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Centralized control of parallel connected power conditioning system in electric vehicle charge–discharge and storage integration station

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Abstract This study presents a centralized control scheme that coordinates parallel operations of power conditioning system (PCS) for the grid interactions of electric vehicles (EVs) in EV charge–discharge and storage integration station. Key issues for the control and operation of PCS under various operation modes are discussed, including vehicle to grid (V2G) mode, stand-alone mode and seamless transfer mode. The intelligent multi-mode charge–discharge method is utilized for the V2G mode, and the parallel control method based on communication network is adopted for the stand-alone mode. In addition, a novel seamless transfer strategy is proposed, which is able to implement PCS transition between V2G mode and stand-alone mode. The detailed process of the seamless transfer between the two modes is illustrated. Experimental results are presented to show the performance and feasibility of this strategy.

1 Introduction

The needs to reduce pollutant gas emissions and the increasing energy consumption have led to an increase of the

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electric vehicles (EVs) and renewable energy generation [1–4]. Large-scale utilization of EVs has the potential to reduce greenhouse gases emission, save fuel cost for EV drivers, enhance power system security, and increase penetration of renewable energy [5–7]. The development of the microgrid concept endows distribution networks with increased reliability and resilience and offers an adequate management and control solution for massive deployment of renewable energy generation and EVs [8–10]. EVs are considered as both a new type of load and flexible generation resources with vehicle-to-grid (V2G) technology.

The charge–discharge and storage integration station, consisting of bi-directional converters and hierarchical control structure, is able to realize bidirectional power flow between EVs and power grid. Many research works on designing the topologies and controllers of bi-directional power electronic converters for EV application, which are able to function as battery charger and to transfer electrical energy between battery pack and the grid [11–13]. In addition, the centralized control system for parallel operation of the converters during grid-connected and stand-alone operations has been conducted [14–16]. The issue of seamless transition between the V2G mode and stand-alone mode is discussed widely. A phase locked loop (PLL)-based seamless transfer control method between grid-connected and islanding modes is applied in a three-phase grid-connected inverter [17]. The performance of the transfer process is highly dependent on the characterization of PLL. In [18], a control strategy based on the frequency and magnitude droop control is used for the distributed generation (DG) to achieve a seamless transfer between grid-tied mode and islanding mode. However, both the magnitude and the frequency of the output voltage are varied due to the droop operation. In [19], a transfer strategy based on indirect current control is proposed for the three-phase inverter in the DG. However, it is difficult

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to realize the current limiting control because the inductance current is not controlled in both operation modes. In [20], a transfer methodology is presented for the three-phase grid-tied inverter without static transfer switch. In this case, because the instantaneous grid current is not introduced in the control algorithm, the harmonic performance of the grid current may not be good. Compared with the existing strategies for the grid-connected inverters [17–20], the contribution of this paper on the mode transfer strategy can be concluded into two points. First, an improved transfer control strategy based on indirect current control is proposed according to the model of three-phase (power conditioning system) PCS in the synchronous reference frame. In the seamless transfer mode, double closed-loop control technology is applied, the outer loops track instructions mutually while the inner loop remains the same. Second, particular issues of bidirectional converter are considered, including the charging state and discharging state during seamless transfer between V2G mode and stand-alone mode.

In this paper, a flexible and efficient centralized control scheme is developed for the parallel connected PCS in EV charge–discharge and storage integration station. The system configuration and theoretical analysis of three operation modes principles are described. Moreover, a novel seamless transfer method of PCS between V2G and stand-alone modes is presented. Finally, the control scheme has been verified on a 1 MW parallel connected PCS prototype.

2 System configuration

Figure 1 shows the infrastructure of EV charge–discharge and storage integration station with parallel
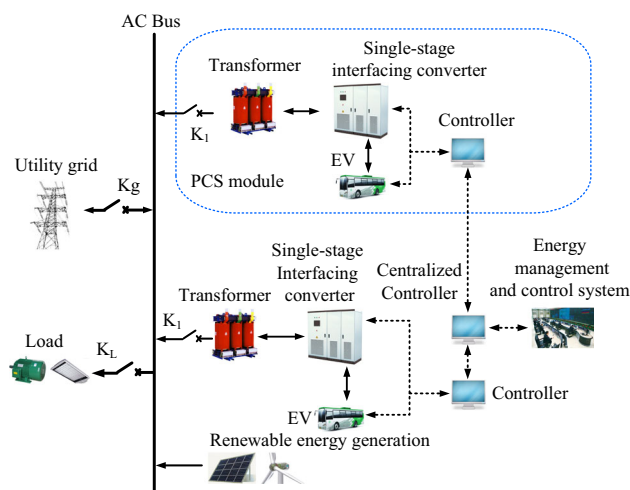

