Experimental Verification of Vehicle-to-Grid Charger for Demand Response Service

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***Abstract*— This paper introduces a Vehicle-to-Grid charger and a Vehicle-to-Grid energy management algorithm for the power grid demand response application. The Vehicle-to-Grid charger is designed to allow bidirectional power flow according to power demand. This charger is capable of adjusting the amount of power absorbed from and supplied to the grid, while prioritizing the battery health and safety. Moreover, the proposed charger is utilized in the Vehicle-to-Grid energy management algorithm to integrate electric vehicles to achieve demand response objectives. The Vehicle-to-Grid energy management algorithm controls the power flow of each grid-connected electric vehicle to achieve peak load shaving and load leveling services, while ensuring the electric vehicle users' benefits by preventing over charging, over discharging and over battery depletion. A laboratory experiment was conducted to examine the feasibility of the Vehicle-to-Grid system. The experimental results showed that the Vehicle-to-Grid charger has accurately followed the dual directional power demand instructed by the energy management algorithm to realize the demand response services.**

Keywords*— *Battery chargers, design for experiments, electric vehicles, energy management, vehicle-to-grid.

I. Introduction

Global Greenhouse Gas (GHG) emissions rate has been increasing at a steady pace since year 1970. The latest emissions gap report showed that the top GHG emitters that contributed up to 56 percent of total global GHG emissions were China, USA, Europe and India [1]. In regard to this concern, The Paris Agreement was implemented to bring all nations together with a common goal to combat the global warming issue. In general, The Paris Agreement aims to keep the raising of global warming below 2°C by the year 2100 [2]. This agreement enhances the financial and technology supports from developed countries to developing countries in preventing further GHG emissions. Until today, up to 195 countries across nations are committed to this agreement and agree to reduce 70 to 80 percent of GHG emissions by the year 2050 [2].

Malaysia as a member of the Paris Agreement is also committed to transform the country into a low-carbon society. This goal is reflected in one of the latest Malaysian agenda, Green Technology Master Plan, which is supported by the Ministry of Energy, Science, Technology, Environment & Climate Change [3]. In the transportation context, the government is urging the replacement of Internal Combustion Engine (ICE) vehicle with Energy Efficient Vehicle (EEV), which includes Electric Vehicle (EV). The Green Technology Master Plan aims to hit 100% of EEV on-road by the year 2030. Hence, the Malaysian government is paying much attentions into stimulating the adoption of EV in the country. Different from the traditional ICE vehicle, EV propels using electricity which requires recharging from the power grid. Massive adoption of EVs will lead to a significant increase of power grid demand. This can potentially expose the power system with risks, such as harmonics, voltage drop and overloading issues [4]-[10].

Although large EV charging demands can possibly harm the power system, grid-connected EV can be a supportive element to the system when it is treated as a massive energy storage. The inclusion of EVs will introduce great flexibility to the power system to achieve higher system reliability and sustainability. This new concept is called the Vehicle-to-Grid (V2G) technology [14]. If utilized properly, these mobile energy storages can greatly help the power grid in achieving spinning reserve service, peak load shaving, system backup and grid voltage regulation [11]-[13]. Nevertheless, the amount, location and condition of these grid-connected EVs are dynamic and indeterminate, which will create many uncertainties to the power grid [15]. Thus, proper system planning, intelligent control strategy and reliable design of V2G technology and infrastructure are essential to ensure the safety and practicality of the V2G technology to be deployed.

Hence, this paper focuses on the development of V2G technology by proposing a design of V2G charger and V2G energy management algorithm. The performance of the proposed V2G charger and control algorithm are examined using laboratory prototype. The contributions of this paper can be highlighted in several points, which are: i) to design a charger with bidirectional power transfer capability for flexible V2G application, ii) to design V2G energy management algorithm for power grid peak load shaving and load leveling services, and iii) to validate the proposed V2G charger and energy management algorithm using laboratory prototype.

