

Adaptive Bidirectional Droop Control for Electric Vehicles Parking with Vehicle-to-grid Service in Microgrid

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Abstract—With the popularity of electric vehicles (EVs), a large number of EVs will become a burden to the future grid with arbitrary charging management. It is of vital significance to the control of the EVs charging and discharging state appropriately to enable the EVs to become friendly to the grid. Therefore, considering the potential for EVs seen as energy storage devices, this paper proposes a multiport DC-DC solid state transformer topology for bidirectional photovoltaic/battery-assisted EV parking lot with vehicle-to-grid service (V2G-PVBP). Relying on the energy storage function of EVs, V2G-PVBP is able to not only satisfy the normal requirements of EVs' owner, but also provide the function of load shifting and load regulation to the microgrid. In this paper, EVs are categorized into limited EV and freedom EV. Limited EVs are always kept in charging state and freedom EVs can take part in the load regulation of the microgrid. The proposed adaptive bidirectional droop control is designed for freedom EVs to make them autonomously charge or discharge with certain power which according to each EV's state of charge, battery capacity, leaving time, and other factors to maintain the stability of the future microgrid. Eventually, the simulation and experiment of the adaptive bidirectional droop control based V2G-PVBP are provided to prove the availability of V2G-PVBP.

Index Terms—Adaptive bidirectional droop control, DC-DC, multiport, microgrid, parking lot, solid-state transformer, V2G.

I. INTRODUCTION

ELECTRIC vehicles (EVs), as a new kind of transportation means, have become more and more popular all over the world. Compared with conventional vehicles, EVs are able to not only reduce the carbon emission, but also reduce the dependence on fossil fuels for human society. Nowadays, with the popularity of EVs, EVs charging stations and parking lots with charging function have become common infrastructures in most cities.

Considering the energy storage, distributed distribution and other special characteristics of EVs, vehicle-to-grid (V2G), with the function of load shifting and load regulation for the microgrid, has gradually become a necessary research hotspot. With the benefits of boosting electrical reliability, promoting renewable energy, etc., the microgrid is becoming more and more common in our life. In order to limit the voltage fluctuation in the microgrid, the management of the EVs charging is very important. Actually, when EVs gradually take the place of conventional vehicles, the ancillary services of V2G system are of vital significance to the stability of frequency and voltage in the future microgrid. Without reasonable group management of the EV's charging/discharging, the chaos management of EV's charging/discharging is most likely to have a negative influence on the microgrid stability.

This paper focuses on the study of the parking lot. With the increasing number of the EV, the parking lot with EV charging function is of vital significance to the EV's owner. In most cases, the voltage of the microgrid is not as stable as the main grid. Thus, it is essential to keep the stability of the microgrid. Moreover, the weak grid can be seen as the microgrid [1]. However, without reasonable management, EVs charging can harm the microgrid. Considering that the behaviors of EV's owner are relatively random, a large number of EVs' frequent connection and disconnection with the microgrid through the parking lot can have a bad influence on the stability of the microgrid. Fortunately, although some EVs just park in the parking lot for a short time, in most cases, many EVs park for a long time. Thus, the EVs which park for a longer time can serve as a battery energy system to stabilize the microgrid. Based on the above analyses, this paper proposes an adaptive bidirectional droop control for the parking lot to enable the EVs with the ability to take part in the regulation of the microgrid. It has to be pointed out that the reason this paper does not choose the charging station is that the EVs cannot park at the station for a long time. Thus it is challenging to utilize the EVs at the charging station to regulate the microgrid.

Nowadays, some papers emphasized on the power converter architecture for the EV charging station or EV parking lot. Ref. [2]–[4] proposed the topology for the EV charging based on the dual active bridge (DAB). However, those topologies cannot realize simultaneous charging for multiple EVs. Ref. [5] proposed a modular multiport power electronic

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transformer for the EV charging station. However, the proposed topology can only realize fast charging for EVs and unidirectional power flow restricted by the network topology. Therefore, the proposed topology for charging stations cannot provide V2G service. Ref. [6] proposed a DC-DC multiport module for integrating plug-in EVs in a parking lot. The bidirectional structure of the proposed topology brought about V2G concept for establishing power transactions between EVs and the power grid. An AC-DC converter is proposed in [7] for EV charger with V2G service. However, [6], [7] did not propose a control strategy for EVs to satisfy the energy demand from the grid. Ref. [8] proposed a photovoltaic-assisted charging station (PVCS) and its energy management strategy based on solid state transformer. However, its energy management of the parking lot with V2G function was also based on a central controller. Therefore, a topology that can realize the function of charging EV and V2G service with multiport is important to the parking lot.

For the control of the parking lots with V2G service, many papers focused on the energy management strategy based on the central controller [9]–[16]. Ref. [9] proposed a strategy to utilize the V2G system to mitigate the drawbacks of the PV system. Ref. [10] proposed an objective function for EV to minimize the power purchasing from the grid to realize the grid frequency regulation. With the consideration of the unplanned EV departures, [11] proposed an algorithm to enhance the profits that grid can attain from the V2G system and provide a lower cost of charging power for EV at the same time. Ref. [12] proposed an autonomous distributed V2G control scheme; with the help of the scheme, the EV can seem as a distributed spinning reserve. The scheme can not only satisfy the demand of the consumers, but also keep the stability of the grid. However, the central controller based method needs bidirectional communication and complicated algorithms. Thus, the cost of the central controller based parking lots with V2G service can be expensive.

Instead of central controller based control, this paper proposes a bidirectional droop control for the parking lot. There were few papers that study the bidirectional droop control for EVs parking lot with V2G function. And the past papers mainly focused on the bidirectional droop control for BESS [17]–[20]. Ref. [18] proposed an SoC-based adaptive droop control method to balance the SoC of each energy storage unit (ESU). The droop coefficient was calculated by using the SoC in the discharging process, so the output power of each unit was in proportion to the corresponding SoC. However, ESUs were just charged with maximum input power. Ref. [19] proposed a bidirectional SoC-based droop control method. The droop coefficient was set to be proportional to the n th-order of SoC in the charging process; the droop coefficient was set to be inversely proportional to the n th-order of SoC in the discharging state. However, [19] did not take into account the capacity of each ESU. Although [20] considered the different capacity of different ESUs, it still cannot be applied to the parking lot with V2G function. The purpose of [20] was to balance the SoC of each energy storage unit. However, according to the owner of EV, the SoC of each EV must satisfy the requirement of the EV's owner before

leaving. Therefore, a modified bidirectional droop control for the V2G system is needed.

Although the EVs parking lot with V2G function can be seen as a kind of BESS, the traditional bidirectional droop control for BESS cannot be applied to the EVs parking lot with V2G function directly for the differences as listed below:

1) For EVs parking lot with V2G function and BESS in the DC system, one of their main purposes is to maintain the stability of the DC bus voltage. The bidirectional droop control in BESS is to balance the state-of-charge (SoC) of each battery and equalize the power. However, in EVs parking lot with V2G function, the bidirectional droop control is applied to satisfy the demand of the EVs owner and balance the power distribution of each EV to maintain the stability of the DC bus voltage.

2) According to the demand of the EV's owner, each EV should set a departure time t_{EVi} , the target SoC $SoC_{\text{tar_EVi}}$ for each EV in V2G-PVBP before t_{EVi} and the least acceptable SoC $SoC_{\text{min_EVi}}$ for each EV in V2G-PVBP before t_{EVi} . The value of t_{EVi} , $SoC_{\text{tar_EVi}}$ and $SoC_{\text{min_EVi}}$ for different EV are different. However, in BESS, such factors need not be considered.

3) The EV can drive in or drive out the EVs parking lot at any time. However, the battery in BESS is fixed. Moreover, in the EVs parking lot with V2G function, the rated capacity of each EV Q_{FEV} is different. Furthermore, considering that one parking space can provide service to different EVs at different times, the Q_{FEV} of one parking space is not fixed. On the contrary, in BESS, the rated capacity of each battery is usually the same.

4) In EVs parking lot with V2G function, the EVs are classified into limited EV (LEV) and freedom EV (FEV). The LEV always keeps charging state, and the charging/discharging state of FEV is decided by the voltage of the microgrid and the droop line. However, in BESS, the operation state of each battery is decided by the droop line. Moreover, in EVs parking lot with V2G function, the energy is transmitted among LEVs, FEVs, and microgrid. Meanwhile, in BESS, the energy is transmitted between the batteries and microgrid.