Fig. 1 Infrastructure of EV charge–discharge and storage integration station

connected PCS adopting centralized control architecture. In the V2G mode, integration station is connected to the utility grid. PCS can achieve several major functions: battery charger, active power regulation and reactive power compensation. In the stand-alone mode, integration station is separated from the utility grid. PCS functions as an uninterruptible power supply (UPS) to maintain the output voltage of the integration station. The PCS should transfer between the two modes in order to provide electrical power to the critical load during utility grid interruptions.

The topology of parallel connected PCS for EV charge–discharge and storage integration station is shown in Fig. 2, where V_{bat} is the battery voltage, L_{dc} and C_{dc} are the dc-link filter inductor and capacitor, L_1, L_2 and L are the ac filter inductors, and C is the ac filter capacitor. The dc power acquired by the battery packs is converted to three-phase ac power through two parallel connected IGBT full-bridge with a LCL filter. Compared with the L or LC filter, LCL filter is more suitable in high-power low-switching-frequency grid connected inverter applications due to its better performance on inhibiting grid current harmonics. Power transformer is selected to implement electrical isolation and voltage matching between battery packs and utility grid.

A three-level architecture is designed where complex control tasks are decomposed into simpler and manageable ones. The architecture consists of three levels, namely, level 1 converter control, level 2 centralized control and level 3 energy management system (EMS). The EMS is the highest level which ensures power balance within the EV charge–discharge and storage integration station. The centralized system as the middle level is responsible for coordinating the parallel operation of PCSs. The centralized control center uploads parallel system operation status and obtains the dispatch order from EMS through serial communication interface. The converter controller is the lowest level which handles the primary control of PCS. The converter controller sends the voltage–current instruction and receives the synchronization signal and operation mode instructions from centralized control center by optical fiber cable and controller area network (CAN) respectively.

3 Operational modes and control strategy

3.1 V2G mode

As shown in Fig. 3 the double-loop control uses the grid current loop to generate the reference for the inverter current loop under dq synchronous rotating coordinate. During the discharging process of Li-ion battery packs, PCS modules work as grid-connected inverters, the
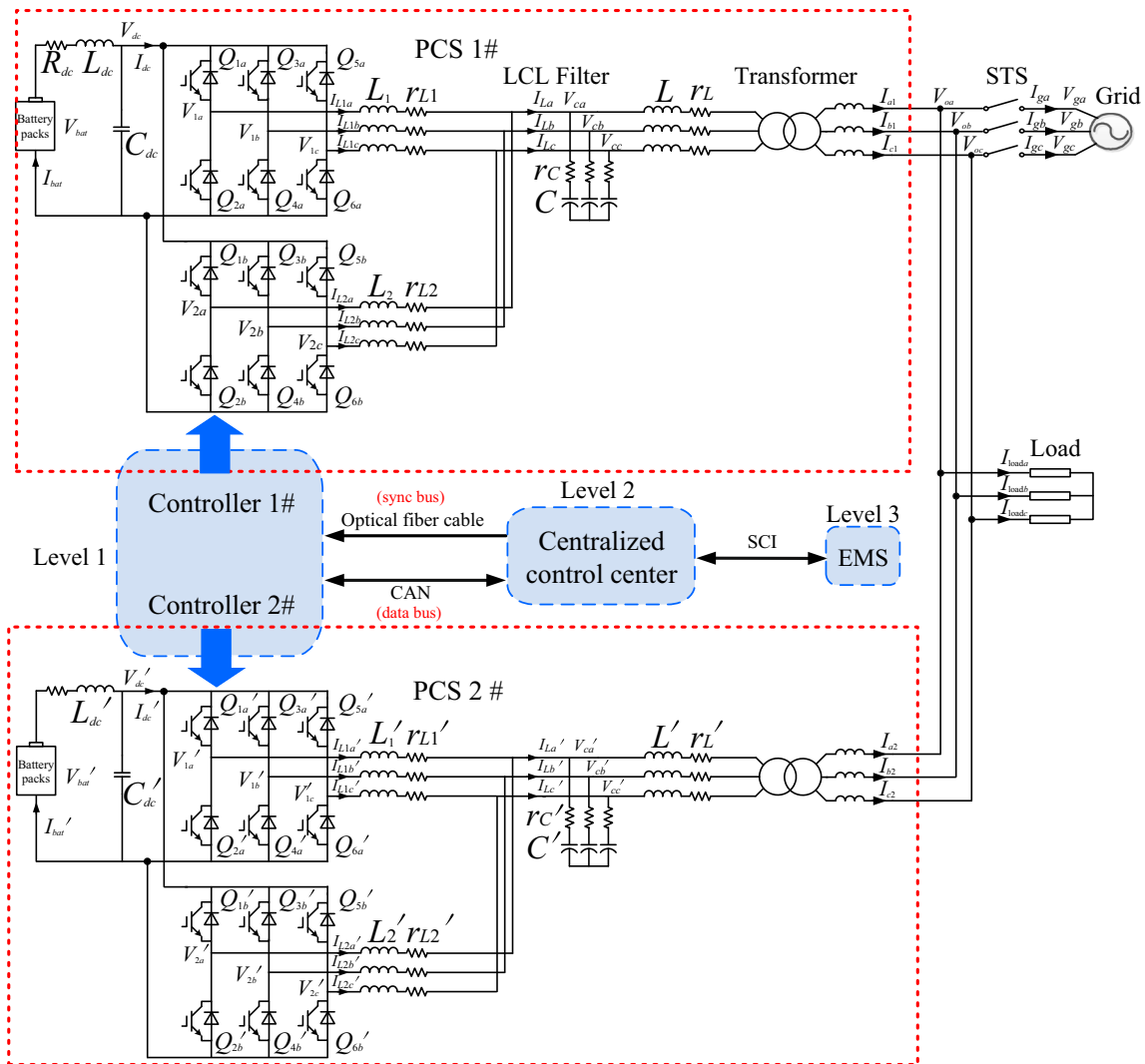
Fig. 2 Topology of parallel connected PCS

