A MW scale charging architecture for supporting extreme fast charging of heavy-duty electric vehicles

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***Abstract*— Extreme fast charging of electric vehicles technologies is coming. Heavy duty electric vehicles (HD-EVs) are in development and are expected to have multipliers bigger in battery capacity compared to the light duty counterparts. To meet short charging times, MW charging will be necessary. This paper presents a MW scale extreme DC fast charger with a communication and control architecture for HD-EVs. The system is validated in a controller hardware in the loop platform.**

***Keywords*—**

Transportation electrification technology has witnessed leaps in development. Consumer models of plug-in hybrid electric (PHEV) and electric vehicles (EV) are expanding [1] as battery technologies have continued to mature and costs have begun to recede [2]. Today, many automotive manufacturers offer EVs with 30kWh-50kWh batteries with some providing systems nearing or exceeding 100kWh [3], [4]. As the battery capacities increase (to support both longer distances and larger vehicles), fast charging infrastructure is becoming more crucial. Across the U.S., DC fast charging infrastructure is being adopted that targets reduced charging times for vehicles in the range of 15 to 30 mins [5].

Beyond consumer vehicles (or light-duty vehicles), heavy-duty electric vehicles (HD-EV) are also growing in interest. Electrification of these vehicle types is expected to have significant financial and environmental benefit for the shipping and construction industries [6]. However, a recent report [7] also highlighted the challenges of HD-EVs: extension in lifetime, multipliers in power and torque for towing, and significantly greater energy storage capacity requirements. Already several semi-truck manufacturers have suggested battery capacities in the range of 250-750kWh [8]-[9], multipliers larger in scale compared to their light duty EV counterparts. As such, today's DC fast charging systems will not be sufficient to support these vehicles in timely charging.

As presented in [10]-[11], systems integration of extreme fast charging stations (xFC) to distribution networks will occur with direct medium voltage AC connections due to the potential MW of power required. As a result, electrical system topologies for xFC include two options: 1) interconnected AC network with series connected AC/DC and DC/DC converters or 2) interconnected DC networks with DC/DC converters. As discussed in [10], the advantages of AC include traditional metering and protection technologies, while DC systems have fewer converters which will improve efficiency and the control can be simplified.

As discussed in [11], there are potential grid impacts associated with the high power charging demands that could lead to voltage fluctuations, harmonic stability challenges, and harmonic emissions. Hence, finding means to mitigate these challenges is key to future expansion of xFCs. This work will focus on a MW scale extreme DC fast charger for HD-EVs. In addition to the charging port, this architecture has the the ability to integrate station energy storage (ES) and photovoltaics (PV) systems, otherwise called a multiport charging system.

This paper presents a real-time operation and control system for medium voltage DC networks for extreme fast charging (XFC) of HD-EVs. The proposed topology and real-time system supports local integration of renewables, or PV systems, and ES technologies. This solution provides an opportunity to use PV and ES and the DC system to reduce potential grid impacts associated with the large power needs of HD-EVs. Due to the high power requirements, multi-level power electronic systems are needed and are part of this real-time control discussion.

This work builds on previous development presented in [12] but extends to discuss the full implementation of a system considering a communication and overall control strategies and direct connection to distribution systems. This is unique in that:

- *the power electronic system as a DC multiport has been designed to directly connect to a distribution network,*
- *the full framework of systems is presented with communication and control design for xFC of HD-EVs,*
- *a central controller logic to help reduce grid impacts considering energy storage is presented, and*
- *the framework is discussed and demonstrated in a controller hardware-in-the-loop platform.*

I. HD-EV CHARGING INFRASTRUCTURE TOPOLOGY

Based on the proposed vehicle battery capacities for HD-EVs, targets of MW charging capability and higher can be anticipated. This will require significant charging infrastructure upgrades including power converter topology changes and charging cable updates including the potential use of multiple charging cables. As presented in [13], maximum cable sizes for a single charger supporting 1000VDC could be approximately 400kW based on OSHA limits for weight. Hence, this work proposes a three-port charging design to support HD-EVs as shown in Fig. 1. While wireless charging could potentially support another option [14], power transfer to-date has been significantly lower than the MW scale needed for HD-EVs [15].

