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A Centralized Shifted Power Control Scheme for Isolated Bidirectional DC-DC Converter in Standalone DC Distribution System

Minh-Duc Pham[1], Tuyen D. Nguyen[2], and Hong-Hee Lee[1]

[1]Department of Electrical Engineering
University of Ulsan, Korea
Phone/Fax number: +82-52-259-2187, e-mail: minhducpham2009@gmail.com, hhlee@mail.ulsan.ac.kr

[2]Faculty of Electrical and Electronics Engineering
Ho Chi Minh City University of Technology, Ho Chi Minh City (HCMUT), Vietnam
[3]Vietnam National University Ho Chi Minh City, Linh Trung Ward, Thu Duc District, Ho Chi Minh City, Vietnam
e-mail: ndtuyen@hcmut.edu.vn

Abstract. When parallel converter structures are considered in modern DC distribution systems, several challenges are faced in the energy management system (EMS). For example, the circuit parameter mismatches of parallel isolated DC-DC converter modules will cause power imbalances, which is the most important concern in DC distribution system. To deal with this issue, this study presents a power management control scheme in the EMS to ensure the power balance of isolated DC-DC converters in DC distribution system. In the proposed method, the proposed shifted voltage is introduced at the output of each converter to compensate the output impedance mismatches. Especially, the shifted voltage is flexibly determined according to the output current sharing error to obtain a balanced output impedance among converters, and the balanced power sharing is achieved by means of the modified voltage reference. The simulation results with the stand-alone DC distribution system are carried out to verify the effectiveness of the proposed control scheme.

Keywords. Bidirectional power sharing, Centralized control approach, dc-dc converter, isolated DC-DC converter.

1. Introduction

Isolated DC-DC converters are widely used for electric vehicles, energy storage systems, and distributed renewable energy sources [1]. In a small DC distribution system, low voltage energy sources are typically connected in parallel using an isolated DC-DC converter to deal with the local power demand. To stabilize the disturbances caused by changes in the loads and generation, it is necessary to integrate the energy management system (EMS) [2]. EMS is considered as a centralized controller to regulate the interfacing energy source converter in a coordinated manner. When a fault occurs in power systems, the DC distribution system operates in a stand-alone mode without the voltage support from the DC main grid. In this mode, it is more challenging to maintain the continuous power

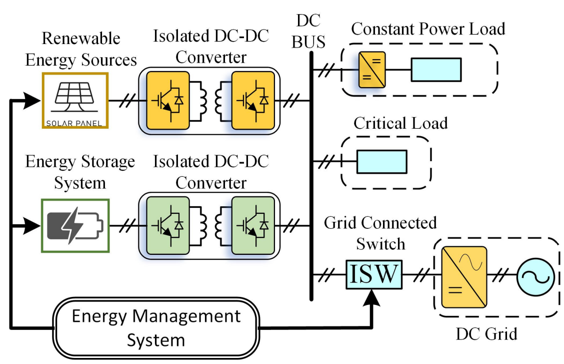

Fig. 1. Stand-alone DC distribution system.

supply to the loads and keep the voltage quality at the rated voltage level [3]. Fig. 1 shows a typical stand-alone DC distribution system, where the renewable energy source (RES) and the energy storage system (ESS) are considered as main power sources. The isolated dual active bridge (DAB) DC-DC converter is used to transfer the power from the energy sources to the DC bus with high power efficiency and provides completely galvanic isolation [4]. The DAB converter is composed of two full-bridge DC-AC converters interfaced by a series inductor and a high-frequency isolation transformer [5]. Because the RES and ESS are connected to the same DC bus, the DAB converter modules are considered to be connected in parallel, as shown in Fig. 1.

Management of the EMS is more difficult comparing to that of a single interfacing converter because multiple DC-DC converters are operated simultaneously and independently [6]. In particular, EMS plays a critical role in the stand-alone DC distribution system because it manages the exchange power among sources and the loads. In the stand-alone DC distribution system, the balance between power generation and load consumption is rather important [7]. Due to mismatched output impedances of energy sources and unpredictable power fluctuations in loads, instantaneous power imbalance may occur and affect the stable operation of the DC system [8]. Thus, an appropriate EMS control scheme is essential to mitigate the power sharing error and compensate deficient power for system stability [2].

