Extreme Fast Charging Employing Partial Power Processing for 400V to 800V Convertible EV Battery

Mahamad Nabab Alam
Department of Electrical Engineering
National Institute of Technology Warangal
Warangal-506004, India
mnalam@nitw.ac.in

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***Abstract*—This work reviews the existing electric vehicle (EV) charging systems to identify the need for Extreme Fast Charging (XFC). EV XFC scheme, which employs Partial Power Processing (PPP), is discussed, and the advantages of a Partial Power Charging Unit (PPCU) over a Full Power Charging Unit (FPCU) are examined with the help of simulations. The possibility of using the PPP scheme to charge a 400 V battery configuration, which can temporarily be converted to 800 V for fast charging, is also discussed. MATLAB Simulink is used to carry out simulations to demonstrate the operation of the converter circuits constituting the XFC and to aid in comparing the FPCU and PPCU. The simulation results indicate that the DC-to-DC conversion stage has processed a significantly small fraction of the total power delivered to the EV battery. An important observation that follows is that the power semiconductor components required for the DC to DC-conversion stage of a partial power charger unit have lower ratings than the components needed for a complete power charger unit.**

***Index Terms*—Fast charging, electric Vehicle, DC-to-DC converter, battery electric vehicle.**

I. Introduction

India has embraced the global trend towards Electric Vehicles (EVs), setting a bold target to transition entirely to EVs by 2030. Despite governmental initiatives and incentives promoting EV adoption, consumer acceptance remains subdued. A primary deterrent to widespread adoption is the prolonged charging duration, which exacerbates concerns over driving range anxiety and is compounded by inadequate charging infrastructure.

Current DC fast chargers, operating at 120 kW, require approximately 30 minutes to fully charge a Battery Electric Vehicle (BEV), considerably longer than the refuelling time at traditional gasoline stations. While Battery-swapping technology, supported by government backing, presents a viable alternative for reducing charging times, regulatory complexities and the diverse landscape of EV batteries and chargers pose significant challenges to its widespread adoption. Therefore, it's imperative to develop charging solutions that match the refuelling efficiency of gasoline vehicles. Extreme Fast Charging (XFC) is a promising solution to address this pressing need.

Automotive manufacturers are increasingly transitioning to higher battery voltages, such as 800 V, to enhance efficiency and reduce charging times [1]. However, upgrading chargers and high-voltage system components to accommodate this higher voltage entails significant costs. Partial power processing converters offer a solution to this challenge on the charging side. At the same time, a 400 V to 800 V convertible battery presents a promising avenue on the vehicle side, promising reduced charging times and increased efficiency while circumventing extensive component upgrades.

Conventional onboard AC chargers, though suitable for extended charging periods, are impractical for rapid charging needs. Off-board chargers, including DC fast chargers, expedite charging by converting AC to DC at dedicated stations. Despite being the quickest among standard charging methods, even state-of-the-art DC fast chargers fall short of matching gasoline refuelling times, posing a significant obstacle to EV adoption among consumers.

The emerging solution to this problem is the XFC of an EV. An XFC station should be able to recharge a BEV in less than 10 minutes and provide approximately 200 miles of additional driving [2]. It must deliver 350 kW to 400 kW or more power to the EV battery. Generally, these XFCs work at an output voltage of 800 V.

Elevating battery voltage, such as 800 V, yields a notable reduction in the requisite current for transferring equivalent power, thereby mitigating conduction losses [3]. Consequently, cooling system demands are diminished. Lower currents correspondingly curtail I^2R losses within the vehicle powertrain, allowing motor windings and cable gauges to be downsized. This dual effect not only heightens efficiency but also downsizes cables. Notably, cable capacity is constrained by the current it can effectively carry, thereby limiting cable length. This reduction in losses facilitates XFC protocols and enables the transmission of higher power loads.

However, these advantages are not without trade-offs, as they necessitate power semiconductor devices with elevated ratings, alongside heightened insulation for all cables and windings, culminating in an enlargement of both size and cost. To counterbalance these drawbacks inherent in conventional DC fast charging, novel methodologies have been proposed, among which the concept of partial power processing stands out.

