Design and Performance Analysis of Ultra-Wide Bandgap Power Devices-Based EV Fast Charger Using Bi-Directional Power Converters

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Abstract –

In recent years, the solutions of sustainable energy and environmentally friendly transport are more and more important for our earth. The development and diffusion of electric vehicles (EVs) has become an important way to decrease the pollution and improve the energy efficiency. The wide-scale adoption and accelerated growth of electric vehicle (EV) use and increasing demand for faster charging necessitate the research and development of power electronic converters to achieve high-power, compact, and reliable EV charging solutions. The research will propose an off-board DC high-power density fast charging infrastructure with grid tie application. The EV station is designed by using ultra-wideband gap (UWBG) material-based power electronic devices to charge the EV vehicles in a few minutes up to an acceptable state of charge. The study will analyze the characteristics of Gallium III oxide (Ga2O3) material power devices by modeling them using MATLAB/Simulink. The research presents the simulink physical modeling of electric vehicle chargers based on Ga2O3 power devices. Design analysis of three-phase bidirectional AC/DC converter and DC/DC isolated full bridge converter is present in this project. Research implements the unity power factor control to improve the power quality requirements of the power grid. The dual active power control of converters provides a wide range of charging power for a variety of EV batteries. The study will provide high current and reliable rapid charging for currently available and upcoming future electric vehicles.

Keywords – Ultra-fast electric vehicle DC charger, Ga2O3 material power devices, AC/DC power converter, DC/DC isolated converter.

I. INTRODUCTION

Electric vehicles (EVs) are fast becoming one of the solutions to the growing need to reduce greenhouse gas emissions and improve energy efficiency. EVs not only reduce dependence on fossil fuels, but also significantly reduce environmental pollution, which is essential for the transition to a sustainable transportation system. Wide-bandgap (WBG) semiconductor technologies, such as gallium nitride (GaN) and silicon carbide (SiC), have become the spearhead of research due to their superior performance in power electronics.

Capable of operating at high voltages, temperatures and frequencies, these technologies are more efficient than traditional silicon-based devices, enabling electric vehicles to be equipped with more efficient power electronics that significantly reduce energy losses and improve fuel efficiency. The Fast-charging station uses power electronic converters to charge electric vehicles. Present technology uses silicon based power electronic devices which limit their efficiencies and switching frequency up to nearly 30kHz. Designing fast-charging stations using these materials is not suitable due to low breakdown potential, less thermal stability, and less power handling abilities. DC-DC and AC-DC converters experience very high voltage stress and reduce system efficiency. Silicon-based IGBT has a limitation of a maximum potential of nearly 6 kV. The current situation needs new substances to combat increasing demands. UWBG devices also have many other advantages like less switching transient, reduced overall size, fewer conduction losses, cutting down voltage and current stress, and efficiency. These devices will be able to handle hundreds of kV potential and can be operated at a higher frequency. Soft switching techniques can be eliminated in UWBG devices. Ga2O3 (UWBG) power devices are not commercially matured to be compared in terms of economics. However, the material Ga2O3 has advantages for device development from a perspective of economic cost due to its easy availability. These materials have a better figure of merits (FOM) and performance as compared to WBG materials. The study focuses on designing aspects of high-density DC fast chargers using efficient power devices. Most of the previous work is done on WBG devices-based DC EV fast chargers. In this research high power charger is discussed and simulated using a physical modeling tool (MATLAB) designed by UWBG power devices is presented.

II. EV BATTERY CHARGERS: PRINCIPLE OF OPERATION

This section will further elaborate the operation of EV Battery Chargers (EVBC) for both on-board and off-board systems. Internally, system of EVBC will consist of power electronic converters and control systems which control the EV battery charging. Figure 1 shows the general structure of an EVBC. It consists of two power electronic converters: one at grid side and other at battery side and digital control system which is common to both converters. The digital control system is responsible to generate gate pulses to turn the power electronics devices ON/OFF. The gate pulses are generated generally by Pulse Width Modulation (PWM) by using closed loop control algorithm. As discussed in the previous section, an EVBC is called on-board charger when the converters are installed inside the EV and it is called as off-board charger when the converters are installed outside the EV.

