Performance Analysis of Electric Vehicle Fast Charging System with Dual Active Bridge Converter using Triple Phase Shift Modulation

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Abstract:- Electric vehicle DC fast charging systems, with power outputs ranging from 50 kW to 350 kW, drastically reduce charging times, enhancing EV convenience by enabling substantial battery charging within minutes. To further improve performance and reduce charging time, there is a growing need for more advanced and efficient DC-DC converter solutions in various charging systems. One of the most widely used solutions is the isolated high-frequency DC-DC Dual Active Bridge (DAB) converter, favored for its high efficiency, compact design, and ability to provide galvanic isolation, which boosts both safety and performance. In this research, a novel 200 kW fast charger was chosen for modeling the fast-charging system. The proposed fast charger consists of two main sections: an AC-DC converter and a DC-DC converter utilizing the DAB technique to perform the charging function. The parameters of the components used in the model are also described. An isolated high-frequency transformer is integrated into the DC-DC converter to ensure isolation between the DC system and the electric vehicle. To enhance power quality, reduce reactive power consumption, and improve fast charging performance, triple phase shift modulation is introduced in this study. The effectiveness of the proposed modulation technique was validated through simulation results, with the modeling and simulations conducted using MATLAB/SIMULINK. The results demonstrate the feasibility of the proposed model.

Keywords:- *Electric Vehicle, Fast Charging System, AC-DC Converter, Dual Active Bridge, Triple Phase Shift Modulation.*

I. INTRODUCTION

The rapid growth in electric vehicle (EV) adoption is transforming the automotive industry, driven by the goal to reduce greenhouse gas emissions and reliance on fossil fuels. As EV usage increases, the need for efficient and reliable charging infrastructure becomes critical. DC fast charging systems are particularly notable for drastically reducing charging times, addressing a key concern for EV owners: the convenience and practicality of daily use. These systems deliver direct current (DC) power directly to the vehicle's battery, bypassing the onboard AC-DC converter, enabling much faster power transfer compared to traditional AC chargers. Typically, DC fast chargers provide power between 50 kW and 350 kW or more, allowing EVs to charge from 20% to 80% in just 20 to 30 minutes. This rapid charging capability is essential for long-distance travel and for those without access to reliable home charging.

The components of a DC fast charging system include high-capacity grid connections, advanced power electronics for AC-to-DC conversion, and cooling systems to manage the heat generated during high-power charging [1-2]. Various connector standards, such as CHAdeMO, Combined Charging System (CCS), and Tesla Supercharger, ensure compatibility with different EV models. These systems are strategically placed at highways, commercial hubs, and urban locations to offer easy access to fast charging. However, the deployment of DC fast charging infrastructure faces challenges, including high installation and operating costs, significant grid upgrades, and the need for universal connector and communication standards. Overcoming these obstacles requires collaboration among policymakers, industry players, and technology innovators. Continued advancements in charging technologies, grid management, and supportive regulations are crucial for addressing these challenges and facilitating widespread adoption of DC fast charging systems.

In conclusion, DC fast charging systems are an essential element of the EV ecosystem, providing a practical solution to reduce charging times and improve user convenience. As technology progresses and infrastructure grows, these systems will play a key role in accelerating the shift to electric mobility, promoting environmental sustainability, and reducing global carbon emissions.

In this work, the triple phase shift (TPS) modulation is presented for DAB control at DC fast charging of electric vehicle. With the TPS modulation, the power quality and charging performance can be improved. The component parameters used in the model are also described. The modeling and simulations are executed using MATLAB/Simulink software. According to the simulation results, the designed fast charging system with TPS modulation can provide efficient control and reduced impact on power quality of the system.

II. MODULATION OF DUAL ACTIVE BRIDGE CONVERTER

To enhance the efficiency of DAB operation, modulation techniques have advanced from single-degree-of-freedom methods to multi-degree-of-freedom strategies, resulting in significant progress in DAB control approaches. Early research on DAB modulation primarily focused on phase-shift modulation, with many scholars conducting comprehensive studies on various phase-shift modulation (PSM) strategies in terms of converter power circulation, RMS current, soft-switching range, and power transmission capabilities.[4]

A. Phase Shift Modulation (PSM)

The PSM technique is widely used in dual active bridge (DAB) converters and can be classified into several types, including single-phase shift (SPS), extended-phase shift (EPS), dual-phase shift (DPS), and triple-phase shift (TPS). Of these, TPS modulation is the most basic and commonly employed method in DAB converters [3]. To overcome the limitations of SPS modulation, researchers later developed DPS and TPS modulation methods, improving converter performance in areas such as circulating power, current stress, and the range of zero voltage switching (ZVS). [4]

