

Implementation of 60-kW Fast Charging System for Electric Vehicle

Suk-Ho Ahn*, Ji-Woong Gong
 Dept. of Energy Conversion Technology
 University of Science & Technology
 Chang-Won, Korea
 whiteyan@keri.re.kr, smarty0@keri.re.kr

Hong-Je Ryoo, Sung-Roc Jang
 Electric Propulsion Research Center
 Korea Electrotechnology Research Institute
 Chang-Won, Korea
 hjryoo@keri.re.kr, scion10@keri.re.kr

Abstract— This paper instructs implementation of electric vehicle (EV) fast charging system which complies with the international standard related with EV conductive charging system. Concretely, design issues and the consideration of EV fast charging system components are presented. In view of this, this paper proposes the 60-kW fast charging system which consists of a master controller communicating with battery managements system (BMS) and EV for safe charging, a smart meter for billing and metering, a charging connector and the output stage formed by six modules of high-efficiency 10kW DC-DC converter for stable output with the input module for passive power factor correction and reducing the ripple of D.C. voltage. The charging system generates output voltage ranges from 50-V to 500-V and maximum output current of 150-A. And, it is tested with a variety of batteries aimed from NEV (Neighborhood Electric Vehicle) to full-speed EV and EV simulator consisted of 20kWh LifePO2 battery to verify excellent performance as a fast charging system. The developed EV fast charging system is installed at Korean EV test infrastructure and practical charging test with various kinds of EVs has been now performing.

Keywords—Electric vehicle fast charger; Fast charger; Resonant converter

I. INTRODUCTION

There has been great attention to eco-friendly EV due to concerns about environment and the regulation on emissions. To promote the utilization of pure EV, there should be further enhancement in building infrastructure that provides the fast charging system. For this reason, various standards which are IEC-61851-23, SAE J1772, CHAdeMO are published for fast charging system. With these standards, the requirements of fast charging system are as follows:

- Fast charge the vehicle battery (with in 30 min.)
- Adapt to various battery types and car models
- The high efficiency in rated operating condition
- Communication function for detection the state of charge (SOC) of the vehicle battery and safe charging
- Automatically bill for the electricity delivered
- Standard compatibility

The fast charging system requires master controller communicating with BMS and EV, smart meter, the input and output stage formed by six modules of high-efficiency DC-DC converter. According to the above requirements and standard's

one which is discussed in this paper, 60-kW 500-V 150-A fast charging system are proposed. And, implementation process is presented.

II. IMPLEMENTATION OF 60-KW FAST CHARGING SYSTEM

Charging system is consists of master controller (MC), user interface (UI), smart meter, and six modules of 10kW DC-DC converter.

A. Master Controller and User Interface

Charging system is connected with EV through charging connector. MC communicates with UI, BMS which is installed in EV, and connector for safety, effective charging. And, MC manages whole charging system as follows.

Vehicle authentication: MC confirms whether EV which is connected with MC is enables to charge. Once verified, UI indicates EV connecting.

Charging Ready: MC checks the connection of charging connector and receives the charging converter modules and BMS states. And, UI indicates charging ready state.