II. Enabling Technology for V2G Application

Implementation of V2G technology requires a well-planned power grid framework. Various power grid and EV factors shall be taken into consideration to succeed this technology, which include the power grid demand, EV mobility, location of EV charging station, communication system, V2G technology facility and energy management system. Fig. 1 shows a framework of V2G charging station connected to the power grid. In this grid environment, EV is allowed to provide energy sharing with the nearby commercial and residential loads. These activities can be beneficial to the power grid reliability via services such as demand response, spinning reserve and power backup support.

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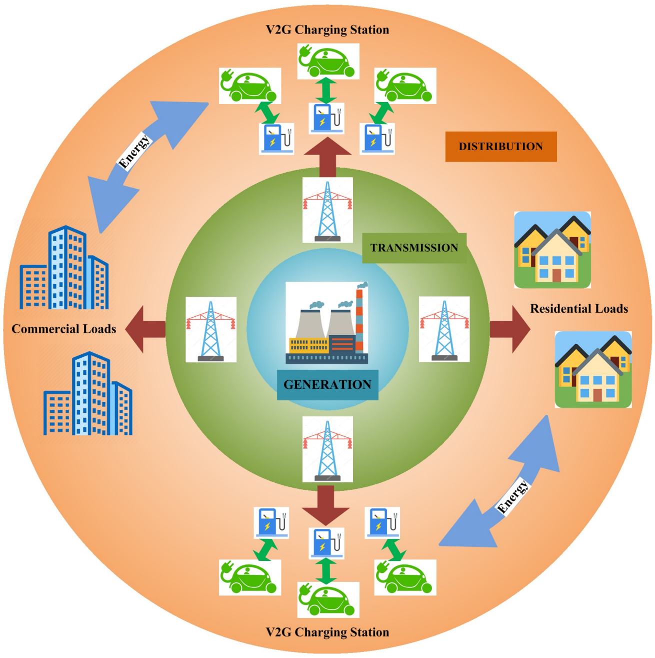

Fig. 1. V2G framework.

The following sub-sections will present the bidirectional charger design and energy management in a V2G charging station. These proposed V2G technologies can provide effective demand response services to the power grid, while ensuring the benefit of EV owners.

A. *V2G Charger Design*

Fig. 2 presents the configuration of the proposed V2G charger, which is designed to have the bidirectional active and reactive power transfer capabilities. This charger contains of a three-phase full bridge AC/DC converter, a DC-link capacitor, and a bidirectional buck-boost DC/DC converter. The V2G charger is connected to the power grid via a passive filter at the front-end while interacting with the EV battery at the back-end. Appropriate controls are developed and employed in both converters of the V2G charger to achieve different purposes.

The control strategy for DC/DC converter mainly manages the active power flow of the charger for EV charging and discharging purposes. For charging control (C-control), active power supplied from the power grid into the V2G charger for EV battery charging. In this research, the charging power can vary flexibly within a range. The V2G charger can conduct charging operation to meet fast charging power. For safe charging operation, the charging voltage should be maintained below the battery maximum voltage. Hence, Constant Current-Constant Voltage (CC-CV) charging technique is adopted. During CC mode, the battery is charged at a constant charging current. Throughout the process, battery voltage will continuously increase as the State of Charge (SOC) raises. To prevent overvoltage charging, the charger will switch to CV mode whenever the battery SOC hits 80 percent. The charging operation beyond this battery SOC level will be regulated at a constant voltage. On the other hand, EV battery discharges energy into the power grid through the V2G charger for active power support. Similarly, the V2G charger supports discharging mode (D-control) with a flexible range of discharging power.

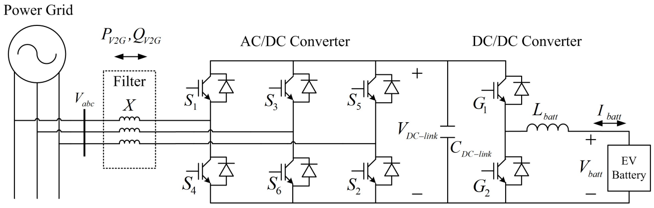

Fig. 2. V2G charger configuration.