B. Triple Phase Shift Modulation

In TPS, there are three degrees of freedom that provide greater flexibility in controlling the DAB converter. The primary waveform of the TPS modulation method is illustrated in Figure 8, where the phase shifts are introduced relative to S1. It can be demonstrated that whether D2 is smaller or larger than D3, the resulting currents, voltages, and power transfer remain the same. Therefore, for simplicity, we assume D2 is always smaller than D3. This allows for the analysis of the circuit in three distinct scenarios, which are as follows:

$$\begin{cases} 0 \le D_1 \le D_2 \le D_3 \le 1 \\ 0 \le D_2 \le D_1 \le D_3 \le 1 \\ 0 \le D_2 \le D_3 \le D_1 \le 1 \end{cases} \tag{1}$$

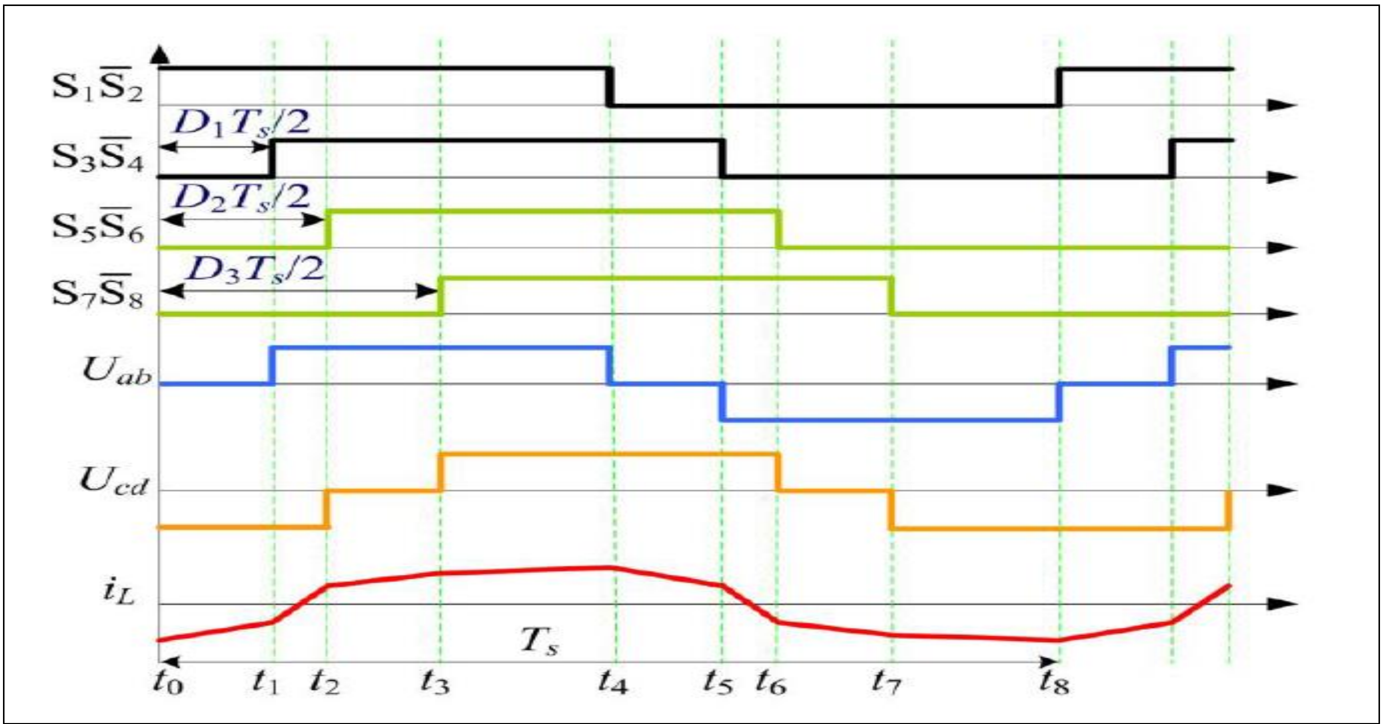

Fig 1: Waveforms of DAB using TPS Modulation [4]

The alogorithm which was used to maintain the phase shift was aimed to reduce the current stresses on the switches. For k>1, it's possible to calculate the unifed current stress as:

$$i_p = \frac{i_p}{i_N} 2\left[D_2 + D_3 - 1 + k\left(1 - D_1\right)\right] \tag{2}$$