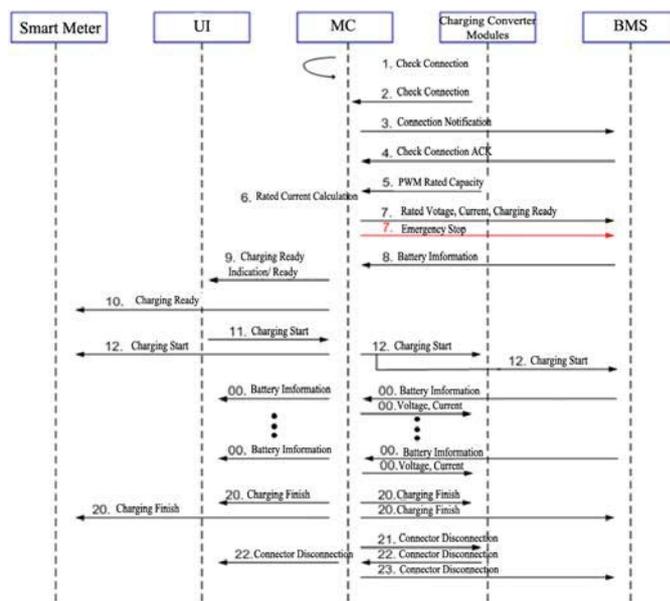


Fig. 1. Charging Procedure



Fig. 2. Picture of MC and UI Units (3 Set)

Charge: After all charging arrangements are completed, MC transfers charging command from BMS to charging converter modules. At this time, MC slowly increases charging current command to target charging current received from BMS. And, MC gen up on battery state, wattage and power rates received from BMS to UI. UI indicates SOC (Stage Of Charge), charging finish time to inform to user

Charge End: After received end of charging command from BMS or user, or reached target SOC or power rates, MC command end of charging to charging converter. And, UI indicates charging end.

Connector Disconnect: After user disconnects connector as UI indicated, UI indicates charging results and stores to memory

Charging procedures with MC is indicated as Fig. 1. MC is consists of PIC24Hj 16-bit Microcontroller charging converter interfaces input/output optic port, CAN port to communicate with BMS, RS485 port to communicate with smart meter and UI. Fig. 2. are the actual outer shape of MC and UI units (3 set).

B. Smart Meter

The smart meter is responsible when authorized, to allow the energy transit between the charging system and the EV at the energy point of delivery. At the beginning of the charging sequence there is an agreement between the EV and the charging system regarding the quantity of energy to provide and the duration of the charging (quality of service). This agreement takes into account the EV identification, the contract identification, verification, as performed by the MC. The duration of charging has to take into account the different rates of the energy during the time interval the charging has to take place, the demand level and the grid constraints. During this energy flow the smart meter monitors the demand according to the profile defined during the setup of the charging session, and takes the proper action accordingly. At the end of the charging session, the smart meter elaborates the billing data related to the charging sequence. The smart meter must have prepayment functionalities. For implementation of these functions, the smart meter is designed as follows.

Power Supply Part: Power supply part is consists of EMC protection circuit, rectifier circuit, PWM/FET, output circuit. Feedback circuit is isolated with photo coupler (primary A.C. secondary D.C.). D.C source is supplied to the smart meter stably although input fluctuates from 176 to 448V.

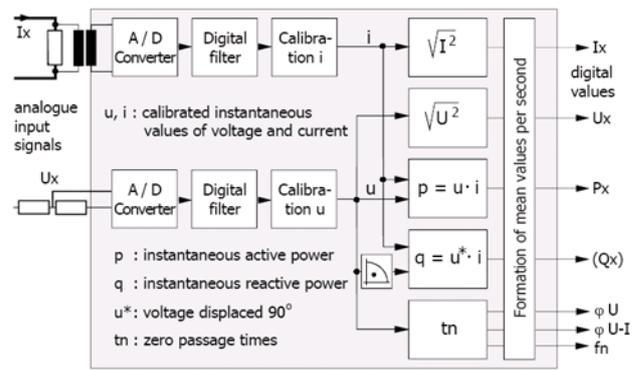


Fig. 3. Algorithm of Smart Meter



Fig. 4. Picture of Implemeted Smart Meter

Voltage/Current Detection Part: the voltage detection part is designed with precision resistor divider method. Measured voltage is converted to max. 500mV. the current detection part is consists of CT (Current Transformer). To decrease error, soft magnetism which has low hysteresis loss is selected as core material

Calculation Part: Measured voltage and current is multiplied and accumulated for calculation of active power. And, Measured current which has phase shifted 90degree is multiplied with measured voltage for calculation of reactive power. Detail algorithm of implemented Smart meter is explained as Fig. 3. Fig . 4 shows picture of implemented smart meter.