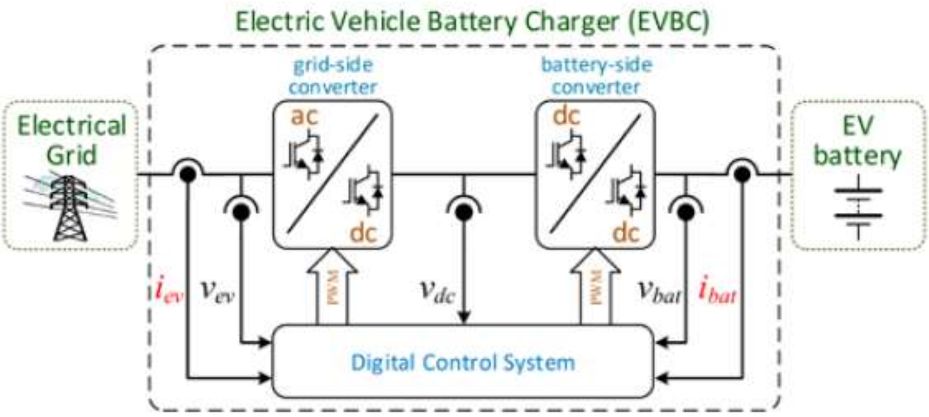


Fig:1 Structure of EV Battery Charger (EVBC) with digital control system

The interface of EV with the grid system through an on-board EVBC and an off-board EVBC is shown in Figure 2. The power converters in on-board EVBC will ensure the bidirectional power flow between the electrical grid and the EV battery.

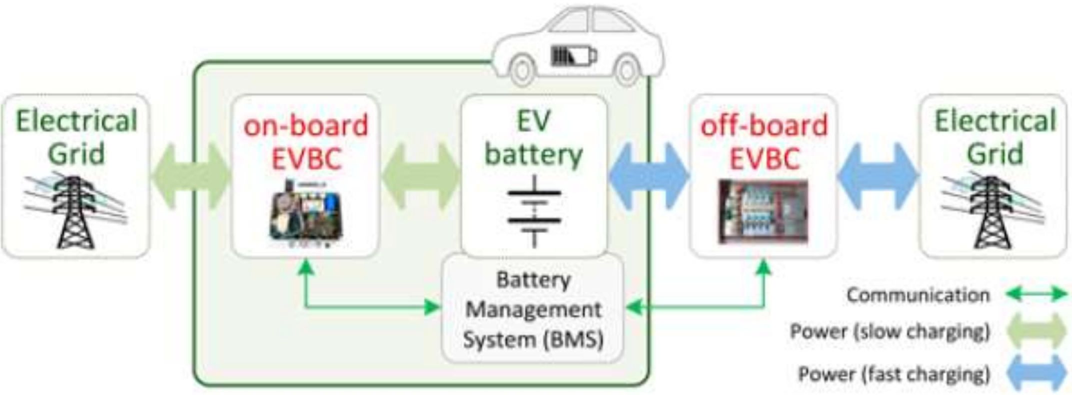


Fig:2 Interface of an EV with the power grid through an on-board EVBC and an off-board EVBC

Both on-board and off-board EVBCs use both grid side converter and battery side converter which can be controlled by either current or voltage as per the selected operating mode of the charging system as shown in Figure 2. Let's say, constant current mode till SoC (State of Charge) of the battery reaches to 75% and then constant voltage mode till full charge. The operating mode is defined by specific control algorithms in continuous interaction with Battery Management System (BMS), i.e., the BMS establishes the limits of voltage and current during the charging or discharging processes. Also, due to weight and volume restrictions from the EV perspective, normally on-board EVBCs are designed for lower power ratings than offboard EVBCs. However, in both on-board and off-board EVBCs, the converters isolate the grid and battery. This will indirectly ensure safe operation and reduce operating voltage levels (i.e., the levels between the grid voltage and the EV battery).

III. PROPOSED SYSTEM

The research proposed a Fast DC charging station that will be able to deliver high power using ultra-wideband gap (UWBG) material power devices. Ga2O3 (UWBG) power devices based 500kW (≈3×165 kW) capacity fast charger is designed for electric vehicle charging as shown in figure 3. The proposed charger is divided into two main sections: an AC-DC (PWM rectifier) converter with unity power factor control and an isolated DC-DC converter module performing a required rating charging function. Full bridge topology is used in DC-DC converter with a high-frequency transformer to obtain isolation. Three separate interleaved DC-DC converter modules topology is used to design the 500kW power EV charger. Each module has a capacity of nearly 165kW and can deliver 100-950V & 0-200A charging voltages and current, respectively. The variety of output range makes it suitable for every kind of electric vehicle and for future E-buses or heavy transport vehicles (HTV). Detailed design analysis for the 165kW charger module is discussed and analyzed below. Three-phase bi-directional power converters can perform both grid-to-vehicle (G2V) and vehicle-to-grid (V2G) operations. The bi-directional converter links the high-power AC bus with the DC bus and controls the power flow from both directions. It will work as a rectifier for AC-DC flow (rectification mode) and act as a DC-AC converter (inversion mode) to the power grid from the DC bus. High switching frequency reduces the filter and transformer size which results in a decrease in overall station weight. PI controller is used to controlling the DC-bus voltages and charging power of the EV battery. The charger module uses constant current and constant voltage (CC-CV) mode for battery charging. This method will reduce the heating effect, improve the charging time, and accomplish stable fast charging of the station. Ga2O3 power MOSFETs are driven by gate drivers which are controlled by separate AC/DC and DC/DC controllers. Figure 4 represents the overall diagram of the charging station including AC/DC and DC/DC power converters with control & power signals.

