A Bi-directional Battery Charger for Electric Vehicles Using Photovoltaic PCS Systems

Gyu-Yeong Choe, Jong-Soo Kim*, Byoung-Kuk Lee*, Chung-Yuen Won*, Tea-Won Lee***

* Sungkyunkwan University, 300, Cheoncheon-dong, Jangan-gu, Suwon-si, Gyeonggi-do, Korea

** Samsung Electro-Mechanics, 314 Maetan-3-dong Yeongtong-gu Suwon City Gyeonggi-do, Korea

***Abstract*-In this paper, a new concept of bi-directional battery charger for PHEV/EV with photovoltaic generation system and operation algorithm of battery charger system is proposed. A novel battery charger system with photovoltaic generation is designed to have function of photovoltaic power conversion and battery charging/discharging. Also, considering sensitive photovoltaic source according to in the environment conditions, grid and battery characteristic, operation algorithms of the system is proposed and these algorithms are analyzed by four cases according to load conditions in detail. Moreover, it is applied to battery charging algorithm of hybrid constant current constant voltage control combined merits of constant current control and constant voltage control. Informative simulation using PSIM and experimental result using 3.3kW lab-prototype set are presented for performance verification.**

I. Introduction

One of the main electrical and mechanical units for electric vehicles (EV) and plug-in hybrid vehicles (PHEV) is battery charger to control the energy balance of entire system. In recent, off-board charger for fast charging and on-board charger for slow charging have been developed. The power rating f battery charger is about more than 50kW for off-board charger and 3.3kW for on-board charger. Therefore, if the primary power of the charger is provided though the utility grid, the entire power rating of existing grid should be increased and several safety and reliability problem should be considered [1]-[2]. With this reason, for EV and PHEV applications renewable energy sources are considered as the alternative solution of limitation of utility grid power capability.

Among of renewable energies, photovoltaic (PV) generation systems are rapidly installed around the world as the major stable and reliable power source, PV generation systems have power condition system (PCS), which consists of de-dc converter and dc-ac inverter. In special, the dc-ac inverter can be operated as ac-dc pwm converter for converting as source to the boosted dc voltage and for the unity power factor correction [3]-[4]. Therefore, if the conventional battery charger is combined with PV PCS, the PFC circuit of the charger can be eliminated and only bi-directional dc-dc converter is connected to the dc-link capacitor bank of PV PCS.

In this paper, a new concept of bi-directional battery charger for EV and PHEV using PV PCS is proposed. The proposed system is operated by four modes according to the generating power condition of PV and load power demand condition. In addition to, battery charging/discharging algorithm applied to hybrid constant current constant voltage control is presented in order to solve long charging time problem [5] that is demerit of constant current control and constant voltage control. Informative simulation is carried out and experiment is performed using 3.3kW lab-prototype to verify the validity.

II. Analysis of the Proposed Battery Charger

A. System Configuration

Fig. 1(a) shows a PV generation systems, which consists of a dc-dc converter for boosting up the output of PV array and maximum power point tracking control (MPPT) and a dc-ac inverter for synchronization of output ac voltage with grid voltage. With this PV system, the conventional battery charger can be connected to the grid and it can be depicted in Fig. 1(b). As shown in Fig. 1(b), the conventional battery charger consists of a boost converter for power factor correction and a dc-dc converter to charge the battery. If the battery power is discharged and delivered to the grid, the boost converter and dc-dc converter should be changed to PWM ac-dc converter and bi-directional dc-dc converter.

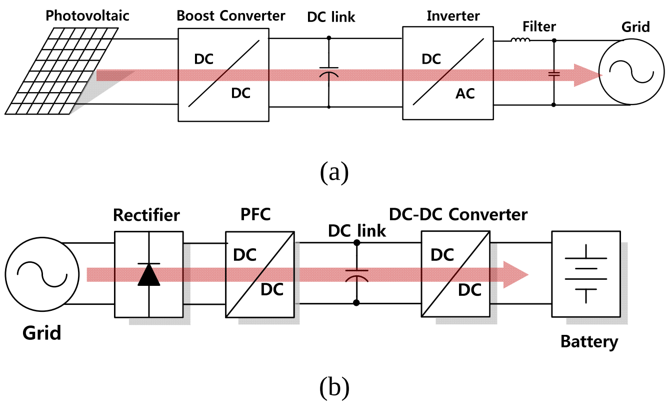


Fig. 1. (a) General PV generation systems and (b) conventional battery charger systems.