C. 10kW DC-DC Converter Modules

EV fast charging system has the object of miniaturization and high efficiency, thus there needs to be a development of DC-DC converter which has higher switching frequency, higher efficiency and power density. This paper proposes LCC-SRC which improves SRC (Series Resonant Converter) operated on CCM (Continuous Conduction Mode) as topology for fast charger module as Fig. 5. Additionally, a gate driver circuit with a simple structure is proposed. it allows soft-switching of a wide load operating range and prevents shoot-through by the dead time compensation function.

Topology Selection: SRC which is operated in CCM has low conduction loss, zero-voltage and zero-current turn-on is made possible and the switching frequency in rated load is

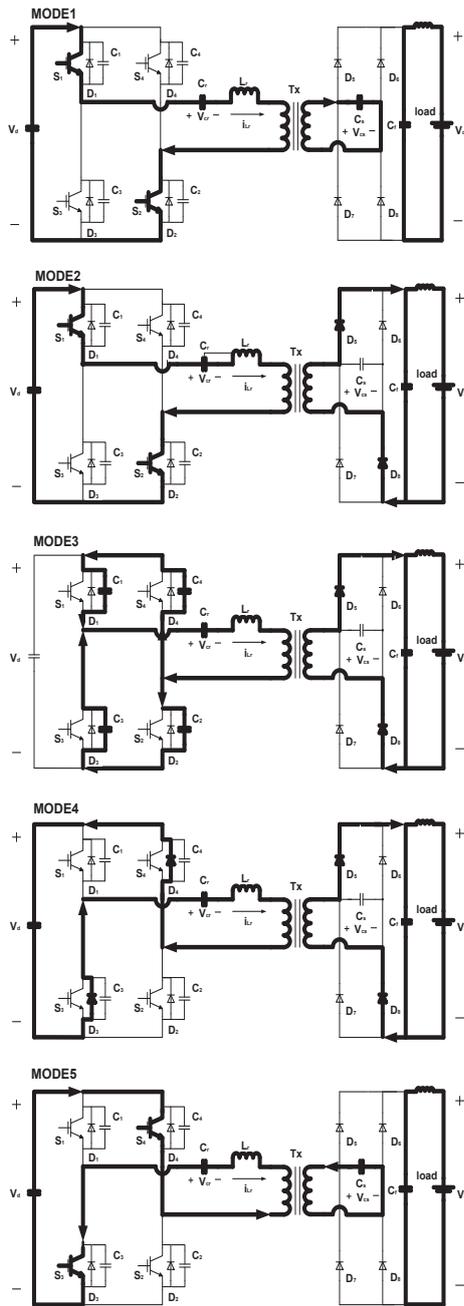


Fig. 5. Scheme of LCC-SRC

lower than the switching frequency of a light load- there are advantages during rated load operation. So, it is appropriate topology for rapid charger which operates in rated load. But, in the case of turn-off, it has turn-off loss by hard switching. Although by the lossless snubber capacitor, the turn-off loss can be reduced, but this type of lossless snubber capacitor must always be discharged at the next switching time and thus the capacitance of the snubber capacitor is limited.

This paper proposes LCC-SRC as topology of fast charging converter. it can decrease conduction loss, also decrease the switching loss by reducing the flowing current in the switching