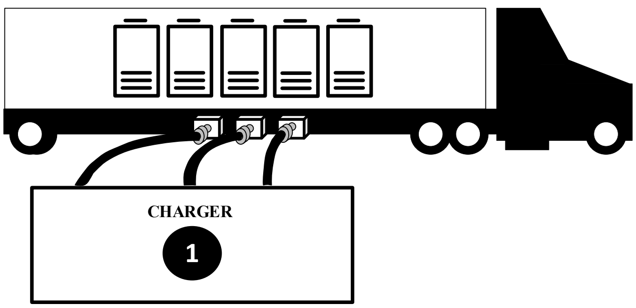

Fig. 1. Conceptual charging of HD-EV.

This work proposes the use of a DC multiport for charging HD-EVs and supporting grid, energy storage, and renewable integration as presented in Fig. 2. A shared 2kV DC bus provides the common interface for integration. In this design, three vehicle charging ports (400kW DC/DC converters) support power delivery to a single HD-EV. The DC/DC topology chosen for the charging ports, grid-side converter, energy storage, and PV integration consist of dual active bridge (DAB) converters, which provide galvanic isolation through a high-frequency transformer. Cascaded H-bridge (CHB) topology is used for the AC/DC conversion stage for medium voltage grid interconnection. In total, 29 different converters make-up this system. In the next sections details on the DAB and CHB topologies and controls are discussed.

1. Grid Converter Design and Control

For interfacing the electric grid or distribution system at 3-phase 13.8 kV (medium voltage), a 3.6MW CHB multilevel converter is employed with four cascaded modules per phase (300kW each). Each cascaded module is interconnected to a 300kW DAB as shown in Fig. 2.

The CHB interface allows direct connection to the MV line eliminating the need for a bulky low-frequency step-down transformer. Furthermore, connecting to the MV grid directly results in lower currents, thus improving efficiency. Lastly, the use of cascaded structure makes the proposed topology scalable to different MV ratings. Control of the CHB is directed to regulating the 3kV DC voltage shared with the series DABs and reactive power injection to the grid as illustrated in Fig. 3. The CHB controller is also equipped with a voltage balancing scheme to maintain the 3kV DC voltage of each CHB module individually.

Controls for the series DABs are directed to regulating the interconnected 2kV DC bus. For DAB control, single phase-shift modulation has been applied. The primary and secondary bridges are switched at fixed 50% duty cycle to generate 2-level square AC voltages at a fixed frequency of 10 kHz. By controlling the phase-shift between the primary and secondary voltages, power flow can be controlled.

2. HD-EV Converter Design and Control

Three DABs, each rated at 400kW, are operated in parallel for charging the HD-EV. These are operated independently and employ the phase-shift modulation technique similar to the grid converter DABs. However, the voltage control loops are replaced by current control loops to control the charge/discharge current of the HD-EVs as shown in Fig. 3. The reference current for the current controller is obtained through the battery management system of the HD-EVs.