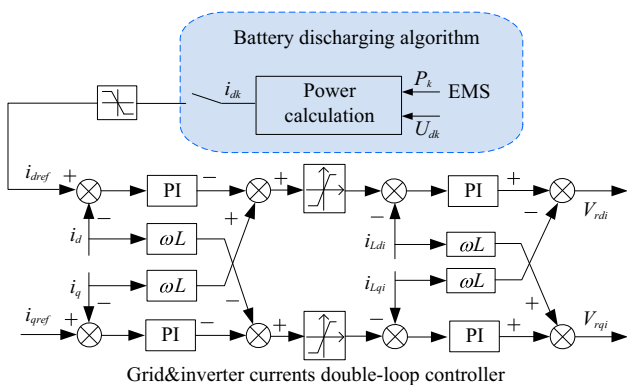Grid&inverter currents double-loop controller

Fig. 3 Controller block of discharging in V2G mode

discharging power is determined by the EMS. The bi-directional converter will control the active–reactive power and insure the output current harmonics to be low.

During the charging process of Li-ion battery packs, PCS modules work as grid-connected rectifiers. The bi-directional converter will control the power factor to unity and insure the input current harmonics to be low. In addition to the double-loop controller above, external controllers are designed to regulate the battery current and battery voltage respectively as shown in Fig. 4. Considering the battery state and application requirement under various conditions, the battery charging algorithm should be flexibly selected.

Constant current–constant voltage (CC–CV) charging method is adopted as conventional charging method. Under the arrangement of CC–CV charging algorithm, a constant current are applied to charge the battery till the transition time from CC to CV determined by terminal voltage of the battery. Then constant voltage is held after reaching the terminal voltage and the charging current will reduce automatically. Finally, the battery packs are fully charged.

This charge strategy can effectively increase the battery life cycle and avoid overcharge.

However, a faster and more efficient charging algorithm is required. The pulse charge with constant voltage (CV-PC) charging method is adopted as advanced charging method. The basic idea of the CV-PC is to adjust the duty cycle of the pulse within a certain range and observe the response of the charging current. This charge strategy can really retard the polarization and reduce the battery-charging time.

3.2 Stand-alone mode

The block diagram of double-loop control in the stand-alone mode is described in Fig. 5.

