Bidirectional Battery Charger for Electric Vehicle

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***Abstract*— Increase in electric vehicle mobility has encouraged the growth of vehicle to grid technology. Vehicle to grid technology allows bidirectional power flow between the battery of electric vehicle and the power grid. This allows peak load shaving, load leveling, voltage regulation and improvements of power system stability. Implementation of the vehicle to grid technology requires dedicated electric vehicle battery charger, which allows bidirectional power flow between power grid and electric vehicle battery. In this paper, a new control strategy for bidirectional battery charger is proposed. The proposed control strategy can charge and discharge an electric vehicle battery in both slow and fast mode. The performance of the bidirectional controller is verified by simulation in PSCAD/EMTDC software under different operating modes, which include fast charging, fast discharging, slow charging and slow discharging. The results show that the proposed control strategy performs well in all four modes.**

***Index Terms*—AC-DC power converter, bidirectional power flow, DC-DC power converters, electric vehicles.**

I. INTRODUCTION

Electric vehicle (EV) has become more competitive compared to the conventional internal combustion engine vehicle due to lower carbon dioxide emissions and rising fossil fuel price [1]. However, EV is not widely adopted into the market due to some limitations, such as high vehicle cost, limited charging infrastructure and limited all-electric drive range [2]. In addition, the integration of EV on the power grid will lead to many challenging issues. For instance, large penetration level of EV charging will increase the power grid loading.

Instead of being an additional electrical load, EV battery can be utilized as an energy storage. This potential has led to the new vehicle to grid (V2G) concept. Apart from charging EV battery, V2G allows interaction between the EV owners and the power utility to enable power injection into the power grid according to the predefined schedule and power rates. Interaction of EV and power grid can introduce various benefits to both the power utility and EV owners. From the perspective of power utility, V2G concept can achieve load leveling, peak load shaving, reactive power support, active power regulation, stability improvement and harmonic filtering [3]-[5]. On the other hand, EV owners can earn extra revenues by selling power to the grid.

Presently, the available EV battery chargers in the market are solely for charging operation. The conventional EV battery charger has unidirectional characteristic, which allows either slow charging or fast charging. The implementation of V2G technology requires dedicated EV charger that allows bidirectional power flow between power grid and EV battery [6], [7]. In this paper, a bidirectional EV battery charger with new control strategy is proposed. The proposed control strategy allows four modes, which are fast charge mode, fast discharge mode, slow charge mode and slow discharge mode.

In section II, V2G concept and its advantages will be discussed. Section III presents the modeling of EV battery. The control strategy for bidirectional battery charger is described in section IV. Section V discuss the simulation results. Section VI concludes and summarizes the key points of the paper.

II. VEHICLE TO GRID

V2G technology has drawn interest from the government, power utilites and EV owners due to its benefits. Proper planning and full participation of all parties are crucial to realize the implementation of V2G concept. A study in [8] shows that the current driving behaviour of EV drivers favors the implementation of V2G concept. According to the vehicle travel trend in [8], the average time for a personal vehicle travels on the road is less than 10 percent of a day. Apart from travelling, these vehicles will be parked in garages or parking lots. Therefore, these EVs can be connected to power grid and utilized for V2G implementation.

The framework of V2G concept involves several important elements, such as energy resources, power utility, system operator, aggregator, bidirectional battery charging facilities, communication facilities, intelligent metering and battery management [2]. Fig. 1 depicts the V2G elements. The communication between the individual EV and the power grid operator allows the information and command to be transferred.

For V2G concept, power flow can be unidirectional or bidirectional according to the requirement of power utility.

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Unidirectional V2G refers to the single directional power flow from the power grid to the EV [7]. Unidirectional V2G needs the participation of grid operators to control and limit the charging time, location and power flow during EV charging event [9]. A new electricity policy with different energy rates can be introduced to encourage the off-peak charging and to avoid the on-peak charging. Implementation of this policy requires less investment cost. Moreover, unidirectional V2G will not introduce extra stress on the battery and can prolong the battery lifespan. The unidirectional V2G also has simple operation, low investment cost and highly available as conventional battery chargers can be adopted for the application of this technology.

On the contrary, bidirectional V2G offers more technical and financial benefits [9]. A bidirectional V2G charger has the similar benefits as unidirectional V2G charger, as well as can achieve load leveling, peak load shaving, reactive power support, active power regulation and harmonic filtering [3]-[5]. Furthermore, a bidirectional V2G concept can provide more system flexibility to power utility and offer significant financial benefits to EV owner.