In the proposed battery charger system, these two power stages can be combined as shown in Fig. 2 and only one bi-

978-1-4244-8218-4/10/$26.00 ©2010 IEEE

directional dc-dc converter is added to the PV PCS in parallel with dc-link capacitor bank of PV PCS.

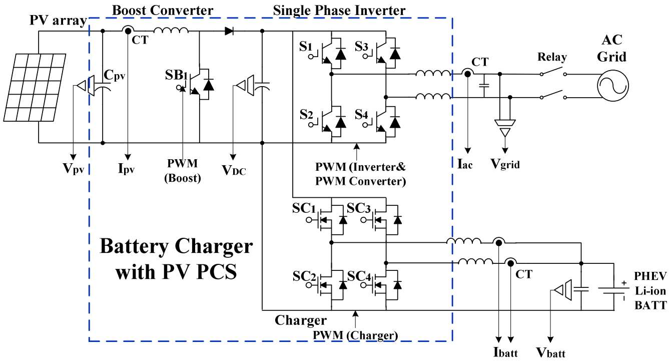


Fig. 2. Proposed battery charger using PV PCS.

B. 2-Phase Interleaving Bi-directional Converter

Fig. 3 presents switching method of bi-directional dc-dc converter. The switching method is used 2-phase interleaving technique which each phase has the 180° phase difference.

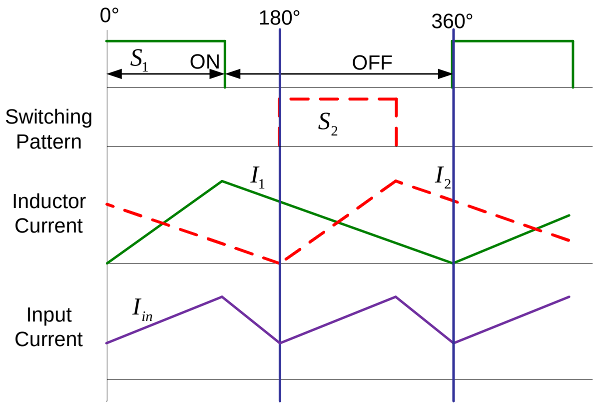


Fig. 3. 2-Phase interleaving technique.

The merit of interleaving technique could change input and output current ripple according to duty ratio [6]. Equation (1) shows the variation of input current ripple according to duty ratio. Variation of output current ripple is also same as input current ripple.

$$\Delta I_{in} = \frac{V_o}{L}\left(N_{on\_sw} - ND\right)\frac{T}{N}d \tag{1}$$

where, N is the number of the phase, T is the switching period, and N_{on_sw} is the number of ON switches during τ .

Fig. 4 shows variation of input current ripple according to duty ratio. In case of 2-phase, input current ripple is minimized at 0.5 duty ratio however it is maximize at 0.25, 0.75 duty. So, at 0.5 duty ratio, output current also is minimized so that battery charging current ripple could be reduced and obtain reduction of battery charging current

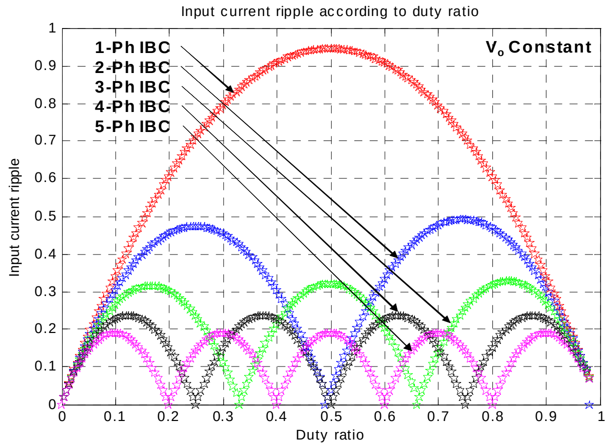


Fig. 4. Variation of input current ripple according to duty ratio.

ripple at 0.35~0.65 duty ratio. Therefore, in these duty ratios, we could minimize deterioration of battery. In order to solve the current unbalance, bi-directional dc-dc converter is controlled current sharing algorithm.

