ISSN: 2321-2152

IJMECE

International Journal of modern electronics and communication engineering

E-Mail
editor.ijmece@gmail.com
editor@ijmece.com

www.ijmece.com

ISSN2321-2152
www.ijmece .com
Vol 12, Issue 3, 2024

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

L.Venkatasewalu[1], M.Mahendra [2], V.Pavan kalyan[3], M.Madhan mohan reddy[4], K.Vamsi krishna[5], S.Kalyani[6], K.Lakshmi Narashima[7]

[1]Asst Professor and [234567]UG Students

[1,2,3,4,5,6,7] Department of Electrical and Electronics Engineering

[1,2,3,4,5,6,7]QIS College Of Engineering and Technology

ABSTRACT

The emphasis on clean and green technologies to curtail greenhouse gas emissions due to fossil fuel-based economies has originated the shift towards electric mobility. As on-road electric vehicles (EVs) have shown exponential growth over the last decade, so have the charging demands. The provision of charging facilities from the low-voltage network will not only increase the distribution system's complexity and dynamics but will also challenge its operational capabilities, and large-scale upgrades will be required to meet the inevitably increasing charging demands. An ultra-fast (UF) charging infrastructure that replicates the gasoline refuelling network is urgently needed to facilitate a seamless transition to EVs and ensure smooth operation. This paper presents a review of state-of-the-art DC fast chargers, the charging infrastructure's current status, motivation, and challenges for medium-voltage (MV) UF charging stations (UFCS). Furthermore, we consider the possible UFCS architectures and suitable power electronics topologies for UF charging applications. To address the peak formation issues in the daily load profile and high operational expenses of UFCSs, integration of renewable energy sources and energy storage systems due to their technological and economic benefits is being considered. The benefits of line frequency transformer (LFT) replacement with a solid-state transformer (SST), SST models, SST-based UF chargers, and MV SST-based UFCS architectures, as well as related MV active front-end and back-end power electronics topologies, are presented. Finally, the application of micro grids' hierarchical control architecture is considered for chargers and system-level control and management of UFCSs.

ISSN2321-2152
www.ijmece .com
Vol 12, Issue 3, 2024

I. INTRODUCTION

Reliance on fossil fuels has significantly increased the concentration of greenhouse gases (GHG) in the atmosphere, resulting in global warming and ecological disorders. With increased awareness, carbon dioxide (CO_2) emissions and the continuous rise in the global mean temperature have become central points of growing concern in the international community [1]. In this regard, the adaptation of the Paris agreement by 196 countries in December 2015 is an example of the collaborative efforts to combat climate change [2]. Under the umbrella of this agreement, various organizations have been working on multiple fronts, ranging from reforestation to the induction of renewable and sustainable technologies having minimal GHG emissions. Furthermore, the transportation sector has been identified as one of the most promising areas that can contribute significantly to achieving the net zero-emission (NZE) goal [3], [4]. Even though commercial production of electric vehicles (EVs) began in 1996 and the EV initiative (EVI), a multi-governmental policy forum, was founded in 2010. However, the adoption of the Paris agreement accelerated the transition towards electric mobility (e-mobility), and campaigns such as EV30@30 [5], with the inspirational aim of achieving a 30% sales share of EVs by 2030, and the global commercial vehicle drive to zero [6], to by 2025, were launched in 2017 and 2020, respectively.

In addition, to support low and middle-income countries' shift towards e-mobility, the global environment facility program for global e-mobility is set to be launched before 2022 [7]. Historically, the three major challenges to EV adoption were high purchase prices, range anxiety, and a lack of charging infrastructure [8]. However, the advancements in battery technology, power electronics, and magnetic and the various subsidies and incentives have substantially normalized these challenges. The exponentially increasing number of on-road EVs is primarily aided by numerous government initiatives to make EVs more accessible and affordable to customers. Section II presents the details of some of these economic perks offered by different countries. In terms of range anxiety, progressions in battery and electric propulsion drive-train technologies have remedied the problem. For instance, the average specific energy of a battery was 110 W-hour per kilogram (Wh/kg) in 2010 [9]. Presently, the specific energy of various lithium-ion (Li-ion) batteries lies between 200 and 250 Wh/kg, and projected to reach 450 Wh/kg till 2030 [10]. Similarly, battery energy density has improved from 310 W-hour per liter (Wh/L) to 580 Wh/L in the recent decade, with the next goal of 1100 Wh/L by by 2030 [11], [12]. Aside from batteries, traction inverters' power density also

ISSN2321-2152
www.ijmece .com
Vol 12, Issue 3, 2024

improved from 10 kilowatts per liter (kW/L) to 30 kW/L and expected to reach 65 kW/L by 2030 [13].