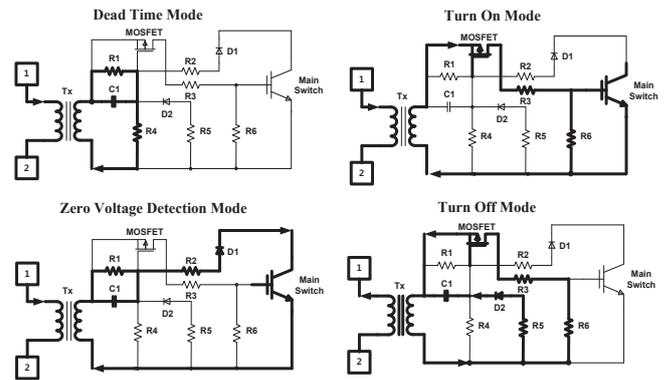


Fig. 6. Operation Diagram of Proposed Gate Driver Circuit

TABLE I. SPECIFICATION OF IMPLEMENTED 10kW DC-DC CONVERTER

DC Link Voltage, V_d	513Vdc \pm 10%
Output Voltage, V_o	0~500V
Output Current, I_o	0~25A
Output Power, P_o	10kW
Resonant Inductance, L_r	115 μ H
Resonant Capacitance, C_r	3 μ F
Second Resonant Capacitance, C_s	0.204 μ F
Transformer Turn Ratio, n	17:14
Switching Frequency, f_s	24kHz-77kHz
Snubber Capacitance, C_1 ~ C_4	33nF
Size(mm)	240*270*180 (W*D*H)
Total Weight	8kg
Maximum Efficiency	98.5%



Fig. 7. Picture of 10kW DC-DC Converter Module

device at turn-off, moreover further lessen the switching loss by effectively increasing the capacitance of lossless snubber capacitor which is used to lessen the switching loss. Suggested topology has a wide load range and is able to increase the efficiency when operating in rated load.

Gate Driver Circuit: The conventional gate driver that has fixed dead time is difficult to apply to the implemented charging converter because the implemented charging converter which is consisted on the universal fast charging system operates with soft switching within wide load range. This paper proposes the gate driver that has variable dead time and simple structures by detecting the voltage across switching devices and determining when to turn on as Fig. 6. The proposed gate driver does not need two opposite control signal with dead time, while it uses a single control signal with half

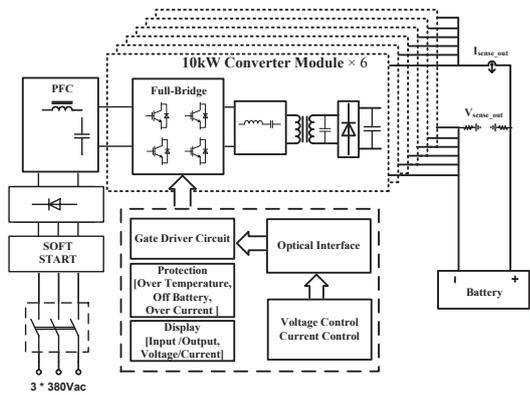


Fig. 8. Overall Structure of 60kW Charger

TABLE II. SPECIFICATION OF 60kW FAST CHARGING SYSTEM

Size (mm, W × H × D)	896 × 1520 × 650
Output	60kW [500V, 150A]
Maximum Efficiency	97%
Power Factor	0.93
Power Density (ℓ / kW)	14.75



Fig. 9. Overall Structure of 60kW Fast Charging System

duty that only has operating frequency. As the control signal is simplified, it facilitates the use of a transformer for isolation and photoelectric elements, having a competitive advantage in digitalization

Tab. 1. shows specification and design parameters of the Implemented 10kW DC-DC converter module shown as Fig. 7.

D. Configuration of Fast Charger

The developed Fast charger has output voltage 50V~500V, output power 60kW to provide charge voltage for products such as NEV use batteries to high speed electric vehicles which are installed with a variety of battery cells (15kWh~25kWh) and the charge current was developed to allow a wide range of change. Also, a stable system was built as the charger is a modularized structure which allows for expansion of the capacity and has redundancy capabilities. 60kW charger is consists of six modules of 10kW DC-DC converter as Fig. 8. Which