In [9] and [10], the power sharing control scheme is presented which regulates converter output voltage based on a constant coefficient. The control scheme enables RES and ESS to autonomously share their output power based on their power coefficients, which are also termed as virtual resistance [9], [10]. However, these control schemes suffer from poor voltage regulation and restricted power sharing [11]. As a result, researchers must choose a tradeoff between voltage regulating and power sharing. To improve the power sharing performance, several improved control schemes have been presented including a high droop gain method in [12] and a nonlinear droop method in [13]. Even though there are some improvements in terms of power sharing over the conventional methods, the power sharing error is not sufficiently mitigated. A power sharing scheme in [14] adaptively adjusts the sharing coefficient according to the relative capacity that balances the power among ESSs. However, the control scheme is still susceptible to output resistance, and it is valid only for small DC systems with short distribution lines.

To address the power sharing inaccuracy in the stand-alone DC distribution system, a control scheme based on the average DC output current in each DC-DC converter was proposed [15]. Although the power sharing performance is improved, the control scheme requires detailed system parameters to design the containment-based controller. The two-layer multi-agent control scheme is employed to achieve precise current sharing without requiring system information [16]. On the other hand, a swarm algorithm is proposed to predict and distribute the load power between RES and ESS [17]. Nevertheless, the DC bus voltage is needed to be measured and feedbacked systematically, and a complicated computation is also required.

Taking the aforementioned discussions into account, in this paper, in order to eliminate the power sharing error for a stand-alone DC distribution system, a centralized shifted power control scheme is proposed. The proposed method only requires the discrete sampled values of converter output current, and no overall system parameters such as the average load current, average DC bus voltage, and global power sharing coefficient are needed. Specifically, an external EMS control loop is employed to adjust the shifted voltage according to the output current sharing error between RES and ESS, and accurate load power sharing is well recognized between RES and ESS regardless of load variation. The proposed method is applied to two isolated DAB converters connected in parallel, and its performance is evaluated.

2. System Description

A. Isolated DC-DC converters

Isolated DC-DC converters are an attractive alternative for interfacing sources such as photovoltaics, batteries, and fuel cells [18]. Hence, there is a growing study of bidirectional isolated DC-DC converters to ensure the power flow between different energy storage elements. The DAB converter is identified as one of the most promising

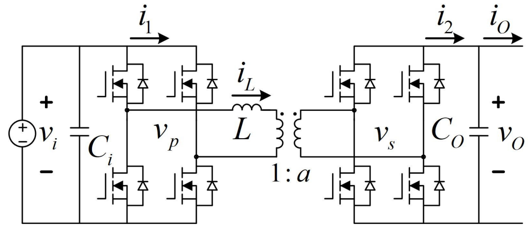

Fig. 2 Circuit diagram of the isolated dual active bridge (DAB) converter.

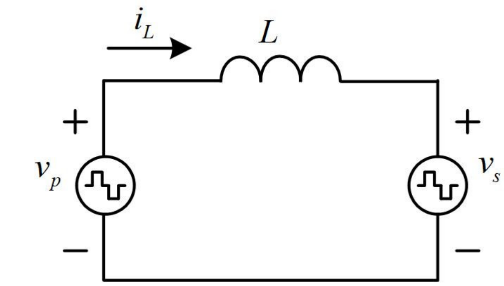

Fig. 3 Simplified model of DAB converter

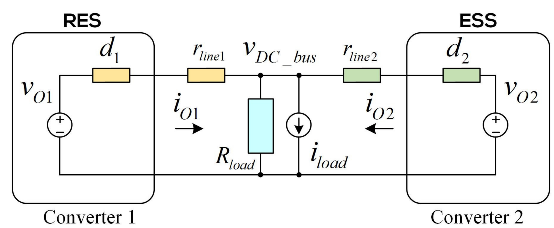

Fig. 4 Simplified circuit of stand-alone DC distribution system.

converter topologies for modern power electronic systems, which require bidirectional power flow, galvanic isolation, and efficient power conversion [5]. Fig. 2 shows the circuit diagram of a DAB converter, where L is the DAB storage inductor; C_i and C_O are the input and output capacitors; a is the turns ratio of the high-frequency transformer; v_i and v_O are the dc input and output voltages; i_1 is the input current of the DAB input H-bridge; i_2 is the output current of the DAB output H-bridge; i_L is the DAB inductor current; and i_O is the DAB converter output current [4].