Moreover, by calculating the voltage across the inductor, the unified output power can be written as:

$$P = \frac{P}{P_N} \tag{3}$$

$$\begin{cases} 2\begin{pmatrix} -D_1 + D_2 + D_3 - D_1^2 \\ -D_2^2 - D_3^2 + D_1D_2 + D_1D_3 \end{pmatrix} D_1 \le D_2 \le D_3 \le 1 \\ 2\begin{pmatrix} -D_1 + D_2 + D_3 - D_1^2 \\ -D_2^2 - D_3^2 + D_1D_2 + D_1D_3 \end{pmatrix} D_2 \le D_1 \le D_3 \le 1 \\ 2\begin{pmatrix} -D_1 + D_2 + D_3 - D_1^2 \\ -D_2^2 - D_3^2 + D_1D_2 + D_1D_3 \end{pmatrix} D_3 \le D_1 \le D_2 \le 1 \end{cases} \tag{4}$$

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Where P_N is:

$$P_N = \frac{nT_S U_{in} U_O}{8L} \tag{5}$$

By taking the partial derivatives of the Lagrangian function in Eq. 5 and solving the resulting equations set to zero, formulas can be derived to determine the phase shifts that minimize current stress, as shown in Eq. 6 and Eq. 7.

$$E = i_P + \lambda(P - P^*) \tag{6}$$

$$I_{rms} = \frac{2}{\sqrt{3}}\left[(1-k)^2(3-2D_1)D_1^2 + 4k(3D_1 - D_2)D_2^2\right] \tag{7}$$

$$P = 2k\left[2kD_1D_2D_2^2\right] \tag{8}$$

$$S = \frac{(1+k)}{\sqrt{3}}\sqrt{(1-k)^2(3-2D_1)D_1^3 + 4kD_1D_2^2(3D_1 - D_2)D_2^2} \tag{9}$$

III. MODELING OF FAST CHARGING SYSTEM WITH DAB USING TPS MODULATION

Matlab/SIMULINK Software is used to model the fast-charging system. The fast-charging system consists of LCL filter, AC-DC Active Bridge Rectifier, High-Frequency Isolated DC-DC Dual Active Bridge Converter using TPS modulation and Battery Management System. The function of LCL Filter is to reduce the harmonic distortion at the input power source. The Active Bridge Rectifier is to converter the AC input voltage to the desired DC output voltage. The DAB converter using TPS performs the isolation function and produces the specific DC voltage level which is suitable for fast charging to the battery. Battery management system is to optimize charging efficiency, ensure battery safety and improve battery life. Figure illustrates the SIMULINK model for fast charging system with DAB using TPS modulation.

There are two controllers in fast charging system as; (a) AC-DC converter controller and (b) DAB controller as shown in Figure 3. AC-DC converter control system consists of DC voltage control loop and AC voltage control loop. Proportional plus integral (PI) controllers are used to maintain the desired voltages. The DAB controller consists of DC voltage control loop and DC current control loop with proportional plus integral plus derivative (PID) controllers.

Table 1: Parameters for Modeling of Fast Charger with Triple Phase Shift at DAB Converter

No.	Parameter	Unit	Value
1	(V_{in}) (AC)	V	400
2	(V_{out}) (DC)	V	1000
3	(I_{out})	A	250
4	(P_{out})	kW	250
5	Switching frequency(f_{sw})	kHz	20
6	Battery Capacity	kWh	74
7	Battery Nominal Voltage	V	1000
9	C_f	μF	99
10	C_{dc}	mF	22.2
11	L_r	mH	0.165
12	(L_{grid})	mH	0.0965