This paper proposes a topology for a bidirectional PV/battery-assisted EVs charging lot with V2G service (V2G-PVBP) based on multiport DC-DC SST. In V2G-PVBP, assisted battery energy storage system (BESS) and PV system are designed to compensate for the difference of transmission power between the microgrid and V2G-PVBP. With the proposed topology, the fluctuation power in a microgrid can be reduced. Considering that the DC bus voltage of DC-DC SST is related to the microgrid voltage, this paper also proposes an adaptive bidirectional droop control for the EV's charging/discharging process to maintain the DC bus voltage of microgrid with less communication. The influence of the EV battery capacity, the SoC of the EV battery, and the leaving time of the EV are considered in the adaptive bidirectional control. Moreover, this paper also analyses the power flow control between each port in multiport DC-DC solid state transformer based V2G-PVBP.

With the proposed topology of the V2G-PVBP, the power fluctuation of the microgrid caused by the parking lot can be

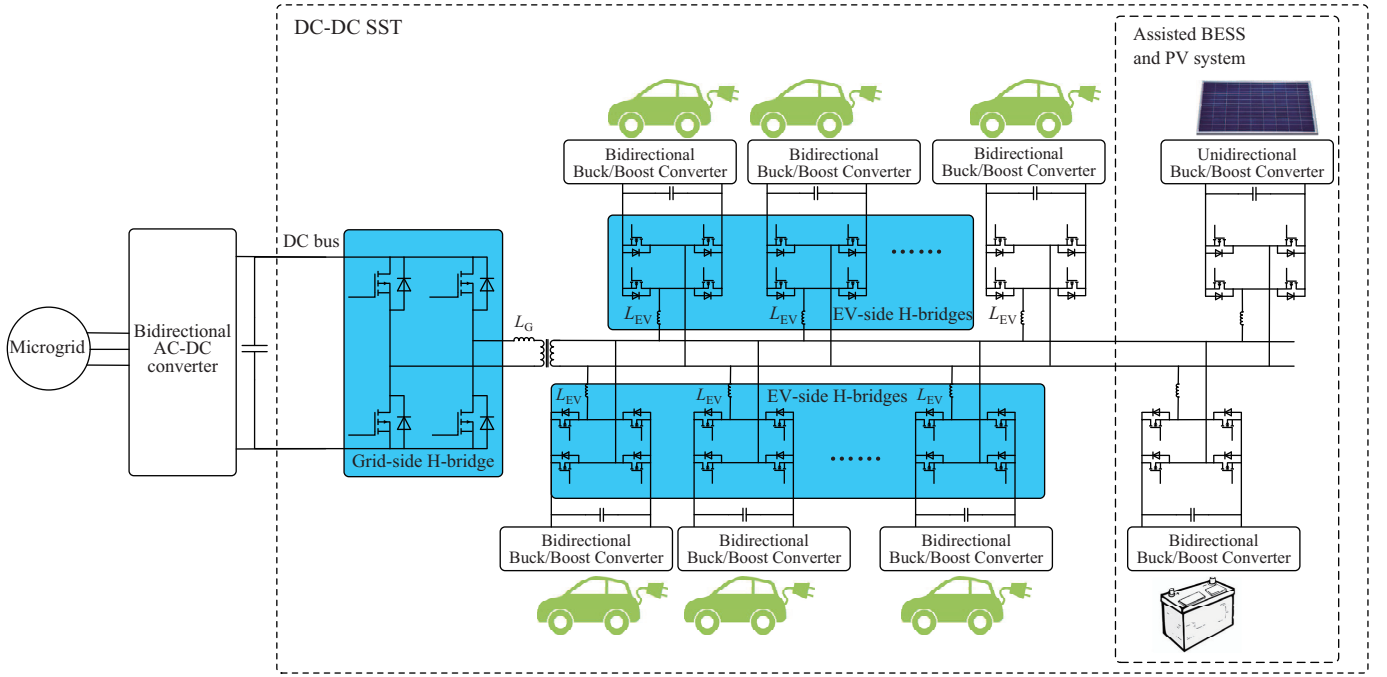


Fig. 1. Structure of bidirectional PV/battery-assisted EVs charging lot with V2G service based on multiport DC-DC SST.

reduced. Moreover, based on the proposed adaptive bidirectional droop control which is first proposed for EVs parking lot in this paper, not only the EVs are able to be charged according to the required SoC before leaving, but also the EVs can take part in the stability regulation of the microgrid.

II. SYSTEM DESCRIPTION

Generally, there are two main structures for EV parking lots, distributed structure, and a centralized structure. For distributed structure [5], each EV charger is modularized, which means each charger possesses a whole AC-DC, DC-DC converter. Meanwhile, as shown in Fig. 1, a centralized structure only has one port to interface with the AC microgrid; that is to say, it only needs one higher power level AC-DC converter. And the DC-DC converter based chargers are connected to the high power AC-DC converter. Compared with the distributed structure, the centralized structure offers more advantages, such as reducing the number of switching devices, simplifying the control of the system, achieving the centralized management of bidirectional power flow, and other aspects.

A. Structure of the V2G-PVBP

According to the comparison of the two structures, for bidirectional PV/battery-assisted EVs charging lot with V2G service (V2G-PVBP), considering its characteristics of power transmission among the microgrid, EVs, assisted BESS and assisted PV, the centralized structure should be preferred. Moreover, for AC microgrid, DC voltage, which converted from the grid, should be seen as the DC bus voltage. For DC microgrid, the DC bus voltage refers to the DC voltage from the microgrid. Fig. 1 illustrates the structure of V2G-PVBP.

As Fig. 1 shows, DC bus, EVs, assisted BESS, and assisted PV are connected through grid-side H-bridge, EV-side H-

bridge, BESS-side H-bridge, and PV-side H-bridge, respectively. And the power transmission among microgrid, EVs, assisted BESS, and assisted PV is realized by the structure of multi-port DAB. Fig. 2 shows the basic topology of DAB. Equation (1) shows the transmission power of DAB, which is influenced by the value of inductance L and phase shift (PS). The direction of transmission power is also determined by the value of PS.

$$P_{\text{trans}}(\alpha) = \frac{nV_1V_2}{fL}\alpha(1-\alpha) \quad (1)$$

where α means the PS between two H-bridges, V_1 and V_2 means the voltage of the primary side and secondary side, n means the transformer ratio, f means the frequency of high frequency switches and L means the power transmission power inductance.

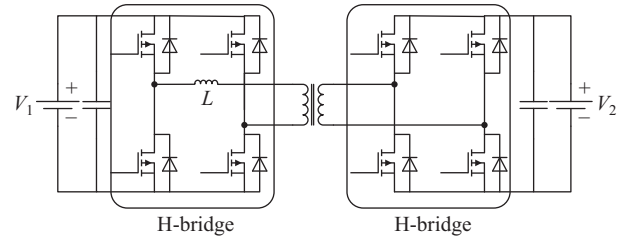


Fig. 2. Basic topology of dual-active-bridge.

Thus, the multiport DC-DC SST is composed of the grid-side, EV-side, BESS-side, PV-side H-bridges. Through appropriately controlling the phase shift (PS) among the H-bridge of grid-side, EV-side, BESS-side, the power flow direction of microgrid, EV, and battery can be managed. It has to be noticed that the assisted PV system always provides power to the V2G-PVBP. Therefore, the power flow of the assisted PV system is unidirectional.

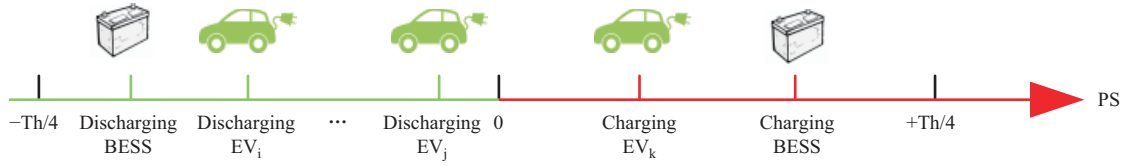


Fig. 3. Phase shift relationships in V2G-PVBP.

This paper sets the phase shift of grid-side H-bridge as reference. When the phase shift of BESS-side or the EV-side H-bridge is positive/negative, the battery or the EV is charging/discharging. Absolutely, because of the difference of each EV-side H-bridge's PS, there will be power sharing between discharging EV and charging EV. Generally, the power sharing between charging EV and discharging EV is expected, in that it can reduce the power exchange between the microgrid and EV. Fig. 3 illustrates the PS relationships in V2G-PVBP. In Fig. 3, the coordinate of PS does not mean the exact coordinate. The PS of BESS can be located at a positive axis. T_h means the half period of switching devices, and EV_i means the charging EV with different PS.

When the DC bus voltage of V2G-PVBP changes, the DC bus voltage can return to the rated value by managing the charging or discharging state of EVs and BESS to satisfy the microgrid demand. Therefore, through controlling the PS among DC bus, EVs and BESS, V2G-PVBP can take part in the microgrid power smoothing, in other words, balancing the supply and demand of the microgrid. However, it needs to be pointed out that the V2G-PVBP's capacity of microgrid power smoothing is related to the overall capacity of EVs and BESS, and the output of PV. Thus, if the microgrid voltage deviates from the normal value too much, V2G-PVBP still cannot satisfy the microgrid demand. Because V2G-PVBP cannot provide or absorb sufficient power for the microgrid to maintain the normal value.