C. Control Algorithm and Operation Modes

In this paper, based on photovoltaic, dc link, battery and inverter power, operation mode and control algorithm is divided. Equation (2)~(5) shows the photovoltaic, inverter, battery charger and dc link power.

$$P_{PV} = V_{PV} \times I_{PV} \tag{2}$$

$$P_{INV} = V_{INV} \times I_{INV} \tag{3}$$

$$P_{CH} = V_{CH} \times I_{CH} \tag{4}$$

$$P_{DC} = V_{DC} \times I_{DC} \tag{5}$$

In equation (6), photovoltaic power is equal to dc link power. Dc link power is the sum of inverter power and battery charger power in (7). Inverter power presents the multiplication inverter (grid voltage) and current. In equation (3), grid voltage is constant however, grid current is varied so, inverter power is changed. Battery charger power also changes high dependence on charging current.

Therefore, power variation of dc link is caused by inverter and battery charger power. It is presented from dc link voltage variation in (8). In other word, we could sense the power variation from dc link voltage and generate the each current reference.

$$P_{PV} = P_{DC} \tag{6}$$

$$P_{DC} = P_{INV} + P_{CH} \tag{7}$$

$$V_{DC} = C\frac{di_{DC}}{dt} \tag{8}$$

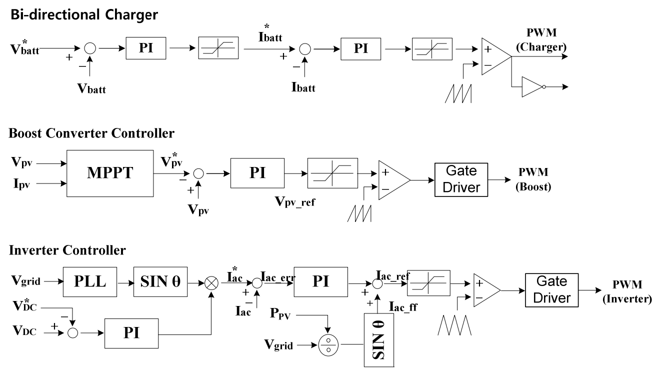


Fig. 5. System control block diagram.

Fig. 5 presents the proposed system control block diagram. The proposed algorithm is carried out organically according to load and source condition.

Equation (9)~(14) show the algorithm that could perform organically inverter and PWM converter mode. This algorithm is operated two algorithm modes without any modification of program.

$$V_{DC\_err} = V^{*}_{DC} - V_{DC} \tag{9}$$

$$I_{DC\_ref} = V_{DC\_err}\left(K_p + \frac{K_i}{s}\right) \tag{10}$$

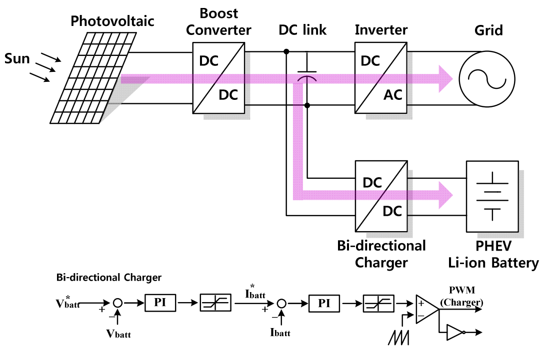
$$I^{*}_{ac} = I_{DC\_ref}\sin\theta \tag{11}$$

$$I_{ac\_err} = I^{*}_{ac} - I_{ac} \tag{12}$$

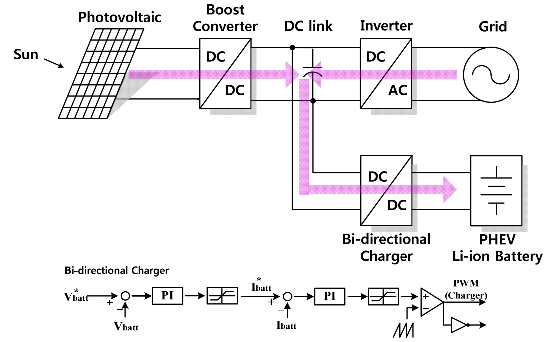
$$I_{ac\_ref\_pre} = I_{ac\_err}\left(K_p + \frac{K_i}{s}\right) \tag{13}$$