To manage the power flow in DAB converter, two phase-shifted high-frequency AC voltages (quasi-square or square wave) are generated and applied to the two ends of an energy-transfer inductor. Thereby, energy flows from the leading AC voltage to the lagging AC voltage. The power flow is regulated via the direction and amount of the inductor current, which is similar way to power transmission in typical AC power systems. Fig. 3 shows the simplified model for controlling the power flow direction and magnitude of DAB converter. The direction of inductor current i_L is changed by adjusting the phase shift between ac voltages (square-wave or quasi-square-wave) v_p and v_s of primary and secondary H-bridges, as shown in Fig. 3.

B. Primary Power Sharing Control Loop

In a stand-alone DC distribution system, multiple RES and ESS converters are usually connected in parallel for maintainability and reliability, and autonomous power sharing is an important objective. Ideally, the power distribution between RES and ESS converters should comply with their rated capacity. Thus, the load must be shared proportionally among sources. The power sharing coefficient is set inversely as the rated capacity at the primary control level to achieve this goal. Whereby, the voltage reference is generated as [6]:

$$v_{Oi}^{ref} = v_{Oi}^{nor} - d_i i_{Oi}, \tag{1}$$

where v_{Oi}^{nor} is the output voltage at no load, d_i is the power sharing coefficient, and i_{Oi} is the output current of the isolated converter i $(i = 1, 2)$. By assuming that the local controller of RES and ESS can track their voltage references properly, the following condition is satisfied:

$$v_{Oi} = v_{Oi}^{ref}. \tag{2}$$

Since RES and ESS are connected in parallel, the simplified circuit of the stand-alone DC distribution system can be established shown in Fig. 4. In Fig. 4, r_{line1} and r_{line2} are the output line resistance caused by a long distance between RES and ESS. Isolated converters 1 and 2 are the RES and ESS interfacing converters, respectively. The DC bus voltage can be derived in Fig. 4 as

$$\begin{aligned} v_{DC\_bus} &= v_{O1} - d_1 i_{O1} - r_{line1} i_{O1} \\ &= v_{O2} - d_2 i_{O2} - r_{line2} i_{O2} \end{aligned}. \tag{3}$$

By taking (2) and (3) into account,

$$\frac{i_{O1}}{i_{O2}} = \frac{d_2 + r_{line2}}{d_1 + r_{line1}} \approx \frac{d_2}{d_1}. \tag{4}$$

When the value of d_i dominates the output resistance $r_{line\,i}$ ($d_1 \gg r_{line1}, d_2 \gg r_{line2}$), the accurate current (power) sharing ratio is obtained. The larger d_i is selected, the more precise power sharing is achieved, which is mentioned in the high gain control method in [12]. However, it is not feasible when increasing d_i because it will deteriorate the voltage at the DC bus. In other words, power sharing and voltage regulation are mutually exclusive. In order to remove this tradeoff and obtain the high power sharing performance, it is necessary to adjust each converter voltage reference properly.

3. Proposed EMS Control Loop

A. EMS Control Loop

A centralized shifted power control scheme is designed for a stand-alone DC distribution system. In the RES and ESS converter modules, the local interfacing controller is supposed to be independently controlled by its primary power sharing control loop. In the proposed control approach, an additional control signal u_i is designed in each local interfacing controller. Thereby, the equation (1) is modified as following:

$$v_{Oi}^{ref} = v_{Oi}^{nor} - d_i i_{Oi} + u_i. \tag{5}$$

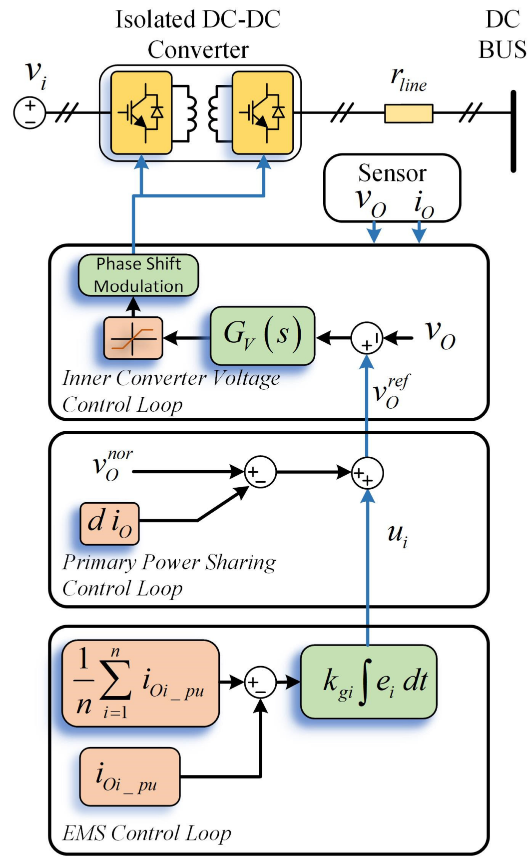

Fig. 5 Control diagram of a centralized shifted power control scheme.

Applying the voltage reference in equation (5) to DC-DC converter in Fig. 4, the DC bus voltage is derived:

$$\begin{aligned} v_{DC\_bus} &= v_{O1} - d_1 i_{O1} - r_{line1} i_{O1} + u_1 \\ &= v_{O2} - d_2 i_{O2} - r_{line2} i_{O2} + u_2 \end{aligned}. \tag{6}$$

In order to achieve the current sharing accuracy, the effect of $r_{line\,i}$ on the distribution system should be mitigated. There exists a constraint $u_i (i = 1, 2)$ that output currents are shared proportionally in the steady-state, i.e., $i_{O1} / i_{O2} = d_2 / d_1$. To achieve the aforementioned requirements, a centralized feedback control law is designed:

$$u_i = k_{gi} \int e_i\, dt, \tag{7}$$

where $k_{gi} \in \mathbb{R}^+$ is the control coefficient and e_i is current sharing error, which is defined as

$$\begin{aligned} e_i &= i_{Oi\_pu}^{ref} - i_{Oi\_pu} \\ &= \left[\frac{1}{n} \sum_{i=1}^{n} i_{Oi\_pu} \right] - i_{Oi\_pu}, \\ i_{Oi\_pu} &= \frac{i_{Oi}}{i_{Oi\_rate}}, \end{aligned} \tag{8}$$

Table I. DC Distribution System Parameters

Parameters	Value
Nominal Voltage (v_O^{nor})	180V
Rated Output Power and Current (P_{1_rate}; i_{O1_rate})	1800W; 10A
Droop coefficient (d_1, d_2)	0.5
Line impedances 1 and 2 (r_{line1}; r_{line2})	0.1Ω; 0.2Ω
Load 1	15Ω
Load 2	45Ω
Control gain K_{pV}, K_{iV}	0.0001, 0.080
Switching frequency (f_{sw})	20kHz
Centralized control sampling time	1ms
Output capacitor (C)	$200\mu F$
Inductor (L)	$10\mu H$
Input Voltage (v_{in})	96V
Transformer ratio (1:a)	1:2

where i_{Oi_rate} is considered as the maximum converter output current, $i_{Oi\_pu}^{ref}$ is the per-unit current reference, and n is the total number of converters in the stand-alone DC distribution system. To determine the voltage control u_i, the EMS collects the output current of each independent converter, and adjusts the voltage reference in (5) based on the current sharing error. As a result, the current is properly shared between RES and ESS in the stand-alone DC distribution system without requiring the line resistance estimation and detection.

B. Inner Converter Voltage Control Loop

For good tracking performance, both RES and ESS converters use a single voltage control loop with a voltage reference determined from (5). The calculated phase shift is generated by the voltage loop, and it is fed into the modulation block for the gating signal generator. The proportional-integral controller is selected as a voltage controller thanks to its simplicity and reliability. The transfer function of the voltage control loop is derived as

$$G_V(s) = K_{pV} + K_{iV}/s, \tag{9}$$

where K_{pV} and K_{iV} are the gains of $G_V(s)$. The bandwidth of single voltage control loop $G_V(s)$ is normally set as 1/10 of the switching frequency (f_{sw}) for switching noise rejection. The designed parameters of the RES converter controller are listed in Table I.