Unlike conventional approaches, where the entire power from the DC link is channelled through the converter, partial power processing involves only a portion of it being handled by the DC converter stage. A partial power converter operates as a series or parallel element alongside the load, processing only a fraction of the total power [4]. This technique, widely adopted in Photovoltaic (PV) and energy storage applications, has shown promising potential in EV battery charging scenarios, where it was observed that the Partial Power Converter Unit (PPCU) processes a mere 27% of the total power load.

This study comprehensively reviews existing EV charging systems to pinpoint the imperative for XFC. Subsequently, the EV XFC scheme, integrating Partial Power Processing (PPP), is elucidated, focusing on delineating the advantages of a PPCU in contrast to a Full Power Charging Unit (FPCU). Furthermore, the feasibility of employing the PPP scheme for charging a 400 V battery configuration, temporarily convertible to 800 V for rapid charging, is explored. Using MATLAB Simulink, simulations illustrate the operation of the converter circuits constituting the XFC framework and facilitate a comparative analysis between the FPCU and PPCU configurations.

II. EV Charging Infrastructure

An EV runs on a powerful electric motor (or motors) connected to the drive shaft, which ultimately rotates the wheels. This electric motor comes with different power ratings, from 100 kW for normal vehicles to 250 kW for EV buses and 500 kW or more for sporty vehicles. Two chargers are placed inside almost every EV; one is a single phase, and the other three phases both are onboard, which means inside the EV where AC is converted to DC and again DC to DC within a range of 120-800 V, which is needed to charge the battery.

There are three levels of EV chargers in the market [2]:

Level-1 AC Charging: This charger supports 120 V in the US or 230 V in India, featuring a control box and power cord integrated into the EV. It is highly convenient, and affordable, requires no installation, and plugs directly into a standard domestic AC outlet. However, it takes 12-16 hours to fully charge a 60 kWh EV, making it suitable for overnight charging.

Level-2 AC Charging: Supporting up to 240 V in the US and 440 V in India, Level-2 chargers require Electric Vehicle Supply Equipment (EVSE) and wiring capable of handling higher power from 3-phase AC lines. This charger is significantly faster than Level-1, taking 7 to 8 hours to charge a 60 kWh EV. Level-2 chargers are commonly used in residential settings, workplaces, apartments, small offices, hospitality venues, and retail stores.

DC Fast Charging: Also known as Level-3 charging, DC fast chargers can charge a vehicle up to 80% in just 30 minutes by converting high-voltage AC power directly into DC power for the EV battery. These chargers are primarily used at public charging stations. Although more expensive than Level-1 and Level-2 chargers, they are essential for vehicle fleets and public transportation, such as electric buses, due to their ability to charge multiple vehicles quickly and simultaneously.

Two power electronics-conversion stages in modern DC fast chargers convert three-phase AC voltage up to 480 V into the desired DC voltage:

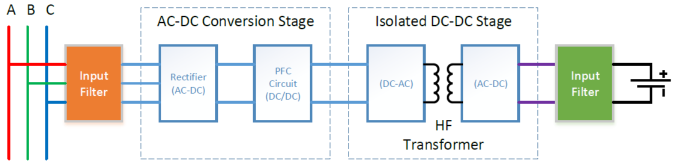

Fig. 1. DC XFC scheme.

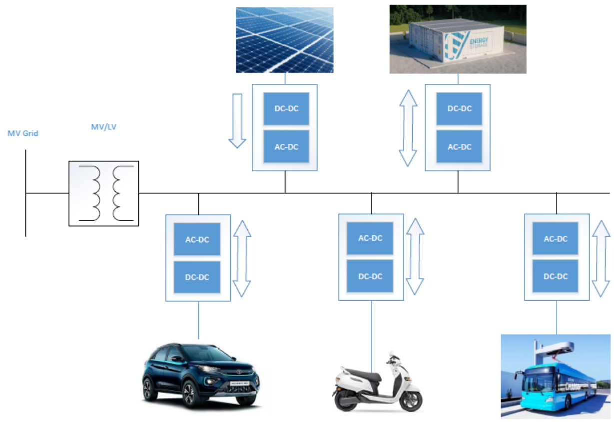

Fig. 2. AC-connected system XFC substation.

