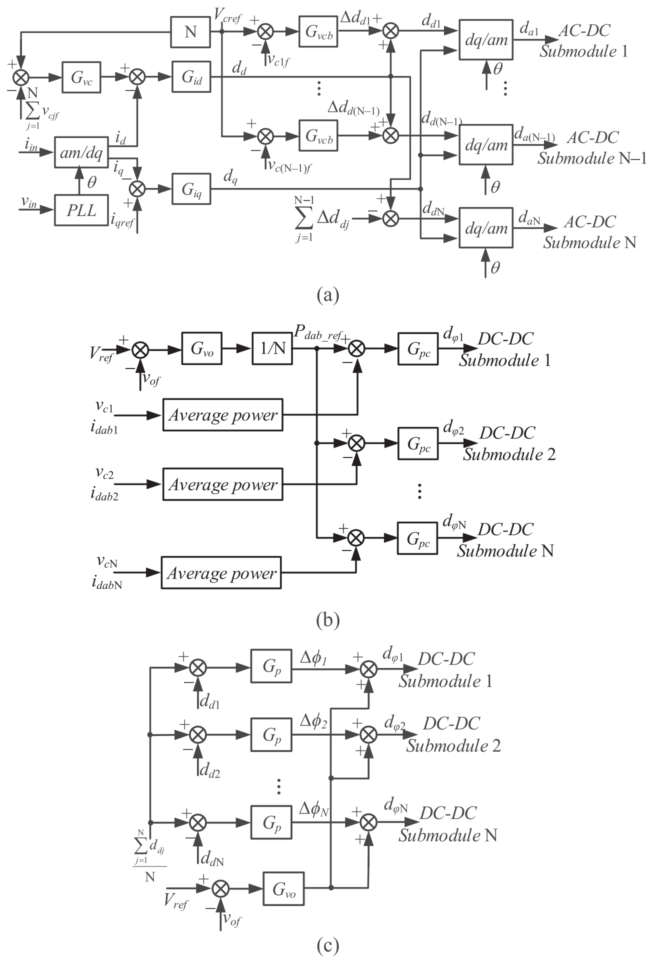

Fig. 12. DLVB controlled by CHB rectifier and power balance controlled by dc–dc converters. (a) DLVB control strategy for CHB rectifiers [107]. (b) Power balance control strategy for dc–dc converters [107]. (c) Current sensorless power balance control strategy for dc–dc converters [109].

strategy for dc–dc converters is shown in Fig. 12(b). A power reference for all the DAB modules is generated by the system output voltage regulator. Then, each power regulator compares the average power of each DAB module with the power reference and generates the phase-shift angle for the corresponding DAB module. In [108], the voltage-fed DAB converter is replaced by a current-fed DAB converter to realize wide voltage conversion and current ripple reduction, and all the current references of the current-fed DAB converters are set identical. Thus, power balance is obtained for all modules.

In order to remove the current sensors used for power balance in [107] and [108], a current sensorless power balance control strategy for dc–dc converters is proposed in [109] and [110], as shown in Fig. 12(c), in which the active power components of duty cycles in CHB rectifiers are used as the feedback signals for the power balance controllers in the dc–dc stage; thus, no additional current sensor is needed. In [111], a hybrid modulation of low- and high-frequency PWM is proposed for CHB rectifier to realize DLVB with reduced switching loss, and power balance is ensured by dc–dc converters with the same current references. In [112], the CHB rectifier is replaced by a cascaded dual-boost/buck half-bridge converter in the ac–dc stage, which also guarantees DLVB by regulating the duty cycles of dual-boost/buck half-bridge modules, and power balance is ensured by dc–dc converters with current sharing control scheme.

VI. Voltage/Current Sharing Approaches for DC–AC Series–Parallel Systems

Different from a dc–dc converter, the output of a dc–ac inverter is in the form of alternating current. Therefore, in dc–ac series–parallel systems, the output power balance includes not only the equaling of amplitude and frequency of module output voltage and current but also the equaling of the phases of them. This means that the equilibrium of the real and reactive power should be actualized.