$$I_{ac\_ref} = I_{ac\_ref\_pre} + I_{ac\_ff} \tag{14}$$

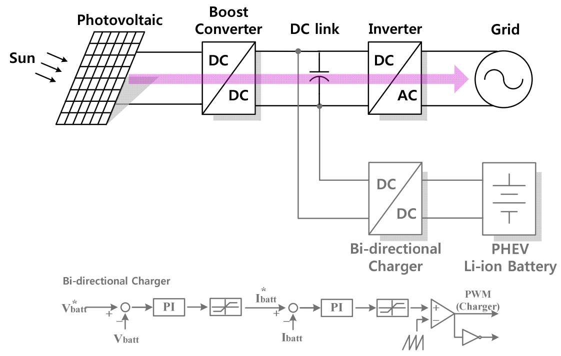
The operational modes of the proposed battery charger can be divided into four modes according to the source and load conditions as shown in Fig. 6.



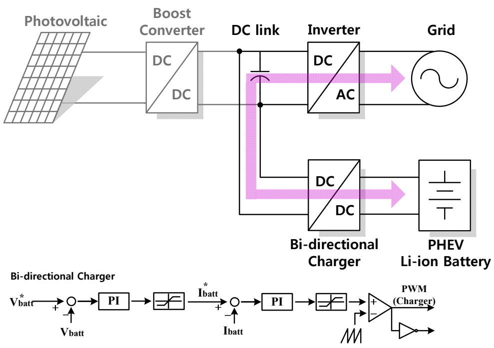
(a) Mode I



(b) Mode II



(c) Mode III



(d) Mode IV

Fig. 6. Battery charging and discharging algorithms according to source and load conditions.

- *Mode I*

PV PCS generates a proper ac voltage and transfers the power to the grid. When the battery starts charging with small power, it is supplied from PV power and the surplus of PV power is transferred to the grid. Mode I can be defined that PV power is large than charging power of battery.

- *Mode II*

When the battery required power exceeds the PV power, all PV generation power is transferred to the battery and the difference of battery power and PV power is provided from the grid. In this case, the operation mode of dc-ac inverter is changed to pwm ac-dc converter and the grid power flow becomes negative.

- *Mode III*

When the battery is fully charged, the bi-directional dc-dc converter is not operated and only PV PCS is operated and all power of PV is transferred to the grid. This mode can be treated as normal operation of PV generation systems.

- *Mode IV*

When PV cannot generate power, such as night time, low radiation and bad weather condition, all battery power is provided from the grid. Also, sometimes the battery power is needed to be discharged. During charging mode, dc-ac inverter is operated as PWM ac-dc converter to obtain dc-link voltage and the battery is charged by bi-directional converter. On the other hand, in case of discharging mode, the power is flowed through bi-directional dc-dc converter and dc-ac inverter to the grid.

III. Simulation and Experimental Results

Fig. 7 shows the simulation platform and consists of power part and controller part.