Bidirectional V2G technology brings flexibility to control and manage the operation of power system. However, there are some impediments and challenges during the transition of V2G implementation. One of the barriers is the battery degradation issue [9], [10]. V2G operation requires frequent charging and discharging the EV battery but the rechargeable EV battery has limited charge and discharge lifecycle. Apart from that, other impediments of V2G implementation are the need for intensive communication between power grid and EV, power system reinforcement, high investment of V2G facilities and social obstacles [2]. These barriers can be resolved by well-planned V2G strategy, infrastructure and standards.

III. BATTERY MODELING

From the perspective of power grid, an EV is viewed as a load during charging and as a source during discharging. In this study, EV is represented by the battery and charger components. The battery modeling is discussed in this section. The modeling of the proposed bidirectional EV battery charger and its control strategy will be presented in the next section.

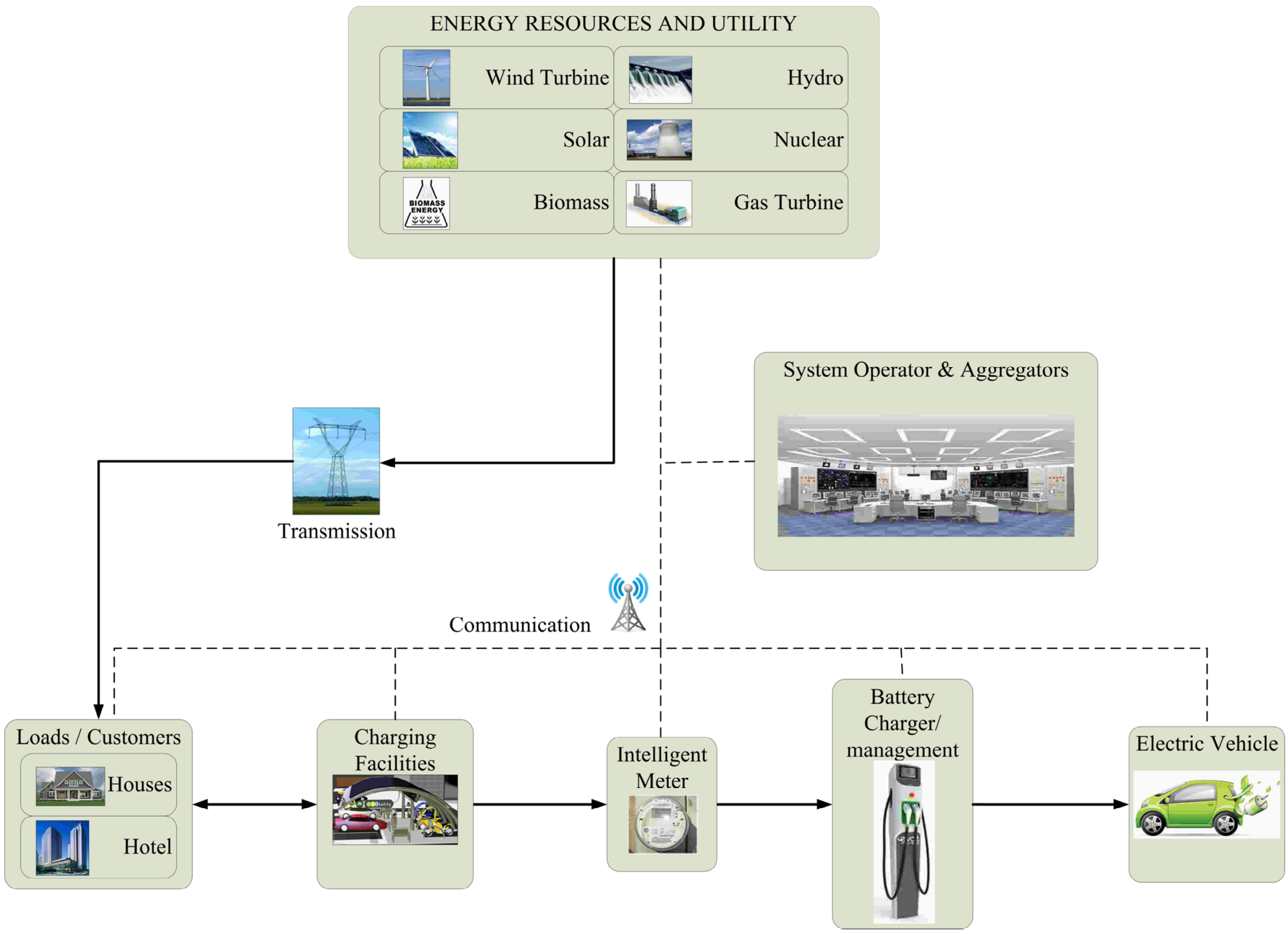

Figure 1. Elements of V2G [7]