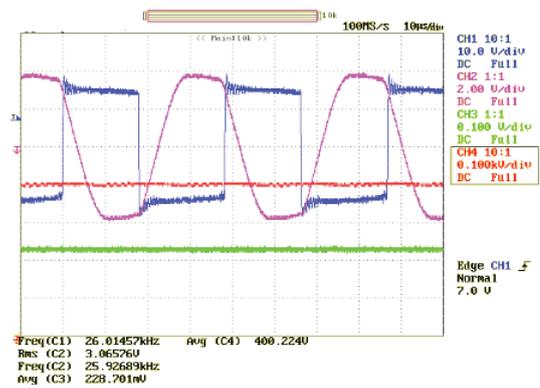


Fig. 10. 10kW DC-DC Converter Output Waveform under Maximum Rated Output (Ch1 : Resonant Current (20A/div), Ch3 : Output Current (50A/div), Ch4 : Output Voltage (100V/div), Time : 5us/div)

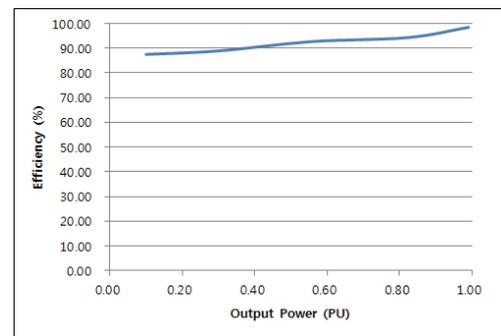
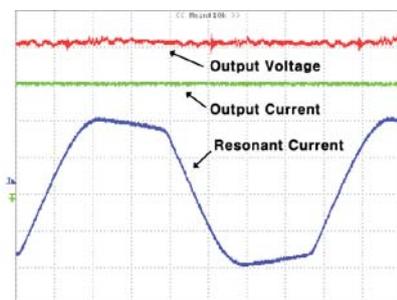
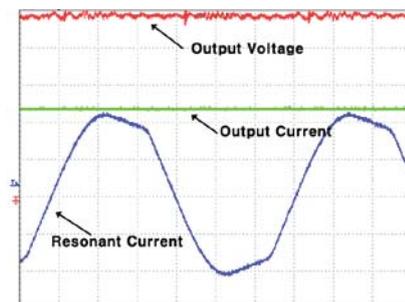


Fig. 11. Efficiency Curve of 10kW DC-DC Converter



(a) Output voltage : 400V



(b) Output voltage : 500V

Fig. 12. Experimental results of 60kW EV rapid charger (Time Scale: 5us/div. Resonant Current ,20A/div. Output Current, 50A/div. Output Voltage, 100V/div)