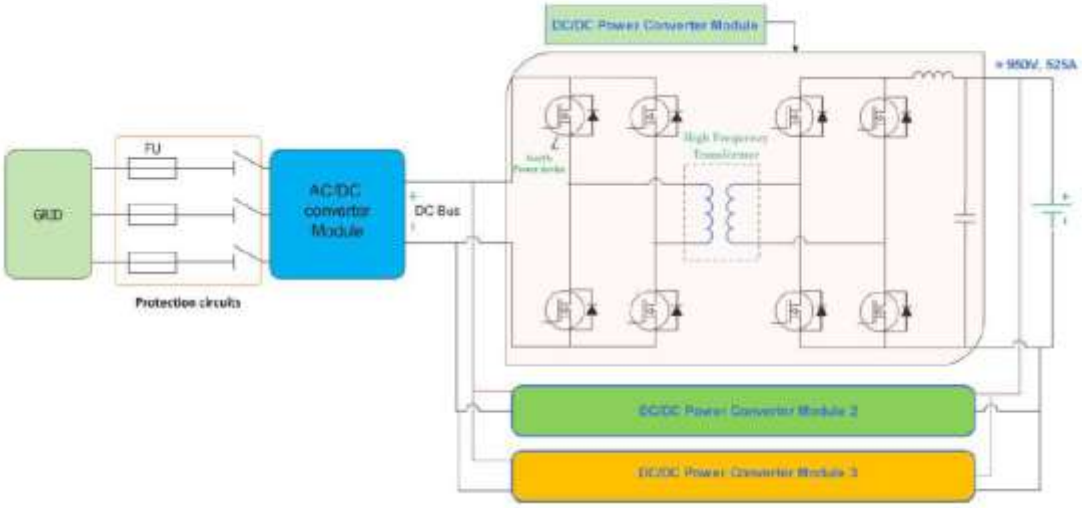
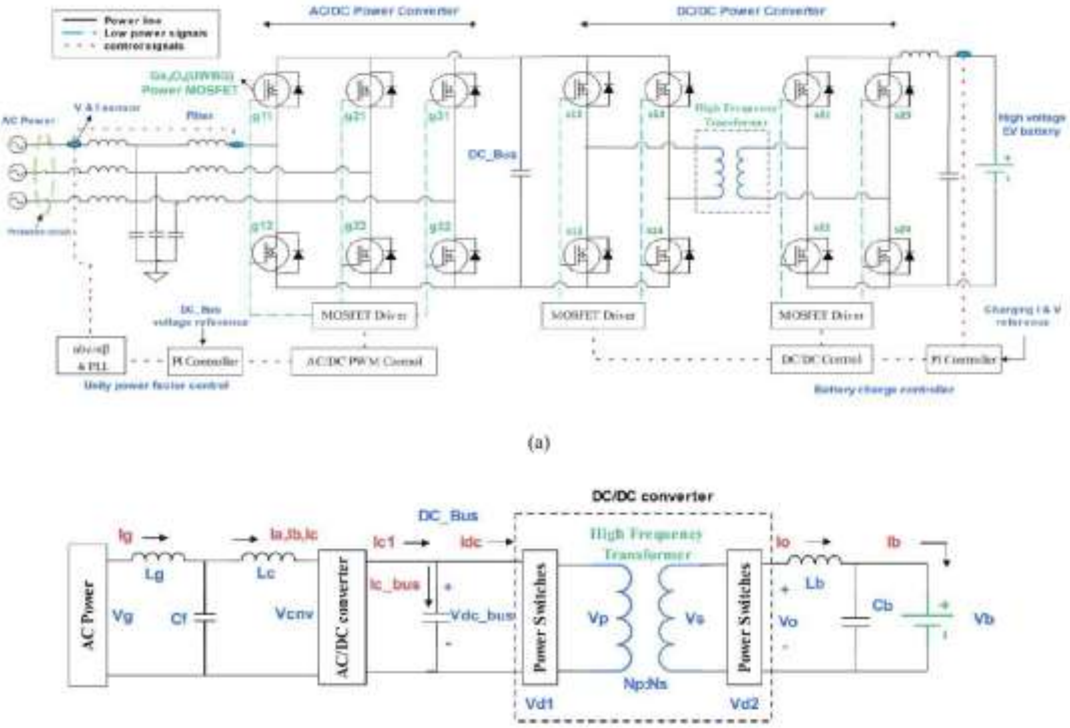


Fig.3 High Power DC ultra-fast EV charger topology.