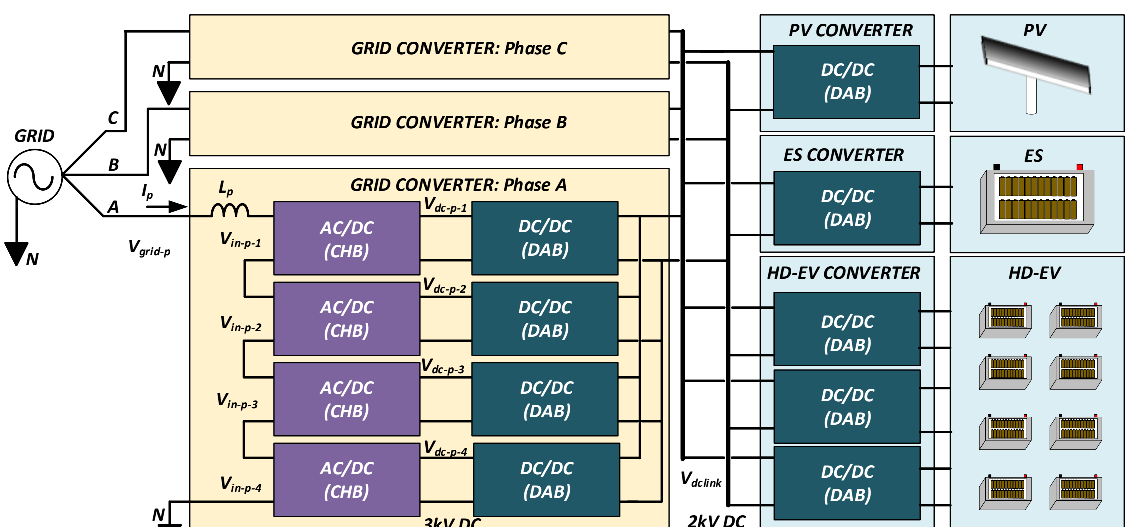

Fig. 2. Single multiport architecture with photovoltaics (PV), energy storage (ES), and a heavy-duty electric vehicle (HD-EV) using cascaded H-bridge (CHB) and dual-active bridge (DAB) converter topologies.

3. PV and ES Converter Design and Control

DAB converters with bi-directional controls are also employed for interfacing an energy storage system to the shared DC bus due to the requirements for charging and discharging of ES. The DAB converter topology is also applied to the PV system, but as a single directional generation system. As the case with the HD-EV chargers, these DABs are also rated at 400kW each. Constant real power and maximum power point tracking (MPPT) have been integrated as control solutions for the PV and ES controllers, respectively. An additional outer power control loop is introduced for the control schemes, which is cascaded with the current control loop discussed previously. The reference power for the PV controller is generated through the MPPT scheme.

II. System Communication and Control Approach

A communication and control architecture, as presented in Fig. 4, has been applied to the power electronic topologies. This multi-hierarchal set of controllers and systems interconnect the power electronic systems and interconnected resources to a central controller (or resource management controller-RMC as shown). The converter controllers contain the closed-loop controls presented for the different topologies along with fault detection, state machines, and a user datagram protocol (UDP). The UDP communication link is used to obtain control, setpoint, and settings and send status, measurements, and configuration data to resource integration controller (RIC). Where multiple converters are needed to operate in parallel as a single converter system (such as the case of the grid converter), single converter controllers are used with separate programmed control loops developed for each power stack.

The RIC has been developed to support integration of the power electronic converters and resource controllers or models using an agent-based system in a plug-and-play environment [16]-[17]. The agents within the RIC perform the decision-making on how the integration is performed and perform a secondary safety check on boundary conditions of integration. For example, an energy storage system and electric vehicle both utilize battery management systems (BMS) that monitor and

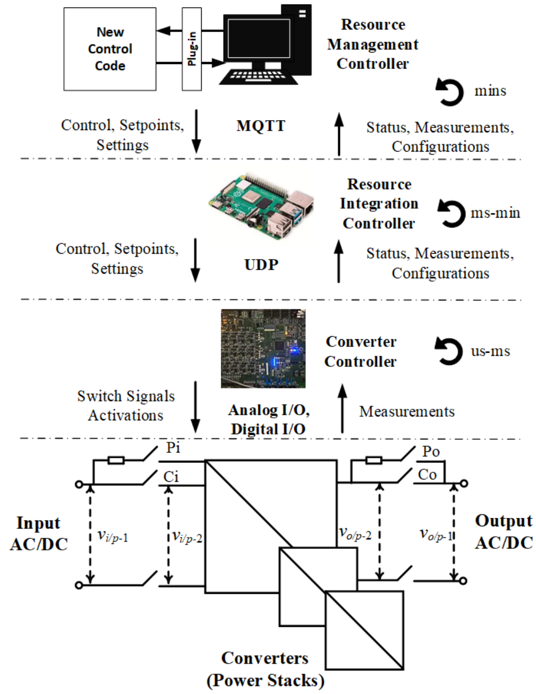

Fig. 4. Communication architecture to support XFC stations with renewable and energy storage systems [15].

control access to battery systems. The pack voltage is compared to the maximum and minimum voltage limits of the converter to create a sub-set of operational limits or to notify the user of incorrect system configuration. Examples of the RIC integration of resources are provided in [16]. The RIC acts as the interface to the resource system and communicates to the RMC via a Message Queuing Telemetry Transport (MQTT) protocol. This protocol provides flexibility to create plug-and-play solutions and to create peer-to-peer device coordination [17].

