PEBB Based Bi-directional Rapid Charging System for EV Traction Battery

Taewon Kang, Beomseok Chae, and Yongsug Suh

Dept. of Electrical Engineering Chonbuk National University

666-13 Baekje-daero, Duckjin-gu, Jeonju, 556-756, Korea

Abstract

This paper presents a simple and cost-effective stand-alone rapid battery charging system of 30kW for electric vehicles. The proposed system mainly consists of active front-end rectifier of neutral point clamped 3-level type and non-isolated bi-directional dc-dc converter of multi-phase interleaved half-bridge topology. The charging system is designed to operate for both lithium-polymer and lithium-ion batteries. The complete charging sequence is made up of three sub-interval operating modes; pre-charge mode, constant-current mode, and constant-voltage mode. The pre-charge mode employs the stair-case shaped current profile to accomplish shorter charging time while maintaining the reliable operation of the battery. The proposed system is specified to reach the full-charge state within less than 16min for the battery capacity of 8kWh by supplying the charging current of 78A. Owing to the simple and compact power conversion scheme, the proposed solution has superior module-friendly mechanical structure which is absolutely required to realize flexible power expansion capability in a very high-current rapid charging system.

1. Introduction

Plug-in Hybrid Electric Vehicle (PHEV) is becoming an attractive alternative to internal combustion engine vehicles in modern transportation industry. One way to achieve the practical all-electric cruising range of electric vehicles is to implement well distributed fast charger infrastructure. Such a structure would provide greater mobility for the PHEV user, since during short stops the PHEV batteries could be charged from typically 20 to 80% of nominal charge. Usually single phase solutions are used for Levels 1 and 2. Level 3 is intended for commercial and public applications, operating like a filling station, and three-phase solutions normally apply. These fast chargers(Level 3) will be installed in highway rest areas and convenient city refueling points. The newly developed dc fast chargers support very fast charging sequences even for heavy vehicles [1]-[5].

In this paper charging system mainly consists of active front-end rectifier of neutral point clamped 3-level type and non-isolated bi-directional dc-dc converter of multi-phase interleaved half-bridge topology. The charging system is designed to operate for both lithium-polymer and lithium-ion batteries. The control algorithm for the proposed system is set to meet the long life-cycle and safe operating requirement of both type of battery. The complete power converter system can deal with bi-directional power flow between the ac grid and energy storage devices. The discharging operation mode of energy storage device can be effectively utilized for feeding the stored energy back to local grid by PHEV in smart grid concept, i.e. Vehicle to Grid(V2G) operation or ancillary service to u-grid.

The proposed charging system in this paper is equipped with a line-frequency transformer for galvanic isolation at the ac input side of system. Despite of its weight and volume, this low-frequency transformer has the cutting-edge advantage of low cost and simple interface in a separate off-line charging station. The power converter topology proposed in this paper has less number of power switches as compared to those of state-of-the-art solutions employing isolated bi-directional dc-dc converters, particularly for on-board chargers.

2. Operation of Active Front-end Rectifier and Bi-directional DC-DC Converter

Figure 1 shows the schematic of rapid charger system proposed in this paper. Overall battery charging and discharging system consists of active front-end rectifier of neutral point clamped 3-level type and non-isolated bi-directional dc-dc converter of multi-phase interleaved half-bridge topology. The Active Rectifier Unit (ARU) regulates the dc link voltage typically at 858V. The Battery Charging Unit (BCU) in the proposed system consists of multiple non-isolated bi-directional dc-dc converter modules. As shown in Fig. 2 the basic building blocks of two-phase interleaved half-bridge topology are connected in parallel depending on the system requirement of charging/discharging capacity. In this paper, three modules are employed to realize the maximum charging current of 78A. Power can flow in both directions within BCU, thus coping with charging and discharging mode of battery; buck-operation mode and boost-operation mode.

When the energy flows from grid to the vehicle (G2V), it operates under buck-operation mode to charge the battery in electric vehicles. When the energy flows from vehicle to the grid (V2G), it operates under boost-operation mode.

In this boost-operation mode, electric vehicle's users can sell the extra electricity to grid management as an ancillary service to u-grid. These two bi-directional operation modes are controlled by both voltage regulator and current regulator.