1) An AC to DC rectification stage with power factor correction converts three-phase input AC voltage into an intermediate DC voltage.
2) A DC to DC conversion stage converts the intermediate DC voltage into a regulated DC voltage required to charge the EV.

These stages are accompanied by appropriate filter circuit links and are connected across a DC link capacitance between the two stages, as shown in Fig. 1.

In the design of a charging scheme, galvanic isolation among the two conversion stages is essential. One of the two approaches below can be used to establish galvanic isolation between the grid and the EV battery. To establish grid isolation, the first alternative is to install a line-frequency transformer before the AC to DC conversion stage. A non-isolated converter follows the next DC to DC stage. The second alternative is to use a high-frequency transformer to achieve isolation inside an isolated DC-to-DC converter.

In the first approach, a step-down transformer connects the distribution network to a three-phase AC bus operating at 250–480 V line-to-line voltage for AC-connected equipment, as shown in Fig. 2. Each charger at the station is powered by an AC bus, and each charger has its AC-to-DC stage. The number of conversion stages between the distribution network and the DC ports is significantly increased with this strategy. An AC-connected system's number of conversion stages increases its complexity and expense while lowering efficiency.

In the second approach, one central front-end AC-to-DC converter produces a DC bus for DC-connected systems, as shown in Fig. 2. This enables interfacing DC energy storage systems and renewable energy sources to be more energy-efficient. A low-frequency transformer is used in the middle front end, followed by an LV

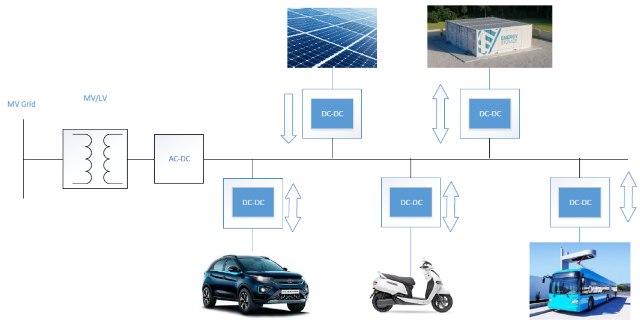

Fig. 3. DC- Connected XFC substation configurations.

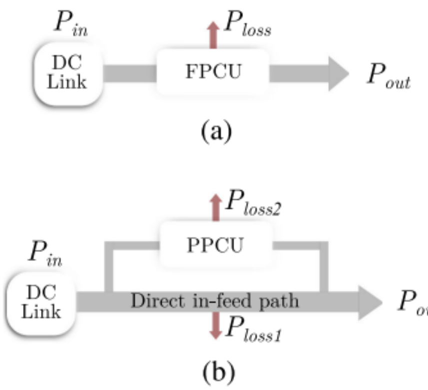

Fig. 4. Illustrative power flow diagram: (a) Full-Power Charging Unit (b) Series-pass Partial Power Charging Unit [2].

(250 – 480 V) rectifier stage or an SST that combines rectification, voltage step-down, and isolation into a single unit. The DC bus voltage is generally less than 1000 V to accommodate the current battery voltage range (about 400 V). Individual AC-to-DC converters are eliminated because each charger is interfaced between the DC bus and a DC-to-DC converter. When compared to AC-connected systems, the system efficiency is improved by reducing the number of conversion stages. The ”DC distribution” solution can benefit from a single link to the utility through the central front end.

III. Partial Power Processing

Instead of processing all the power through the converter, only a portion is handled by the DC converter stage. A partial power converter is configured as a series or parallel element with a load that processes only a fraction of the total power [4].

The typical approach to building an XFC station involves using a centralized front-end converter (FEC) unit with a line frequency transformer to interface with the MV grid. Most systems use full-rated DC-to-DC converters for the battery charging stage. A novel power delivery architecture based on partial PPCUs for an XFC station is proposed in [4]. This design retains the front-end converter and solid-state transformers (SST) from the conventional FPCU, but introduces a low-voltage DC link connecting to local DC microgrids. The charging units are only rated to handle a fraction of the power required for battery charging, reducing installation and operation costs while improving system efficiency. This method, often called differential power processing, modifies the traditional converter's terminal connection to function as a partial power processing element, and has been successfully applied in solar panel integration and battery charging systems to enhance performance.