An appropriate battery model is necessary to accurately represent the characteristics of an EV battery. There are three methods to model a battery, which are experimental-based model, electrochemical-based model and electric circuit-based model. For this paper, electric circuit-based model is chosen for its capability to represent the electric characteristic of a battery. The battery model is represented by a controlled voltage source in series with an internal resistance as shown in Fig. 2. The controlled voltage source is described by an equation developed by Shepherd [11]. This equation describes the electrochemical behavior of a battery in terms of state of charge (SOC), terminal voltage, open circuit voltage, internal resistance and discharge current [11]. One of the available EV batteries in the market is laminated lithium ion type, which has high energy density and power density. In this paper, an available laminated lithium ion battery is chosen for the study. The equation of lithium ion battery is given by [11], as follows:

$$V_{batt} = E_0 - R.i - K\frac{Q}{it-0.1Q}i* - K\frac{Q}{Q-it}it + A\exp(-B.it) \quad (1)$$

where V_{batt} is the battery voltage (V), E_0 is the battery constant voltage (V), R is the internal resistance (Ω), i is the battery current (A), K is the polarization constant (Ω), it is the actual battery charge (Ah), Q is the battery capacitor (Ah), $i*$ is the filtered current, A is the exponential zone amplitude (V) and finally B is the exponential zone time constant inverse $(\text{Ah})^{-1}$.

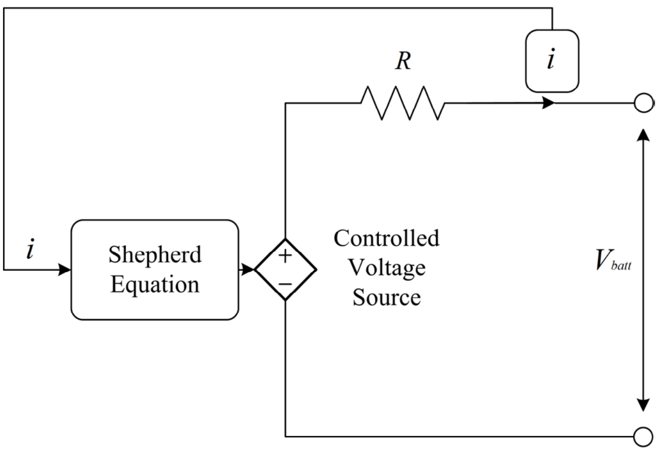

Figure 2. Electrical battery model [12]

Equation (1) can be used by obtaining a few parameters from the battery discharge curve. These parameters are the fully charge battery voltage (V_{full}), the capacity and voltage at the end of the exponential zone ($Q_{\exp}, V_{\exp}$), and the capacity and voltage at the end of the nominal zone (Q_{nom}, V_{nom}). A typical battery discharge curve is shown in Fig. 3.

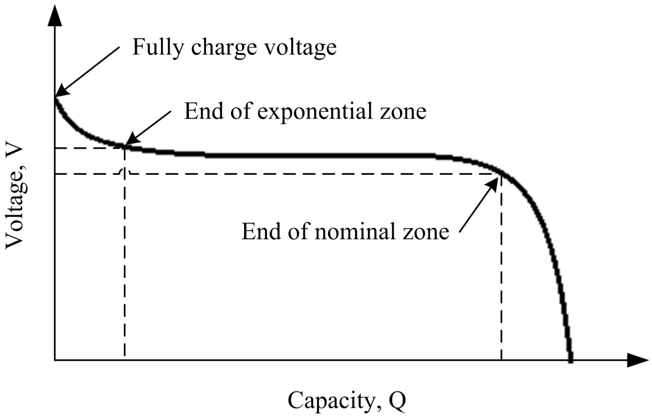

Figure 3. Typical battery discharge curve [11]

From the data of the discharging curve, the parameters of equation such as A, B, E_0 and K can be determined by (2)-(5) [11], [12].

$$A = V_{full} - V_{\exp} \quad (2)$$

$$B = \frac{3}{Q_{\exp}} \quad (3)$$

$$E_0 = V_{full} - A + R.i \quad (4)$$

$$\begin{aligned} K = &\left[E_0 - V_{nom} - R.i + A\exp\left(-3.Q_{nom}/Q_{\exp}\right)\right] \\ &\times\left[\left(Q - Q_{nom}\right)/Q\left(Q_{nom} + i\right)\right] \end{aligned} \quad (5)$$

In this paper, the chosen EV lithium ion battery model has a capacity of 50 Ah and 330 V battery nominal voltage [13]. TABLE 1 shows the values extracted from the chosen battery discharge curve.

