A Design and Control of Bi-directional Non-isolated DC-DC Converter with Coupled Inductors for Rapid Electric Vehicle Charging System

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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 with coupled inductors. 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-charging mode, constant-current mode, and constant-voltage mode. The pre-charging 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 able to reach the full-charge state within less than 16min for the battery capacity of 8kWh by supplying the charging current of 67A. The optimal discharging algorithm for Vehicle to the Grid (V2G) operation has been adopted to maintain the discharging current of 1C. 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 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 crusing 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 [1]-[4].

In most of charger systems for electric vehicles, bi-directional converters for charging and discharging the batteries are required. The bi-directional converter may be transformer-isolated or non-isolated, depending on the application [5].

This paper presents a simple and cost-effective rapid battery charging system for electric vehicles. The proposed 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 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

Fig. 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.

Bi-directional dc-dc converter plays a significant role both in system performance and cost. The Battery Charging Unit (BCU) in the proposed system consists of multiple non-isolated bi-directional dc-dc converter modules. In this paper, three modules are employed to realize the maximum charging current of 67A.

As shown in Fig. 2, 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; upper switches in half-bridge are controlled to regulate the output. When the energy flows from vehicle to the

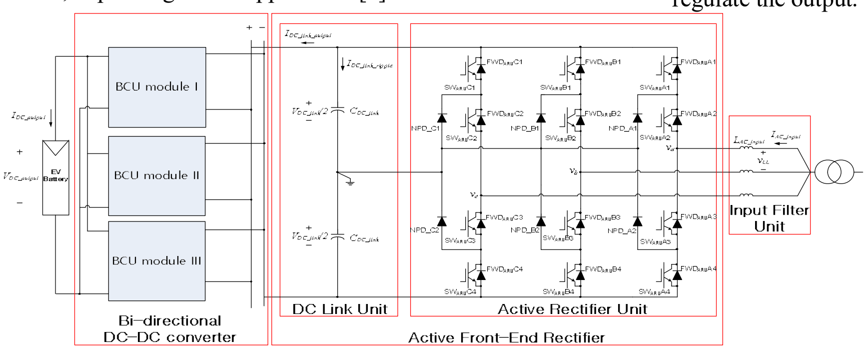

Fig. 1 30kW Battery charging and discharging inverter system

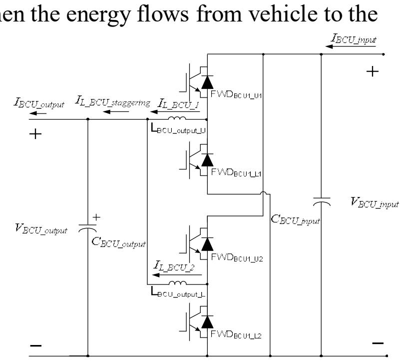

Fig. 2 Bi-directional DC-DC converter

grid (V2G), it operates under boost-operation mode; lower switches are controlled to regulate the dc link voltage.

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. According to the characteristics and the operation limits of the lithium–ion and lithium-polymer battery pack, the charging system handles the various charging sequences. The proposed charging algorithm consists of three sub-interval charging sequences. The three sub-interval waveforms are illustrated in Fig. 3

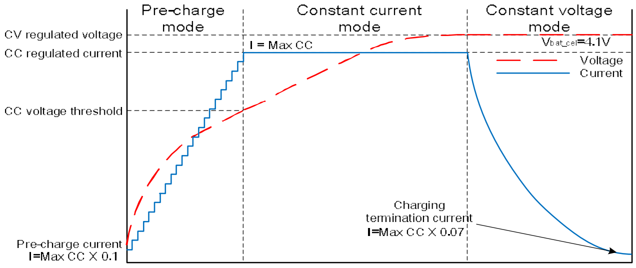

Fig. 3 Charging profile of Li-Poly battery

3. Coupled Inductor

In order to reduce the output current ripple and inductor size, small size inductances need to be designed. The large current ripples impose stresses to the output capacitor and battery life time. Coupled inductor can reduce the core number and complexity of DC-DC converter.

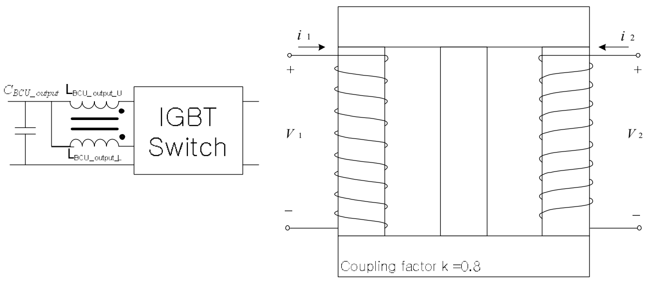

Fig. 4 Coupled Inductor Design

4. System Verification

Table I.
Specification of Electric Vehicle Battery Charge System

Specification	Values	Specification	Values
Rated power	30kW	Pre-charging mode voltage	292V
AC input voltage	380V	Pre-charging mode current	17A
AC input current	47A	Constant voltage mode voltage	440V
DC-link voltage	858V	Constant current mode current	67A
Serial battery stack number(ns)	108	Output current ripple factor	Under 1%
Charging termination current	5A	Output voltage ripple factor	Under 1%

The operating condition for the simulation and experimental verification is specified in Table I. The rated power of complete charging system is set to 30kW. The nominal input voltage is selected to be 380V. The output voltage at the battery side of bi-directional dc-dc converter is designed to cover between 50V and 450V. This wide operating range makes it possible for the charger to effectively realize proposed charging sequences of the battery.

The negative value of input current to BCU reveals the discharging power flow of the system.

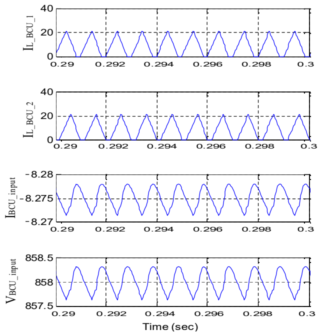

Fig. 5 Inductor current, output current and output voltage waveform under discharge mode

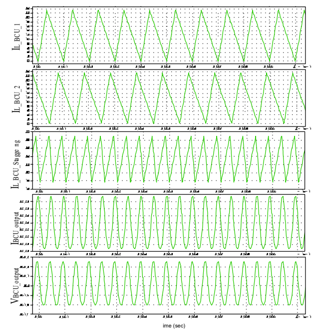

Fig. 6 Inductor current, output current and output voltage waveform under pre-charge mode

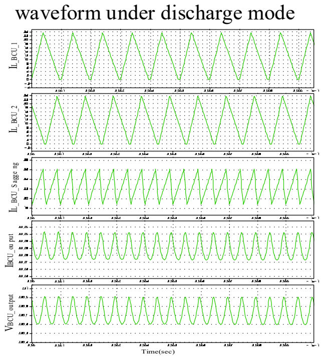

Fig. 7 Inductor current, output current and output voltage waveform under CC mode

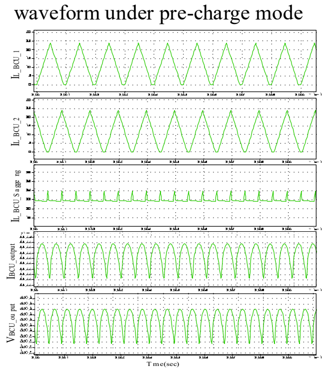

Fig. 8 Inductor current, output current and output voltage waveform under CV mode

5. Conclusion

This paper presents a simple and cost-effective rapid battery charging system of 30kW 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.

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