IV. Simulink Simulation Models

A. Battery Model

To demonstrate the function of XFC, a battery model is needed to act as the load to the charger circuits, which can simulate the rise in voltage of the battery as it gets charged. For this purpose, a mathematical model of a battery cell that gives its open circuit voltage as a function of its state of charge, as described in [5], is employed. The expression used pertains to the data of NMCO (nickel-manganese-cobalt-oxide)/graphite lithium-ion cell chemistry. The cell's state of charge is determined by the simple 'Coulomb Counting' or 'Ampere-hour method' by integrating the current through the cell. The cell's voltage thus obtained is multiplied by the number of cells in series to get the required battery pack voltage.

The selected battery configuration charges from a minimum voltage of 725 V to a maximum voltage of 800 V with a constant current of 400 A in about 10 minutes. 725 V corresponds to about 20% of the state of charge (SoC), while 800 V corresponds to 80% of the state of charge. Here, only the constant current (CC) charging mode till 80% of SoC is considered, and the charging is stopped afterwards. Fast charging systems generally avoid the slow constant voltage (CV) charging mode.

$$V_{cell}(SoC) = 3.5 - 0.0334(-log(Soc))^2 - 0.105SoC + 0.7399e^{1.403(SoC-1)} \quad (1)$$

From the given characteristics of the battery pack, we can determine the capacity of the pack needed for the 'Coulomb Counting' calculations: Battery pack charges from 20% SoC to 80% SoC (i.e. it charges equivalent to 60% of its capacity in 10 minutes) with a constant current of 400 A. So, the battery capacity C_{batt} can be calculated as:

$$C_{batt} = 400A \times (10/60)h = 111.11Ah \quad (2)$$

The instantaneous SoC is obtained using the Coulomb Counting method [6].

$$SoC(t_k) = SoC(t_0) + \frac{\eta}{C_{batt}} \int_{t_0}^{t_k} i(t)^2 \, dt \quad (3)$$

where
$SoC(t_k)$ = state of charge at a time t_k
$SoC(t_0)$ = state of charge at a time t_0
$i(t)$ = charging current (A)
η = charging efficiency (assumed equal to 1)

Now, using equation Eq. (1), the SoC obtained in Eq. (3) can be used to calculate the cell voltage and multiplied with the required number of cells in series (n_s), selected to obtain the voltage of 800 V at 80% SoC.

$$V_{batt}(s) = n_s V_{cell}(s) \quad (4)$$

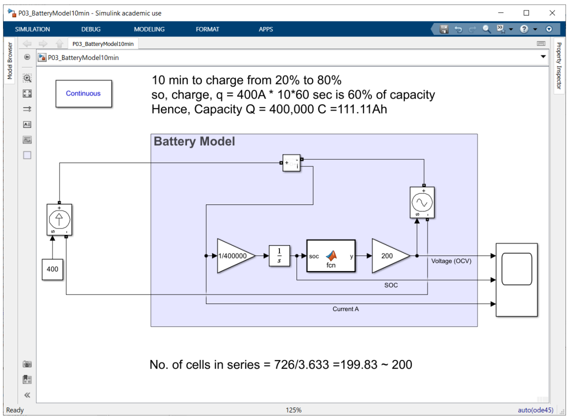

Fig. 5. Simulink modelling of battery pack using constant current source.

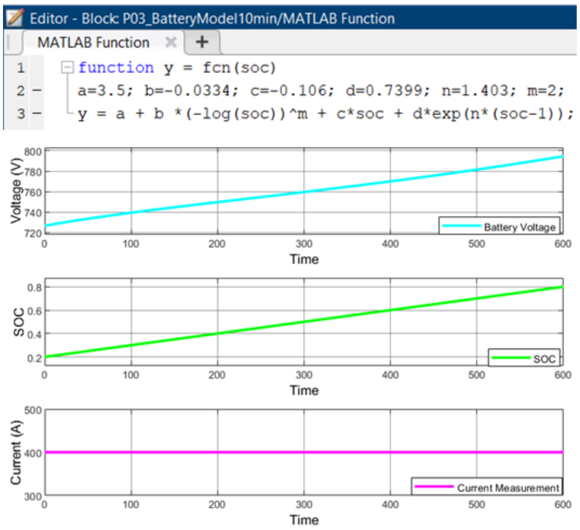

Fig. 6. Mathematical modelling of Li-ion cell and resulting constant current charging profiles.