Fig. 3 shows the control block diagram of the proposed DC/DC converter's controller for the V2G charger. For both C-control and D-control, the charger firstly takes in the active power measurement between V2G charger and power grid (P_{V2G}) and compares with the active power reference ($P_{V2G,\ ref}$). With positive $P_{V2G,\ ref}$ value, the charger performs C-control; whilst a negative $P_{V2G,\ ref}$ value will initiate D-control. The power difference will pass through a Proportional Integral Derivative (PID) controller to determine an appropriate battery current reference ($I_{batt,\ ref}$) required to satisfy the $P_{V2G,\ ref}$. Afterwards, $I_{batt,\ ref}$ will be compared with the measured battery current (I_{batt}) and channel to another PID controller. This PID controller will decide the duty cycle of the DC/DC converter's switches to perform the battery charging or discharging under CC mode. Nevertheless for C-control, CV mode will take place whenever the battery SOC is more than 80 percent by alleviating battery overvoltage for safety concerns.

Conventional EV charger tends to absorb reactive power during charger operation, which introduces additional losses. Hence, the AC/DC converter's controller is designed to regulate the charger power factor (PF-control) at unity power factor to maintain high charger efficiency. In addition, Vdclink-control is developed for the AC/DC converter to regulate the DC-link voltage ($V_{DC\text{-}link}$) for stable V2G charger operation. Fig. 4 depicts the control block diagram of the AC/DC converter. PF-control and Vdclink-control are conducted simultaneously throughout the charger operation. In PF-control, power factor reference (PF_{ref}) is firstly converted into reactive power reference (Q_{ref}). Subsequently, the error between Q_{ref} and reactive power measurement between V2G charger and power grid (Q_{V2G}) is monitored. The error is then channeled to a PID controller. This PID controller will generate the magnitude of the modulating signal (*mag*). Meanwhile, the Vdclink-control takes in the measured DC-link voltage ($V_{DC\text{-}link}$) and compares with a preset DC-link voltage reference ($V_{DC\text{-}link,\ ref}$). A PID controller will response to the voltage difference and generate a phase shift angle (δ) to regulate the $V_{DC\text{-}link}$. For power grid synchronization purposes, the power grid voltages (V_{abc}) are used by a Phase Lock Loop (PLL) module to determine the power grid angle (θ). The modulating signal angle (α), is obtained by adding the phase shift angle (δ) and the power grid angle (θ). Lastly, the Sinusoidal Pulse Width Modulator (SPWM) converts the modulating signals into pulses for AC/DC converter's switches.

B. *V2G Energy Management Algorithm*

In a V2G charging station, an appropriate energy management is crucial to help managing the EV fleets. This sub-section presents a V2G energy management algorithm that integrates all connected EVs to achieve power grid

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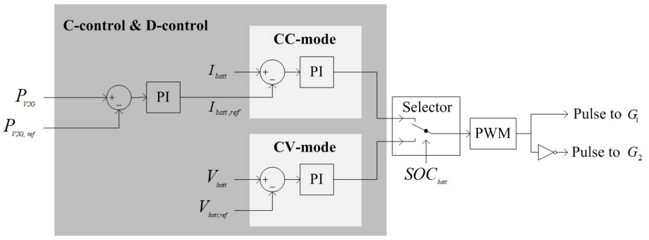

Fig. 3. Control block diagram of the DC/DC converter's controller.