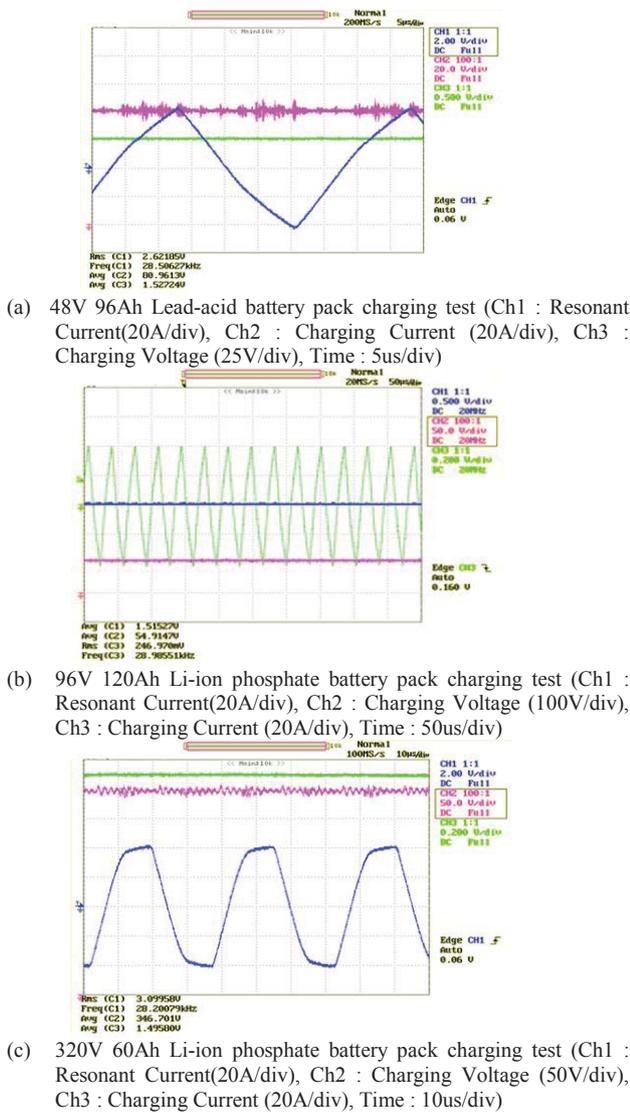


Fig. 13. Various Battery Charging Test Results

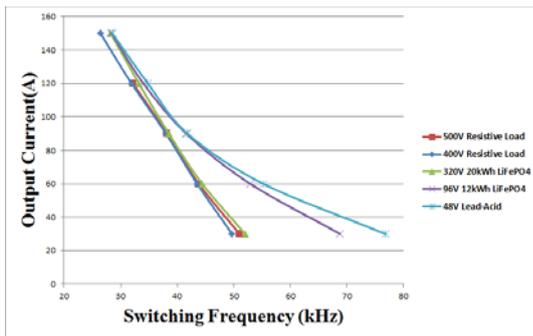


Fig. 14. Result of Output Current vs. Switching Frequency for Load Change for Different Load Condition

illustrates the whole structure of 60kW EV rapid charger, comprised of circuit breaker, the soft start part to prevent inrush current, rectifying section, the PFC part for power factor correction and reducing the ripple of DC voltage, the converter

module part which connects the six proposed 10kW converter in parallel, and the control part for stable output and converter protection. Specification of 60kW fast charging system is explained on Tab. 2 and Fig. 9. Shows overall structure of 60kW fast charging system.

III. EXPERIMENTAL RESULTS

To test the operation character and functions, experiments for maximum output, output variation, actual loading, and effectiveness measure were conducted with regard to 10kW converter module and 60kW rapid charger by utilizing simulated test resistance load and a various kinds of batteries. Fig. 10. is the experiment waveform that shows output voltage, output current, resonant current, and switching signal when 10kW converter modules operate in the maximum rated output. The effectiveness was measured as 98.5%, and as shown in Fig. 11. high efficiency was maintained under various output conditions. To prove that it is possible to install the massive capacity EV rapid charger in the form of parallel combination of the converter module, six converter modules connected in parallel with 60kW rapid charger were experimented. Fig. 12. is the experiment waveform that confirms steady state operation under 60kW maximum output when it comes to

The output voltage, output current, and resonant current when it comes to simulated test resistance load for charging battery of 400V and 500V condition. At that time, measured maximum efficiency was 97 % under the condition of 454V, 139A. To verify of the universal fast charger which enable to charger from NEV to high-speed EV, (a) 48V 3.8kWh Lead-Acid battery, (b) 96V, 12kWh Li-ion phosphate battery, (c) 320V 19.2kWh Li-ion phosphate battery charging test is conducted. The results are shown Fig.13. The experiment result of charging current depending on the variation of switching frequency under various kinds of load condition in order to verify its performance with real battery charging condition is shown as Fig. 14. When it operates with 48V, 3.8kWh Lead-Acid, 96V 12kWh LiFePO4 battery, 320V 19.2kWh LiFePO4 battery, and variable resistive load for simulating higher voltage battery charging condition of 400V and 500V, the experiment was performed to test the common use of rapid chargers varying from output charging voltage of 50V to 500V. To verify operation performance and algorithm of MC and smart meter, Charging performance of 60kW fast charger,