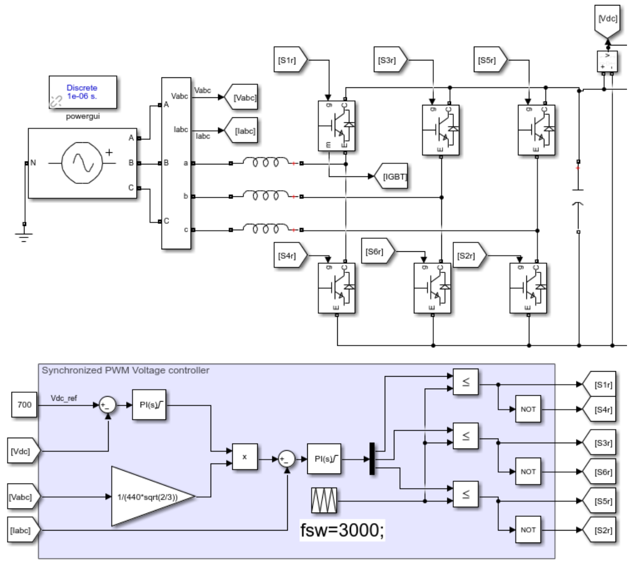

Fig. 7. Front End - PWM converter with synchronized voltage PWM controller.

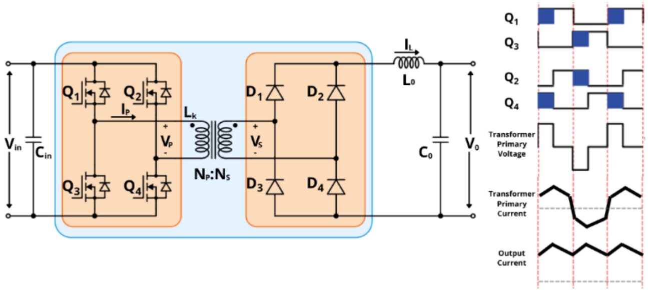

Fig. 8. Phase Shift Full Bridge Converter with switching states, voltage, and current waveforms [2], [7], [8].

Figs. 5 and 6 show the Simulink and mathematical modelling of constant current source and charging profiles.

B. Front-End PWM Converter

The PWM converter is selected as the front-end converter for the EV charger. It is supplied from a three-phase 440 V (line-to-line) AC supply and employs 6 IGBT switches for rectification. A three-phase L filter, which filters out harmonics from the DC side from affecting the grid, is used at the supply end of the converter. The IGBT switches are controlled by a synchronous reference frame-based active rectifier controller. In this control scheme, the gate switching pulses are obtained using a carrier signal with three-phase modulating signals and a pair of switches on the same leg controlled by complimentary gate signals. The modulating signal is generated by a voltage PI controller as the outer loop and a current PI controller as the inner loop. Fig. 7 shows the Simulink model of the front-end PWM converter.

C. Phase Shift Full-Bridge (PSFB) Converter

The Phase Shift Full-Bridge Converter, or PSFB converter, is a commonly used DC-to-DC converter topology for charging EV batteries. It employs four switching devices, four diodes, and a high-frequency transformer. This makes it less complex than other DC-to-DC converter topologies like the Dual Active Bridge converter. Fig. 8 shows a generalized PSFB converter topology.