B. EV-port Transmission Power

Before each EV parks at V2G-PVBP, each EV should set the departure time t_{EV_i} , the target SoC after t_{EV_i} , $SoC_{tar_EV_i}$, and the least acceptable SoC when EV leaves V2G-PVBP before the set departure time $SoC_{min_EV_i}$. According to the variables mentioned above, each EV is classified as freedom EV (FEV) and limited EV (LEV). In detail, FEVs can take part in the DC bus voltage regulation by exchanging the state between charging and discharging; meanwhile, LEVs are only able to be charged to $SoC_{tar_EV_i}$ to satisfy the need of the EVs' owner. When the DC bus voltage is higher or lower than the rated DC bus voltage, LEV has to keep charging state to satisfy $SoC_{tar_EV_i}$ after t_{EV_i} . Additionally, FEV has to transform to LEV when the FEV has to be charged to satisfy the $SoC_{tar_EV_i}$ after t_{EV_i} . Considering that the number of FEV is changing with time, the FEVs are seen as the changeable sources to maintain the stability of the DC bus voltage. The traditional bidirectional droop control cannot be utilized for the parking lot.

With the constant charging power $P_{char_LEV_i}$ for LEVs, the duration of LEV charged to the $SoC_{tar_EV_i}$ is able to be expressed as

$$t_{tar_EV_i} = \frac{[SoC_{tar_EV_i} - SoC_{EV_i}(t)]Q_{EV_i}}{P_{char_LEV_i}} \quad (2)$$

where $SoC_{EV_i}(t)$ is the EV's state of charge at time t and Q_{EV_i} is the rated capacity of the EV battery.

When $t_{tar_EV_i} \leq t_{EV_i}$, the EV is classified into FEV; when $t_{tar_EV_i} > t_{EV_i}$, the EV is classified into LEV. Therefore, for each FEV, the difference between the EV's SoC $SoC_{EV_i}(t)$ and the least acceptable SoC $SoC_{min_EV_i}$ is able to be applied to regulate the DC bus voltage when it is less than the rated value. Meanwhile, for each FEV and LEV, the difference between the EV's 100% SoC and the EV's SoC $SoC_{EV_i}(t)$ is able to be applied to regulate the DC bus voltage when it is higher than the rated value. Accordingly, for each FEV, this paper defines two new variables ($\lambda_{dis_FEV_i}$ and $\lambda_{char_FEV_i}$) to measure the regulation ability of FEV. $\lambda_{dis_FEV_i}$ is the regulation ability of FEV when the DC bus voltage is less than the rated value; $\lambda_{char_FEV_i}$ is the regulation ability of FEV when the DC bus voltage is higher than the rated value. They can be expressed as

$$\lambda_{dis_FEV_i} = SoC_{EV_i}(t) - SoC_{min_EV_i} \quad (3)$$

$$\lambda_{char_FEV_i} = 1 - SoC_{EV_i}(t) \quad (4)$$

In most cases, the amount of DAB's transmission power is controlled by the PS and inductance. The change of the inductance cannot realize continuous control of transmission power; through changing the PS, the transmission power is able to change continuously. Therefore, with the changeable DC bus voltage, and the changeable EV's battery voltage, the constant power charging for each LEV is realized by the control of PS. Fig. 4 shows the transformation between the FEV and LEV, and the charging state transformation for the FEV. V_{bus} means the DC bus voltage and V_{bus^*} means the reference voltage of the transformation between charging and discharging state for FEVs.

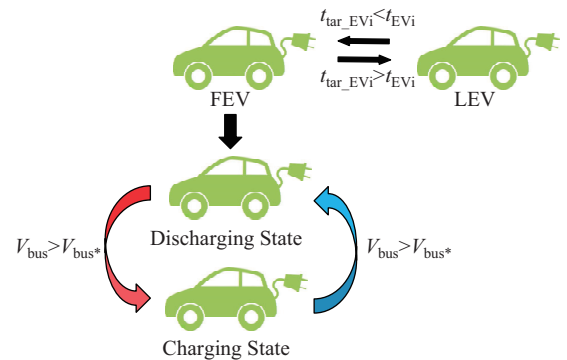


Fig. 4. The state transformation of EVs in V2G-PVBP.

According to (1), the transmission power between the EV and microgrid through the DC-DC solid state transformer can

be achieved.

$$P_{MG-EVi} = \frac{nV_{EVi}V_{port}}{f(L_{EVi} + L_{MG})}d_{EVi}(1 - |d_{EVi}|) \quad (5)$$

where n means the high frequency transformer ratio; d_{EVi} means the phase shift between the grid-side H-bridge and EV-side H-bridge when the phase shift of grid-side H-bridge is seen as zero; V_{port} means the voltage of the grid-side H-bridge; V_{EVi} means the voltage of the EV's battery; L_{EVi} means the inductance of EV-side H-bridge; L_{MG} means the inductance of microgrid-side H-bridge; f means the frequency of the switch devices.

When $d_{EVi} > 0$, $P_{MG-EVi} > 0$ the EV is operating at charging mode and the power is transmitted from the microgrid to the EV. When $d_{EVi} < 0$, $P_{MG-EVi} < 0$ the EV is operating at discharging mode and the power is transmitted from the EV to the microgrid.

Accordingly, transmission power between the EVs $P_{EVj-EVi}$, between the BESS and EV P_{B-EVi} are also able to be achieved. For a single EV, the transmission power is from the microgrid (which accounts for a large amount), other EVs, assisted BESS, and PV system. The transmission power direction is decided by the PS. Therefore, the transmission power of an EV is able to be expressed as

$$\begin{aligned} P_{EVi} &= \Sigma(P_{EVj-EVi}) + P_{MG-EVi} + P_{B-EVi} + P_{PV-EVi} \\ &= \frac{V_{EVi}}{f} \left[\sum_{j=1}^{N-1} \frac{V_{EVj}}{2fL_{EVi}} \Delta d_{EVj-i}(1 - |\Delta d_{EVj-i}|) \right. \\ &\quad + \frac{nV_{port}}{f(L_{EVi} + L_{MG})}d_{EVi}(1 - |d_{EVi}|) \\ &\quad + \left. \frac{V_B}{f(L_{EVi} + L_B)}\Delta d_{B-EVi}(1 - |\Delta d_{B-EVi}|) \right] \\ &\quad + P_{PV-EVi} \end{aligned} \quad (6)$$

where N means the number of EV parking at the V2G-PVBP; P_{PV-EVi} means the transmission power between the EV and the PV; $\Delta d_{EVj-i} = d_{EVj} - d_{EVi}$ means the PS between EV_j and EV_i , when $\Delta d_{EVj-i} > 0$ the power is transmitted from the EV_j to EV_i and vice versa; $\Delta d_{B-EVi} = d_B - d_{EVi}$ means the PS between BESS and EV_i , when $\Delta d_{B-EVi} > 0$ the power is transmitted from the BESS to EV_i and vice versa; L_B means the inductance of the BESS side H-bridge.

When the value of P_{EVi} is positive/negative, the EV is in charging/discharging state. For FEV, the charging/discharging state is determined by V_{bus} . Meanwhile, for LEV, no matter how the DC voltage changes, it still keeps charging.

C. Grid-port Transmission Power

In most cases, the microgrid is connected with the grid, and EVs are connected with the microgrid. In order to reduce the influence of the EVs to the microgrid, the EVs are managed through V2G-PVBP.

For microgrid side, the transmission power is derived from EVs, assisted BESS and PV system. Therefore, the transmission power of the grid side is

$$\begin{aligned} P_{MG} &= \Sigma(P_{EVi-MG}) + P_{B-MG} + P_{PV-MG} \\ &= \frac{nV_{bus}}{f} \left[\sum_{i=1}^N \frac{-V_{EVi}}{f(L_{EVi} + L_{MG})}d_{EVi}(1 - |d_{EVi}|) \right. \\ &\quad + \left. \frac{-V_B}{f(L_B + L_{MG})}d_B(1 - |d_B|) \right] + P_{PV-MG} \end{aligned} \quad (7)$$

where P_{EVi-MG} means the transmission power between the microgrid and EVs, when $d_{EVi} > 0$, $P_{EVi-MG} < 0$ the power is transmitted from the EV_i to microgrid and vice versa; P_{B-MG} means the transmission power between the microgrid and BESS, when $d_B > 0$, $P_{B-MG} < 0$ the power is transmitted from the BESS to microgrid and vice versa; P_{PV-MG} means the transmission power between the microgrid and PV system and N means the number of EV which includes LEVs and FEVs.