The proposed charging algorithm consists of three sub-interval charging sequences. The three sub-interval waveforms are illustrated in Fig. 3

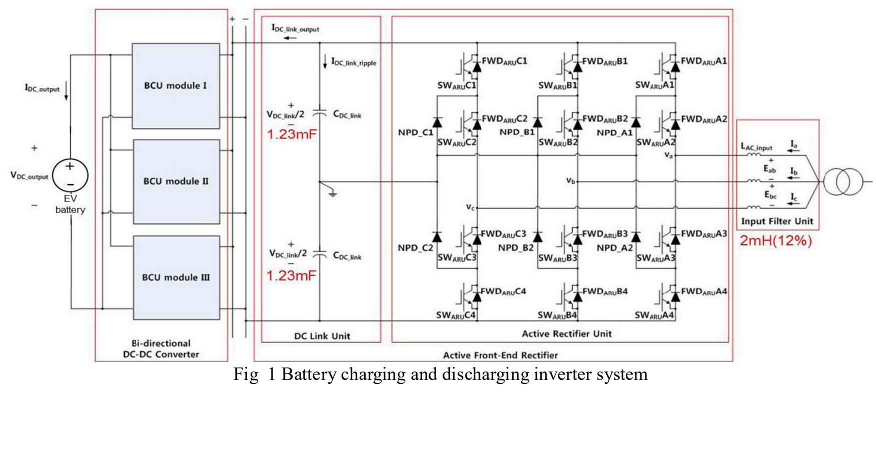

Fig 1 Battery charging and discharging inverter system

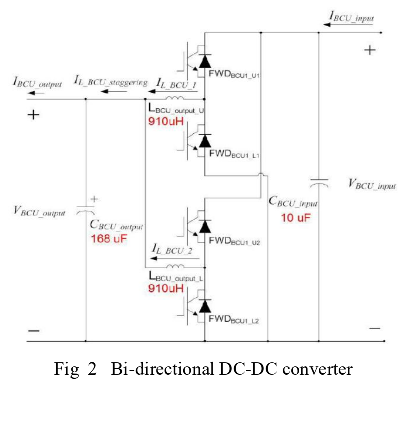

Fig 2 Bi-directional DC-DC converter

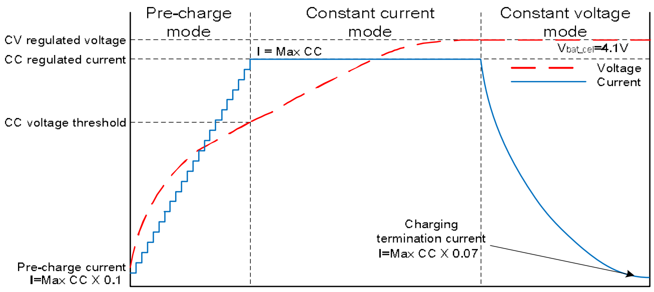

Fig 3 Charging profile of Li-Ion Polymer battery

3. Control Algorithm of Li-Ion Polymer Battery Charging System

The control algorithm of battery charging operation in this paper has been designed to meet the long life-cycle and safe operating requirement of lithium-Ion and lithium-polymer battery. During the charging state, the cell voltage should not exceed its end-of-charge voltage (about 4.1V/cell) to prevent over-charging and dissolving the copper in electrolyte which would damage the active materials of the lithium–ion and lithium-polymer cell. If cell voltage is below the threshold voltage of 2.7V/cell, the charger gradually ramps up charging current to avoid damaging the battery. This charging sequence is called as Pre-charge Mode. When the cell voltage increases over the threshold voltage of 2.7V/cell, charging sequence moves to Constant Current (CC) Charging Mode. During CC mode, maximum current is supplied for rapid charging so that the charging time is maintained within about 16min to attain 80% state-of-charge(SOC). As the battery voltage reaches the end-of-charge voltage of 4.1V/cell, Constant Voltage (CV) Charging Mode is initiated to fully charge the battery maintaining the voltage at its end-of-charge voltage.

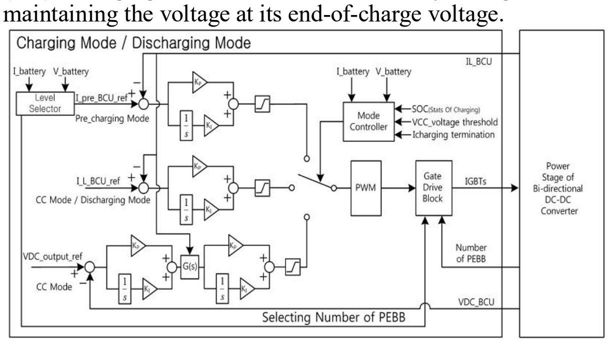

Fig 4 Overall control block diagram of battery charging and discharging

4. System Verification

Table I.
Specifications of Electric Vehicle Battery Charge System

Specification	Values	Specification	Values
Rated power	30kW	Pre-charging mode voltage	292V
AC input voltage	342~506V	Pre-charging mode current	0~78A
AC input current	77A	Constant voltage mode voltage	440V
DC-link voltage	858V	Constant current mode current	78A
Battery capacity	8kWh	DC output voltage	50~450V