While the RMC can support optimization and dispatch formulations, discussion on optimization of HD-EVs and multiports will be left to future work. Instead, a plug-in module configuration has been added to allow the connectivity of

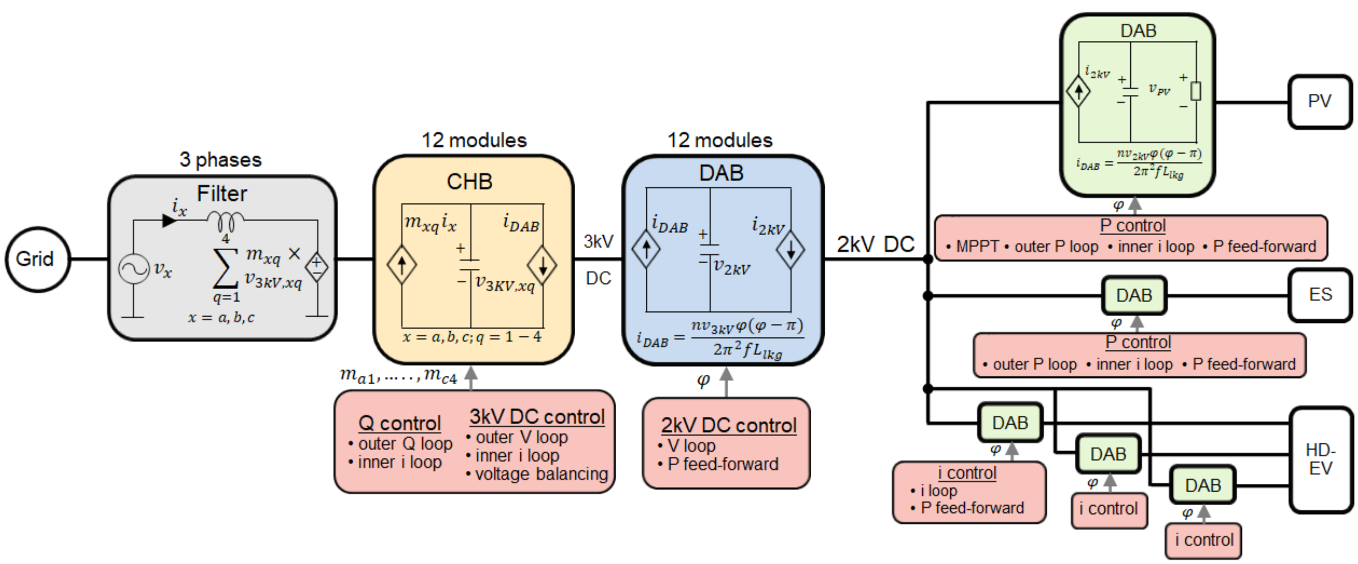

Fig. 3. Individual converter control schemes of the XFC multiport.

decision-making systems to instead take control over the different resources. For this work a simplified control has been enacted to demonstrate that the communication and control system is able to coordinate the systems. This formulation is presented in Fig. 5.

The implemented control is focused on the dispatch of the ES system to reduce the loading impact of the HD-EV charging. Hence, the objective of the ES system is to charge when the HD-EV system is not connected and charging and to discharge when the HD-EV is connected and charging (up to the allowable range of the energy storage system state of charge (SOC).) However,

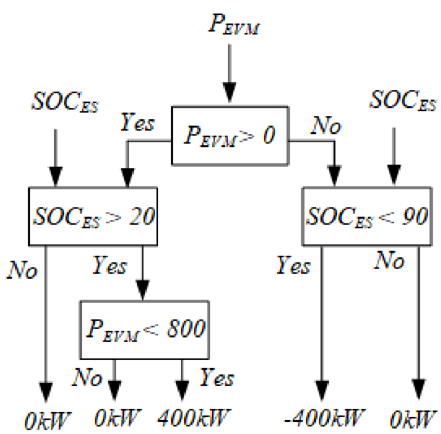

Fig. 5. Control formulation (P_{EVM} is measured electric vehicle power, SOC_{ES} is the measured energy storage state of charge)

an additional constraint in operation has been added for the condition in which the EV is only partially charging to reduce the potential for power being sent back to the grid through the grid converter. In the next section, the implementation within a controller hardware in the loop platform are discussed.