C. Centralized Control Loop Analysis

Fig. 5 shows the control diagram with the centralized shifted power control scheme. Assuming that the value of converter output voltage in the steady-state is equal to that of the voltage reference, and the output voltage is not

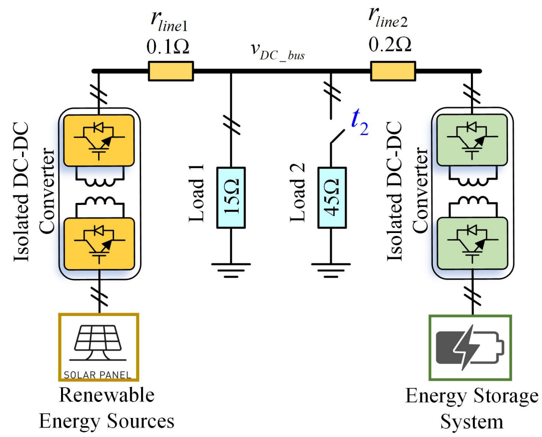

Fig. 6 Stand-alone DC distribution system used in simulation.

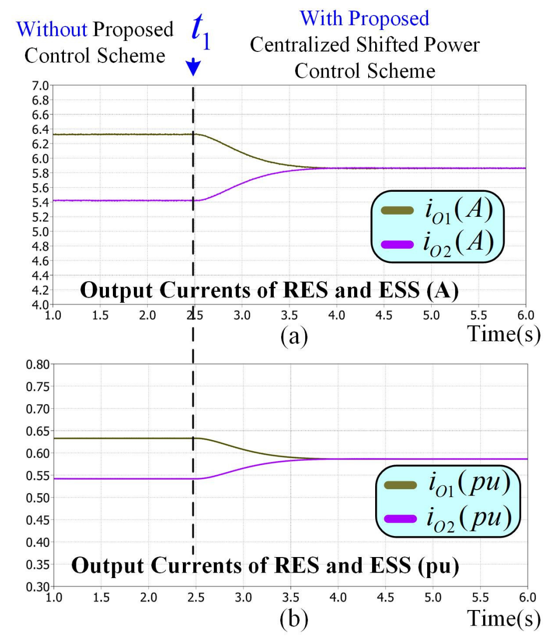

Fig. 7 Performance of the DC microgrid with and without the proposed shifted power control scheme. (a) RES and ESS current sharing in ample unit (b) RES and ESS current sharing in per-unit.

rapidly changed during one sampling frequency, the following condition is derived:

$$\begin{aligned} v_{Oi} &= v_{Oi}^{nor} + u_i - d_i i_{Oi} \\ &= v_{Oi}^{nor} + G_{Central}(s)\left(\left[\frac{1}{n}\sum_{i=1}^{n} i_{Oi\_pu}\right] - i_{Oi\_pu}\right) - d_i i_{Oi} \end{aligned}, \tag{10}$$

where

$$\begin{aligned} G_{Central}(s) &= (k_{gi}/s), \\ i_{Oi\_pu} &= i_{Oi}/i_{Oi\_rate}. \end{aligned} \tag{11}$$

The third term u_i in (10) shows that the proposed centralized shifted power control scheme can adjust the output voltage of the RES unit. On the other hand, the third term ($-d_i i_{Oi}$) indicates the inevitable voltage drop by the power sharing coefficient d_i. Thanks to the proposed shifted voltage, the negative influence of the power sharing loop ($-d_i i_{Oi}$) is reduced so the power sharing performance is improved. From (10), we can see that the response of the centralized controller mainly depends on the controller gain k_{gi}. Thereby, the bandwidth of $G_{Central}(s)$ is equal to the bandwidth between a centralized controller and RES to ensure stability. By controlling the variable u_i, the proposed centralized power control scheme compensates the impact of decreased voltage caused by primary power sharing loop, resulting in a balanced output current between RES and ESS.

4. Simulation Results

To evaluate the performance of the centralized power control scheme, a stand-alone DC distribution system with RES and ESS is simulated by using PLECS simulation software. The system configuration used in the simulation is shown in Fig. 6 with parameters listed in Table I. For simplicity, the rated powers of RES and ESS are consider to be the same. Each power source in the DC distribution system composes of an isolated DC–DC converter, and it is centrally managed by EMS. For simplicity, both RES and ESS rated power are considered to be the same ($P_{1\_rate} = P_{2\_rate}$).

Figs. 7(a) and (b) show the current sharing performance of the DC microgrid with and without the proposed shifted power sharing scheme. Before $t = t_1(2.5s)$, only load 1 is connected to the system, and RES and ESS are operated using the primary power sharing loop. In Fig. 7(a), even though their rated powers are the same, the output currents of RES and ESS are not distributed properly because their output line impedances have some mismatches. By applying the proposed scheme at $t = t_1$, the output currents of two converters in Fig. 7(a) converge on the desired value. Consequently, the per-unit currents of RES and ESS are accurately distributed as shown in Fig. 7(b).