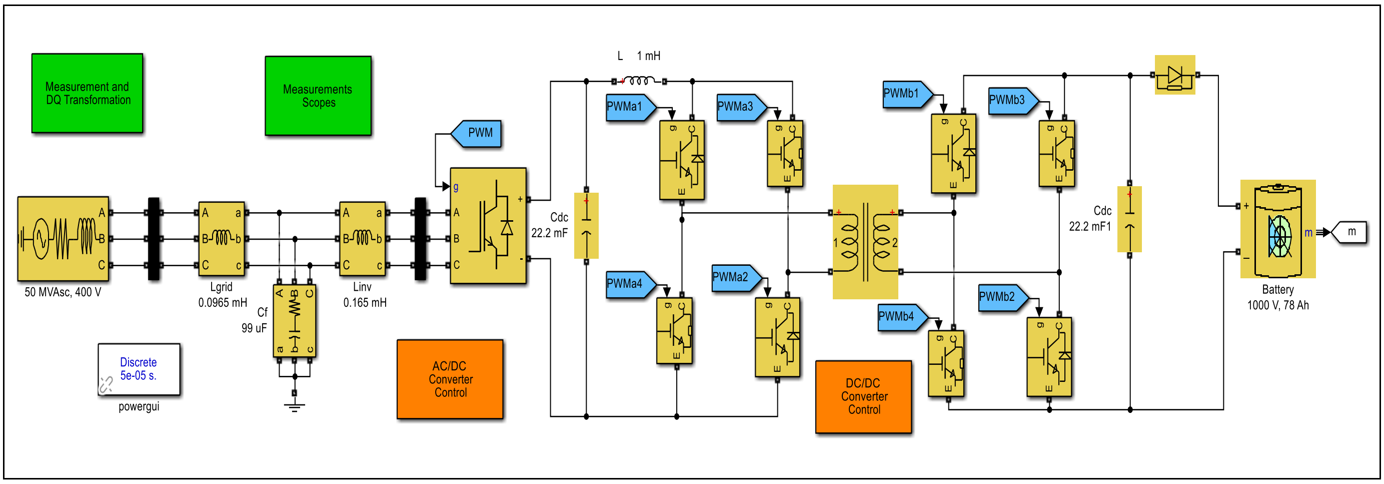

Fig 2: SIMULINK Model of DC Fast Charging System with DAB using TPS modulation

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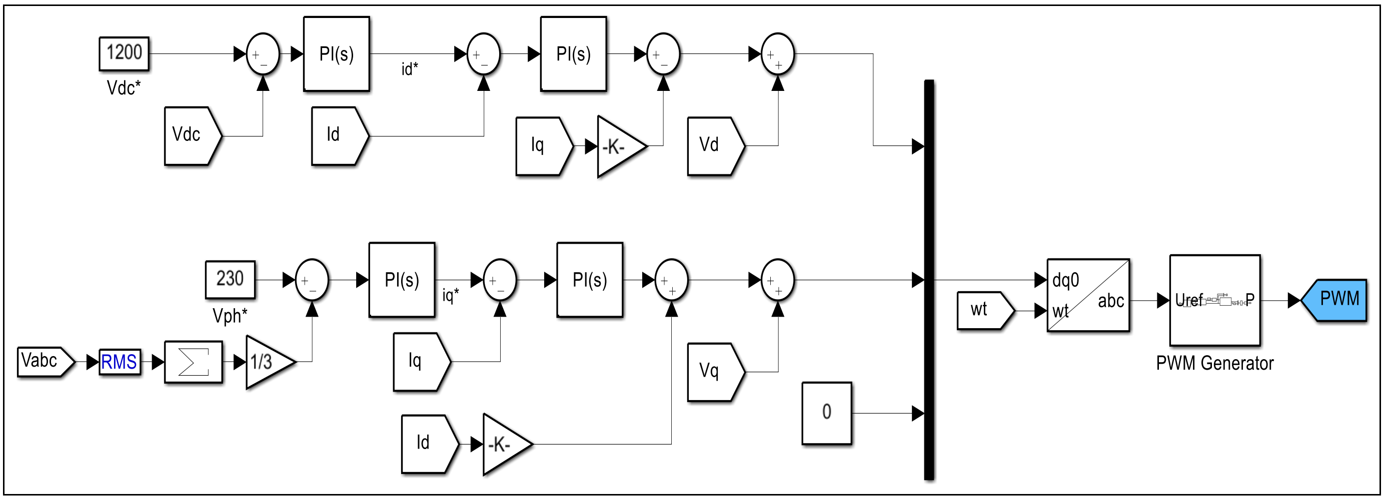
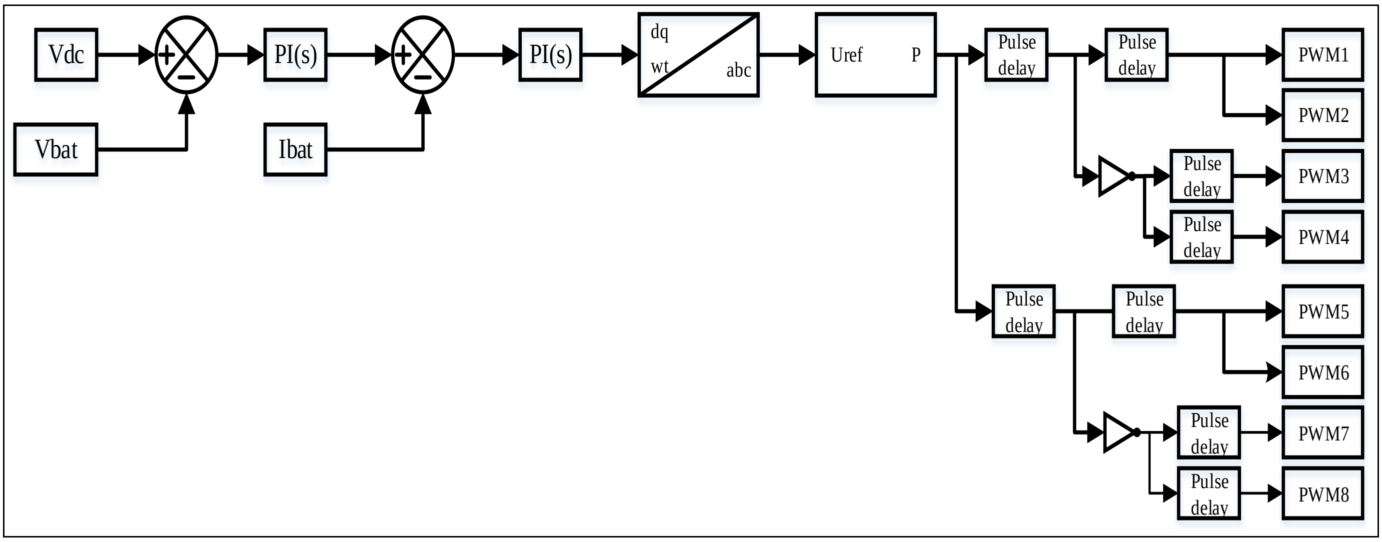