A. ISOP DC–AC System

In order to ensure proper operation of ISOP dc–ac system, equal sharing of input voltages and sharing of output currents among the constituent inverters must be ensured. The relationship between IVS and OCS of ISOP dc–ac system is analyzed in [113] and [114], and it is concluded that IVS will be achieved automatically if OCS is realized, while achieving IVS can only ensure the module output active power is equal and the module reactive power sharing could not be guaranteed, and if, in the meanwhile, either the rms values or the power factor angles of the module output currents are equal, OCS is achieved. To achieve IVS and OCS, a three-loop control strategy, consisting of a common output voltage loop, IVS loops, and individual inner current loops, is proposed, as shown in Fig. 13. The common output voltage loop regulates the dc–ac system at the desired output voltage and provides the basic current reference for inner current loops which are adjusted by corresponding IVS loops to achieve IVS. To guarantee all the module output currents have the same power factor angles, the output error signal of each IVS loop is multiplied by the basic current reference and then subtracted from it to obtain the final current reference of the respective inner current loop. Thus, all the current references of inner current loops have the same phase angles, and OCS is achieved. As an alternative, the output current amplitude can also be used to ensure OCS combined with IVS control [115].

The control strategies [113]–[115] are actually centralized control method, which restricts the modularity of ISOP dc–ac system, and the system tends to collapse if the central control unit goes wrong. In [116], a distributed control method is proposed, in which all the modules have their own control loops, and three buses, i.e., an IVS bus, a system output voltage reference synchronous bus, and an average current bus, are added. The IVS control combined with the same power factor angle method is used to achieve IVS and OCS. The distributed control method is applied in an ISOP dc–ac grid-connected system in [117] with two communication buses. Although the distributed control method improves the modularity of ISOP dc–ac system, the communication buses are susceptible to interference. Similar to the POVG method for ISOP dc–dc system shown in Fig. 4, a full modular control strategy based on positive output-voltage-amplitude gradient is proposed for

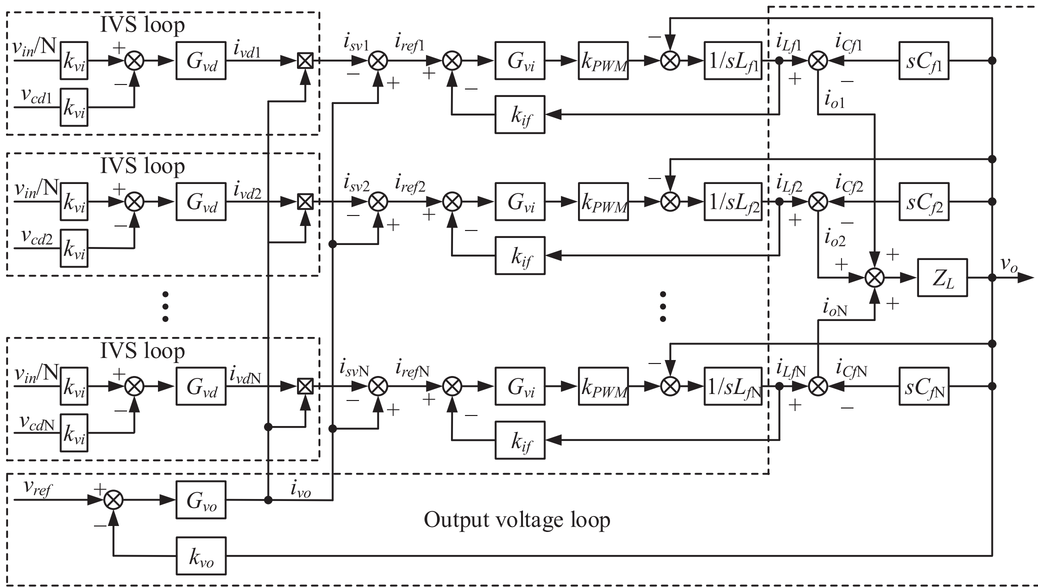

Fig. 13. Control strategy of ISOP dc–ac system [114].

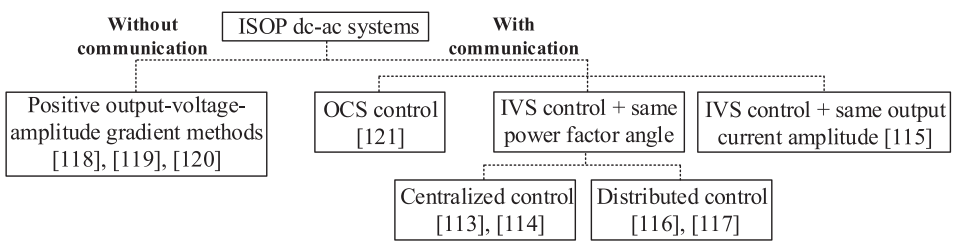

Fig. 14. Categorization of voltage/current balancing methods of ISOP dc–ac systems.