Figs. 8(a) and (b) show the current sharing performance when load 2 (45Ω) is connected to the DC bus at $t = t_2(7s)$. Even though there are some mismatches current sharing during the load transient, these small errors are fully compensated in a short period of time thanks to the proposed centralized control scheme. In addition, two converters maintain the accurate per-unit current sharing in the steady-state, as shown in Fig. 8(b).

Figs. 9(a) and (b) show the DC bus voltage quality during the process of the enabled proposed algorithm and load changes. From t_1 to t_2 in Fig. 9(a), the DC bus voltage is not distorted even when the proposed control scheme is applied. In addition, the DC bus voltage drop caused by connecting the load 2 is recovered within a short transient time of 0.04s, as shown in Fig. 9(b). From the simulation results in Figs. 7, 8, and 9, the proposed control scheme confirms that adequate load power sharing is well recognized between RES and ESS regardless of load variation.

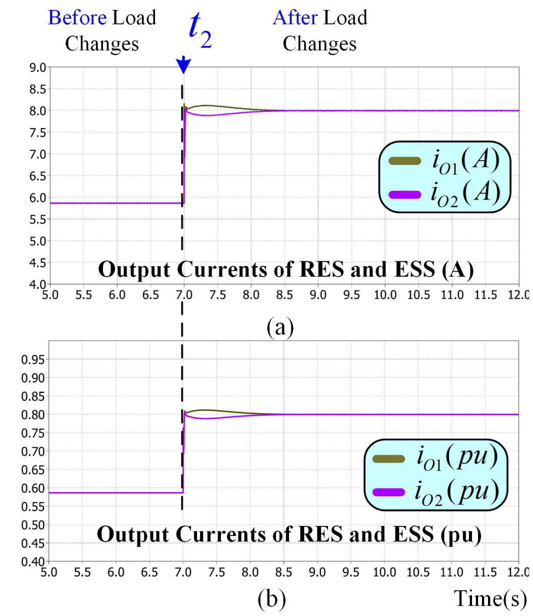

Fig. 8 Performance of the DC distribution system during load changes. (a) RES and ESS current sharing in ample unit (b) RES and ESS current sharing in per-unit.

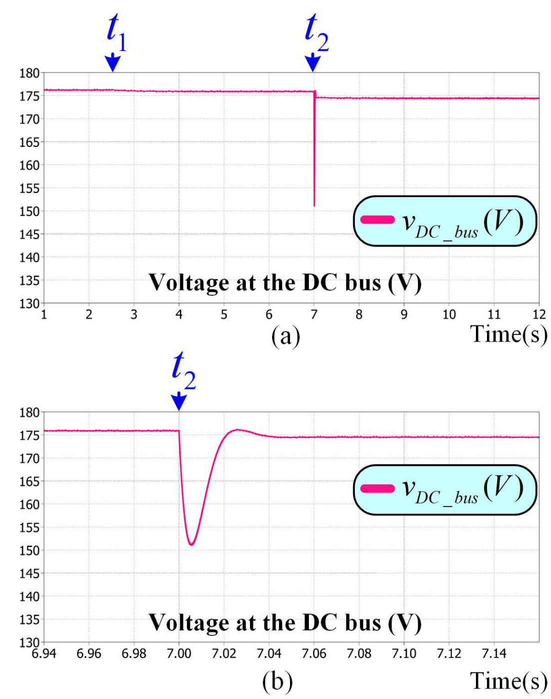

Fig. 9 Voltage quality at the DC bus. (a) Overall waveform of DC bus voltage (b) DC bus voltage waveform during load changes.

5. Conclusion

In this work, the shifted voltage was inserted into the local voltage control loop to create a centralized power sharing scheme. For output current regulation, the shifted control variable is adaptively adjusted by utilizing the per-unit current sharing mismatches. By mitigating the mismatched output line impedances between RES and ESS, the voltage reference is adequately adjusted, and proportionate and precise load power sharing is achieved. Despite of the load power variation, the proposed centralized control approach properly maintains power sharing without degrading the DC bus voltage.

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