The capacitor voltage loop generates the reference for the inverter current loop under dq synchronous rotating coordinate. PCS module works as voltage source converter, the output voltage should keep strictly sinusoidal. When PCS modules are connected in parallel, circulating currents will inevitably occur due to the asynchronous switching process and module parameter difference. In order to effectively solve the impact of circulating current and to achieve superior accuracy of current sharing, the power-sharing controller is designed besides the double-loop controller.

Due to the voltage source nature, each PCS module has to be strictly consistent in output voltage amplitude, frequency and phase to suppress the circulating current. Synchronization is essential to achieve reliable parallel operation, which can be solved by a synchronization bus through the optical fiber cable. Rapid transmission rate of optical fiber can ensure the minimal synchronous error. The introduced power sharing strategy depends on the active-reactive power and output impedance of PCS module. The data exchange between centralized controller and converter
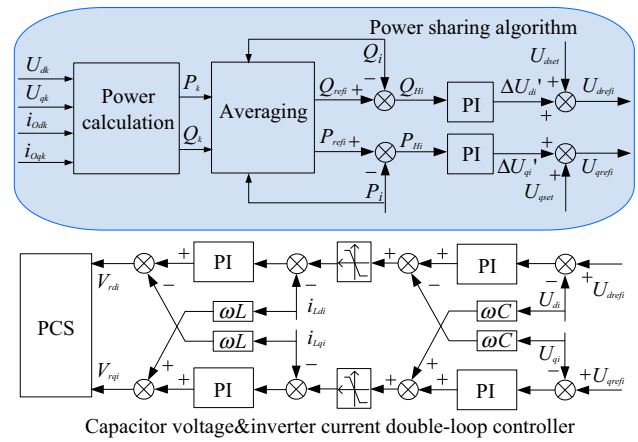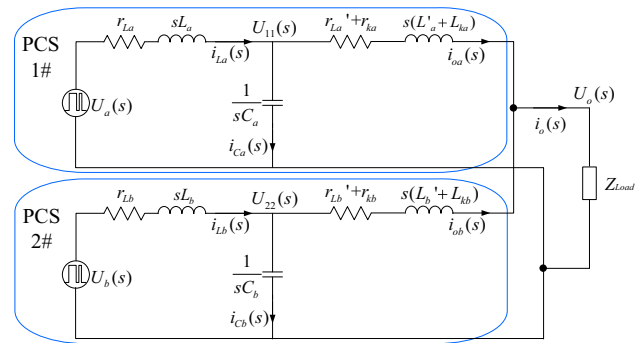

Fig. 5 Control strategy of stand-alone mode

Fig. 6 Equivalent circuit of paralleled PCS in stand-alone mode

controllers are achieved by CAN, including active-reactive power, battery status and control instructions. The module output impedance is highly inductive because of the transformer leakage inductance and inductance on the grid side of LCL filter. Therefore, the active power flow and reactive power flow are mainly influenced by the phase angle and the amplitude of the output voltage respectively. The decoupling control of d/q-axis voltage reference and active-reactive power error are realized effectively under dq synchronous rotating coordinate. The equivalent circuit of parallel connected PCS in the stand-alone mode is shown in Fig. 6.

3.3 Seamless transfer mode

Figure 7 shows the proposed control block diagram for V2G and stand-alone operations of PCS module. When PCS transfers between V2G mode and stand-alone mode, the outer loop simultaneously changes from the grid current control mode for V2G operation to the capacitor voltage control mode for stand-alone operation. The voltage–current double-loop control in the stand-alone mode is a conventional strategy, widely used in three-phase voltage
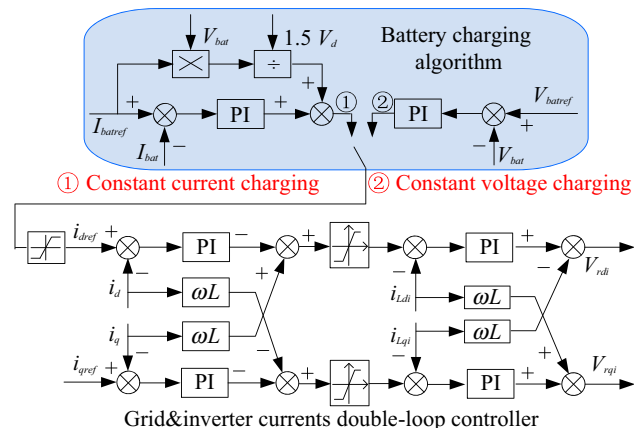