III. Controller Hardware in the Loop System

For proof of principle of the communicaiton and hardware architecture and proposed power electronic system topology and control, a CHIL Opal-RT system has been constucted. This is presented in Fig. 6. The Opal-RT system is a OP5707 system with analog and digital connections.

A set of hardware converter controllers (digital signal processors – DSPs) have been interconnected to the Opal-RT platform through analog and digital input and output ports for performing closed-loop converter control. Raspberry Pi 4s have been programmed with the agent system to represent the RIC. The enthernet port within the Raspberry Pi has been tied directly to the converter controllers which have built-in ethernet ports. USB to ethernet adapters have been connected to the RICs to provide another communication network for hosting the MQTT communications with the RMC. A computer running Linux is used as the RMC and hosts the control formulation for energy storage dispatch. A historian is embedded in the RMC to capture measurements for plotting.

Due to the large number of converter models, resource models, and system interconnections, switching models are not achievable with this real-time platform. Instead, average models have been developed and used to capture the dynamic behavior of the power electronics as represented in Fig. 3. The average models have been derived and validated against switching models individually. An example as applied to the CHB in the grid converter is shown in Fig. 7 and Fig. 8. A switching model and average model have both been simulated under step changes: a) 1MW to 1.5MW, b) 1.5MW to 2MW and c) 2MW to 1MW. The mathematical equations representing the average models are shown to follow the developed switching model behavior. Hence, system dynamic performance and stability of control can still be assessed.

The PV, ES, and HD-EV models are based on a combination of developed models, existing within CHIL platform. The PV model is PV array with Soltech 1STH-340-WH modules

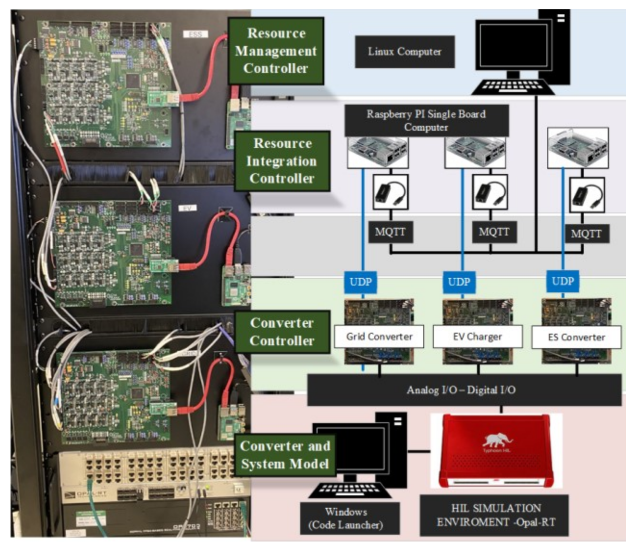

Fig. 7. Controller hardware-in-the-loop implementation

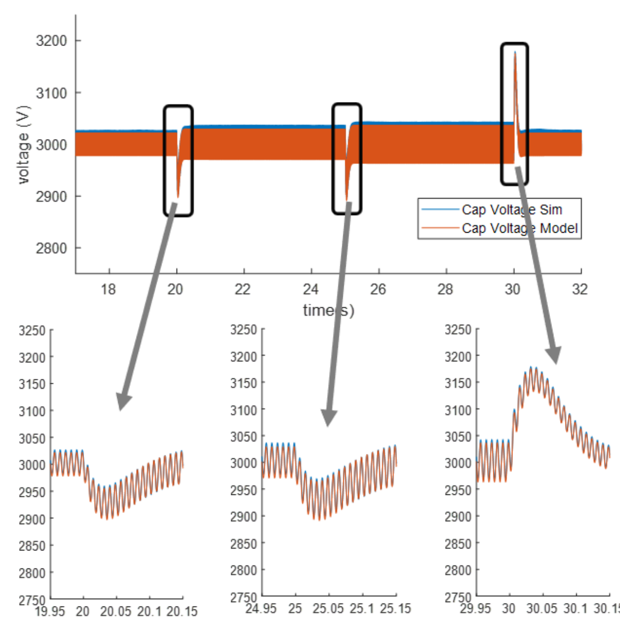

Fig. 6. CHB simulated comparison of switching model (Sim) versus average model (Model) voltage as power is increased from 1MW to 1.5 MW to 2MW and then back to 1MW