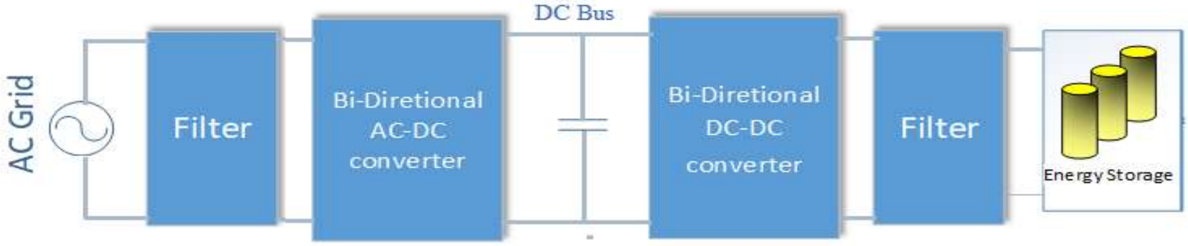


FIGURE 1. General bi-directional EV charging topology.

Similarly, inverters' peak efficiency increased from 92% to 96%; wide band-gap technologies such as silicon carbide (SiC) and gallium nitride (GaN) have shown efficiencies up to 99% [14], [15]. Moreover, it is projected that the applications of SiC and GaN in traction inverters will achieve a power density of 65 kW/L [16], and 800 V internal DC-link will achieve up to 40% reduction in volume [17]. Although, the range anxiety and battery cost issues have been significantly resolved with the earlier mentioned developments.

However, EVs' range per charge is still limited as compared to gasoline vehicles have an average energy density of 12000 Wh/kg [18], [19]. Even exclusive of battery limitations, the absence of a refuelling infrastructure capable of rapidly replenishing an EV's battery, especially during longer trips, still remains a decisive barrier. In countries with emerging numbers of on-road EVs, the drivers demand more flexible and efficient charging infrastructure. For over 10 million EVs, the reported num installed EV supply equipment (EVSE) was 1.3 million globallytill 2020, with only 30% of which were fast chargers. The statistics of public charging infrastructure in EV-concentrated regions are presented in Section II.