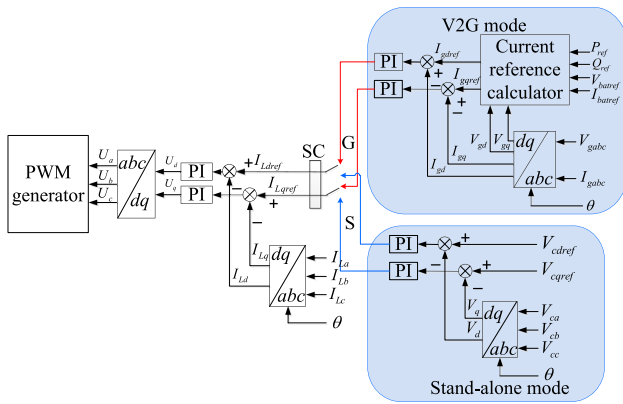Fig. 4 Controller block of charging in V2G mode

Fig. 7 Novel seamless transfer control strategy

source inverter. The parameter design and stability analysis of current double-loop control in the V2G mode is discussed in [21, 22]. During the process of transfer, the outer loops track current instruction mutually while the inner loop for inverter current control remains the same. In this case, it can be regarded as change in control instructions rather than change in controllers, the stability in both the stand-alone mode and the V2G mode guarantees the stable transition period between stand-alone mode and V2G mode.

A detailed sequence for the seamless transfer from V2G to stand-alone operation is summarized as follows. The process of the seamless transfer from V2G to stand-alone mode is illustrated in Fig. 8.

1) Judge a fault or scheduled maintenance on the grid.
2) Preparing for mode transfer adhere to stand-alone specification.
3) The static transfer switch (STS) is tripped in order to disconnect the PCS from the utility grid.
4) The control switch S_c is connected to 'S' from 'G', PCS changes its control from current control mode to voltage control mode.
5) Gradually change voltage references V_{cdref} and V_{cqref} to the desired values. The initial value of the V_{cdref} and V_{cqref} is determined by grid voltage V_{gd} and V_{gq}, which is calculated from the measured three-phase grid voltages at the transfer point.

In the meanwhile, a detailed sequence for the seamless transfer from stand-alone to V2G operation is summarized as follows. The process of the seamless transfer from stand-alone to V2G mode is illustrated in Fig. 9.

1) Detect that the grid voltage is within the normal operating range.
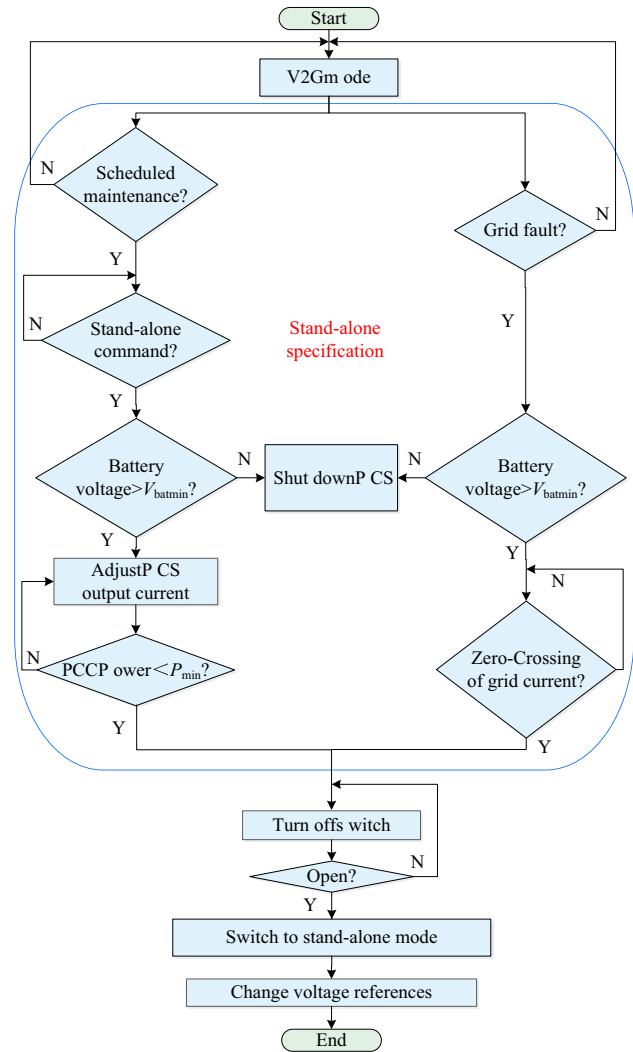2) Preparing for mode transfer adhere to V2G specification.