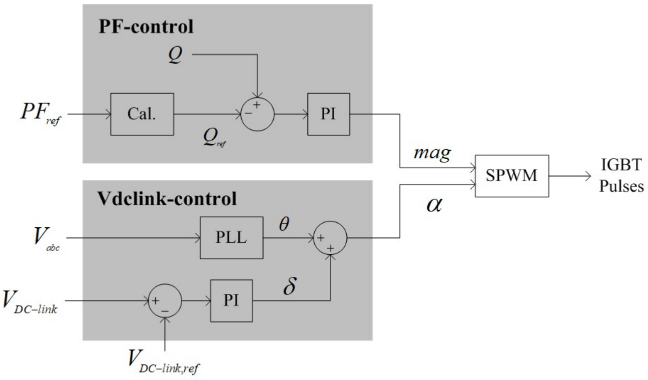

Fig. 4. Control block diagram of the AC/DC converter's controller.

demand response service. The objectives of the V2G energy management used in this paper are to achieve peak load shaving and load leveling services for power grid.

Fig. 5 illustrates the concept of peak load shaving and load leveling services adopted in the V2G energy management algorithm. This figure presents a typical grid power demand profile with the maximum and minimum power targets. As shown in Fig. 5, the period where grid demand is higher than the maximum power target (P_{max}) falls into the peak load shaving region. During this period, EVs are encouraged to be discharged for power grid support. Meanwhile, when the grid demand is lesser than the minimum power target (P_{min}), it is included in the load leveling region. During this period, EVs are encouraged to be charged. In the period where grid demand is within the maximum and minimum power targets, EV charging or discharging event shall be avoided.

To achieve the aforementioned peak load shaving and load leveling services, specific system response is arranged according to several system conditions. The related system conditions include the grid power supply (P_{grid}), the EV availability (A_{EV}) and the EV battery SOC (SOC_{EV}). These system conditions are monitored from time to time for appropriate real time system response. These conditions and related decisions include:

- Power grid consumption is lesser than minimum power target ($P_{grid} < P_{target,\ min}$): This condition is used to understand if the power grid is in load leveling region.
- Power grid consumption is larger than maximum power target ($P_{grid} > P_{target,\ max}$): This condition is used to understand if the power grid is in peak load shaving region.
- EV is connected to the power grid ($A_{EV} = 1$): This condition is to check if the EV is available for V2G service.

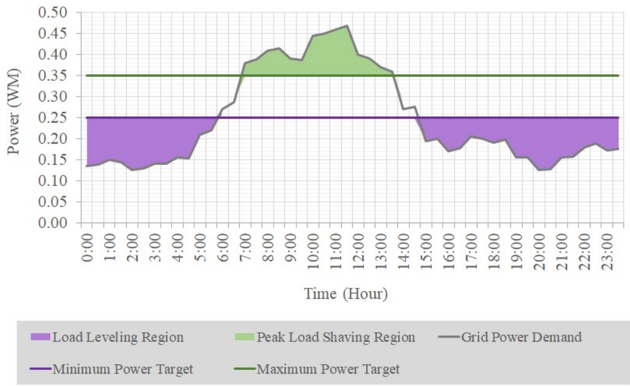

Fig. 5. Concept of peak load shaving and load leveling services.

- SOC of the EV battery is larger than 60 percent ($SOC_{EV} >$ 60 %): If the battery SOC is lesser than 60 percent, any discharging activities shall not be conducted to ensure that the EV has enough power for on-road propulsion purpose. Hence, this condition is to study if the EV is ready for peak load shaving service.
- SOC of the EV battery is larger than 80 percent ($SOC_{EV} >$ 80 %): As discussed in Section II(A), EV shall adopt CV mode during charging operation with battery SOC larger than 80 percent. Hence, this condition is to check if the EV shall be sent into CV charging mode.
- SOC of the EV battery is lesser than 100 percent (SOC_{EV} < 100%): This condition indicates that the battery is not available for load leveling service.

Table I shows the summary of all possible scenarios and their related decisions for the V2G charger operation.