ISOP dc–ac system [118] to achieve IVS and OCS, in which each of the modules has its own controller without any control signal interconnection among the constituent inverters, leading to superior modularity and reliability. Compared with [118] and [119], the module output active power rather than module input voltage is used to generate the amplitude reference of module output voltage in [120]; so the high-voltage sensors are eliminated, leading to reduced cost and volume of the system.

In [121], a cross-feedback OCS control strategy is proposed for single-stage ISOP dc–ac system, in which a single-stage high-frequency ac-link inverter is taken as the basic module. However, such control inevitably restricts the modularity of ISOP dc–ac system.

Fig. 14 shows the categorization of voltage/current balancing methods of ISOP dc–ac systems.

B. ISOS DC–AC System

In order to ensure the proper operation of ISOS dc–ac system, equal sharing of input voltages and sharing of output voltages among the constituent inverters must be ensured. The relationship between IVS and OVS of ISOS dc–ac system is analyzed in [122], and it is concluded that IVS will be achieved automatically if OVS is realized, while only active component of the module output power can be balanced if only IVS is accomplished. If IVS is achieved and either the magnitudes or phases of all output voltages are equal, then OVS is achieved. Based on the analysis, a compound control strategy combining IVS and output voltage phase synchronization is proposed for ISOS dc–ac system, as shown in Fig. 15. Individual output signal of IVS loop is multiplied by the output signal of output voltage regulator to adjust the reference for individual inner current loop, in which the output filter capacitor current is controlled. Thus, all the output filter capacitor currents achieve phase synchronization as well as the output voltages of all modules. A corresponding distributed control strategy of ISOS dc–ac system is proposed in [123] to improve system modularity. In [124], a cross-feedback OVS control strategy is proposed for single-stage ISOS dc–ac system, in which a single-stage high-frequency ac-link inverter is taken as the basic module.

VII. Summations and Discussions on the Sharing Techniques of ISOP, IPOS, and ISOS Systems

From the above review of voltage/current sharing techniques for the ISOP, IPOS, and ISOS dc–dc systems, one can obtain a relationship among the balancing control strategies of the

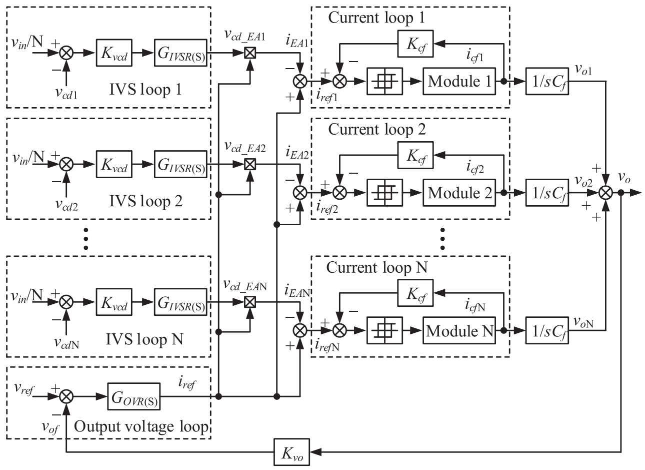

Fig. 15. Compound control strategy of ISOS dc–ac system.

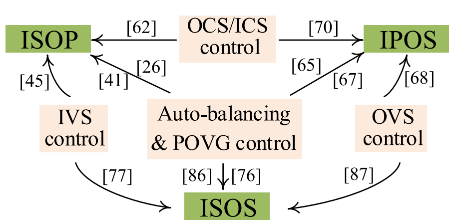

Fig. 16. Relationship among the balancing control strategies of ISOP, IPOS, and ISOS dc–dc systems.

three series–parallel systems, as shown in Fig. 16, in which only one representative reference is listed for each control method. It can be found that both the auto-balancing mechanisms and POVG methods can be employed for all three series–parallel systems. However, some difference still exists for the specific balancing methods. For instance, the auto-balancing mechanism with the constituent modules operating in dc transformer mode is effective for both ISOP and IPOS systems, but it cannot work in the ISOS system, while the auto-balancing mechanism with the constituent modules presenting output voltage drop characteristics is effective for all three series–parallel systems. IVS control can be used for both ISOP and ISOS systems, and the feedback logic is the same, i.e., when the input voltage of one module is lower than the average input voltage, the corresponding duty cycle of the module will be regulated to decrease to rebalance the system [45], [77]. However, although OVS control can be used for both IPOS and ISOS systems, the feedback logic is opposite, and when the output voltage of one module in IPOS system is lower than the average output voltage, the corresponding duty cycle of the module will be regulated to increase [68], while in the ISOS system, the duty cycle of the module with lower output voltage will be regulated to decrease; in other words, the OVS loops in the ISOS system are in positive feedback operation for system stability. Similar to the OVS control for IPOS and ISOS systems, the current sharing control strategies for the ISOP (OCS) and IPOS (ICS) systems also have the opposite feedback logic. When the input current of one module in IPOS