The PSFB converter consists of an H-bridge on the input side. The two switches on the left form the lagging leg, while the switches on the right form the leading leg. PWM signals of 50% duty cycle control all the switches [3]. The gate pulses controlling Q1 and Q4 are complementary (180° out of phase) to those controlling Q2 and Q3, respectively. The converter's duty cycle is controlled by varying the phase difference between the gate pulses of the switches on the leading leg and the gate pulses of switches on the lagging leg. The output of the H-bridge is connected to the primary of the high-frequency transformer with leakage inductance, which plays an essential role on the primary side as the resonant inductor named Lk. The secondary of the transformer is connected to a full-wave diode bridge rectifier. The rectified output is fed to an LC filter stage to reduce ripples before being used to charge the high-voltage EV battery. Before employing the PSFB converter for the charging application, it is essential to understand how it works as an independent unit. The operation of PSFB is similar to that of a buck converter and can be divided into many modes for better understanding [7].

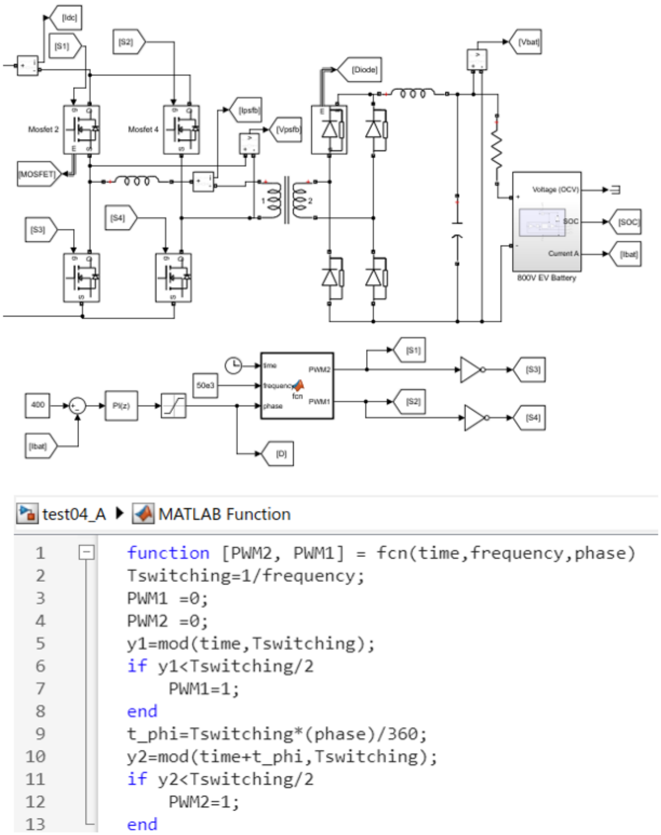

Fig. 9. PSFB Simulink model and phase-shifted PWM signals.

The PSFB circuit is modelled in MATLAB Simulink by taking the following parameters: Lk = 1.7 μH, Lf = 520 μH, Cf = 20 μF.

The phase shift in the switching signals is generated using a PI controller, ensuring a constant current of 400 A is delivered to the battery. The PI controller gives the required phase difference between the leading and lagging legs to a function block shown in Fig. 9. This function has a simple script to generate gating signals with the input phase shift.

V. Results and Discussion

The front-end AC to DC PWM rectifier/converter and the DC to DC phase shift full bridge converter models are connected. They are supplied from a three-phase AC supply with 440 V phase voltage and are connected to the grid side (AC side) of the PWM converter. On the DC side, the output of the PSFB is given to the battery model. The battery model imposes the EV battery's typical charging profile at the converter's output.

To arrive at the PPCU configuration, the lower end of the output rectifier of PSFB is connected to the positive DC link voltage terminal. Instead of being connected to the output of the rectifier bridge, the filter capacitor is connected across the output terminal of the complete circuit. That is, it is connected across the EV battery. Figs. 10 and 11 show the FPCU and PPCU of the developed approach.

The outputs obtained by simulating the FPCU and PPCU circuits are shown below and on the following pages. The average power, though, is shown in displays in

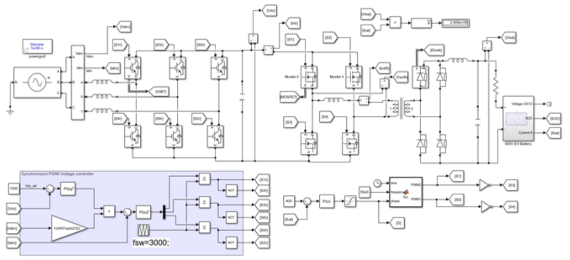

Fig. 10. Complete FPCU Charging Circuit.