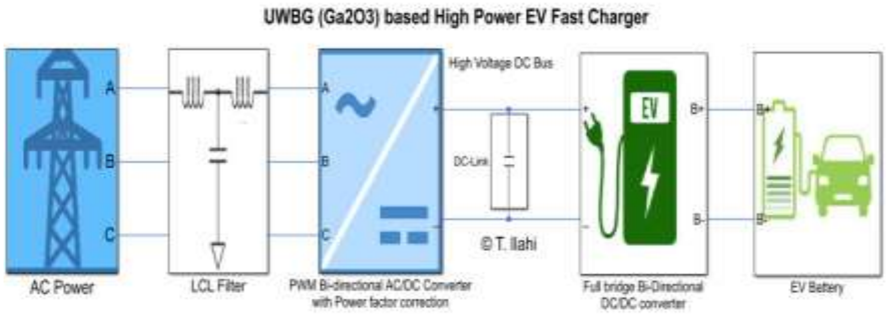


FIGURE 2. *Simscape MATLAB model of UWBG high power EV fast charger*

Presently, low-voltage (LV) distribution networks power the slow and fast charging facilities. Coupled with the charging rates, another point of concern is the exponential growth in EVs. For the projected number of 40 million on-road EVs by 2050 [20], the provision of charging facilities from the LV network will not only increase the distribution system's complexity and dynamics. However, it will also challenge its operational capabilities, and large-scale upgrades will be required to meet the inevitably increasing charging demands. For this reason, an ultra-fast (UF) charging infrastructure with a dedicated medium-voltage (MV) grid connection is urgently required to replicate the existing gas oline infrastructure. This article reviews EVs and corresponding EVSEs' current trends, presents the anticipated number of on-road EVs and indicates the exponential increase in the past decade. To facilitate a seamless transition towards EVs, state-of-the-art DC fast chargers have been evaluated and emphasized in grouping several fast chargers to form a UF charging station (UFCS). State-of-the-art DC fast chargers have been evaluated, and the grouping of several fast chargers to form a UFCS has been emphasized. A 350 kW can recharge a 60 kWh battery to more than 90% state of charge (SOC) in 10 minutes. However, such an impulsive charging demand requires the grid to maintain high spinning reserves; therefore, this issue has been addressed with the energy storage systems in UFCSs. A solid-state transformer (SST) poses numerous advantages over conventional line frequency transformers(LFT), especially in AC/DC applications, SST models, SST-based UF chargers, and MV SST-based UFCS architectures have been presented. Section IV elaborates on the motivation, requirements and challenges for MV connected UFCSs.

The rest of the paper is organized as follows: Section II provides an overview of EV trends, initiatives aimed at facilitating a seamless transition towards e-mobility, the evolution of battery technologies, and EVSE global statistics. The working principles of alternating current (AC) and direct current (DC) chargers and most relevant international standards are presented in Section III. The motivation and challenges for UFCSs are addressed in Section IV, and Section V look at the AC and DC common bus architectures of UFCSs, respectively. Moreover, the benefits of replacing a line-frequency transformer (LFT) with a solid-state transformer (SST) and SST-based possible configurations have also been explained in Section V. In Section VI, the significance of renewable energy sources (RESs) and energy storage systems (ESSs) integration, as well as their impacts on peak demand and operational expenses of UFCSs, have been discussed. Section VII discusses the future trends and suggestions proposed in the literature regarding EVs and EVSEs, SST, and SST-based integration of UFCSs with MV-grid. Section VIII presents a review of the AC/DC and DC/DC power electronics converters that have been extensively studied for EV charging applications. Moreover, the potential MV AC/DC and DC/DC that can be used for UFCS MV-grid integration have been presented in Section VIII. Section IX accesses hierarchical control structures for dynamic response and ancillary grid services such as power system frequency and voltage.

SIMULATION MODEL AND RESULTS

Physical modelling of EV chargers is performed using Sim scape (MATLAB) to verify the theoretical design and above calculations. The Block model of a high-power fast EV charger based on subsystem is shown in figure 5 and system parameters are summarized in Table. MATLAB Sim scape enables you to rapidly create models of physical systems within the Simulink environment [46]. Simscape helps build physical power converter models based on physical connections and configurable SPICE models which effectively provide the designed system's dynamic response [47]. The dynamic behavior of Ga2O3 Power MOSFET is verified by comparing characteristic analysis of the MOSFET model with Salvico TCAD as shown previously in figure 2. Ga2O3 power MOSFET module used in Simscape physical power converters modeling with the characteristic curve is shown in figure 6. Three-phase Ga2O3-based bidirectionalge regulation, chargers, UFCS-level control, energy management .