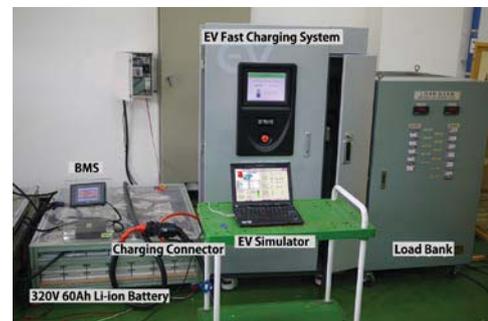


Fig. 15. EV fast charging system and test setup with EV simulator consisted of 20kWh LiFePO4 Battery

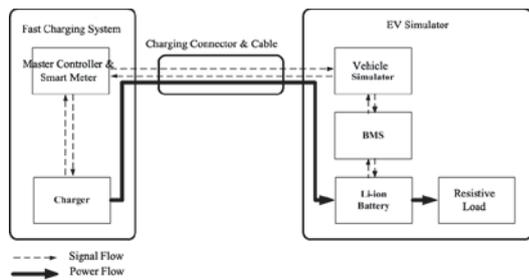


Fig. 16. Block Diagram of EV Simulator

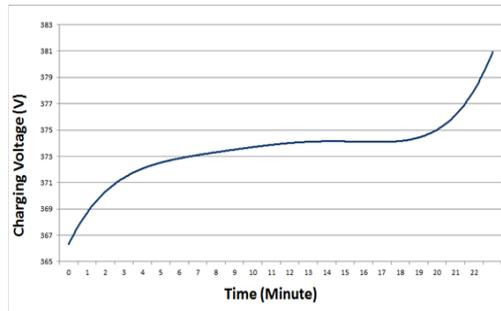


Fig. 17. Voltage plot of 320V 60Ah LiFePO2 battery for charging time measurement

charging procedure, EV simulator is designed. Designed EV simulator communicates with BMS to receive battery information and simulates vehicle's other states as EV. EV simulator consists of charging connector, charging cable, vehicle simulator, 320V 20kWh Li-ion phosphate battery pack and resistive load. EV Simulator is set up as Fig. 15. Fig. 16. Shows block diagram of test set up with EV simulator. Currently used for the full speed EV, 320V and 19.2kWh LiFePO4 batteries were experimented with EV Simulator to measure charging time and charging function. Fig. 17. shows charging voltage based on charging time. And, operation performance and algorithm of MC and smart meter, charging performance of 60kW fast charger, charging procedure is verified with EV Simulator test.

IV. CONCLUSIONS

In this paper, implementation of electric vehicle (EV) fast charging system was explained in view point of a master controller communicating with battery managements system (BMS) and EV for safe charging, a smart meter for billing and metering, a charging connector and the output stage formed by six modules of 10kW DC-DC converter for stable output with the input module for passive power factor correction and reducing the ripple of D.C. voltage, Implemented 60kW fast charging system generates output voltage ranges from 50-V to 500-V and maximum output current of 150-A. And, it is tested with a variety of batteries aimed from NEV to full-speed EV and EV simulator consisted of 20kWh LifePO2 battery to verify excellent performance as a fast charging system. From the experiments, maximum efficiency was measured as 98.5% for 10kW DC-DC module, and 97% for a 60kw AC to DC EV fast charging system including rectifying circuits. For the fast

charging of 320V, 19.2kWh LiFePO4 battery, the charging time from 10% to 90% SOC was measured as 17 minutes. It was verified from various kinds of tests that proposed converter is suitable for the high efficiency EV fast charging system which is usually operated at maximum rated charging current condition. The developed EV rapid charger was installed at Korean EV test infrastructure and practical charging test with various kinds of EVs has been now performing.