(a)



(b)

3(a) AC-DC converter convrtol and (b) DAB using TPS modulation control

IV. SIMULATION AND ANALYSIS

In dual active bridge converters, two H-bridges are used. The bridge H1 is connected to AC-DC converter and bridge H2 is connected to the battery. In ordinary single phase shift modulation, the phase shift is applied for the pulses applied to H2 bridge. In triple phase shift modulation, the additional phase shift is created between switch 1 and switch 2 as well as switch 3 and switch 4 as shown in figure 4. These phase shifts are applied for bridge H1 and bridge H2. With the dual phase shift modulation, the resulting switching pulses are shown in figure 4.

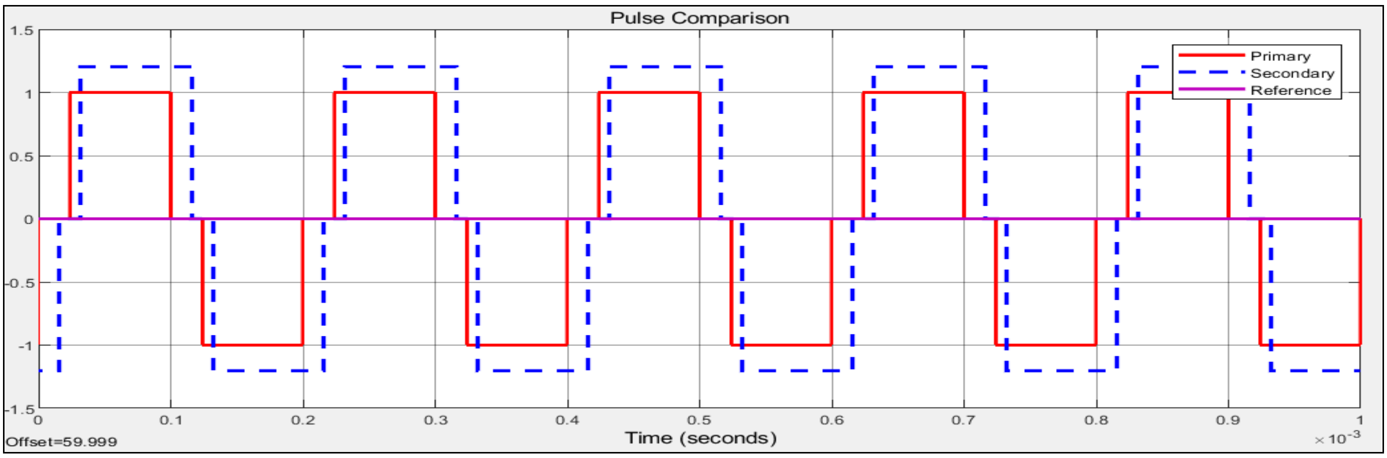


Fig 4: Switching Pulse Applied to H Bridge Switches with TPS

Figure 4 illustrates the switching pulse applied to H bridge switches with TPS modulation. The pulse applied to switch S2 is with delay compared to the pulse applied to switch 1. The delay occurs at turn on as well as turn off pulses. The similar delay can be seen at switch 3 and switch 4. To examine the performance of the designed fast charging system, the measurements are carried out for the voltages, currents and powers. Figure 5 shows the AC input voltage and current at the supply terminal. With the use of filter, the harmonic distortion is small i.e., about 2.1 % at voltage and about 4.3 % at current and within the harmonic regulation limits. With TPS modulation, the voltage harmonic distortion can be reduced to 0.87 % and current harmonic distortion can be reduced to 1.47%.