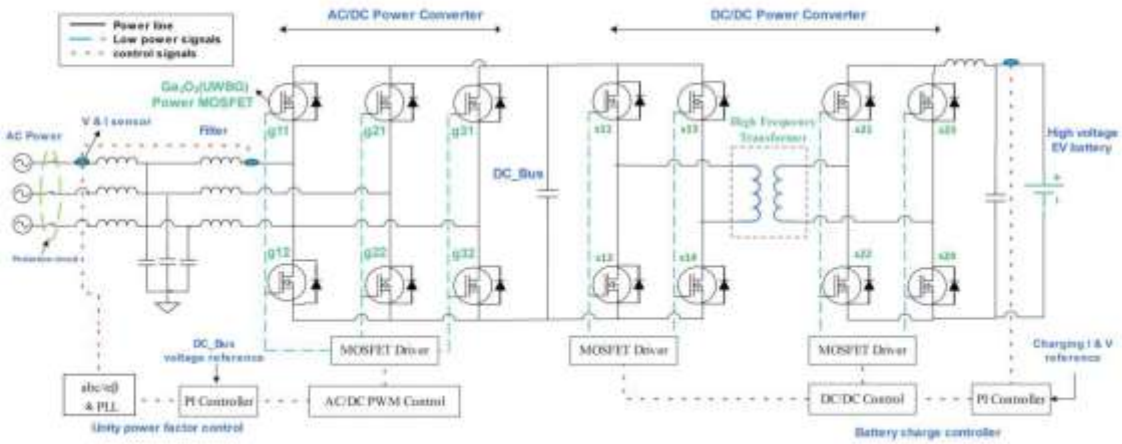
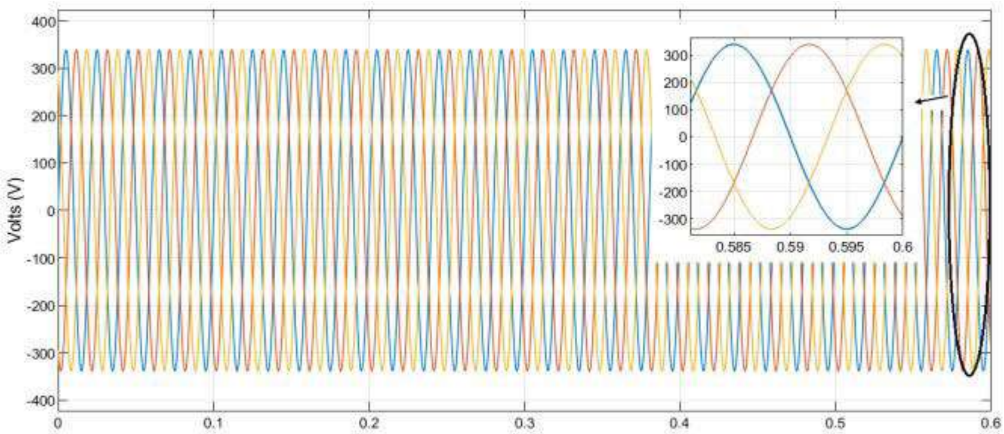
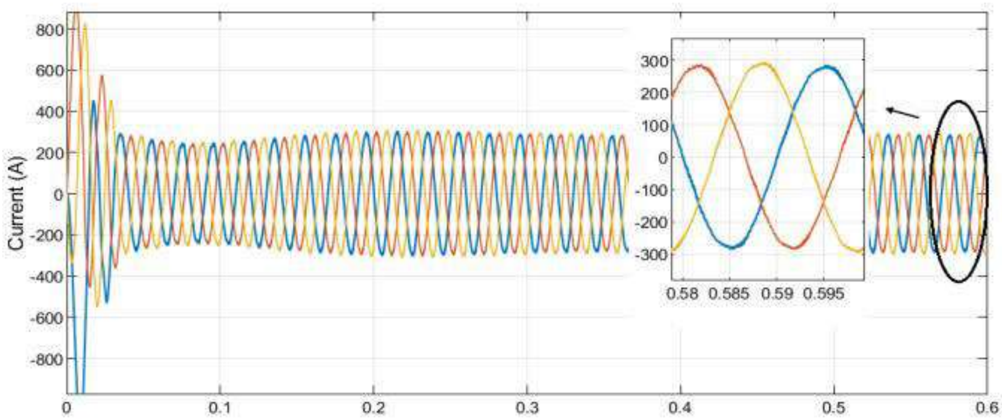