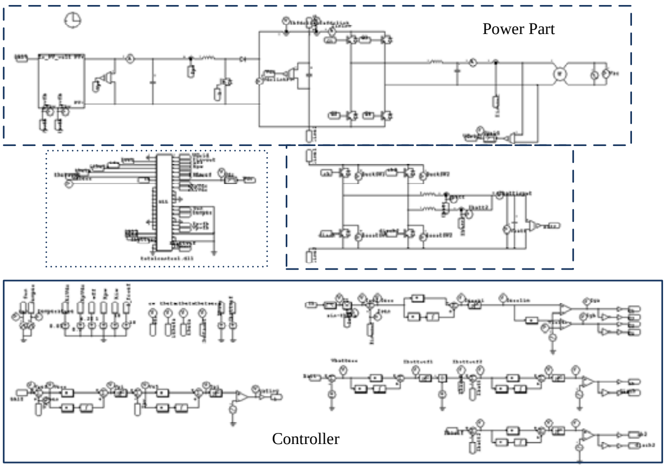
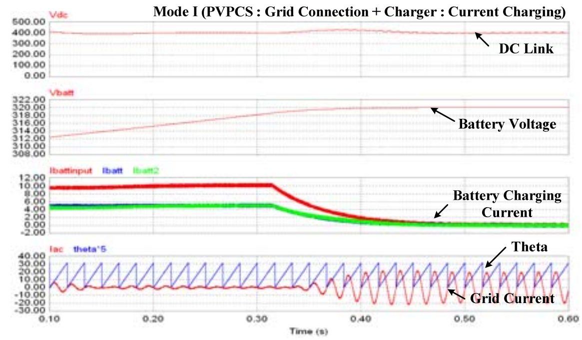
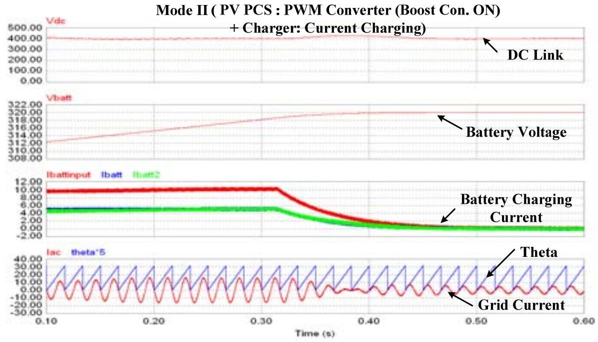


Fig. 7. Simulation platform.

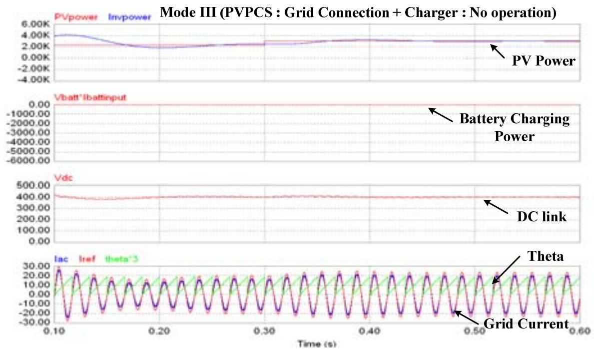
Fig. 8 presents simulation results according to operational modes and PSIM 6.0 is used for this purpose. Fig. 8(a) shows that dc-link is controlled to 400V and output current of grid is increased after battery is charged. Fig. 8(b) presents that battery receives power from grid and PV delivers power to grid after battery is charged. Fig. 8(c) shows general PV generation mode. Fig. 8(d) shows that dc-ac inverter is operated as pwm ac-dc converter and battery is charged from grid only.



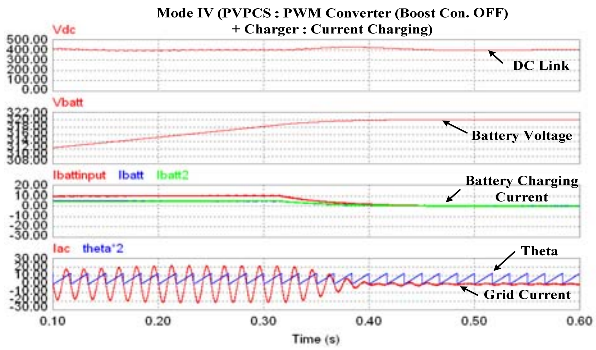
(a) Mode I



(b) Mode II



(c) Mode III



(d) Mode IV

Fig. 8. Simulation results.

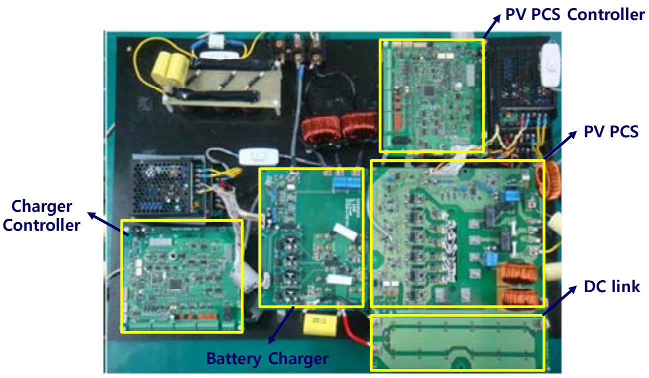


Fig. 9. 3.3kW lab-prototype battery charger.