(a)

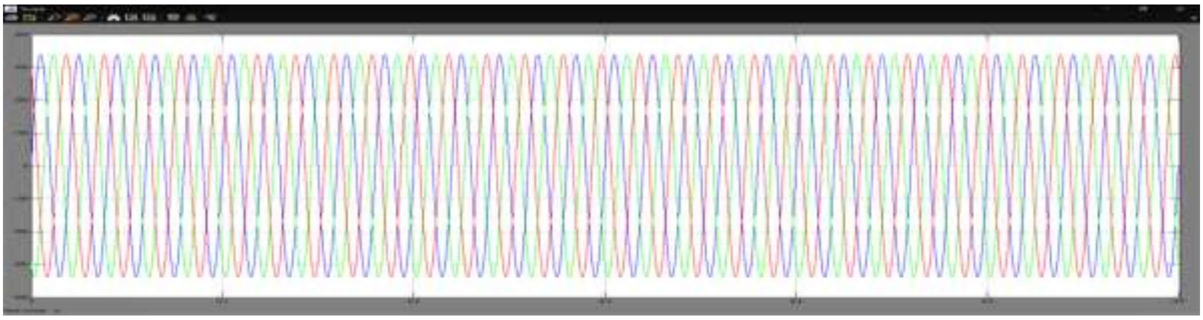
(b)

Fig.4 Ga2O3 Power devices-based EV fast charger design (a) schematic diagram of the EV charger using bidirectional converters (b) single phase equivalent EV fast charger diagram.

The input LCL filter between grid and AC/DC converter reduces harmonics and is helpful to achieving unity power factor at the grid side using PWM control. While designing the filter capacitor of the LCL filter total reactive power of the converter should be limited at grid frequency. Three phase bi-directional power converter also named PWM rectifier is a well-known converter to achieve desired DC bus voltage by a feedback control loop. Connecting an AC grid power with a DC system by using uncontrolled rectifiers established unwanted distortion in current and voltages at the grid side. PWM rectifier produces a nearly sinusoidal current at the source side and with the power factor (PF) control technique unity PF at the grid side can be achieved. From figure 4b the grid voltages can be equated with AC/DC converter voltages in the following terms by neglecting the filter capacitor. DC/DC Full bridge power converter topology is used to connect DC-bus with the EV battery. The power converter controls the wide range of charging voltage from 100 to nearly Vdc-bus along with current control. A fully controlled power switch on both the primary and secondary sides makes it a bidirectional power converter. A High-frequency transformer (HFT) provides galvanic isolation between the charger and battery. Ga2O3 power devices can switch at high frequency at fewer losses with proper biasing and complementary circuits as compared to the same power Si-based IGBT/MOSFET. The switching frequency of the DC/DC converter is selected 50kHz (fs2) by considering the frequency limitations of available high-power HFT. Assume the voltage drop of the Ga2O3 power devices of the primary and secondary side of HFT is Vd1 and Vd2, respectively.

IV. SIMULATION RESULTS

MATLAB/Simulink enables you to rapidly create models of physical systems within the Simulink environment.



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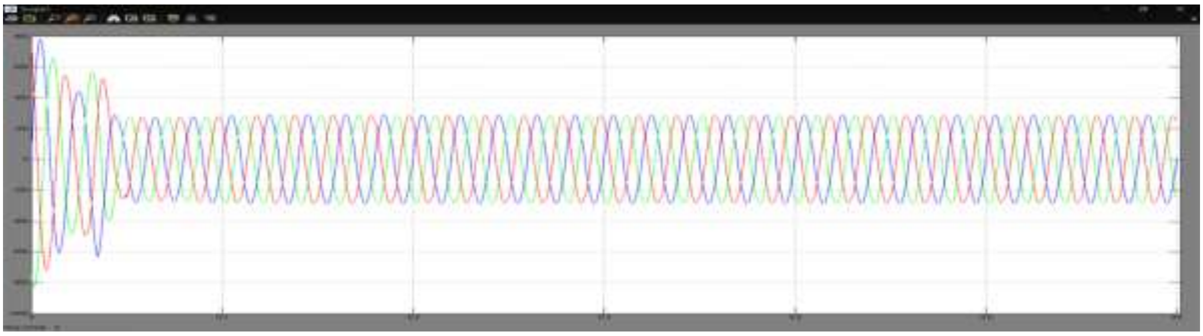