FIGURE 3. Sims cape MATLAB model of UWBG high power EV fast charge AC-DC

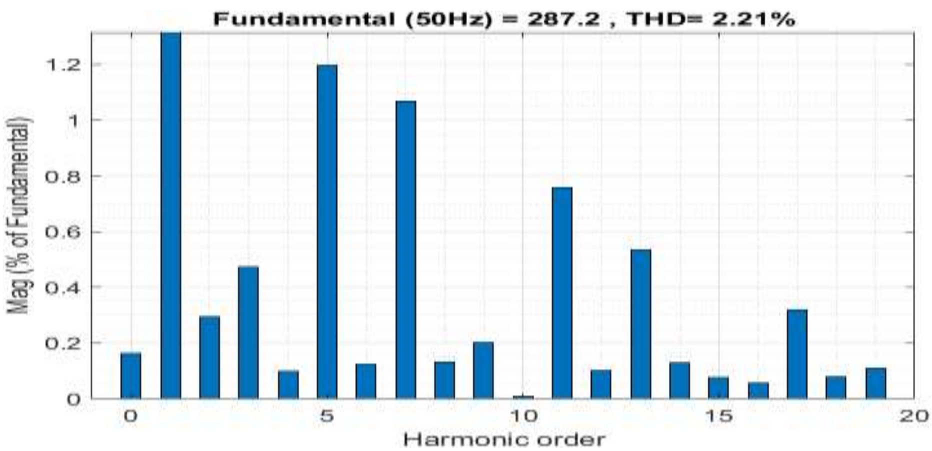
converter topology connects the AC grid with the DC voltage bus. A DC capacitor is connected across DC-bus to provide better voltage regulation. The bidirectional AC-DC converter can operate in two modes, rectification and inversion mode which is useful for grid-to-vehicle and vehicle-to grid power transfer. In simulation only rectification mode is discusse which is charging of high voltage EV battery from gird. Figures 3& 4 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 in figure. Steady-state behaviour is achieved within 0.15s of charging and starting over current can be reduced from the current limiting protection devices



(a)



(b).



(c)

FIGURE 4. Grid three-phase voltage and current response during EV battery charging (a) Grid three-phase voltages (b) Grid three-phase current (c) Total harmonic distortion (THD).

The full-bridge topology of the DC/DC converter is used to connect the DC bus and battery pack. The output filter circuit consists of inductor Lb and capacitor Cb. The DC bus voltage and current of the EV station is the main control object. Therefore, the most widely used control strategy, the voltage outer-loop, and current inner-loop double PI control are applied in this simulation. The maximum charging current is set to 200A for the charging port during constant current (CC) operation for a bulk mode of charging as shown in figure 10. In the simulation, only bulk mode constant current charging is observed using high-power Ga2O3 power devices. Dynamic performance of EV fast charger using Simscape model illustrates the correct response of both AC/DC & DC/DC power converter using Ga2O3 power devices. The system starts stable charging of high voltage EV battery

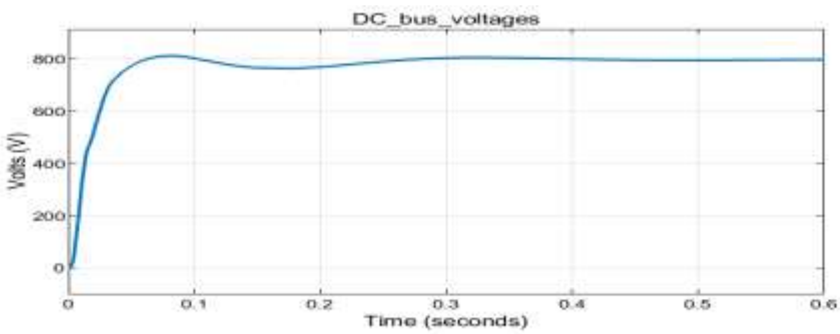


fig.5. *High voltage DCbus voltage response*.