Fig 5 EV and rapid charger of test

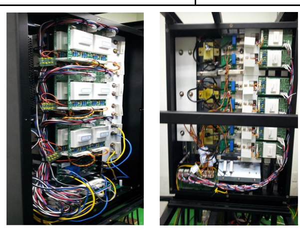

Fig 6 Photo of power stack

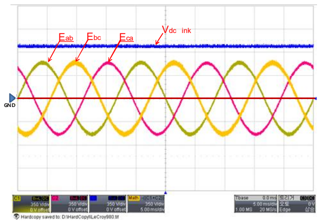

Fig 7 Experiment waveform of ac input voltage (E_{ab}, E_{bc}, E_{ca}, V_{dc_link} [350V/div, 50us/div])

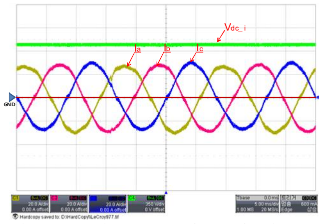

Fig 8 Experiment waveform of ac input current (I_a, I_b, I_c [20A/div, 50us/div] V_{dc_link}[350V/div])

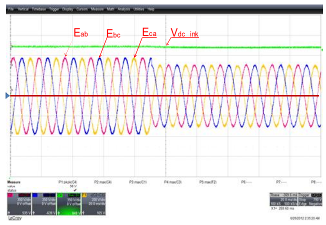

Fig 9 Experiment waveforms of dc link transient response under ac line input drop by 18% (E_{ab}, E_{bc}, E_{ca}, and V_{dc_link}[350V/div, 20ms/div])

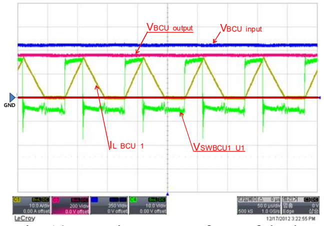

Fig 10 Experiment waveform of dc-dc converter (V_{BCU_input}[350V/div, 50us/div], V_{BCU_output}[200V/div], $I_{L\_BCU\_1}$[10A/div], and V_{swBCU1_U1}[10V/div])

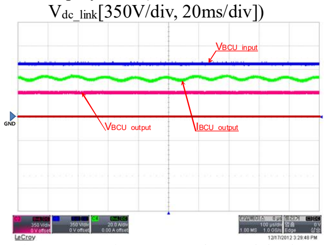

Fig 11 Experiment waveform of dc-dc converter (V_{BCU_input},V_{BCU_output}[350V/div, 50us/div], and I_{BCU_output}[20A/div])

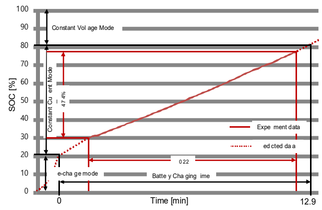

Fig 12 Charging profile (SOC vs Time) obtained from test result (Solid line: measured data, dotted line: predicted data)

5. Conclusion

This paper presents a simple and cost-effective rapid battery charging system for electric vehicles. The proposed stand-alone off-line charging system mainly consists of active front-end rectifier of neutral point clamped 3-level type and non-isolated bi-directional dc-dc converter of multi-phase interleaved half-bridge topology. The complete charging sequence is made up of three sub-interval operating modes; pre-charging mode, constant-current mode, and constant-voltage mode.

The proposed charging system in this paper is equipped with a line-frequency transformer for galvanic isolation at the ac input side of system. The power converter topology proposed in this paper has less number of power switches as compared to those of state-of-the-art solutions employing isolated bi-directional dc-dc converters, particularly for on-board chargers. Owing to the simple and compact power conversion scheme, the proposed solution has superior module-friendly mechanical structure which is absolutely required to realize flexible power expansion capability in a very high-current rapid charging system.

References

[1] M Bojrup, P Karlsson, M Alakula and B Simonsson, "A Dual Purpose Battery Charger for Electric Vehicles," in *IEEE 1998 Power Electronics Specialists Conference*, vol 1, pp 565-570, 1998

[2] D Aggeler, F Canales, H Zelaya-De La Parra, A Coccia, N Butcher and O Apeldoorn, "Ultra-fast DC-charge infra structures for EV-mobility and future smart grids," in *IEEE 2010 Innovative Smart Grid Technologies Conference*, pp 1-8, 2010

[3] C C Chan and K T Chau, "An overview of power electronics in electric vehicles," in *IEEE Trans. Ind. Appl.*, vol 44, no 1, pp 3-13, Feb 1997

[4] S G Wirasingha, N Schofield, A Emadi, "Plug-in hybrid electric vehicle developments in the US: Trends, barriers, and economic feasibility," in *IEEE 2008 Vehicle Power and Propulsion Conference*, pp 1-8, 2008

[5] Murat Yilmaz, and Philip T Krein, "Review of Battery Charger Topologies, Charging Power Levels, and Infrastructure for Plug-In Electric and Hybrid Vehicles" in *IEEE Trans. on Power Electronics*, vol 28, no 5, pp 2151-2169, 2013