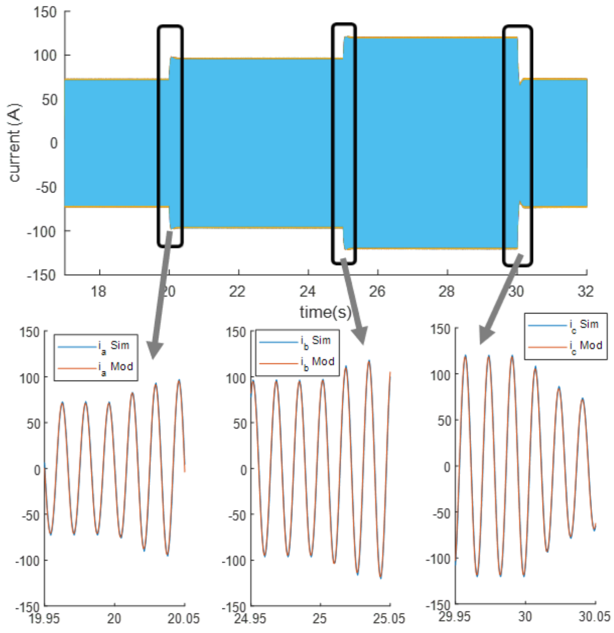

Fig. 10. CHB simulated comparison of switching model (Sim) versus average model (Model) current as power is increased from 1MW to 1.5 MW to 2MW and then back to 1MW CHB Model.

interconnected as 33 parallel strings and 36 series connections (400kW). The energy storage system and electric vehicle battery are based on lithium-ion models with 400kWh and 500kWh respectively. The EV battery was also charged based on a charging profile as presented in [9] for electric vheicles. This is presented in Fig 9. Results of a CHIL use case and example run are presented in the next section.

IV. CHIL Results

For validation of the entire framework, a single use-case demonstration has been developed. The use case is driven by the need to reduce short duration large power swings observed by the grid while charging a HD-EV. For demonstration, the use case consists of a single HD-EV arriving to charge at the multiport while the energy storage system is at a starting SOC of approximately 45%.

In preparing for the use case, the multiport is started by applying a startup optimization routine described in [18]. This start-up routine examines the system voltage controlling resources (grid converter) and activates this converter first along with the appropriate control mode (DC voltage regulation) and setpoint (2kV), followed by the ES (constant P at min P). The HD-EV charger is also activated (put into a NORMAL state) but remains in standby until the electric vehicle charging function has been enacted.

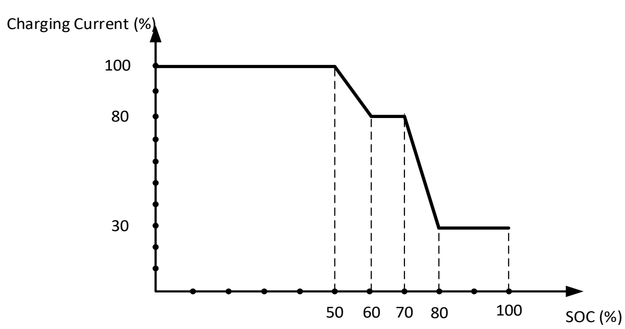

Fig. 9. EV charging scheme modeled [9].

For the first five minutes, the implemented plug-in control module enacts a charging of the ES system (-400kW where a negative sign represents charging) as no HD-EV is present and the ES SOC is below the maximum defined threshold of 90% as shown in Fig. 10. Fig. 11 presents the SOC of the energy storage system during this simulation. Since, the grid converter is regulating the DC bus, 400kW of power is observed by the grid converter as a load (positive value).