ISSN2321-2152
www.ijmece .com
Vol 12, Issue 3, 2024

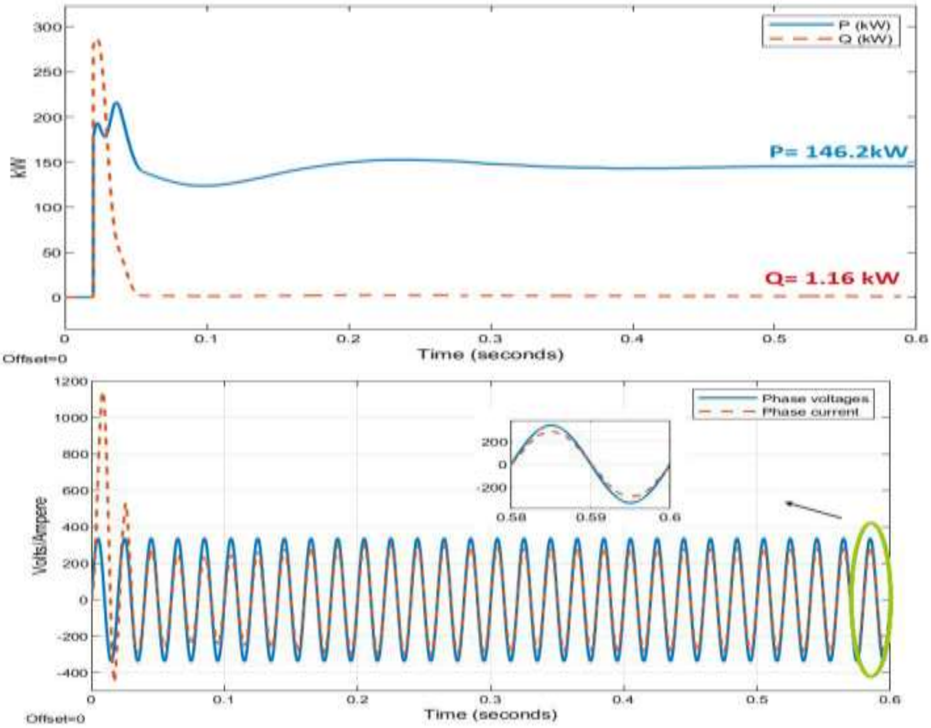


Fig5.. *Power Grid unity power factor control (a) Grid active and reactive power (b) Grid phase voltage and current within 0.15s using dual separate active control systems.*

EV battery initial state of the charger (SOC) is 20% the charging response over 0.6s is observed in figure 11. The proposed charger can charge a 100kWh capacity EV battery within 10 minutes up to 80% SOC. Where as, approximately100kWh capacity EV vehicle will charge in 15 to 45 minutes from the currently available DC fast charger. Nearly 30% of charging time will be reduced from the proposed EV charger.

The accurate measurement of the total charging time of the battery needs a sophisticated algorithm. The simplified equation to estimate the charging time of the charger is given. where, Bcap is capacity of EV battery and charger defines the EV charger power. The latest EV model like the Mercedes EQS, Ford Mustang Mach-E, Tesla Model S, etc. has a battery capacity of 100kWh. The total estimated speed of charging a 100kWh battery from 0 to 100% is approximately 12 minutes.

CONCLUSION

Regardless of the exponential increase in the number of on-road EVs and their environmental benefits, the absence of an adequate charging infrastructure to provide rapid and reliable charging facilities during long trips poses challenges to the smooth operation of EVs. To address this issue without compromising the power system's stability and reliability due to the unexpected arrival and impulsive charging demands of EVs, UFCSs with integrated RESs and ESSs having flat load curves and minimal operational expenses are the need of the hour. The standard AC bus design is adopted by state-of-the-art UFCSs due to mature AC/DC rectifier technology, well established standards for AC distribution systems, separately developed standards for AC bus UFCSs, and standardized protection methods. In addition to EVs' DC power requirements, the inherent DC nature of RESs and ESSs increases the number of conversion stages in the AC bus architecture and reduces efficiency. On the other hand, standard DC bus design minimizes the conversion stages due to one central AC/DC at the front-end with simple control improved efficiency. It enables the use of partial power converters. Although no standards for DC systems' coordinated control have been developed yet, at a voltage level below 1 kV, DC bus architecture can comply with the AC standards. Suitable power electronics converters for AC and DC bus designs are presented and compared. The charging profile of EVs requires a converter to operate within a broad range of voltage and power gains while providing high efficiency and high power density. A 350 kW DC UF charger shortens the recharging duration to 10 minutes, which is comparable to the refueling experience of gasoline vehicles. However, because of the associated high power demands, increased capital investment, and MV grid connection, installing a single UF charger is prohibitively expensive. In contrast, a UFCS with multiple chargers makes more economic sense than a single-port charger. The high power demand for UF charging means the UFCS acts as a massive load center for the power system, and integrated RESs.and ESSs not only normalized the power demand and reduced the operational expenses of the UFCSs significantly but also enabled UFCSs to provide ancillary grid services such as voltage and frequency support services.