When V_{bus} is higher than its rated value, the microgrid need to release power to V2G-PVBP and P_{MG} is positive; when V_{bus} is lower than its rated value, the microgrid need to absorb power from the V2G-PVBP and P_{MG} is negative.

In detail, ΣP_{EVi-MG} contains the transmission power of the charging and discharging EVs to the microgrid. As shown in Fig. 5, when V_{bus} is lower than its rated value, all FEVs operate in discharging state. The power flows from the FEVs, BESS and PV to microgrid and LEVs. If the power supported by the FEVs, assisted PV and BESS can satisfy the microgrid demand, the microgrid voltage can return to the rated value.

When V_{bus} is higher than its rated value, the V2G-PVBP absorbs the extra power from the microgrid to maintain the stability of the voltage. If the V2G-PVBP is able to absorb the extra power from microgrid appropriately, the microgrid voltage can return to the rated value. When V_{bus} is higher than its rated value, the operation of V2G-PVBP can be divided into two situations. In situation I, as shown in Fig. 6, the extra power from the microgrid can be absorbed by the LEVs. In this situation, FEVs and BESS operate in discharging state and the power flows from the FEVs, BESS, PV and microgrid to LEVs. In situation II, as shown in Fig. 7, the extra power from the microgrid cannot be totally absorbed by the LEVs. In this situation, FEVs and BESS operate in charging state and the power flows from the microgrid and PV to LEVs, FEVs and BESS.

III. SYSTEM CONTROL

A. Overall Control of V2G-PVBP

When EVs are classified as LEVs, they are always under constant charging state. Only when the microgrid needs to absorb power from the V2G-PVBP, LEVs can benefit the DC bus voltage regulation. Therefore, the reasonable management of the FEVs plays a significant role in the V2G-PVBP. Apart from the assisted PV and BESS, FEVs can benefit the microgrid when the demand is higher than the supply in the microgrid.

Because the FEV's available power is determined by the present SoC $SoC_{EVi}(t)$ and the least power need $SoC_{min,EVi}$, the available power P_{dis_FEVi} for each FEV to transmit to the microgrid and the available power P_{char_FEVi} for each FEV to

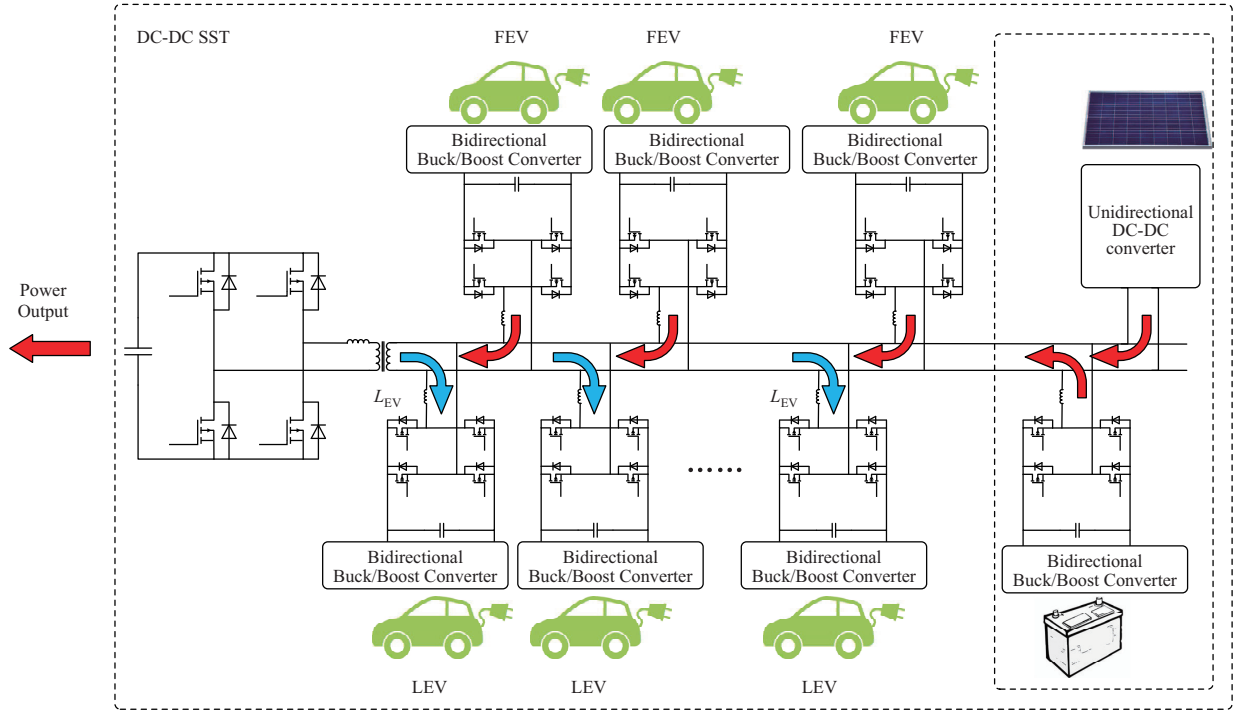


Fig. 5. Power flow of V2G-PVBP when V_{bus} is lower than its rated value.

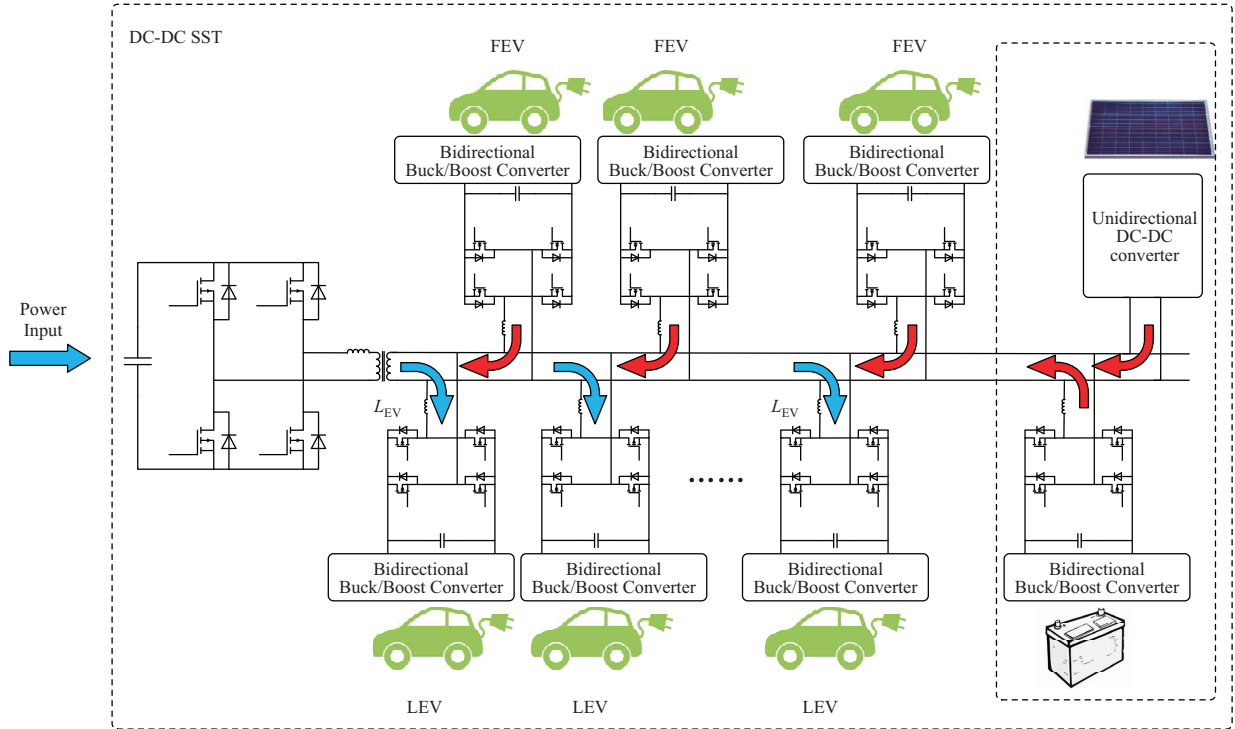


Fig. 6. Power flow of V2G-PVBP when V_{bus} is higher than its rated value and the charging power of LEVs can totally absorb the extra power from the microgrid.

absorb from the microgrid can be derived from

$$P_{dis_FEVi} = \lambda_{dis_FEVi} Q_{FEVi} \quad (8)$$

$$P_{char_FEVi} = \lambda_{char_FEVi} Q_{FEVi} \quad (9)$$

where Q_{FEVi} means the rated capacity of the FEVi.