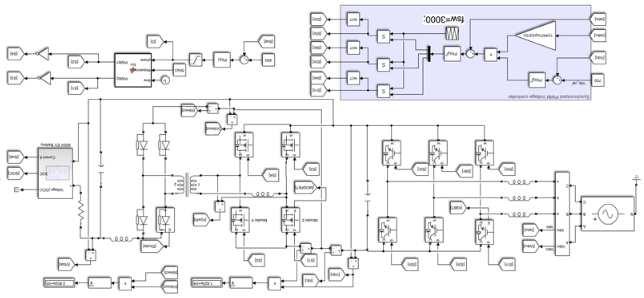

Fig. 11. Complete PPCU Charging Circuit.

Figs 12 and 13. According to the simulation results, in the PPCU, the DC-to-DC conversion stage (PSFB converter) processes a power of about 18 kW. In comparison, the direct infeed path transfers active power of about 28 kW. This means the PSFB circuit only processes nearly 6% of the total power delivered to the battery. This is considerably less than that mentioned in [4]. The possible reasons are the lack of practical losses in the circuit and the difference in some parameters.

After around 1 second, both circuits attain a steady state with a continuous output current of 400 A, as the battery model requires to charge the battery from 20% to 80% state of charge levels in 10 minutes. The circuits can deliver a power of around 320 kW to the EV battery, thus providing extremely fast charging.

The switching frequency of 3 kHz was used for the 3-phase AC to DC PWM converter. For the PSFB converter, the switching frequency of 50 kHz was chosen. As a result, the current waveforms have a ripple of frequency twice that of the switching frequency. The ripple amplitude is limited to less than 1 A in both schemes.

The Peak Voltages and Currents across the IGBTs, MOSFETs and Diodes are given in Table I.

VI. Conclusion

The presented work investigates Extreme Fast Charging (XFC) for electric vehicles (EVs) with 400 V and 800 V battery packs. It reviews existing EV charging

TABLE I
Peak Voltages and Currents across the IGBTs, MOSFETs and Diodes

Semiconductor Devices	FPCU Peak voltage (V)	FPCU Peak current (A)	PPCU Peak voltage (V)	PPCU Peak current (A)
IGBT	750	590	700	560
MOSFET	753	656	700	140
Rectifier diode	1230	330	227	400