(b)

Fig.5 Grid three-phase voltage and current response during EV battery charging (a) Grid three-phase voltages (b) Grid three-phase current. (proposed system)

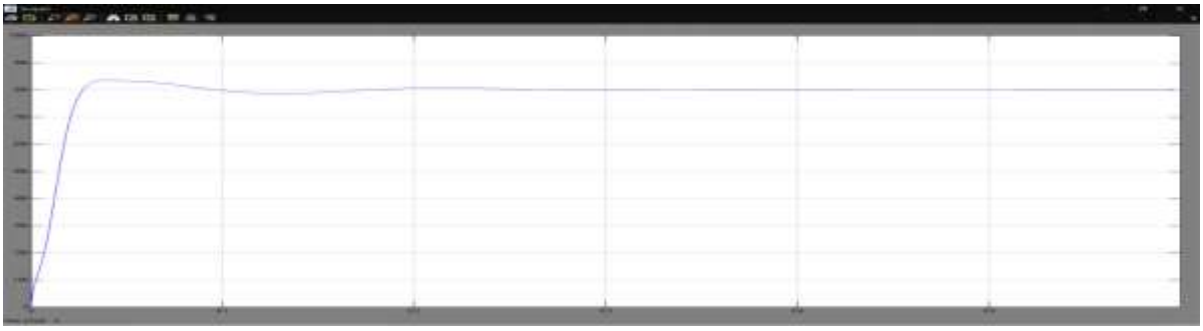
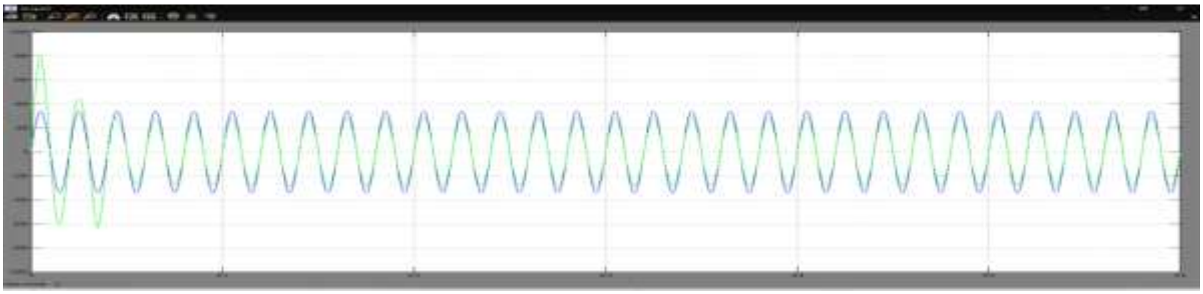


Fig.6 High voltage DC-bus voltage response. (Proposed system)

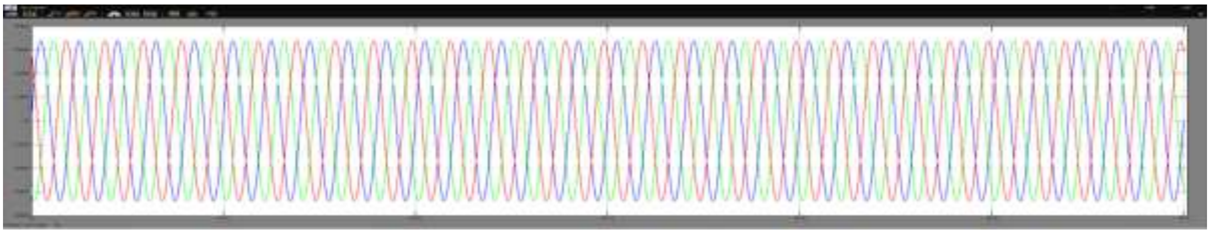
(a)



(b)

Fig.7 Power Grid unity power factor control (a) Grid active and reactive power (b) Grid phase voltage and current. (Proposed system)

Three-phase Ga2O3-based bidirectional AC-DC converter topology connects the AC grid with the DC voltage bus. A DC capacitor is connected across DC-bus to provide better voltage regulation. The bidirectional AC-DC converter can operate in two modes, rectification and inversion mode which is useful for grid-to-vehicle and vehicle-to grid power transfer. In simulation only rectification mode is discussed which is charging of high voltage EV battery from gird. Figures 5 & 6 show the grid three-phase V & I response and DC-bus voltage behavior. The total harmonic distortion (THD) response of the systems at the fundamental frequency of 50Hz is presented. Steady-state behavior is achieved within 0.15s of charging and starting over current can be reduced from the current limiting protection devices. The unity power factor control is applied in simulation using the phase-lock loop (PLL) technique and by abc/σβ & σβ/dq transforms. The d-axis in the d-q coordinate system controls the active power (P) and q-axis represents the reactive power (Q). To achieve a unity power factor, the reference value of the reactive power current is set to zero (igq =0) and the PWM rectifier starts operating in a unity power factor state. Grid active and reactive power with phase voltage & current response is shown in figure 7.