The available power P_{dis_FEVi} of each FEV can be utilized to

compensate for the extra demand of the microgrid. Considering that each FEV owns its different $SoC_{FEVi(t)}$ and SoC_{min_FEVi} , the potential of each FEV to take part in the DC bus voltage regulation is different. Here, this paper considers the assisted BESS as a special FEV with $SoC_{min_FEVi} = SoC_{min_BESS}$ and $Q_{FEVi} = Q_B$, where SoC_{min_BESS} means the minimum

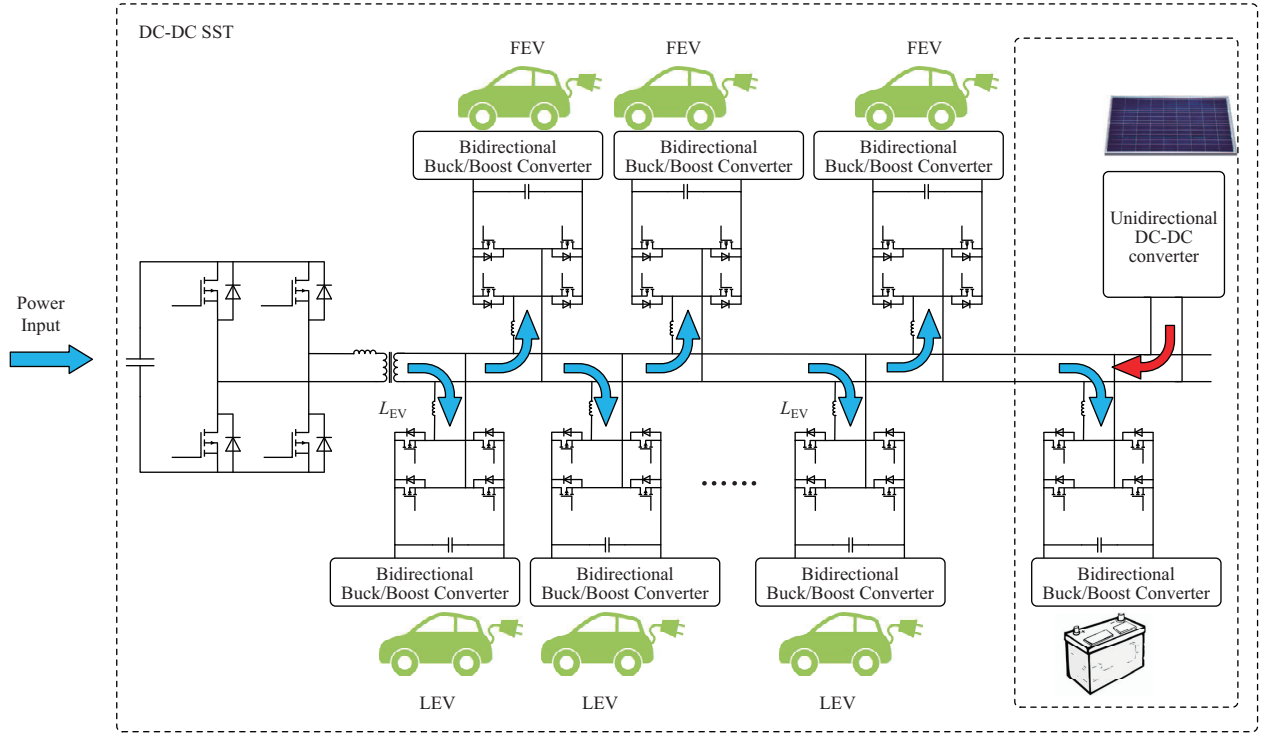


Fig. 7. Power flow of V2G-PVBP when V_{bus} is higher than its rated value and the charging power of LEVs cannot totally absorb the extra power from the microgrid.

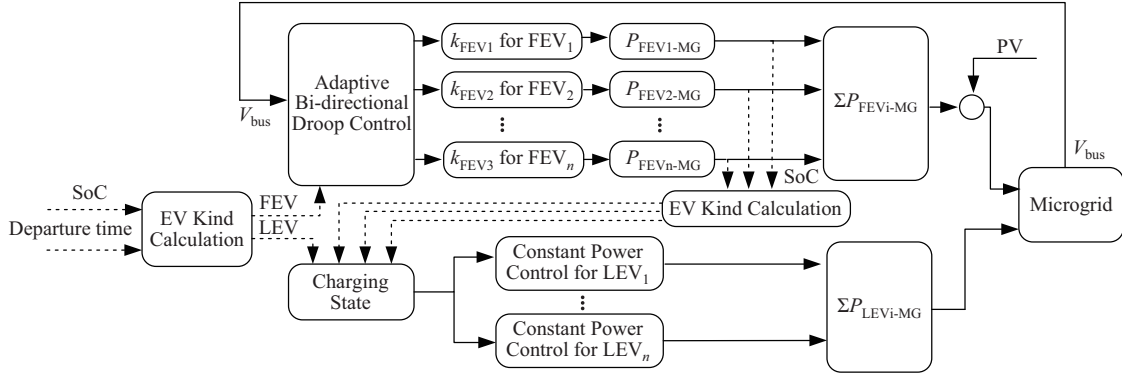


Fig. 8. Overall control of V2G-PVBP.

discharge level of the BESS, and Q_B means the rated capacity of the assisted BESS. Thus, in the next part, this paper supposes the assisted BESS as a special FEV. Accordingly, except for the assisted PV system, the overall power of FEVs which can be utilized to regulate the DC bus voltage can be attained

$$P_{pro_FEV} = \sum_{i=1}^{n_{FEV}} P_{dis_FEVi} = \sum_{i=1}^{n_{FEV}} \lambda_{dis_FEVi} Q_{FEVi} \quad (10)$$

$$P_{abs_FEV} = \sum_{i=1}^{n_{FEV}} P_{char_FEVi} = \sum_{i=1}^{n_{FEV}} \lambda_{char_FEVi} Q_{FEVi} \quad (11)$$

where n_{FEV} means the number of FEV which includes the assisted BESS; P_{pro_FEV} means the total power of the FEVs can provide to the microgrid and P_{abs_FEV} means the total power of the FEVs can absorb from the microgrid.

When P_{pro_FEV} and P_{abs_FEV} can satisfy the need of the

microgrid, the V2G-PVBP can help the voltage of microgrid go back to normal.

Figure 8 illustrates the overall control of V2G-PVBP. When a new EV drives into V2G-PVBP, according to SoC and departure time and (2), the system will categorize it into FEV or LEV. For LEVs, they keep constant charging through the control of PS no matter V_{bus} is lower or higher than its rated value. For FEVs (which include assisted BESS), their PS of H-bridges is ensured by the DC bus voltage V_{bus} and their adaptive bidirectional droop characteristics to participate in the bus voltage regulation. Moreover, when the FEV has to satisfy the SoC_{tar_FEVi} after t_{EVi} , in other words, when $t_{tar_FEVi} > t_{EVi}$, the corresponding FEV has to transform into a LEV and begins constant charging state. It needs to be pointed out that the assisted BESS is always seen as a FEV, and it cannot transform to a LEV. Therefore, according to the overall control of V2G-PVBP, for EVs' owner, their EVs can charge to SoC_{tar_FEVi} if

they drive out the V2G-PVBP after t_{EVi} . Meanwhile, their EVs can satisfy the requirement of SoC_{min_EVi} if they drive out the V2G-PVBP before t_{EVi} . For microgrid, the V2G-PVBP can successfully participate in the regulation of the voltage of the microgrid.

B. Droop Control for FEVs

V_{port} and DC bus voltage V_{bus} . P_{MG} flow in or flow out from the microgrid through grid-side H-bridge and take effect on V_{bus} .

$$P_{MG} = V_{port} \left(\frac{V_{port} - V_{bus}}{R} \right) \quad (12)$$

where R means the line resistance between V_{port} and V_{bus} .

According to (12), equation (13) shows the relationship between P_{MG} and V_{bus} . And equation (13) ensures that the V2G-PVBP regulate the DC bus voltage V_{bus} by changing P_{MG} .

$$V_{bus} = V_{port} - \frac{R}{V_{port}} P_{MG} \quad (13)$$

As expressed in (13), the voltage of DC bus is proportional to the transmission power of the microgrid, in other words, the voltage of DC bus V_{bus} can be regulated by the transmission power of the microgrid P_{MG} . Thus, by adjusting the transmission power of the microgrid, the voltage of the DC bus is under control.

Then the DC bus voltage droop regulation through the microgrid transmission power can be achieved.

$$V_{bus} - V_{bus0} = -k_{bus}(P_{MG} - P_{MG0}) \quad (14)$$

where V_{bus0} is the rated voltage of the DC bus voltage; P_{MG0} is the corresponding point of the power from V2G-PVBP and $k_{bus} = \frac{R}{V_{port}}$.