III. Experimental Results and Discussion

An experimental prototype was built to examine the performance of the proposed V2G charger and energy management algorithm. Fig. 6 shows the framework of the V2G system, where V2G charger and a variable load were connected to the power grid at a common bus. The power grid was simplified and represented by a 400 V three-phase supply. Meanwhile, the connected variable load in the system was to represent the power grid varying load and the connected charger was for V2G application. For safety reason, the V2G charger prototype was downscaled to a 2 kVA system with an EV battery with the capacity of 10 Ah and 48 V. In order to comply with the downscaled V2G charger, a Variable Voltage Transformer (variac) was used to step down the voltage level of power grid from 400 V to 40 V.

The V2G charger control and energy management algorithm were implemented using the eZdsp F28335 Digital Signal Processor (DSP). A set of voltage and current sensors were utilized to collect related system measurements and fed to the DSP for real time system process. Appropriate IGBT pulses were sent to the AC/DC converter and DC/DC converter accordingly. Fig. 7 presents the laboratory setup for the experiment.

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TABLE I. SUMMARY OF ALL POSSIBLE SCENARIOS AND DECISIONS FOR $P_{V2G,\ REF}$

	$P_{grid} < P_{target,\ min}$	$P_{grid} > P_{target,\ max}$	$A_{EV} = 1$	$SOC_{EV} >$ 60%	$SOC_{EV} >$ 80%	$SOC_{EV} <$ 100%	Binary code	$P_{V2G,\ ref}$
Load Leveling	1	0	1	1	0	1	101101	P_{min} - P_{grid}
	1	0	0	1	0	1	100101	0
	1	0	1	0	0	1	101001	P_{min} - P_{grid}
	1	0	0	0	0	1	100001	0
	1	0	1	1	1	1	101111	CV charging mode
	1	0	0	1	1	1	100111	0
Peak Load Shaving	0	1	1	1	0	1	011101	P_{max} - P_{grid}
	0	1	0	1	0	1	010101	0
	0	1	1	0	0	1	011001	0
	0	1	0	0	0	1	010001	0
	0	1	1	1	1	1	011111	P_{max} - P_{grid}
	0	1	0	1	1	1	010111	0
Power within $P_{target,\ max}$ and $P_{target,\ min}$	0	0	1	1	0	1	001101	0
	0	0	0	1	0	1	000101	0
	0	0	1	0	0	1	001001	0
	0	0	0	0	0	1	000001	0
	0	0	1	1	1	1	001111	0
	0	0	0	1	1	1	000111	0

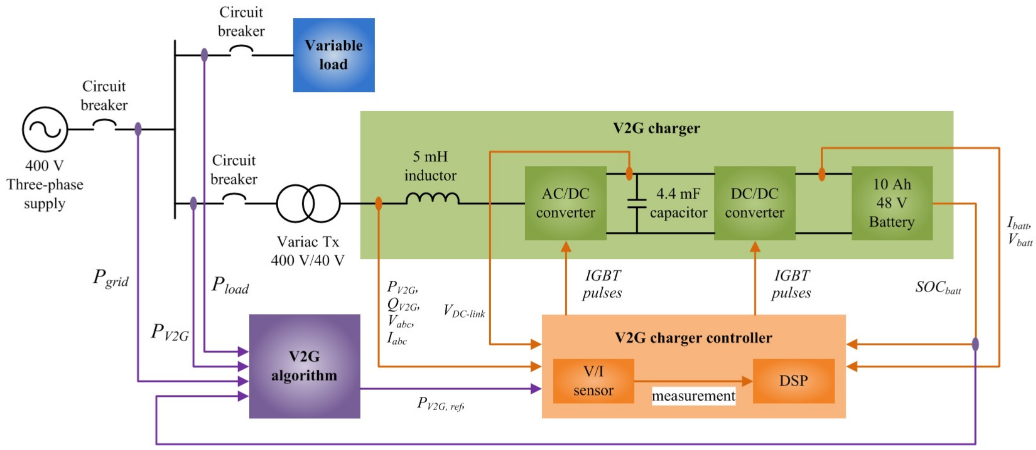

Fig. 6. Framework for the experiment prototype of V2G system.