Fig. 8 Transfer sequence from V2G to stand-alone mode

3) When the frequency, phase and magnitude of the PCS output voltage match the grid voltage, the STS is closed. The PCS is connected to the utility grid afterwards.
4) The control switch S_c is connected to 'G' from 'S', PCS changes its control from voltage control mode to current control mode.
5) Gradually change the current reference I_{gdref} and I_{gqref} to the desired values.

4 Experimental results

An experimental device of parallel-connected PCS has been built to verify the proposed control method with the parameters and prototype shown in Table 1 and Fig. 10 respectively.
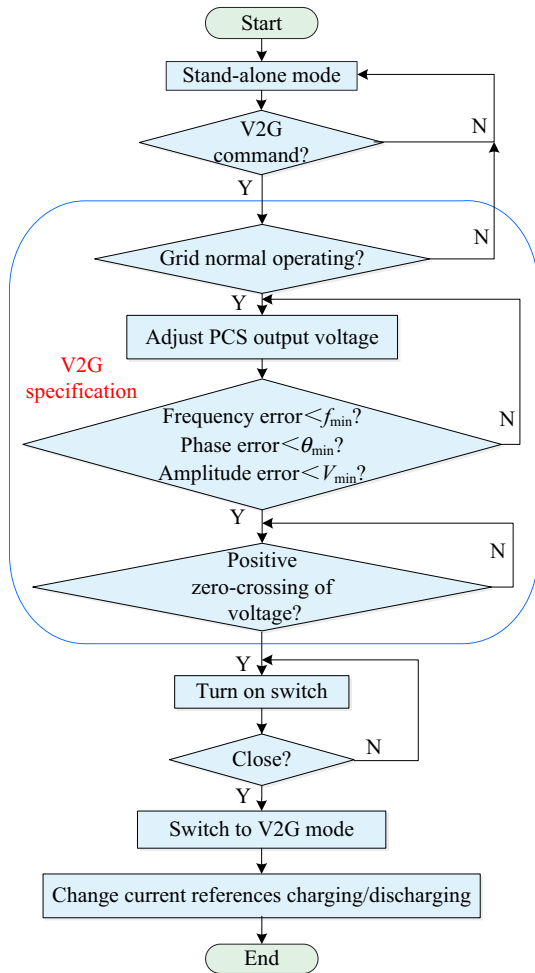
Fig. 9 Transfer sequence from stand-alone to V2G mode

Fig. 10 Experimental device of parallel-connected PCSs

(a) Discharging
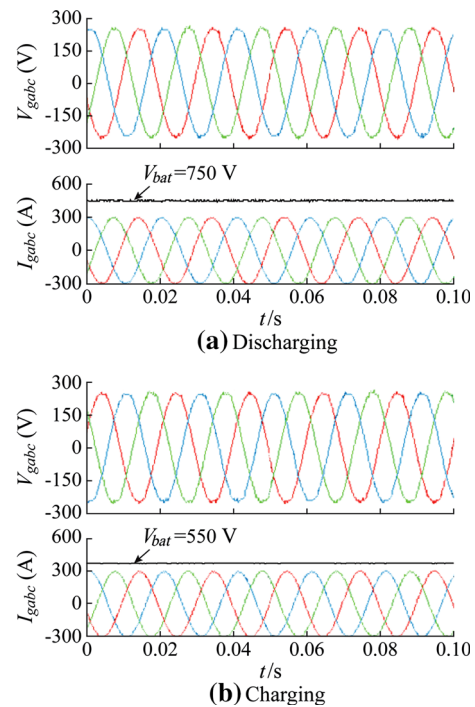
(b) Charging

Fig. 11 Experimental waveforms of charging and discharging process in the V2G mode

Table 1 Experiment specification of PCS module

Parameter	Symbol	Value
Rated power	S	500 kVA
Grid voltage	V_g	380 V/50 Hz
Switching frequency	F_s	3 kHz
△-Y Transformer ratio	N	315:380
DC filter inductance	L_{dc}	0.17 mH
DC bus capacitor	C_{dc}	22 mF
Inverter-side inductance	L_1/L_2	0.36 mH
Grid-side inductance	L	0.05 mH
AC filter capacitor	C	200 μF