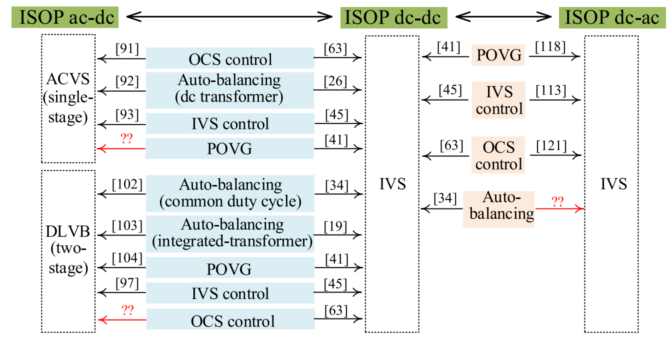

Fig. 17. Relationship among the balancing control strategies of ISOP dc–dc, ac–dc, and dc–ac systems.

system is lower than the average input current, the corresponding duty cycle of the module will be regulated to increase [70], while in the ISOP system, the duty cycle of the module with lower output current will be regulated to decrease [62]. It can be concluded that only for the input-series-connected systems (ISOP and ISOS) and meanwhile the variables at output sides are used for balancing control, i.e., output current for ISOP system and output voltage for ISOS system, then the current/voltage sharing control loops must be in positive feedback operation for system stability.

Fig. 17 shows the relationship among the sharing control strategies of ISOP dc–dc, ac—dc, and dc–ac systems, in which it can be seen that there are many similarities. For instance, for the single-stage ISOP ac–dc system, a cross-feedback OCS-controlled method is used to achieve ACVS [91], which is also used to achieve IVS for ISOP dc–dc system by the same authors [63]. Based on the classification and summary, one can deduce that the POVG method is also a potential solution for the single-stage ISOP ac–dc system because its circuit structure is very similar to the ISOP dc–dc system. Moreover, for the two-stage ISOP ac–dc system in which the common duty cycle control is adopted for the front stage CHB rectifiers, one can deduce that the OCS control is also a potential solution. For the ISOP dc–ac system, the auto-balancing mechanism method has not yet been found in literature, which is theoretically possible.

VIII. Special Structures and Module Topologies

In Fig. 1, each block not only represents a single power converter module but also can represent a series–parallel combination of multiple sub-modules; for instance, each block represents a two-submodule IPOS stack in an ISOS system in [129], as shown in Fig. 18(a). Fig. 18(b) shows its control scheme. For the ISOS system, IVS control loops are employed for stable operation of the input series stage, while for the two IPOS stacks, OVS control loops are employed to ensure the output voltage balancing. In [18], an IPOS system that consists of nine two-submodule ISOP stacks is proposed for a solid-state 2.88-MW/115-kV long pulse modulator. For the ISOP stacks, auxiliary balancing circuits shown in Fig. 2(f) are used to achieve input voltage balancing, while for the IPOS