The replacement of the LFT with the SST provides the voltage step-down, conversion, and isolation with several unique features, suconvertibility, better controllability, reduced footprint, higher efficiency at light load, modularity, fault-tolerant structure, A[nd bidirectional power flow. However, SST technology is still at the research and development phase and has not matured yet. Some of the common concerns and deficiencies that must be addressed are as follows:

_ The use of SS devices significantly reduces the weight and size of SST, but it also increases the price of SST many times more than LFT. As a result, the use of LV SS devices with low losses and HF operation characteristics can help to reduce the required heat sinks and passive components, contributing to the overall cost reduction of SST. Similarly, the use of wide-bandgap devices such as SiC and GaN can help to reduce the number of SS devices and their corresponding heat sinks. _ Although SST offers high power density, it suffers from efficiency and reliability issues. Most of the MV and HV applications are currently realized by modular SSTs, which results in high cost and power quality concerns. The single-cell SST is a promising approach, but it experiences reliability concerns due to its non-modular structure.

_ A robust control and protection mechanism is the key performance indicator of SST. Due to the limited in-built overvoltage and over current protection schemes, SST's protection reliability is lower than LFT. To compensate for this drawback, external protection devices compromised the weight and size of the SST. The use of SS protection devices, on the other hand, requires a less robust control structure, but it is still far away from practical implementation at the MV level. _ Real-time data exchange between the SST and the grid station is required for advanced protection schemes. As a result, communication systems that satisfy the latency, security, and reliability requirements need to be selected appropriately.

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, doi: 10.1016/j.cliser.2016.07.001.

[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, doi: 10.3390/en15041276.

[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, doi: 10.17775/CSEEJPES.2019.02700.

[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, doi: 10.1109/ACCESS.2021.3112189.

[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, plugin hybrid electric vehicles and fast charging stations: State of the art and future trends,’’ *Energies*, vol. 12, no. 8, p. 1569, Apr. 2019, doi: 10.3390/en12081569.

[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, doi: 10.1016/j.trd.2018.03.004.

[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, doi: 10.1016/j.rser.2016.11.078.

[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, doi: 10.1109/TPEL.2012.2212917.

[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, doi: 10.1016/j.rser.2019.06.042.

[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, doi: 10.1109/TIE.2016.2623261.

[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, doi: 10.11591/ijpeds.v7.i1.pp114-123.

[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, doi: 10.2172/1169249.

[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, doi: 10.1109/ECCE.2011.6063826.

[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, doi: 10.1109/TPWRD.2010.2047874.

[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, doi: 10.1109/TSG.2011.2159278.

[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, doi: 10.1016/j.trb.2012.09.007.

[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, doi: 10.3390/en12101839.

[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, doi: 10.1109/IEVC.2012.6183208.

[20] V. A. Boicea, ‘‘Energy storage technologies: The past and the present,’’ *Proc. IEEE*, vol. 102, no. 11, pp. 1777–1794, Nov. 2014, doi: 10.1109/JPROC.2014.2359545.

[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, doi: 10.1109/TPEL.2012.2217354.

[22] Z. Huang, Z. Li, C. S. Lai, Z. Zhao, X. Wu, X. Li, N. Tong, and L. L. Lai, ‘‘A novel power market mechanism based on blockchain for electric vehicle charging stations,’’ *Electronics*, vol. 10, no. 3, p. 307, Jan. 2021, doi: 10.3390/electronics10030307.

[23] G. Konstantinidis, F. Kanellos, and K. Kalaitzakis, ‘‘A simple multiparameter method for efficient charging scheduling of electric vehicles,’’ *Appl. Syst. Innov.*, vol. 4, no. 3, p. 58, Aug. 2021, doi: 10.3390/asi4030058.

[24] D. S. Abraham, R. Verma, L. Kanagaraj, S. R. G. T. Raman, N. Rajamanickam, B. Chokkalingam, K. Marimuthu Sekar, and L. Mihet-Popa, ‘‘Electric vehicles charging stations’ architectures, criteria, power converters, and control strategies in microgrids,’’ *Electronics*, vol. 10, no. 16, p. 1895, Aug. 2021, doi: 10.3390/electronics10161895.