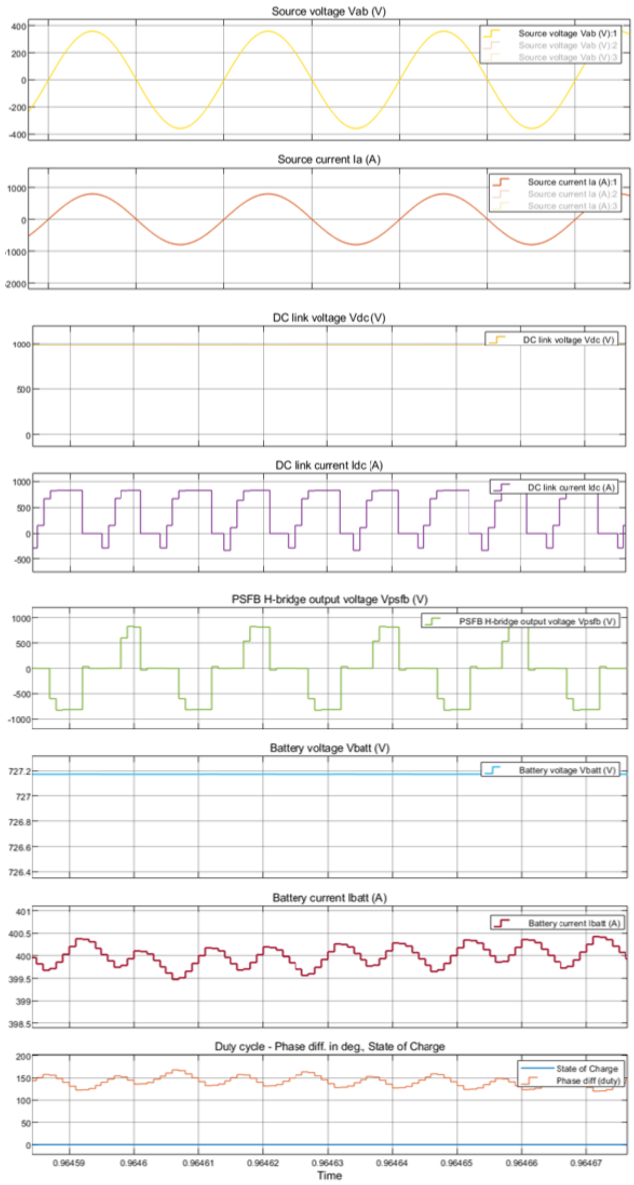

Fig. 12. Simulation results for FPCU circuit.

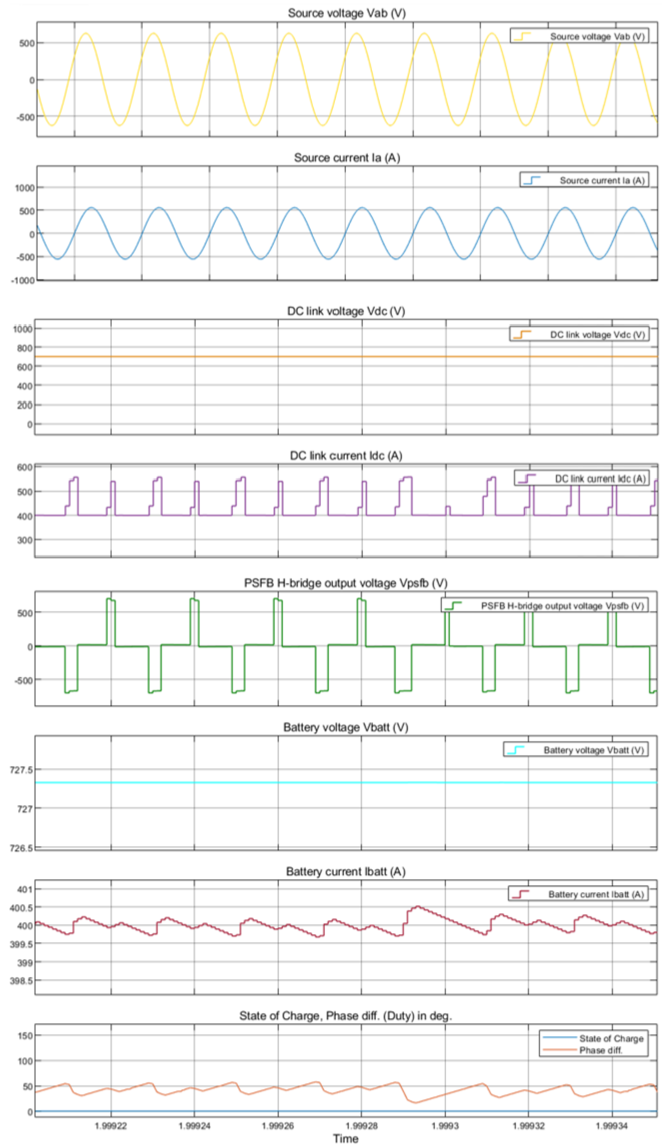

Fig. 13. Simulation results for PPCU circuit.

systems, highlighting the need for faster charging solutions. The study focuses on XFC schemes employing Partial Power Processing (PPP) and associated converter topologies. MATLAB Simulink simulations compare Full Power Charger Unit (FPCU) and Partial Power Charger Unit (PPCU) performance, aiming to deliver a constant 400 A to charge an 800 V battery. Results show both schemes can provide desired currents, indicating suitability for XFC. The advantages of PPCU over FPCU are examined, revealing reduced stress on components and higher efficiency due to minimized power transfer through the DC-to-DC converter. Performance differences include higher ripple content in FPCU's DC link current and varying duty cycles. Overall, the study suggests that PPCU offers efficiency gains and reduced stress on components, making it a promising solution for XFC in EV charging.

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