Figure 6 illustrates the RMS voltage and current at the supply terminal. According to the measurement, the rms phase voltage is about 230 V and RMS current are about 331.5 A. The active and reactive power at the supply terminal is shown in figure 7. The active power is about 230 kW and the reactive power is about 17.5 kVAR. Thus, power factor is about 0.9971 (lagging) and is acceptable. With other phase shifts, the reactive power is about 20 kVAR. Thus, TPS can provide better reactive power performance than other phase shift modulation methods.

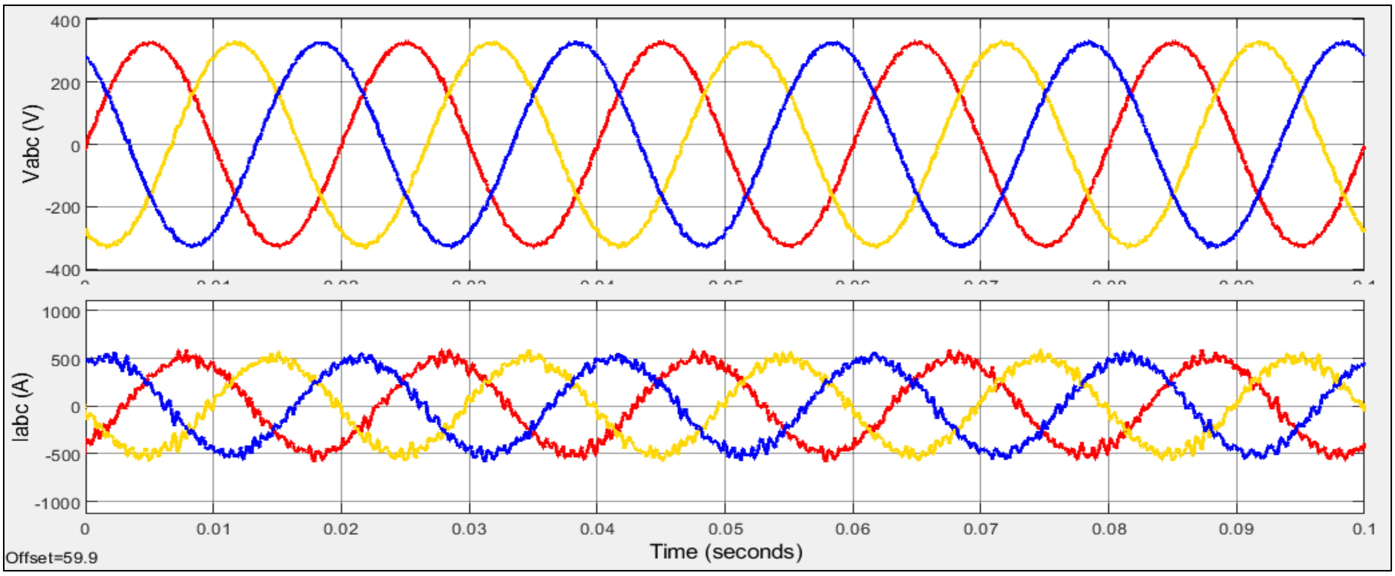


Fig 5: AC Voltage and Current Waveform at Supply

Since the reference DC voltage is set at 1200 V for AC-DC converter, the DC voltage is constant at about 1100 V. The DC current is about 190 A and thus the corresponding converter output power is about 200 kW. Figure 9 shows the voltage, current and power at the battery terminal. In the simulation, 1000 V, 78 Ah Li-ion battery is used. For the fast charging, the battery is charged at 1200 V.