Three different experiments were conducted to inspect the capability of the proposed V2G charger and energy management algorithm. These scenarios included: (i) Case I: load leveling scenario, (ii) Case II: peak load shaving scenario, and (iii) Case III: no action scenario.

A. *Case I: Load Leveling Scenario*

This case examined the capability of V2G charger and energy management algorithm to perform load leveling service. Fig. 8 presents the results for Case I. Initially, the load power consumption (P_{load}) was 600 W and the V2G charger was not connected to the system. Hence, P_{grid} showed a similar power consumption as P_{load}. At time, $t = 10$ s, V2G charger was connected to the grid. As the $P_{target,\ min}$ was set at 650 W, the V2G energy management algorithm instructed the V2G charger to absorb 50 W of active power. As a result, P_{V2G} was equal to 50 W and P_{grid} was successfully leveled to 650 W. During this period, the I_{batt} was regulated at approximately 1 A as shown in Fig. 8(b). At $t = 30$ s, P_{load} has dropped to 300 W. In order to achieve the $P_{target,\ min}$ of 650 W, the V2G algorithm requested the V2G charger to absorb 350 W of charging power. Nevertheless, the I_{batt} has reached its maximum charging current, which was limited at 2 A. The maximum charging power that a single battery can absorb was approximately 100 W. Hence, Fig. 8(a) shows that the P_{grid} can only be leveled to 400 W. In summary, these results showed that the V2G charger and V2G algorithm was capable of accurately regulating V2G system consumption to achieve load leveling service. In addition, over charging was successfully prevented when power demand exceeded the battery capacity.

B. *Case II: Peak Load Shaving Scenario*

The second case examined the performance of V2G charger and energy management algorithm to conduct peak load shaving service. Fig. 9 shows the results for peak load shaving experiment. The experiment started with P_{load} of 1200 W. Initially, the V2G system was without the connection of V2G charger. Thus, P_{grid} was equal to P_{load}. At $t = 10$ s, V2G charger was connected to the system. As the $P_{target,\ max}$ was set at 1150 W, the V2G energy management algorithm instructed the V2G charger to supply 50 W of

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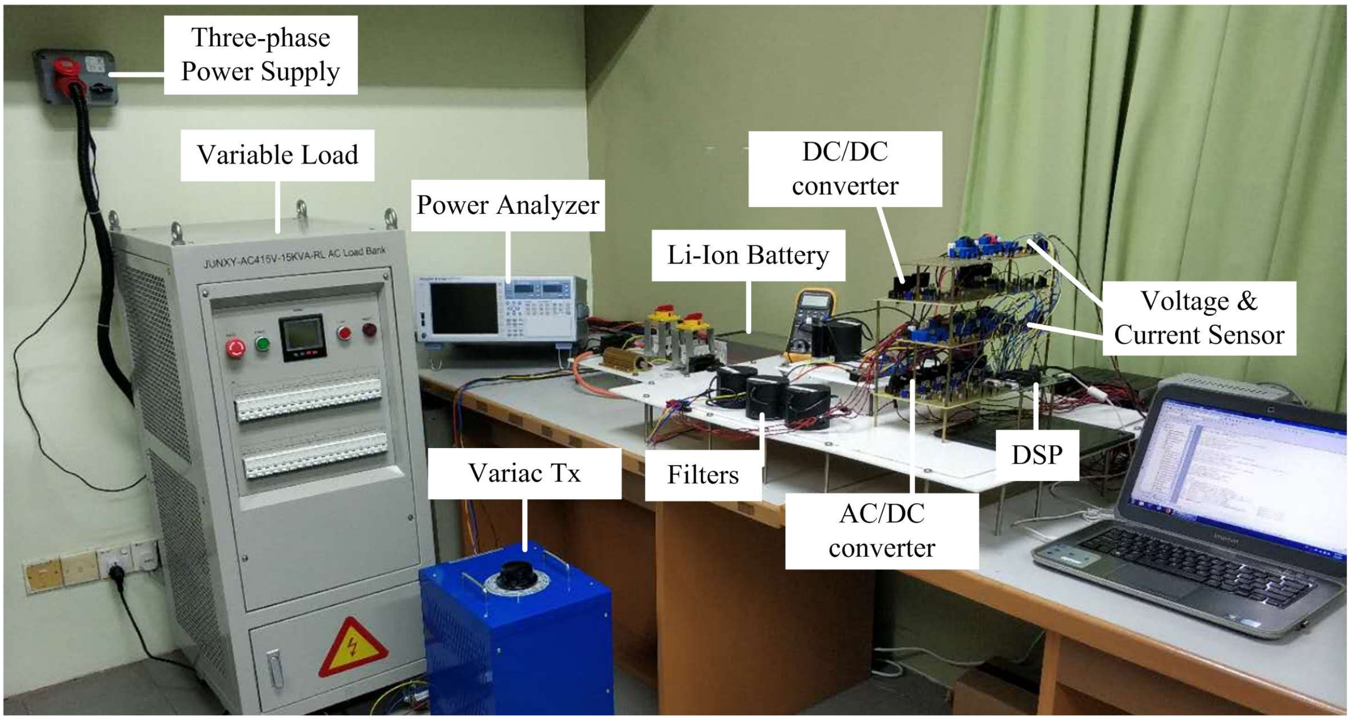