TABLE 1. Values extracted from discharge curve

Parameters	Lithium Ion Battery 330V, 50Ah
V_{full}	380 V
Q_{exp}	4.5 Ah
V_{exp}	360 V
Q_{nom}	53.5 Ah
Q_{nom}	330 V

The electrical battery model is able to calculate the SOC of the battery by using (6) [11].

$$SOC = 100\left(1 - \frac{it}{Q}\right) \quad (6)$$

IV. Bidirectional Charger Modelling

A. Charger

A battery charger can be installed on-board or off-board of the vehicle. On-board chargers are usually smaller in size and is suitable for slow charging. On the other hand, off-board charger has larger size and is installed at fixed location. In this paper, the proposed EV battery charger is designed as a bidirectional V2G charger, which allows slow charging, fast charging, slow discharging and fast discharging.

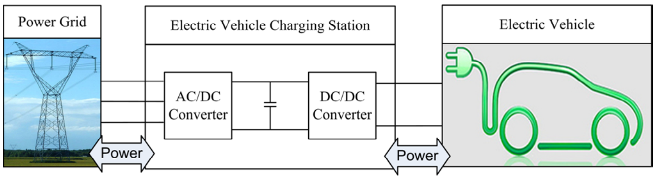

Figure 4. Vehicle to grid power flow diagram

The key components for an EV bidirectional battery charger are AC/DC converter and DC/DC converter as shown in Fig. 4. During EV charging mode, an AC/DC bidirectional converter rectifies the AC power to DC power. Meanwhile, the AC/DC bidirectional converter inverts the DC power of the EV battery to AC power and inject to power grid during EV discharging mode. On the other hand, the DC/DC converter is responsible to control the bidirectional power flow by using direct current control technique. It acts as a buck or boost converter during charging or discharging mode, respectively [4].

The complete V2G bidirectional battery charger is modeled by using PSCAD/EMTDC software. The power converters of the proposed bidirectional battery charger used for the simulation is shown in Fig. 5.

B. Control Strategy

The direction of power flow can be represented by the direction of the current. In this paper, the direct current control technique is used to control the bidirectional power flow for V2G implementation. With reference to Fig. 5, this control strategy is applied to the DC/DC converter where it acts as a buck converter when IGBT1 is triggerred and as a boost converter when IGBT2 is triggerred.

Fig. 6. shows the control strategy of the DC/DC converter. DC/DC converter's controller can be categorized into two control parts, which are the charging control and discharging control. Initially, this controller compares the reference battery current with the measured battery current to decide between the charging or discharging mode. This is an important procedure to decide the next step of the controller. For charging mode, the error between the measured battery current and reference battery current is computed. This error passes through the PI controller for tuning. The output of the PI controller will be used to generate pulses by using sinusoidal pulse width modulation (SPWM) technique. The pulses generated in this stage is used to trigger IGBT1. Throughout the charging process, IGBT2 is turned OFF. For discharging mode, controller computes the error between the reference battery current and measured battery current. Then, the PI controller will perform the tuning of the calculated error. The output is sent to SPWM to generate the necessary pulses for IGBT2. During the discharging mode, IGBT2 is turned OFF.