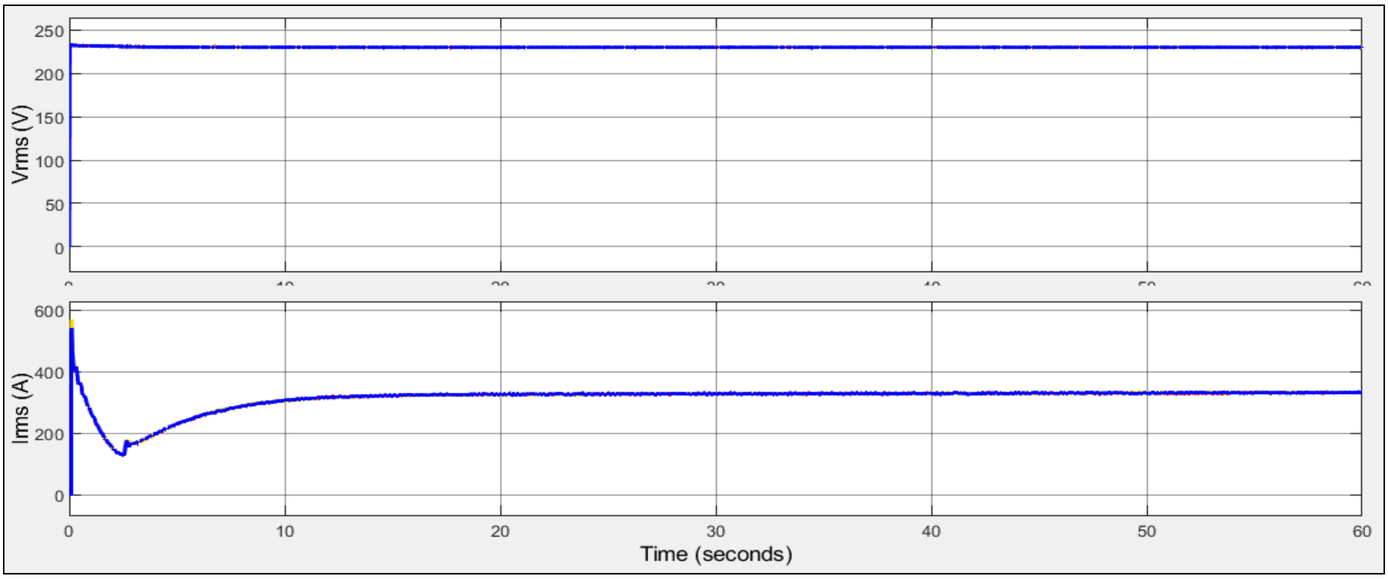


Fig 6: RMS Voltage and Current at Supply

The DC voltage and current at AC/DC converter output i.e., DAB converter input is shown in figure 8.

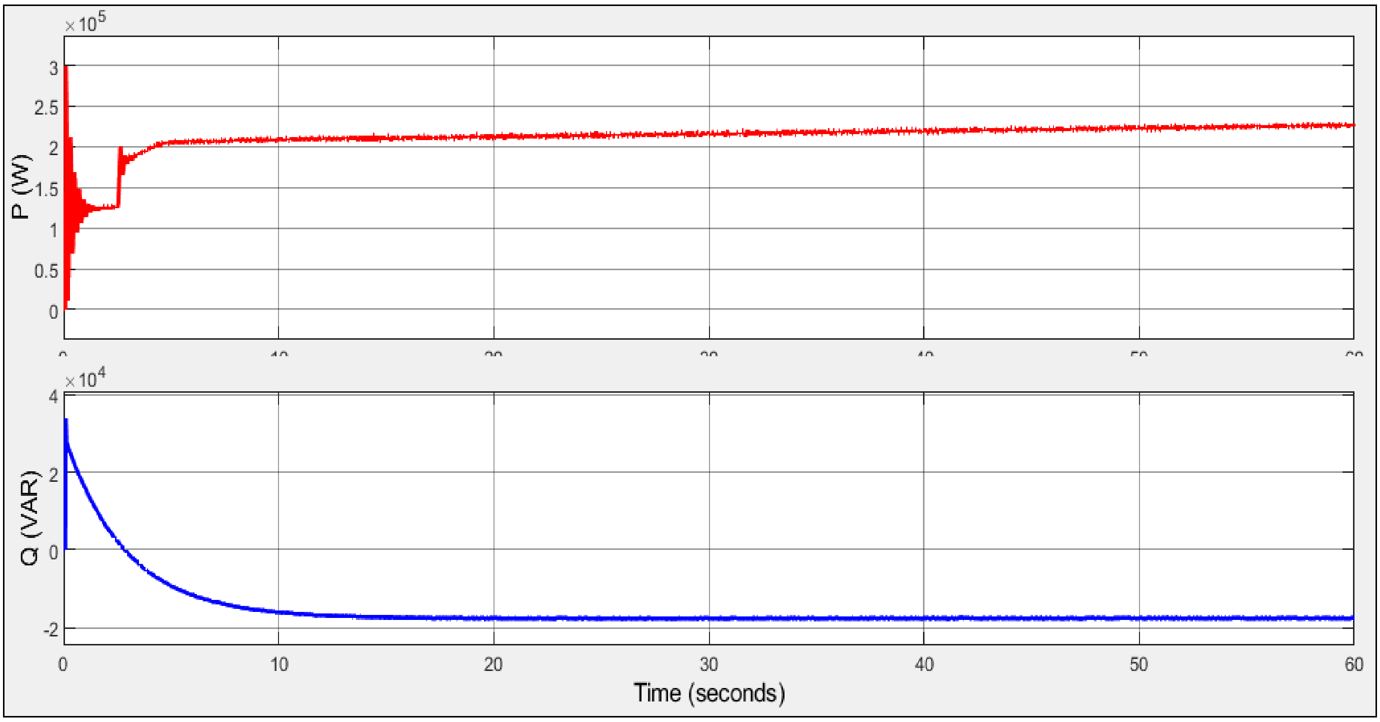


Fig 7: Active and Reactive Power at Supply

Thus, the battery terminal voltage is about 1080 V during charging. The charging current is about 200 A and the power is about 215 kW. During the charging process, the voltage, current and power are at steady state and there is no fluctuation.