Fig. 7. Experiment setup for V2G system.

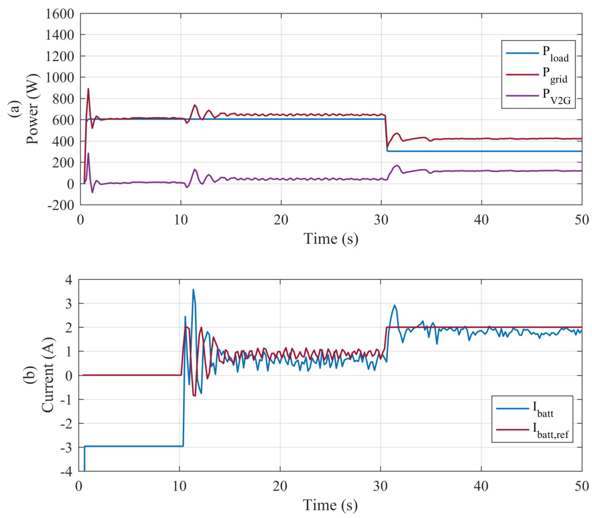

Fig. 8. Experiment results for Case I: (a) grid power supply, load power consumption and V2G charger power, and (b) Battery current and battery current reference.

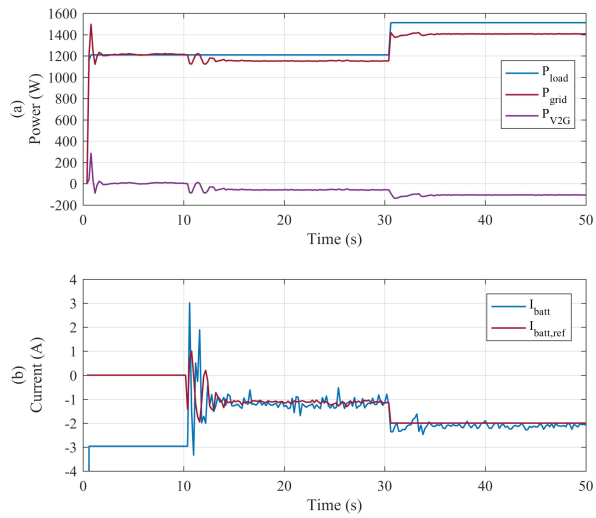

Fig. 9. Experiment results for Case II: (a) grid power supply, load power consumption and V2G charger power, and (b) Battery current and battery current reference.