Fig. 9 shows the 3.3kW lab-prototype battery charger. The controller of proposed battery charger system is used two TI TMS320F2811 and each DSP is not connected by communication. However, DSP controllers are sensed common dc link voltage.

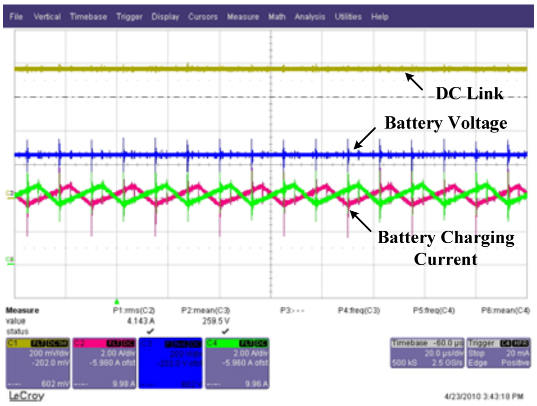
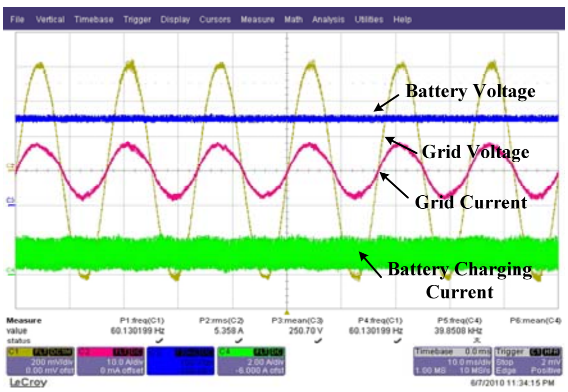
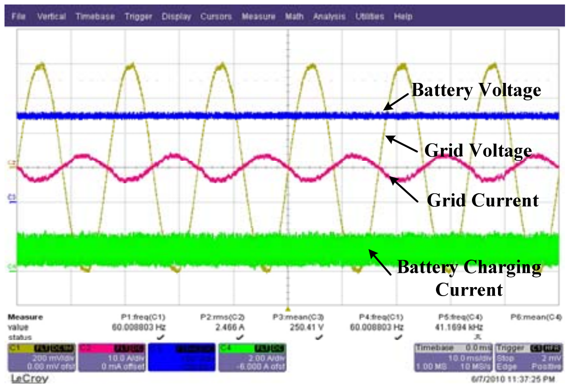


Fig. 10. Battery charging current and voltage.

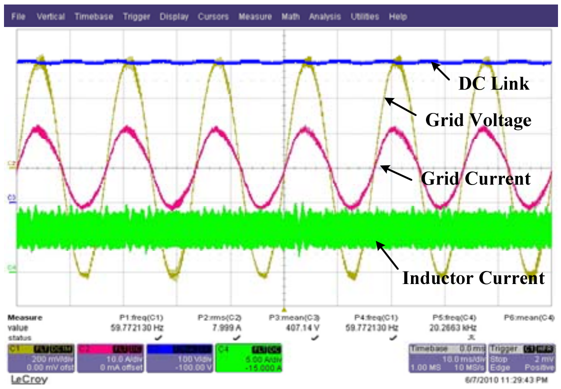
Fig. 10 shows battery charging current and voltage. Battery voltage is 250V and charging power is 2kW. The battery charging current has the 180˚ phase difference due to interleaving technique. In order to solve the current unbalance, the controller of phase current is applied so that each phase current is controlled equally.



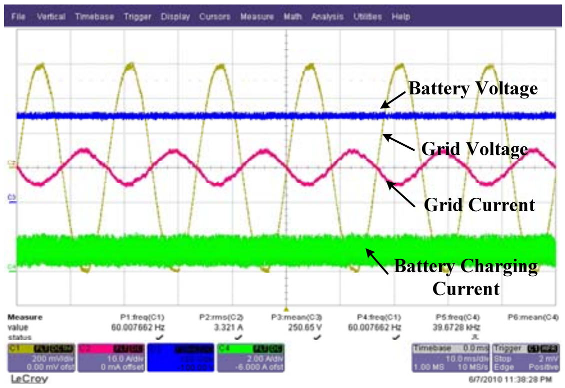
(a) Mode I



(b) Mode II



(c) Mode III



(d) Mode IV

Fig. 11. Experimental results according to operation mode.