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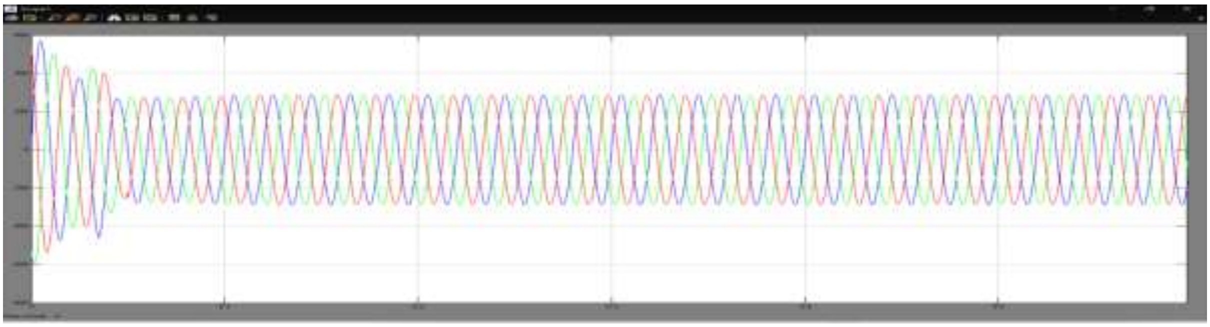


(b)

Fig.8 Grid three-phase voltage and current response during EV battery charging (a) Grid three-phase voltages (b) Grid three-phase current. (Extension system)

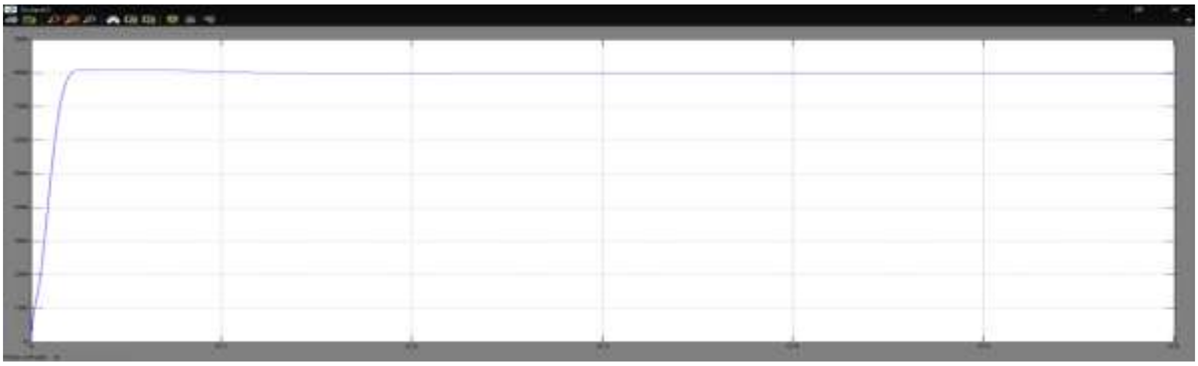
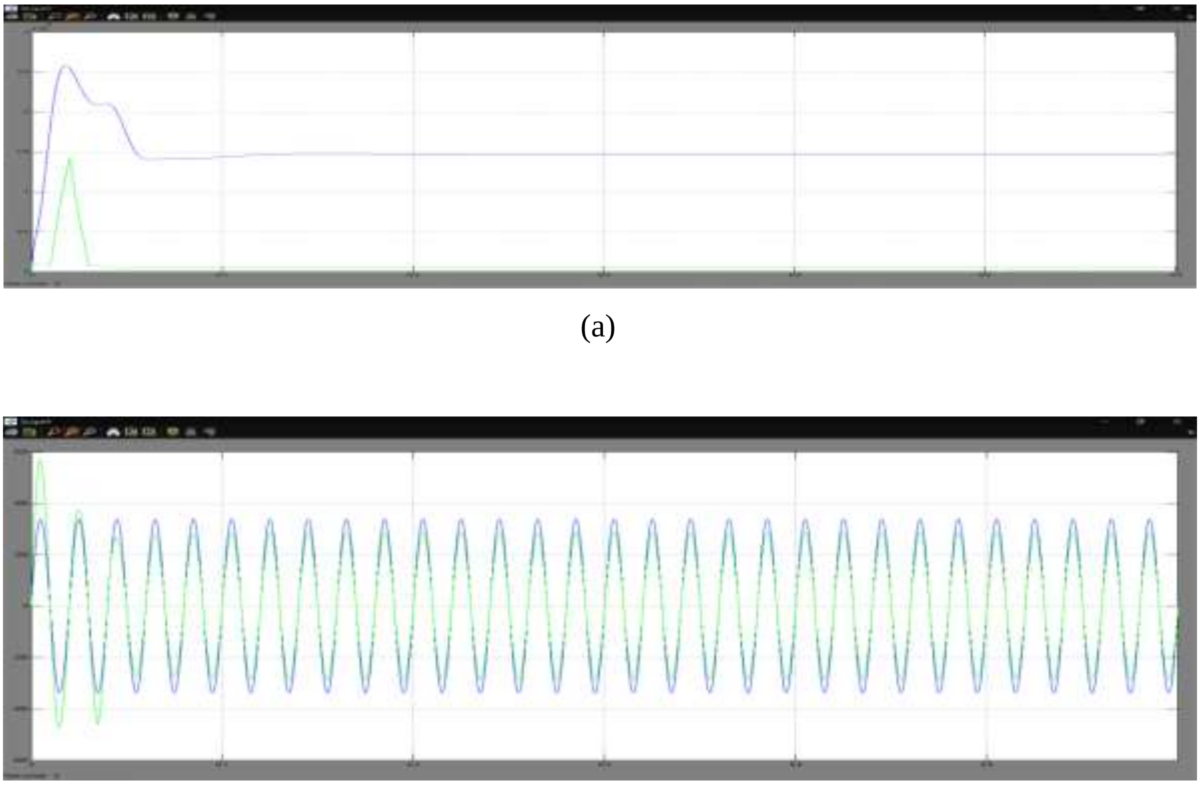