Figure 11 shows the experimental waveforms of both charging and discharging process in the V2G mode. The THD of grid-side current fulfills the grid standard, and DC bus voltage ripple is limited.
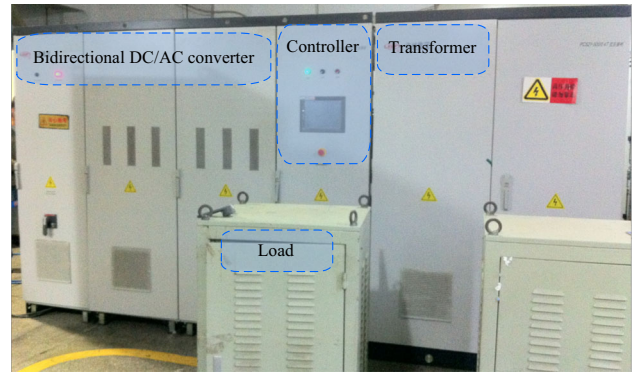
Figure 12 shows the experimental waveforms of load current sharing in the stand-alone mode. It is clearly that the steady-state and dynamic performance of parallel connected PCS is excellent during load variation.

Figure 13 shows the experimental waveforms of the seamless transfer process from V2G mode to stand-alone mode. Figure 14 shows the experimental waveforms of the seamless transfer process from stand-alone mode to V2G mode when grid fault occurs. The proposed transfer strategy is capable of providing the critical loads with a stable and seamless sinusoidal voltage during the whole transition period.
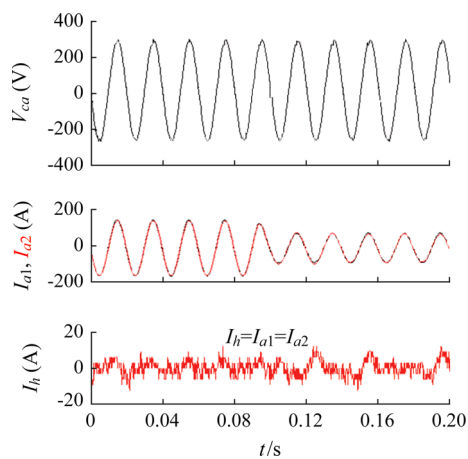
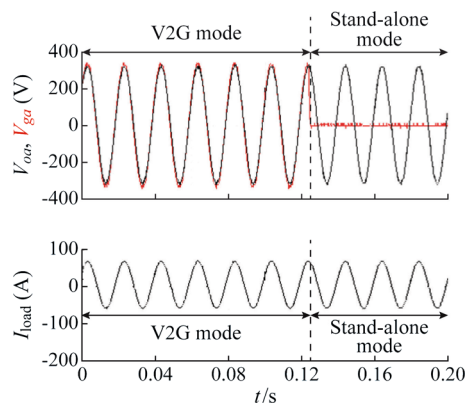**Fig. 12** Experimental waveforms of load sharing in the stand-alone mode

Fig. 13 Experimental waveforms of the proposed control showing a mode transfer from V2G mode to stand-alone mode
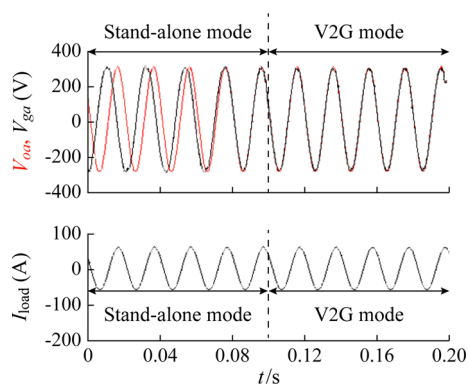

Fig. 14 Experimental waveforms of the proposed control showing a mode transfer from stand-alone mode to V2G mode

5 Conclusion

In this paper, a centralized control strategy for parallel connected PCS in EV Charge–discharge and storage

integration station is designed. The PCS infrastructure and operational principles are illustrated, controllers are analyzed in both V2G mode and stand-alone mode. A novel seamless transfer strategy and detailed sequence have been proposed and utilized to achieve better performance between V2G mode and stand-alone mode. The effectiveness of the proposed control strategies have been validated with comprehensive experimental results under various operations.

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