Meanwhile, considering the uncontrol of the assisted PV and LEVs, P_{MG} is mainly regulated by FEVs, and the assisted BESS. Here, this paper supposes that the number of FEV is $n_{FEV} - 1$, and the assisted BESS is seen as another FEV. Thus, there are n_{FEV} FEVs to participate in the DC bus voltage regulation. Then, according to (5), the transmission power between each FEV and microgrid can be expressed.

$$P_{FEVi-G} = \frac{-nV_{FEVi}V_{port}}{f(L_{EVi} + L_{MG})} d_{FEVi}(1 - |d_{FEVi}|) \quad (15)$$

where P_{FEVi-G} means the power which transmitted from $FEVi$ to microgrid and d_{FEVi} means the phase shift of the $FEVi$.

Moreover, when ignoring the uncertainty of the assisted PV system, according to the analysis above, it can be concluded that

$$\Delta P_{MG} = \Delta \sum_{i=1}^{n_{FEV}} P_{FEVi-MG} = \sum_{i=1}^{n_{FEV}} \Delta P_{FEVi-MG} \quad (16)$$

Considering the different characteristic of FEVs in available power λ_{dis_FEVi} and λ_{char_FEVi} , in order to achieve the cooperative control of FEVs, this paper presents an adaptive bidirectional droop control for different kinds of FEVs based on the available power of each FEV to maintain the rated

voltage of DC bus. According to (14)–(16), we can derive the relationship between DC bus voltage and each FEV.

$$\begin{aligned} \Delta V_{bus} &= -k_{bus} \sum_{i=1}^{n_{FEV}} \Delta P_{FEVi-MG} \\ &= -k_{bus} \frac{nV_{FEVi}V_{port}}{f(L_{EVi} + L_{MG})} \sum_{i=1}^{n_{FEV}} \Delta [d_{FEVi}(1 - |d_{FEVi}|)] \end{aligned} \quad (17)$$

Therefore, through adjusting the phase shift of FEV to control the $P_{FEVi-MG}$ of each FEV, the DC bus voltage can under control. However, because of the variety of each FEV's available power, which conducts by λ_{dis_FEVi} and λ_{char_FEVi} , each FEV's $P_{FEVi-MG}$ to compensate the difference of the grid's transmission power should be different. To realize the cooperative control of FEVs, this paper introduces a variable k_{FEVi} to realize the bidirectional control for the FEVs. Thus, for each FEV, according to (17), the DC bus voltage bidirectional droop control characteristics through FEVs can be expressed.

$$V_{bus} - V_{bus0} = -k_{bus} \sum_{i=1}^{n_{FEV}} k_{FEVi}(P_{FEVi-MG} - P_{FEVi-MG0}) \quad (18)$$

where k_{FEVi} means the slope of the FEV's droop curve; $P_{FEVi-MG0}$ means the transmission power of the FEV corresponding to the situation when $V_{bus} = V_{bus0}$.

To some extent, k_{FEVi} represents the capacity of a FEV to regulate the DC bus voltage. The larger the value of $|k_{FEVi}|$, the higher the regulation capacity of the corresponding FEV. According to the variety of each FEV's available power, the k_{FEVi} value of each FEV is different. With the help of k_{FEVi} , each FEV can regulate the DC bus cooperatively. Detailly, each FEV can acquire power from the microgrid or release the power to the microgrid based on λ_{dis_FEVi} and λ_{char_FEVi} .

The adaptive bidirectional droop control of the DC bus voltage for one FEV is illustrated in Fig. 9. To make the FEV operate more reasonable, the droop characteristics of a FEV at different SoC $k_{FEV(SoC)}$ are different. When $V_{bus} > V_{bus}^*$, the FEV with larger SoC absorbs less energy, and the FEV with smaller SoC absorbs more energy. When $V_{bus} < V_{bus}^*$, the FEV with larger SoC provides more energy, and the FEV with smaller SoC provides less energy. The difference of k_{FEVi} when $P_{FEVi-MG} > 0$ and $P_{FEVi-MG} < 0$ is caused by the difference of λ_{dis_FEVi} and λ_{char_FEVi} . The bidirectional droop line is categorized into three areas, which separated by V_{bus}^* and V_{bus0} . When $V_{bus} = V_{bus}^*$, the power charged by the LEVs can just meet the microgrid. At this moment, there is no power transfer between FEVs and microgrid. Thus, in area 1, the power is transmitted from the microgrid to FEVs and LEVs. In area 2, the power is transmitted from the microgrid and FEVs to LEVs. In area 3, the power is transmitted from the FEVs to microgrid and LEVs. When V_{bus} drops to V_{bus1} , the corresponding EV discharges with $P_{FEVi-MG1}$; when V_{bus} rises to V_{bus2} , the corresponding EV charges with $P_{FEVi-MG2}$.

For different FEVs, k_{FEVi} is different which is influenced by their λ_{dis_FEVi} and λ_{char_FEVi} . Therefore, for the different P_{dis_FEVi} and P_{char_FEVi} , equation (19) defines the different k_{FEVi} for the different FEV when $V_{bus} > V_{bus}^*$ and $V_{bus} < V_{bus}^*$. Moreover, equation (19) also defines the droop characteristics $k_{FEV(SoC)}$ of a FEV at different SoC.

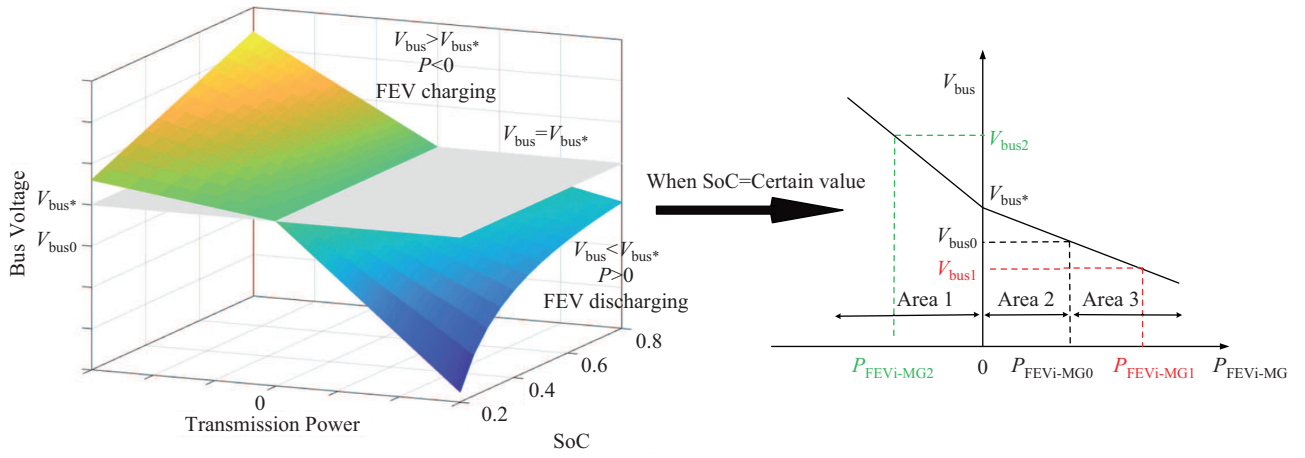


Fig. 9. The bidirectional adaptive droop line of one FEV.

$$\begin{cases}
 \frac{k_{FEVi}}{k_{FEVj}} = \frac{\lambda_{char_FEVi} Q_{FEVi}}{\lambda_{char_FEVj} Q_{FEVj}} & \text{when } V_{bus} > V_{bus*} \\
 \frac{k_{FEVi}}{k_{FEVj}} = \frac{\lambda_{dis_FEVi} Q_{FEVi}}{\lambda_{dis_FEVj} Q_{FEVj}} & \text{when } V_{bus} < V_{bus*} \\
 \frac{k_{FEV} (SoC1)}{k_{FEV} (SoC2)} = \frac{\lambda_{dis_FEV} (SoC1)}{\lambda_{dis_FEV} (SoC2)} & \text{when } V_{bus} < V_{bus*} \\
 \frac{k_{FEV} (SoC1)}{k_{FEV} (SoC2)} = \frac{\lambda_{char_FEV} (SoC1)}{\lambda_{char_FEV} (SoC2)} & \text{when } V_{bus} > V_{bus*}
 \end{cases} \quad (19)$$

IV. SIMULATION

To verify the performance of the proposed V2G-PVBP and bidirectional droop control, a multiport DC-DC SST Simulink has been built.