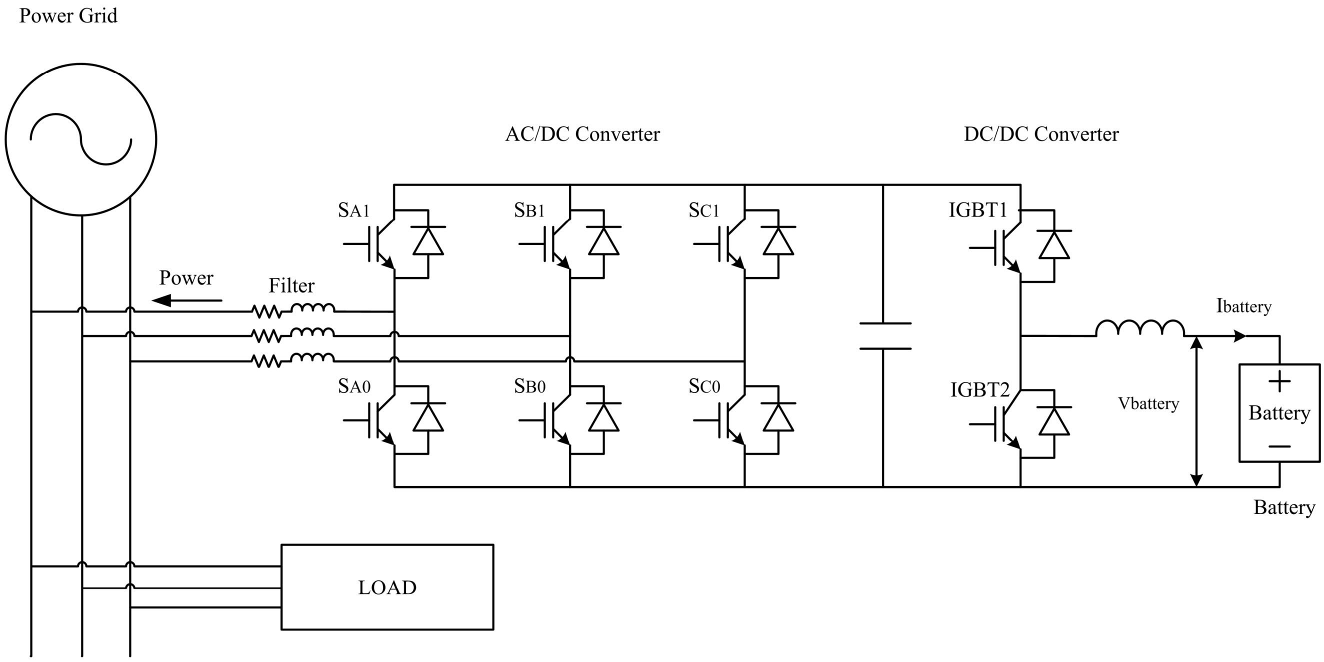

Figure 5. Electric diagram of bidirectional battery charger

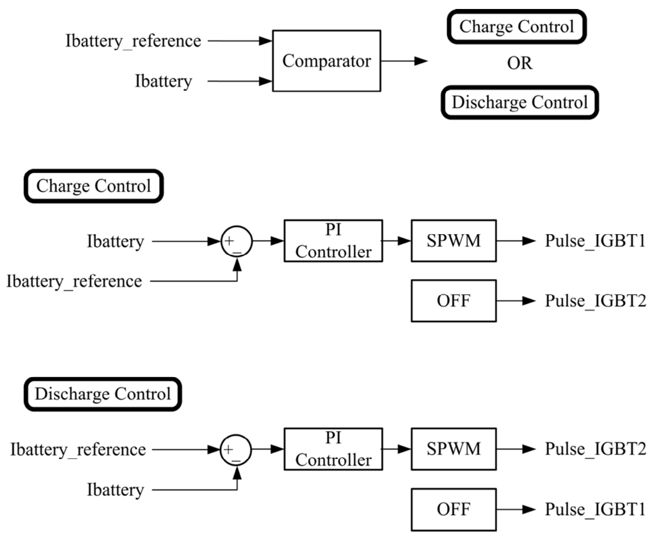

Figure 6. Control block diagram of DC/DC converter

V. Results and Discussion

Simulation is conducted to test the performance of the proposed bidirectional controller under different operating modes, such are fast charging, fast discharging, slow charging and slow discharging. The battery initial SOC is set to 50 percent. This value is chosen to ensure that the battery is able to receive or supply power when necessary. Simulation results are categorized into five regions and shown in Fig. 7.

Initially, the simulation requires some times to start up and stabilize. This procedure takes around 1 minute and is depicted in the first region. During this period, no power flows between the power grid and EV battery. Therefore, the state of charge (SOC) of the battery remains constant. In the second region, the system is instructed to fast charge the battery with 100 A current. Battery absorbs approximately 33 kW of power from the power grid. The battery SOC increased by 0.5 percent in 5 minutes. The third region presents the results of fast discharging process with discharging current of 100 A. The power grid receives around 33 kW of power from the battery and the battery SOC decreases by 0.5 percent.

The forth and fifth regions shows the results of slow charging mode and slow discharging mode. For slow charging, the charging current is set to be 10 A. Power drawn from the grid to charge the EV battery has decreased to around 3.3 kW. This contributes to a slight increment of 0.05 percent to the battery SOC. The final region presents the slow discharging mode of battery with 10 A current. Grid absorbs approximately 3.3 kW of power from the EV battery and the battery SOC is decreased by 0.5 percent. Simulation results show that higher charging and discharging current will have higher rate of change in battery SOC.