[25] H. H. Coban, W. Lewicki, E. Sendek-Matysiak, Z. Łosiewicz, W. Drożdż, and R. Miśkiewicz, ‘‘Electric vehicles and vehicle–Grid interaction in the Turkish electricity system,’’ *Energies*, vol. 15, no. 21, p. 8218, Nov. 2022, doi: 10.3390/en15218218.

[26] S. Madhusoodhanan, A. Tripathi, D. Patel, K. Mainali, A. Kadavelugu, S. Hazra, S. Bhattacharya, and K. Hatua, ‘‘Solid-state transformer and MV grid tie applications enabled by 15 kV SiC IGBTs and 10 kV SiC MOSFETs based multilevel converters,’’ *IEEE Trans. Ind. Appl.*, vol. 51, no. 4, pp. 3343–3360, Jul. 2015, doi: 10.1109/TIA.2015.2412096.

[27] R. J. Kaplar, A. A. Allerman, A. M. Armstrong, M. H. Crawford, J. R. Dickerson, A. J. Fischer, A. G. Baca, and E. A. Douglas, ''Review—Ultra-wide-bandgap AlGaN power electronic devices,'' *ECS J. Solid State Sci. Technol.*, vol. 6, no. 2, pp. Q3061–Q3066, 2017, doi: 10.1149/2.0111702jss.

[28] S. Srdic and S. Lukic, ''Toward extreme fast charging: Challenges and opportunities in directly connecting to medium-voltage line,'' *IEEE Electrific. Mag.*, vol. 7, no. 1, pp. 22–31, Mar. 2019, doi: 10.1109/MELE.2018.2889547.

[29] X. Yan, I. S. Esqueda, J. Ma, J. Tice, and H. Wang, ''High breakdown electric field in β-Ga2O3/graphene vertical barristor heterostructure,'' *Appl. Phys. Lett.*, vol. 112, no. 3, Jan. 2018, Art. no. 032101, doi: 10.1063/1.5002138.

[30] M. H. Wong and M. Higashiwaki, ''Vertical β-Ga2O3 power transistors: A review,'' *IEEE Trans. Electron Devices*, vol. 67, no. 10, pp. 3925–3937, Oct. 2020, doi: 10.1109/TED.2020.3016609.

[31] M. Zhang, Z. Liu, L. Yang, J. Yao, J. Chen, J. Zhang,W.Wei, Y. Guo, and W. Tang, ''β-Ga2O3-based power devices: A concise review,'' *Crystals*, vol. 12, no. 3, p. 406, Mar. 2022, doi: 10.3390/cryst12030406.

[32] S. T. Meraj, N. Z. Yahaya, M. S. H. Lipu, J. Islam, L. K. Haw, K. Hasan, M. S. Miah, S. Ansari, and A. Hussain, ''A hybrid active neutral point clamped inverter utilizing Si and Ga2O3 semiconductors: Modelling and performance analysis,'' *Micromachines*, vol. 12, no. 12, p. 1466, Nov. 2021, doi: 10.3390/mi12121466.

[33] T. Razzak, H. Xue, Z. Xia, S. Hwang, A. Khan, W. Lu, and S. Rajan, ''Ultra-wide band gap materials for high frequency applications,'' in *IEEE MTT-S Int. Microw. Symp. Dig.*, Jul. 2018, pp. 17–19, doi: 10.1109/IMWSAMP. 2018.8457144.

[34] Y. Zhang and T. Palacios, ''(Ultra) wide-bandgap vertical power Fin- FETs,'' *IEEE Trans. Electron Devices*, vol. 67, no. 10, pp. 3960–3971, Oct. 2020.

[35] I. Lee, A.Kumar, K. Zeng, U. Singisetti, and X.Yao, ''Modeling and power loss evaluation of ultra wide band gap Ga2O3 device for high power applications,'' in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Oct. 2017, pp. 4377–4382, doi: 10.1109/ECCE.2017.8096753.