Upon five minutes into the simulation, a HD-EV load is connected and is ramped up to 1.2MW. During this ramp, the plug-in control module observes the measured value of the HD-EV and dispatches the energy storage system from 400kW of charge to 400kW of discharge. This reduces the net power on the DC bus to approximately 800kW which is the power delivered by the grid converter from the AC grid connection to the DC bus. This is a 30% reduction of power that would be observed by the grid.

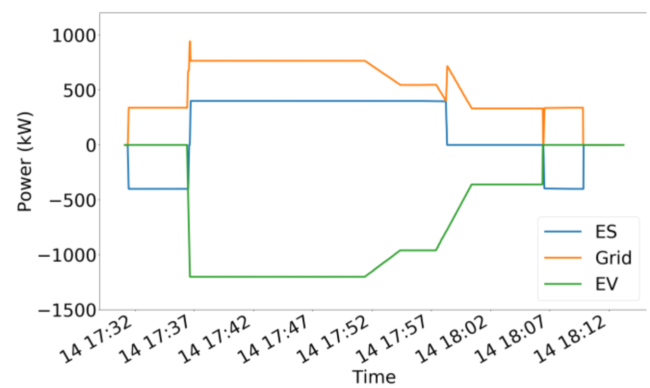

Fig. 11. Measured power results from the respective systems as reported by the converter controllers.

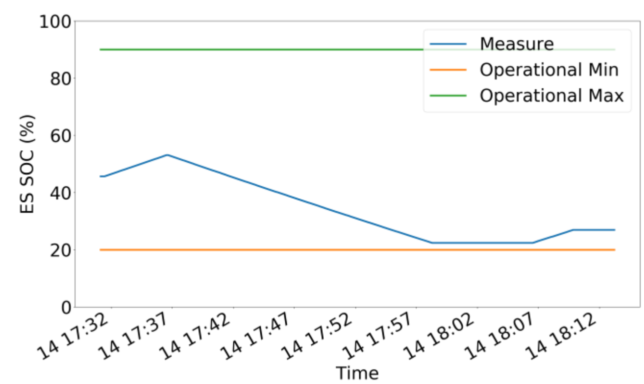

Fig. 8. Measured ES SOC reported from agent system.

The HD-EV continues to charge at 1.2MW until approximately 50% SOC is reached and reduces consumption to 80% at 50% SOC and 30% beyond 70% SOC. During this time, the ES continues to discharge at 400kW until the transition from 80% load to 30% load. At this point, the HD-EV drops below 800kW of consumption and the ES dispatch is changed to zero reducing the swing on the electric grid. Once the EV has charged to 100% and disconnects, the ES is immediately dispatched by the plug-in control module back to charge mode.

During this use case run, the grid converter observed a loading condition between 400kW and 800kW. This is a delta change in power of 400kW. Under a pure HD-EV charging system this would have been 1.2MW. Hence, with the application of an energy storage and DC multiport system, simple control and communication and control architecture, the impact of HD-EV charging can be reduced.

V. Conclusions

This paper presents a direct distribution connected multiport for extreme fast charging (xFC) of heavy-duty electric vehicles (HD-EV). A communication and control architecture for a multiport is also presented and proven in a controller hardware-in-the-loop (CHIL) environment. The modeled multiport topology represents 29 different converter systems including a 1.2MW grid tied converter, a 400kW PV system, a 400kW ES system, and a 1.2MW HD-EV charger.

A use case for HD-EV charging and ES dispatch has been conducted and presented. The use case makes use of the communication and control architecture and multiport model to demonstrate a simple potential solution for reducing grid impacts associated with HD-EV charging considering energy storage. Future work will investigate additional use cases that include the use of PV and an optimization and control solution that will tie to this architecture as well as how this system can be expanded to multiple multiports for HD-EVs.

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References

[1] Department of Energy, Cost and Price Metrics for Automotive Lithium-Ion Batteries, DOE/GO-102016-4908, February 2017, https://www.energy.gov/sites/prod/files/2017/02/f34/67089%20EERE%20LIB%20cost%20vs%20price%20metrics%20r9.pdf

[2] A. Ahmadian, B. Mohammadi-Ivatloo and A. Elkamel, "A Review on Plug-in Electric Vehicles: Introduction, Current Status, and Load Modeling Techniques," in Journal of Modern Power Systems and Clean Energy, vol. 8, no. 3, pp. 412-425, May 2020.