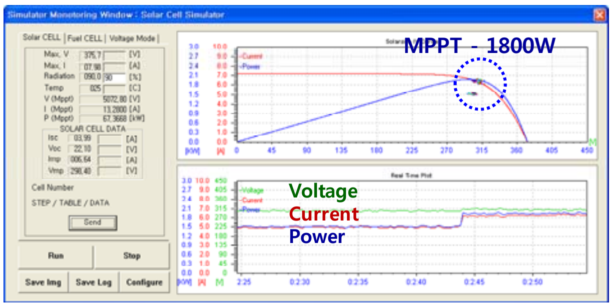


Fig. 12. Performance of photovoltaic MPPT.

Fig. 11 presents experimental results according to operation mode. Fig. 11(a) shows experimental results of mode I. PV power is 1800W and battery charging power is 600W and inverter power transferred to grid is 1200W. Battery voltage is 250V and inverter is controlled power factor 1 control so that grid current phase is grid voltage in phase.

Fig. 11(b) presents that PV power is 100W, PWM converter power is 500W and battery charger power is 600W. In this mode, inverter is operated by PWM converter and phase of grid voltage and current is reverse.

Fig. 11(c) shows the experimental results of PV PCS of algorithm 3. PV PCS transfers 1800W PV power to grid. Fig. 11(d) shows experimental results of mode IV. This algorithm is operated by PWM converter and all battery charging power is obtained from grid.

Fig. 12 shows the performance of MPPT control when the irradiation of photovoltaic is changed in mode III. We could get the results of good MPPT performance when the irradiation of photovoltaic changes 70% to 90%.

IV. CONCLUSION

In this paper, a new concept of bi-directional battery charger for PHEV/EV with photovoltaic generation system and operation algorithm of battery charger system is proposed. Also, proposed algorithms are analyzed by four cases according to load and source characteristic in detail. Moreover, in order to reduce battery charging current ripple, battery charger is applied to interleaving technique. All algorithms are verified by informative simulation and experimental results using 3.3kW lab-prototype.

Therefore, the proposed a bi-directional battery charger for electric vehicles using photovoltaic PCS system and operation algorithm can be used in residential PV system.

REFERENCES

[1] M. G. Egan, D. L. O'Sullivan, J. G. Hayes, M. J. Willers, C. P. Henze, "Power-Factor-Corrected Single-Stage Inductive Charger for Electric Vehicle Batteries," IEEE Transactions on Ind. Elect., vol. 54, no. 2, pp. 1217-1226, April, 2007.

[2] B. P. McGrath, D. G. Holmes. P. J. McGoldrick, A. D. McIver, "Design of a Soft-Switched 6-kW Battery Charger for Traction Applications," IEEE Transactions on Power Electronics, vol. 22, no. 4, pp. 1136-1144, July, 2007.

[3] F. Boico, B. Lehman, K. Shujaee, "Solar Battery Chargers for NiMH Batteries," IEEE Transactions on Power Electronics, vol. 22, no. 5, pp. 1600-1609, Sept., 2007.

[4] X. Zhou, G. Wang, X. Zhou, Lukic, S. Bhattacharya, A. Huang, "Multi-function bi-directional battery charger for plug-in hybrid electric vehicle application" IEEE Energy Conv. Congr.Exp. ECCE2009, pp. 3930-3936, 2009.

[5] J. J. Chen; F. C. Yang; C. C. Lai; Y. S. Hwang; R. G. Lee, "A High-Efficiency Multimode Li–Ion Battery Charger With Variable Current Source and Controlling Previous-Stage Supply Voltage, IEEE Transactions on Ind. Elect., vol. 56, no. 7, pp. 2469-2478, July, 2009.

[6] G. Y. Choe, J. S. Kim, H. S. Kang, B. K. Lee, "A Optimal design methodology of an interleaved boost converter for fuel cell application", Journal of Elect. Eng. Tech., vol. 5, no. 2, pp. 319-328, 2010.