Fig.9 High voltage DC-bus voltage response. (Extension system)



(a)

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Fig.10 Power Grid unity power factor control (a) Grid active and reactive power (b) Grid phase voltage and current. (Extension system)

V. CONCLUSION

The research provides the new Ga2O3 power devices based high power Ultra-fast charger using a bi-directional power converter. The proposed solution improves the charging infrastructure power capacity, efficiency and reduces charging time. Research proves that the efficiency of high-capacity power converters increases up to more than 98% by using UWBG power devices. High electric field density, switching ability, current density with low leakage current, and forward voltage drop provide a new market for Ga2O3 power devices. The proposed solution resolves the complexity of charging for currently available or future high-voltage EV batteries. The project successfully presented the Ga2O3 power device response using MATLAB model. The dual active power control of converters provides a wide range of charging power for a variety of EV service providers. A wide range of power control reduces the complexity of using different chargers. The future Ga2O3 based power electronics devices reduce the overall weight, size, and cost of high-power electric vehicles charger.

REFERENCES

[1] A. Damm, J. Köberl, F. Prettenthaler, N. Rogler, and C. Töglhofer, ‘‘Impacts of +2 ◦C global warming on electricity demand in Europe,’’ *Climate Services*, vol. 7, pp. 12–30, Aug. 2017.

[2] G. Town, S. Taghizadeh, and S. Deilami, ‘‘Review of fast charging for electrified transport: Demand, technology, systems, and planning,’’ *Energies*, vol. 15, no. 4, p. 1276, Feb. 2022.

[3] M. A. Abella and F. Chenlo, ‘‘Photovoltaic charging station for electrical vehicles,’’ in *Proc. 3rdWorld Conf. Photovolt. Energy Convers.*, May 2003, pp. 2280–2283.

[4] S. Habib, M. M. Khan, F. Abbas, A. Ali, M. T. Faiz, F. Ehsan, and H. Tang, ‘‘Contemporary trends in power electronics converters for charging solutions of electric vehicles,’’ *CSEE J. Power Energy Syst.*, vol. 6, no. 4, pp. 911–929, Dec. 2020.

[5] M. R. Khalid, I. A. Khan, S. Hameed, M. S. J. Asghar, and J.-S. Ro, ‘‘A comprehensive review on structural topologies, power levels, energy storage systems, and standards for electric vehicle charging stations and their impacts on grid,’’ *IEEE Access*, vol. 9, pp. 128069–128094, 2021.