A. Simulation of V2G-PVBP Under Steady State

For the steady state of V2G-PVBP, this paper considers that the microgrid side voltage is away from the normal voltage, and the number of LEV and FEV is confirmed. In other words, the specific LEVs and FEVs are utilized to regulate the DC bus voltage, and there is no new LEV, or FEV drives in. In this simulation, the rated DC bus voltage is 400 V; there are four FEVs with different λ_{dis_FEVi} and three LEVs. To verify the adaptive bidirectional droop control for V2G-PVBP under different situations, the simulation analyses the performance of V2G-PVBP when DC bus voltage is 395 V, 405 V, and 420 V.

As Fig. 10(a) shows, the initial DC bus voltage is 395 V, and the rated DC bus voltage is 400 V. At first, the DC bus voltage is 395 V; when the V2G-PVBP starts to operate at 0.01 s, the DC bus voltage returns to 399.5 V. Fig. 10(a) shows the DC bus voltage when the V2G-PVBP is applied to regulate the DC bus voltage. Table I shows the transmission power of LEVs and FEVs with different λ_{dis_FEVi} .

In this case, the FEVs operate in discharging mode, and the microgrid absorbs power from the V2G-PVBP. With the proposed bidirectional droop control, the DC bus voltage returns to 399.5 V which is closed to the rated value in about 0.005 s, and the overshoot of DC bus voltage is small. Moreover, the power distribution of each FEV is related to each λ_{dis_FEVi} .

TABLE I
TRANSMISSION POWER OF EVs WITH V2G-PVBP REGULATION WHEN DC BUS VOLTAGE IS 395 V, 405 V, AND 420 V AT FIRST UNDER STEADY STATE

EV	$\frac{k_{FEVi}}{k_{FEV4}}$	Power (395 V)	Power (405 V)	Power (420 V)
LEV ₁	None	1020 W	1050 W	1000 W
LEV ₂	None	1000 W	1040 W	1040 W
LEV ₃	None	1020 W	1020 W	1040 W
FEV ₁	0.55	-692 W	-185 W	485 W
FEV ₂	0.75	-1049 W	-288 W	718 W
FEV ₃	0.90	-1266 W	-353 W	854 W
FEV ₄	1.00	-1412 W	-398 W	943 W

When the DC bus voltage is higher than the normal value, the V2G-PVBP absorbs power from the microgrid to decrease the DC bus voltage back to normal. When the power charged to LEVs can satisfy the DC bus voltage back to normal, the FEVs operate at discharging state, as shown in Fig. 9 area 2. At this moment, the power is transmitted from microgrid and FEVs to LEVs. Fig. 10(b) and Table I show the DC bus voltage and transmission power of each EV when the DC bus voltage is 405 V at first, and the V2G-PVBP operates in area 2. With the proposed adaptive bidirectional droop control, the DC bus voltage returns to 399.7 V, which is closed to the rated value in about 0.005 s, and the overshoot of DC bus voltage is small. Moreover, the power distribution of each FEV is related to each λ_{dis_FEVi} .

When the power charged to LEVs cannot satisfy the DC bus voltage back to normal, the FEVs operate at the charging state, as shown in Fig. 9 area 3. At this moment, the power is transmitted from microgrid to FEVs and LEVs. All EVs need to operate in the charging state to absorb the extra power from the microgrid. When the DC bus voltage is 420 V at first, Fig. 10(c) shows the DC bus voltage when the V2G-PVBP is applied to regulate the DC bus voltage. As Fig. 10(c) shows, the DC bus voltage returns to 400.2 V. Table I shows the amount of transmission power of each FEV. With the proposed adaptive bidirectional droop control, the DC bus voltage returns to 400.2 V, which is closed to the rated value in about 0.005 s, and the overshoot of DC bus voltage is small. Moreover, the power distribution of each FEV is related to the λ_{char_FEVi} of each FEV.

Therefore, under steady state, no matter the DC bus voltage

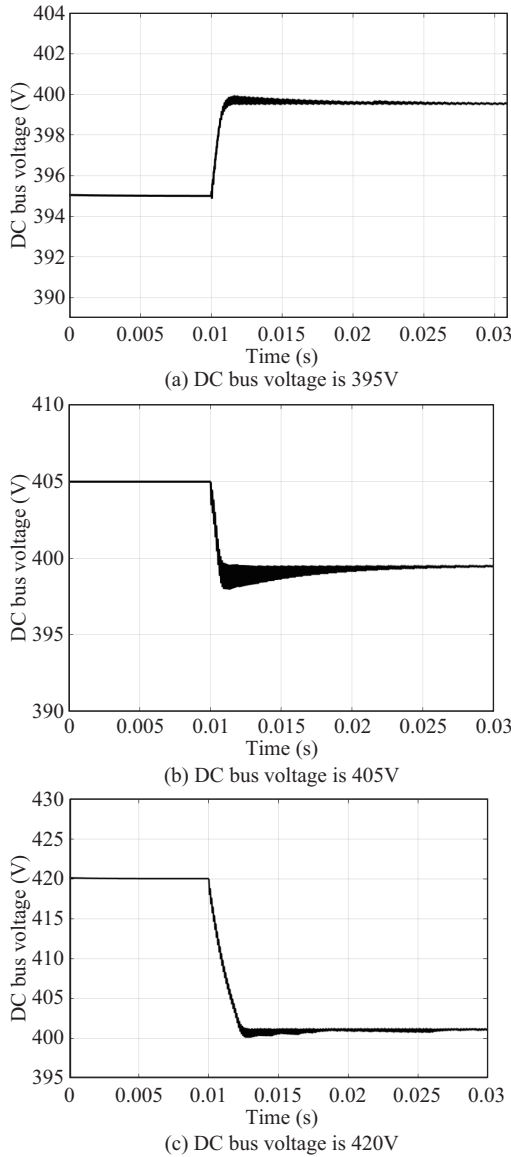


Fig. 10. DC bus voltage of microgrid with V2G-PVBP regulation under steady state when DC bus voltage is (a) 395 V, (b) 405 V and (c) 420 V.

is higher or lower than the rated value, with the proposed adaptive bidirectional droop control, the DC bus voltage of V2G-PVBP is able to go back to normal with small overshoot. Additionally, considering that the transmission power of each FEV is according to λ_{dis_FEVi} and λ_{char_FEVi} , the *SoC* of each EV can be controlled coordinately.

B. Simulation of the V2G-PVBP under Transient State

For the transient state of V2G-PVBP, the number of LEVs and FEVs are not specific. The V2G-PVBP can drive in or drive out new LEVs or FEVs. In this simulation, at first, the DC bus voltage is 395 V, and there are four FEVs and three LEVs parking at the V2G-PVBCS. Then, at 0.3 s, a new LEV drives into the V2G-PVBP. At 0.4 s, a new FEV drives into the V2G-PVBP. Finally, at 0.5 s, a LEV drives out of the V2G-PVBP.

Figure 11(a) shows the DC bus voltage of the V2G-PVBP. At first, the DC bus voltage is 395 V; because of the regulation

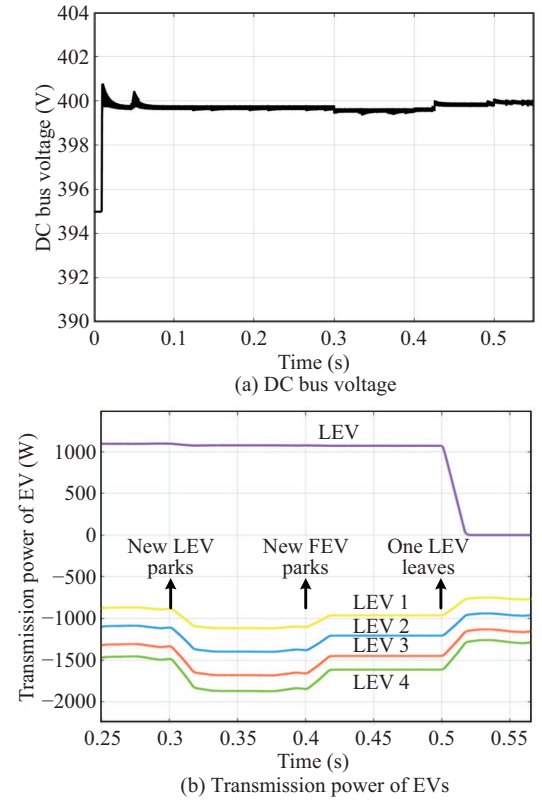


Fig. 11. DC bus voltage and transmission power of FEV with V2G-PVBP regulation under transient state when DC bus voltage is 395 V.

of four FEVs, the DC bus voltage returns to 399.5 V. Then a LEV drives in, a FEV drives in, and a LEV drives out, which causes a small disturbance to the voltage of the microgrid. However, the DC bus voltage still maintains at about 400 V.