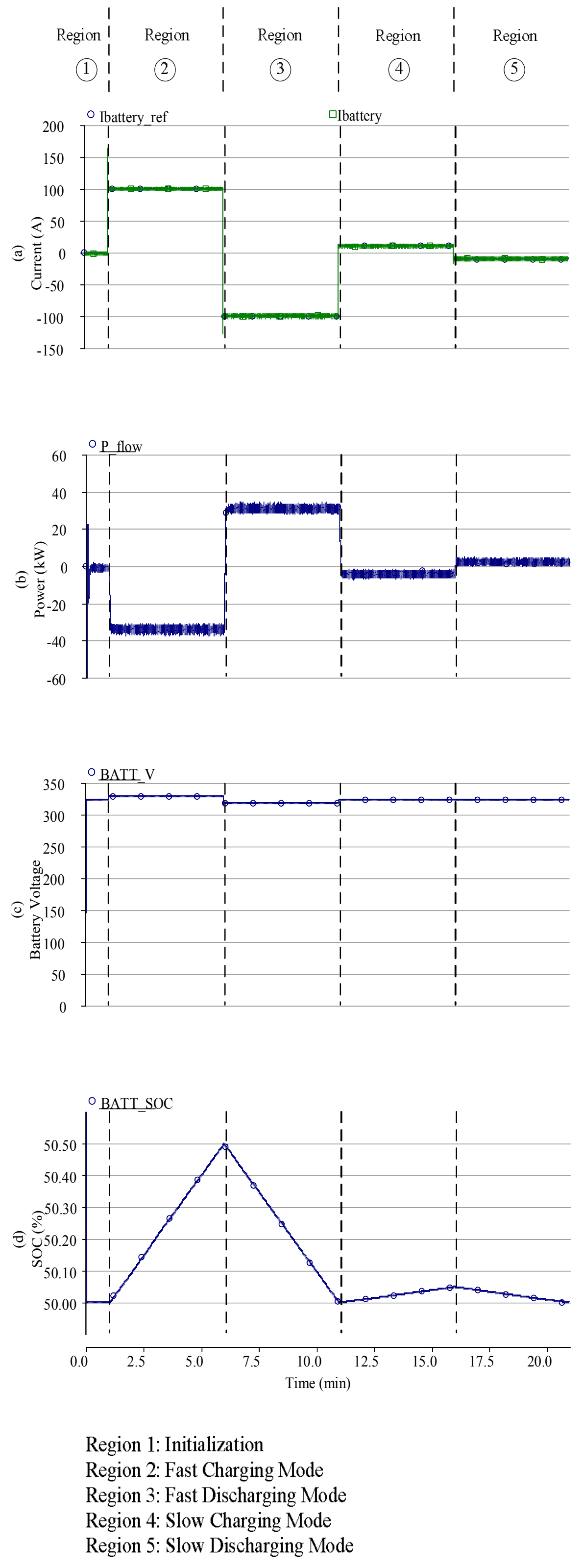

Figure 7. Simulation results. (a) battery current (b) power flow (c) battery voltage (d) battery SOC

With reference to the simulation results, the measured battery current is able to follow the reference battery current throughout the simulation process. This shows that the direct current control for the bidirectional battery charger has successfully controlled the direction and magnitude of current flow. In addition, the control strategy for the bidirectional battery charger is able to achieve high efficiency (more than 97 percent) for all operating modes. The calculated efficiency for all operating modes are shown in TABLE 2.

TABLE 2. Bidirectional battery charger efficiency

Operating Mode	Charging			Discharging		
	Pin (kW)	Pout (kW)	Efficiency (%)	Pin (kW)	Pout (kW)	Efficiency (%)
Slow mode	3.30	3.25	98.48	3.20	3.15	98.43
Fast mode	33.50	32.50	97.01	31.50	30.80	97.77

VI. CONCLUSION

This paper presents the bidirectional EV battery charger with direct current control strategy for V2G operation. The proposed bidirectional battery charger is capable of performing fast charging, fast discharging, slow charging and slow discharging. The results show that the proposed control strategy performs well and achieve high efficiency in all four operating modes. In addition, the simulated results prove that the charging or discharging current has direct proportional relationship with the rate of change in battery SOC. The complete modeling of EV battery and bidirectional charger in PSCAD/EMTDC software are also highlighted.

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