[6] S. Chakraborty, H.-N. Vu, M. M. Hasan, D.-D. Tran, M. E. Baghdadi, and O. Hegazy, ‘‘DC–DC converter topologies for electric vehicles, plug in hybrid electric vehicles and fast charging stations: State of the art and future trends,’’ *Energies*, vol. 12, no. 8, p. 1569, Apr. 2019.

[7] T. Gnann, S. Funke, N. Jakobsson, P. Plötz, F. Sprei, and A. Bennehag, ‘‘Fast charging infrastructure for electric vehicles: Today’s situation and future needs,’’ *Transp. Res. D, Transp. Environ.*, vol. 62, pp. 314–329, Jul. 2018.

[8] N. Sujitha and S. Krithiga, ‘‘RES based EV battery charging system: A review,’’ *Renew. Sustain. Energy Rev.*, vol. 75, pp. 978–988, Aug. 2017.

[9] M.Yilmaz and P. T. Krein, ‘‘Reviewof battery charger topologies, charging power levels, and infrastructure for plug-in electric and hybrid vehicles,’’ *IEEE Trans. Power Electron.*, vol. 28, no. 5, pp. 2151–2169, May 2013.

[10] M. Muratori, E. Kontou, and J. Eichman, ‘‘Electricity rates for electric vehicle direct current fast charging in the United States,’’ *Renew. Sustain. Energy Rev.*, vol. 113, Oct. 2019, Art. no. 109235.

[11] J.-H. Kim, I.-O. Lee, and G.-W. Moon, ‘‘Analysis and design of a hybridtype converter for optimal conversion efficiency in electric vehicle chargers,’’ *IEEE Trans. Ind. Electron.*, vol. 64, no. 4, pp. 2789–2800, Apr. 2017.

[12] A. R. Bhatti, Z. Salam, M. J. B. A. Aziz, and K. P. Yee, ‘‘A comprehensive overview of electric vehicle charging using renewable energy,’’ *Int. J. Power Electron. Drive Syst.*, vol. 7, no. 1, p. 114, Mar. 2016.

[13] J. P. Christophersen, ‘‘U.S. department of energy vehicle technologies program: Battery test manual for plug-in hybrid electric vehicles,’’ U.S. Dept. Energy Nat. Lab., Battelle Energy Alliance, ID, USA, Manual Rep. INL/EXT-15-34184, 2014.

[14] M. Budhia, G. A. Covic, J. T. Boys, and C.-Y. Huang, ‘‘Development and evaluation of single sided flux couplers for contactless electric vehicle charging,’’ in *Proc. IEEE Energy Convers. Congr. Expo.*, Sep. 2011, pp. 614–621.

[15] M. Etezadi-Amoli, K. Choma, and J. Stefani, ‘‘Rapid-charge electricvehicle stations,’’ *IEEE Trans. Power Del.*, vol. 25, no. 3, pp. 1883–1887, Jul. 2010.

[16] S. Bae and A. Kwasinski, ‘‘Spatial and temporal model of electric vehicle charging demand,’’ *IEEE Trans. Smart Grid*, vol. 3, no. 1, pp. 394–403, Mar. 2012.

[17] F. He, D. Wu, Y. Yin, and Y. Guan, ‘‘Optimal deployment of public charging stations for plug-in hybrid electric vehicles,’’ *Transp. Res. B, Methodol.*, vol. 47, pp. 87–101, Jan. 2013.

[18] R. Collin, Y. Miao, A. Yokochi, P. Enjeti, and A. von Jouanne, ‘‘Advanced electric vehicle fast-charging technologies,’’ *Energies*, vol. 12, no. 10, p. 1839, May 2019.

[19] M. Yilmaz and T. Philip Krein, ‘‘Review of charging power levels and infrastructure for plug-in electric and hybrid vehicles,’’ in *Proc. IEEE Int. Electr. Vehicle Conf. (IEVC)*, Mar. 2012, pp. 1–8.

[20] V. A. Boicea, ‘‘Energy storage technologies: The past and the present,’’ *Proc. IEEE*, vol. 102, no. 11, pp. 1777–1794, Nov. 2014.

[21] J. Traube, F. Lu, D. Maksimovic, J. Mossoba, M. Kromer, P. Faill, S. Katz, B. Borowy, S. Nichols, and L. Casey, ‘‘Mitigation of solar irradiance intermittency in photovoltaic power systems with integrated electric-vehicle charging functionality,’’ *IEEE Trans. Power Electron.*, vol. 28, no. 6, pp. 3058–3067, Jun. 2013.