Figure 11(b) shows the transmission power of FEVs and LEVs. At first, there are four FEVs and three LEVs. The four FEVs keep discharging. When a new LEV drives in at 0.3 s, each FEV provides more power, and LEVs keep constant charging. When a new FEV drives in at 0.4 s, each FEV provides less power, and LEVs keep constant charging. When a LEV drives out at 0.5 s, each FEV provides less power, and LEVs keep constant charging.

Therefore, under the adaptive bidirectional droop control for V2G-PVBP, no matter the new LEVs or FEVs drive in or drive out, the DC bus voltage can be maintained at normal value (when the available power of the V2G-PVBP can satisfy the demand of microgrid).

C. Comparison of Power Fluctuation in Microgrid Between V2G-PVBP and Traditional Parking lot

For traditional parking lot with charging function, the charging power of the parking lot directly influences the corresponding microgrid. Therefore, the power transmission between the parking lot and microgrid changes frequently along with the driving in or out of EV. In other words, the power fluctuation between the parking lot and microgrid is huge, which has a negative influence on the microgrid. Meanwhile, for V2G-PVBP, considering that the adaptive bidirectional control manages the charging behavior of the EV, when $V_{bus} < V_{bus0}$, BESS, and FEVs can partly provide the

power charged to the LEVs. Therefore, the power fluctuation in microgrid caused by the driving in or out of EV can be relieved by BESS and FEVs. Moreover, if the power provided by V2G-PVBP can satisfy the demand of the microgrid, the transmission power between microgrid and V2G-PVBP can keep a constant value to support the microgrid.

Figure 12 shows the comparison of power fluctuation in microgrid between V2G-PVBP and traditional parking lot. The DC bus voltage is 405 V, and the rated value of DC bus is 400 V. Three EVs drive in the parking lot at 0.1 s, 0.2 s, 0.3 s, respectively. At 0.4 s, an EV drives out. As shown in Fig. 12, for the traditional parking lot, the transmission power between the parking lot and microgrid changes with the driving in or out of the EV. And the power fluctuation caused by EVs in the traditional parking lot has a negative influence on the microgrid. Meanwhile, for V2G-PVBP, thanks to the contribution of BESS and FEVs, the fluctuation power is small. Moreover, the transmission power is utilized to support the microgrid.

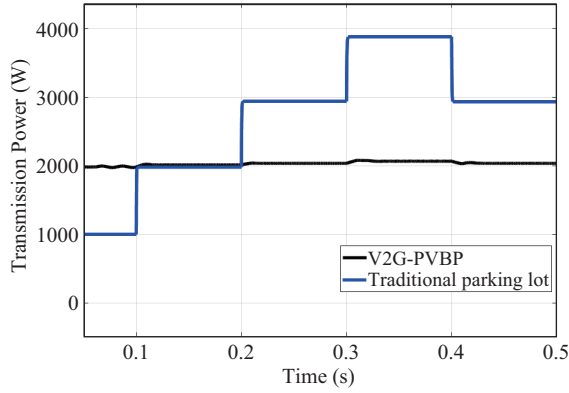


Fig. 12. The comparison of power fluctuation in microgrid between V2G-PVBP and traditional parking lot.

Therefore, compared with the traditional parking lot, the fluctuation power in the microgrid of V2G-PVBP is small.

V. EXPERIMENT

To verify the performance of the proposed DC-DC SST based V2G-PVBP and bidirectional droop control, a low-power four-port experimental prototype (see Fig. 13) has also been built based on DC-DC SST. Table II shows the electrical parameter of the V2G-PVBP experimental prototype. In the experiment, the high frequency transformer works at 20 kHz. For DC-DC SST, there are two ports for FEVs (H-bridge3, H-bridge4), one port for LEV (H-bridge2) and one port for microgrid (H-bridge1). Moreover, we utilize the lithium battery to imitate the charging or discharging process of the three different EVs. And the rated value of the DC bus voltage is 50 V.

As shown in Fig. 14(a), at first, the DC bus voltage is 45 V which is lower than the rated value. After a while, the V2G-PVBP is enabled and starts to operate. The LEV starts to operate at constant power charging and two FEVs start to discharge according to the bidirectional droop control. After about 200 ms, with the help of the proposed bidirectional

TABLE II
ELECTRICAL PARAMETER OF THE V2G-PVBP EXPERIMENTAL PROTOTYPE WITH TWO FEVs AND ONE LEV

Parameters	Value
Transformer voltage ratio	$n = 1$
Switching frequency	$f = 20 \text{ kHz}$
Inductor of grid-side	$L_G = 213 \mu\text{H}$
Inductor of LEV_1 -side	$L_{LEV1} = 225 \mu\text{H}$
Inductor of LEV_2 -side	$L_{LEV2} = 197 \mu\text{H}$
Inductor of FEV -side	$L_{FEV} = 217 \mu\text{H}$
Grid-side capacitor	$C_G = 890 \mu\text{F}$
Lithium battery	24 V 10400 mAh
IGBT	2MBI75U4A-120

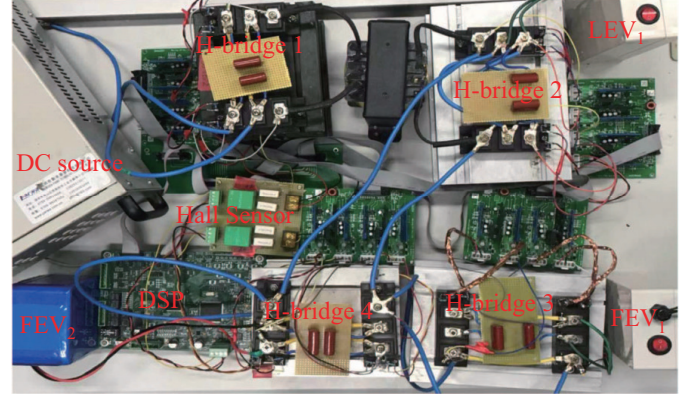


Fig. 13. Experimental DC-DC SST for V2G-PVBP.

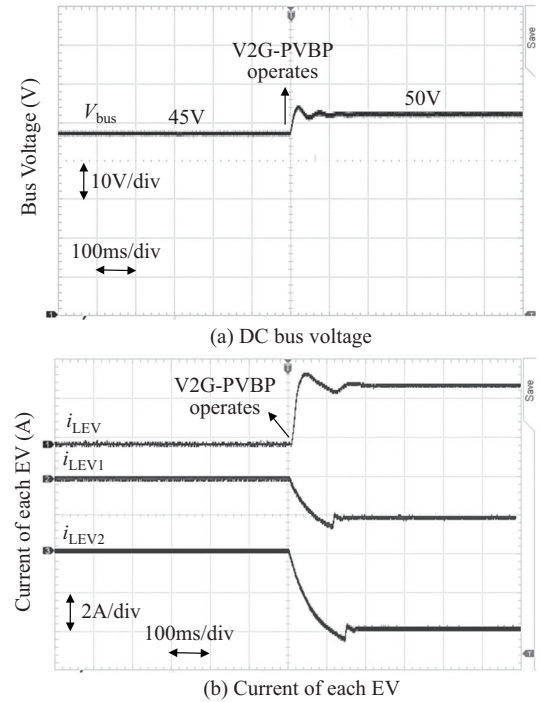


Fig. 14. DC bus voltage and current of each EV of V2G-PVBP when DC bus voltage is lower than the rated value.

droop control, the DC bus voltage is back to 50 V which is close to the rated value. Fig. 14(b) shows the current of LEV i_{LEV} , the current of FEV_1 i_{FEV1} and the current of FEV_2 i_{FEV2} . It can be observed that after V2G-PVBP operates, the LEV absorbs about 60 W from the microgrid. According to the bidirectional droop control, the FEV_1 and FEV_2 provide

about 50 W and 100 W to the microgrid respectively. At this moment, the power is transmitted from the FEVs to LEV and microgrid. Therefore, there is about 90 W power which transmits from the V2G-PVBP to the microgrid to maintain the rated value of the DC bus voltage.

VI. CONCLUSION

This paper proposes a topology of multiport DC-DC solid state transformer based electric vehicles parking lot with vehicle-to-grid service. With the topology of V2G-PVBP, the parking lot can realize bidirectional power flow among microgrid, EVs, and assisted BESS. In V2G-PVBP, to control the V2G-PVBP, this paper defines the LEV, which keeps in charging state and the FEV, which take parts in the microgrid voltage regulation. For FEV, this paper proposes an adaptive bidirectional droop control for FEVs. The bidirectional droop control entirely takes the leaving time, SoC, and capacity of each FEV into account when the EVs take part in the voltage regulation. Thanks to the topology of V2G-PVBP and the proposed adaptive bidirectional droop control, not only the DC bus voltage of V2G-PVBP can be regulated appropriately, but also the EVs can be charged to the SoC as the EVs' owner required. Finally, simulation and experiment verify the feasibility of the proposed V2G-PVBP and the adaptive bidirectional droop control.

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