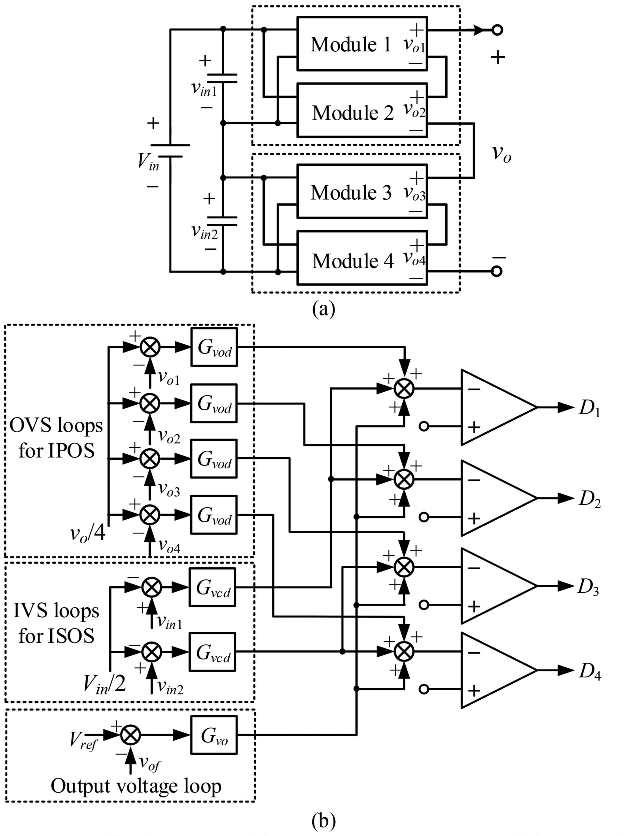

Fig. 18. Combined system with two or more series–parallel connection structures. (a) An ISOS system with two IPOS stacks. (b) Control scheme.

system, an ICS control strategy is used instead of an OVS one to avoid the measurement of the output voltage so that no high-voltage isolated measurement equipment is needed. It can be seen that for the "combined" systems with two or more series–parallel connection structures of IPOP, ISOP, IPOS, and ISOS, the module equilibrium scheme must be used for each series–parallel structure.

To realize series–parallel connection, it is required that the block module must has galvanic isolation. However, some non-isolated converters also can be employed for IPOS structure; for instance, in [130], a boost converter and a buck-boost converter form an IPOS system for offshore wind energy application to realize high-voltage step-up, while an IPOS system consists of a boost converter, and a Ćuk converter is proposed for fuel cell application in [131] and [132]. It can be seen that the number of constituent modules is limited to two for the non-isolated IPOS systems.

Generally, all constituent modules are uniform in a series–parallel system, but the topologies may be different in some applications for unique purposes. For instance, an IPOS system consisting of a full-bridge *LLC* resonant converter and a flyback converter is proposed for PV generation to achieve high conversion efficiency in [133], where most of the PV power is transferred by the full-bridge *LLC* resonant converter, and the voltage difference between the intermediate dc bus voltage and the output voltage of the resonant converter is compensated by the flyback converter. In [59], a four-module ISOP system is proposed to balance the voltages of output-series capacitors of five-level unidirectional T-rectifier, where the outer two dc–dc converters provide bidirectional power flow and the inner two dc–dc converters supply unidirectional power flow. Even different operation modes can be used for the same module topology in a series–parallel system; for instance, all the flyback modules operate in DCM, except one of them operates in CCM in an ISOS system [84].

For the series-parallel systems, besides the conventional and original function as the power supplies to realize voltage/current conversion, and in which the voltage/current sharing among the constituent modules is a necessary rather than its main purpose, in some particular applications of the series-parallel systems, the primary purpose is to realize voltage/current sharing for other equipment. In [59], the primary purpose of the ISOP system is to balance the voltages across the five-level unidirectional T-rectifier output capacitors and its 28-V output for onboard circuitry is a subsidiary function. In [134], an ISOP system is used to inject current into or absorb current from the series-connected PV submodules in order to compensate the maximum power point current mismatch, leading to all PV submodules operating at the same equivalent current. Similarly, in [135], an ISOP system is used to compensate the mismatch power of data center servers to regulate the input voltages of series-connected servers.

IX. Conclusion

This article presents a comprehensive review on the voltage/current sharing approaches for ISOP, IPOS, and ISOS systems. The previous and ongoing technological progress of series–parallel systems are driven by several demands or limits, which contain the voltage stress restriction of available power semiconductor devices, the pursuit of low overall system cost, high reliability, energy efficiency, and power density. In addition, the presented voltage/current sharing approaches in this review have been widely studied and applied in practice projects to ensure equivalent transferred power, input/output voltage/current of each submodule, where high reliability and simple thermal management design can be achieved. Overall, this comprehensive review is provided for both academic and industry readers as a valuable reference resource to deeply understand the series–parallel systems and explore the new and advanced approaches for series–parallel systems.

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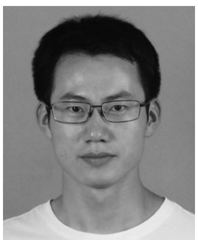

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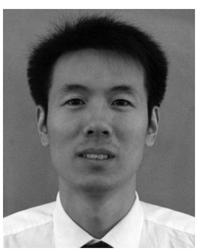

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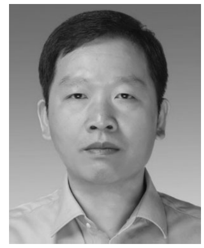

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