active power to the power grid. Hence, P_{V2G} was equal to -50 W. The P_{grid} was successfully shaved to 1150 W. This operation required I_{batt} to discharge at roughly 1 A, as shown in Fig. 9(b). At t = 30 s, the load consumption increased to 1500 W. The V2G energy management algorithm had requested higher power support from the V2G charger. However, the battery protection had limited the discharging current at 2 A. Hence, I_{batt} was regulated at -2 A, which in turn supplied an approximately 100 W of active power to the grid. During this period, the P_{grid} was shaved to 1400 W. These results verified the capability of the V2G system to provide accurate active power supply to the power grid for peak load shaving service. Moreover, over discharging was successfully prevented whenever the power demand exceeded the V2G charger capacity.

C. Case III: No Action Scenario

These experiment studied the response of the proposed V2G charger and V2G algorithm under scenario where the P_{grid} was within $P_{target,\ min}$ and $P_{target,\ max}$. Fig. 10 shows the experimental results for Case III. Initially the P_{load} was consuming 800 W of power, which was within the preset $P_{target,\ min}$ and $P_{target,\ max}$ of 650 W and 1150 W, respectively. At t = 10 s, the V2G charger was connected to the system. Since the P_{grid} was within $P_{target,\ min}$ and $P_{target,\ max}$, no action

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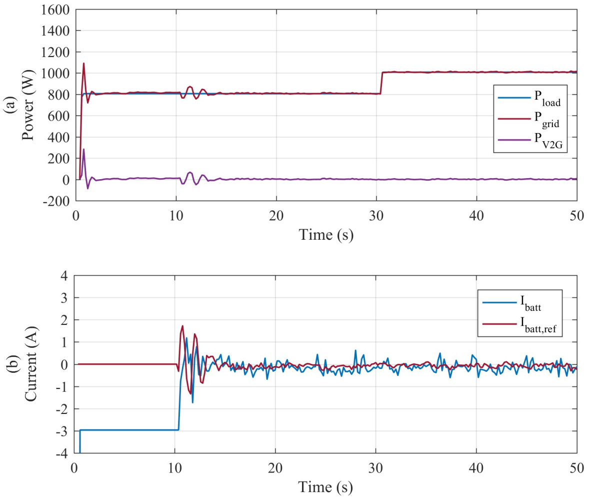

Fig. 10. Experiment results for Case III: (a) grid power supply, load power consumption and V2G charger power, and (b) Battery current and battery current reference.

was instructed by the V2G energy management algorithm. Hence, P_{V2G} was equal to 0 W and I_{batt} was maintained at 0 A. At t = 30 s, P_{load} increased to 1000 W, which was still within $P_{target,\ min}$ and $P_{target,\ max}$. Thus, P_{V2G} and I_{batt} remained unchanged. These results verified the response of V2G system under no action scenario, where P_{V2G} and I_{batt} were successfully maintained at zero value.

IV. Conclusion

This paper introduced a charger and an energy management algorithm for the application of V2G technology. The V2G charger was designed to allow bidirectional power transfer for flexible V2G application. Meanwhile, the proposed V2G energy management algorithm was in charge of managing the power transfer of each EV to meet the peak load shaving and load leveling services in power grid. A laboratory prototype was built to examine the feasibility of the proposed V2G charger and V2G energy management algorithm. Three experiment scenarios were conducted to investigate the performance of the V2G system under different power grid conditions. These scenarios included load leveling scenario, peak load shaving scenario and no action scenario. The experimental results showed that the V2G system were able to provide accurate power flow control to achieve the preset $P_{target,\ min}$ and $P_{target,\ max}$. Nevertheless, when the V2G requirement for peak load shaving and load leveling reached the battery limit, the system was capable of limiting the charging and discharging current to prevent over charging and over discharging. Hence, the proposed V2G charger and energy management algorithm can effectively conducted peak load shaving and load leveling services using the connected EV battery without compromising the battery safety.

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