REFERENCES

- [1] Kutkut, N.H.; Divan, D.M.; Novotny, D.W.; Marion, R., "Design considerations and topology selection for a 120 kW IGBT converter for EV fast charging," *Power Electronics Specialists Conference, 1995. PESC '95 Record., 26th Annual IEEE*, vol.1, no., pp.238,244 vol.1, 18-22 Jun 1995
- [2] Kutkut, N.H., "A full bridge LCL resonant battery charger for an EV conductive coupler," *Power Electronics Specialists Conference, 1998. PESC 98 Record. 29th Annual IEEE*, vol.2, no., pp.2069,2075 vol.2, 17-22 May 1998
- [3] Klontz, K.W.; Esser, A.; Wolfs, P.; Divan, D.M., "Converter selection for electric vehicle charger systems with a high-frequency high-power link," *Power Electronics Specialists Conference, 1993. PESC '93 Record., 24th Annual IEEE*, vol., no., pp.855,861, 20-24 Jun 1993
- [4] Ying-Chun Chuang; Yu-Lung Ke; Hung-Shiang Chuang; Yu-Min Chen, "Analysis and Implementation of Half-Bridge Series-Parallel Resonant Converter for Battery Chargers," *Industry Applications, IEEE Transactions on*, vol.47, no.1, pp.258,270, Jan.-Feb. 2011
- [5] Yilmaz, M.; Krein, P.T., "Review of Battery Charger Topologies, Charging Power Levels, and Infrastructure for Plug-In Electric and Hybrid Vehicles," *Power Electronics, IEEE Transactions on*, vol.28, no.5, pp.2151,2169, May 2013
- [6] Batarseh, I.; Siri, K., "LLC-type series resonant convertor with PWM control," *Circuits, Devices and Systems, IEE Proceedings -*, vol.141, no.2, pp.73,81, Apr 1994
- [7] Soeiro, T.B.; Muhlethaler, J.; Linner, J.; Ranstad, P.; Kolar, J.W., "Automated Design of a High-Power High-Frequency LCC Resonant Converter for Electrostatic Precipitators," *Industrial Electronics, IEEE Transactions on*, vol.60, no.11, pp.4805,4819, Nov. 2013
- [8] Lee, J.Y.; Chae, H.J., "6.6kW On-Board Charger Design Using DCM PFC Converter with Harmonic Modulation Technique and Two-Stage DC/DC Converter," *Industrial Electronics, IEEE Transactions on*, vol. PP, no.99, pp.1,1, 0
- [9] Hyeon, B. -C; Cho, B. -H, "Analysis and Design of the $L_m C$ Resonant Converter for Low Output Current Ripple," *Industrial Electronics, IEEE Transactions on*, vol.59, no.7, pp.2772,2780, July 2012
- [10] Shih-Yu Chen; Zhu Rong Li; Chen, Chern-Lin, "Analysis and Design of Single-Stage AC/DC LLC Resonant Converter," *Industrial Electronics, IEEE Transactions on*, vol.59, no.3, pp.1538,1544, March 2012
- [11] Kuperman, A.; Levy, U.; Goren, J.; Zafransky, A.; Savernin, A., "Battery Charger for Electric Vehicle Traction Battery Switch Station," *Industrial Electronics, IEEE Transactions on*, vol.60, no.12, pp.5391,5399, Dec. 2013
- [12] Haghbin, S.; Lundmark, S.; Alakula, M.; Carlson, O., "Grid-Connected Integrated Battery Chargers in Vehicle Applications: Review and New Solution," *Industrial Electronics, IEEE Transactions on*, vol.60, no.2, pp.459,473, Feb. 2013
- [13] Pahlevaninezhad, M.; Drobnik, J.; Jain, P.K.; Bakshai, A., "A Load Adaptive Control Approach for a Zero-Voltage-Switching DC/DC Converter Used for Electric Vehicles," *Industrial Electronics, IEEE Transactions on*, vol.59, no.2, pp.920,933, Feb. 2012