[3] M. Yilkman and P. T. Krein, "Review of charging power levels and infrastructure for plug-in electric and hybrid vehicles," 2012 IEEE International Electric Vehicle Conference, Greenville, SC, USA, 2012, pp. 1-8.

[4] G. K. Karagiannidis, "Charging Schemes for Plug-In Hybrid Electric Vehicles in Smart Grid: A Survey," in IEEE Access, vol. 4, pp. 6846-6875, 2016.

[5] L. Dickerman and J. Harrison, “A New Car, a New Grid,” IEEE Power Energy Mag., vol. 8, no. 2, pp. 55–61, Mar. 2010.

[6] F. Pilati, I. Zennaro, D. Battini and A. Persona, "The Sustainable Parcel Delivery (SPD) Problem: Economic and Environmental Considerations for 3PLs," in IEEE Access, vol. 8, pp. 71880-71892, 2020.

[7] D. Smith et al, Medium- and Heavy-Duty Vehicle Electrification An Assessment of Technology and Knowledge Gaps, ORNL/SPR-2020/7, December 2019.

[8] https://www.caranddriver.com/news/a34876269/volvo-trucks-electric-semi/

[9] C. Suarez and W. Martinez, "Fast and Ultra-Fast Charging for Battery Electric Vehicles – A Review," 2019 IEEE Energy Conversion Congress and Exposition (ECCE), Baltimore, MD, USA, 2019, pp. 569-575.

[10] H. Tu, H. Feng, S. Srdic and S. Lukic, "Extreme Fast Charging of Electric Vehicles: A Technology Overview," in IEEE Transactions on Transportation Electrification, vol. 5, no. 4, pp. 861-878, Dec. 2019.

[11] L. Wang, Z. Qin, T. Slangen, P. Bauer and T. van Wijk, "Grid Impact of Electric Vehicle Fast Charging Stations: Trends, Standards, Issues and Mitigation Measures - An Overview," in IEEE Open Journal of Power Electronics, vol. 2, pp. 56-74, 2021.

[12] V. M. Iyer, S. Gulur, G. Gohil and S. Bhattacharya, "An Approach Towards Extreme Fast Charging Station Power Delivery for Electric Vehicles with Partial Power Processing," in IEEE Transactions on Industrial Electronics, vol. 67, no. 10, pp. 8076-8087, Oct. 2020.

[13] Andrew Burnham et al., “Enabling fast charging – Infrastructure and economic considerations,” Journal of Power Sources, Volume 367, pp.. 237-249, 2017.

[14] S. A. Q. Mohammed and J. -W. Jung, "A Comprehensive State-of-the-Art Review of Wired/Wireless Charging Technologies for Battery Electric Vehicles: Classification/Common Topologies/Future Research Issues," in IEEE Access, vol. 9, pp. 19572-19585, 2021.

[15] ORNL demonstrates 120-kilowatt wireless charging for vehicles, https://www.ornl.gov/news/ornl-demonstrates-120-kilowatt-wireless-charging-vehicles#:~:text=19%2C%202018%E2%80%94Researchers%20at%20the,a%20gas%20station%20fill%2Dup, March 1, 2022.

[16] M. Starke et al., "Agent-Based Distributed Energy Resources for Supporting Intelligence at the Grid Edge," in IEEE Journal of Emerging and Selected Topics in Industrial Electronics, vol. 3, no. 1, pp. 69-78, Jan. 2022.

[17] M. Starke et al., "A Plug-and-Play Design Suite of Converters for the Electric Grid," 2020 IEEE Energy Conversion Congress and Exposition (ECCE), Detroit, MI, USA, 2020, pp. 2314-2321.

[18] M. Starke, R.K.Moorthy, S. Campbell, M. Chinthavali, “Start-up Optimization Considering Integrated Power Electronic Systems,” IEEE Power and Energy General Meeting, 2022.