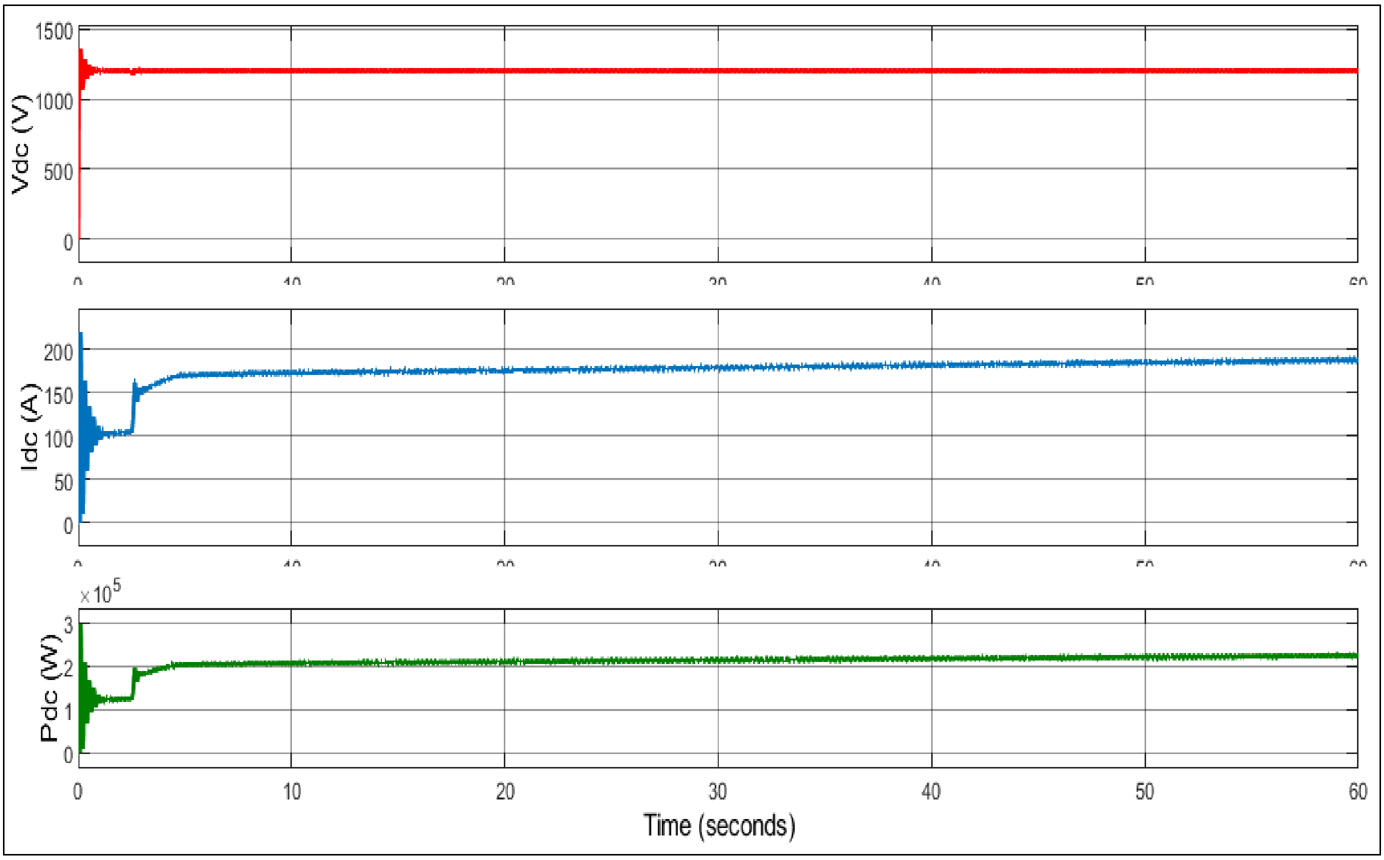


Fig 8: DC Voltage, Current and Power at DAB Input

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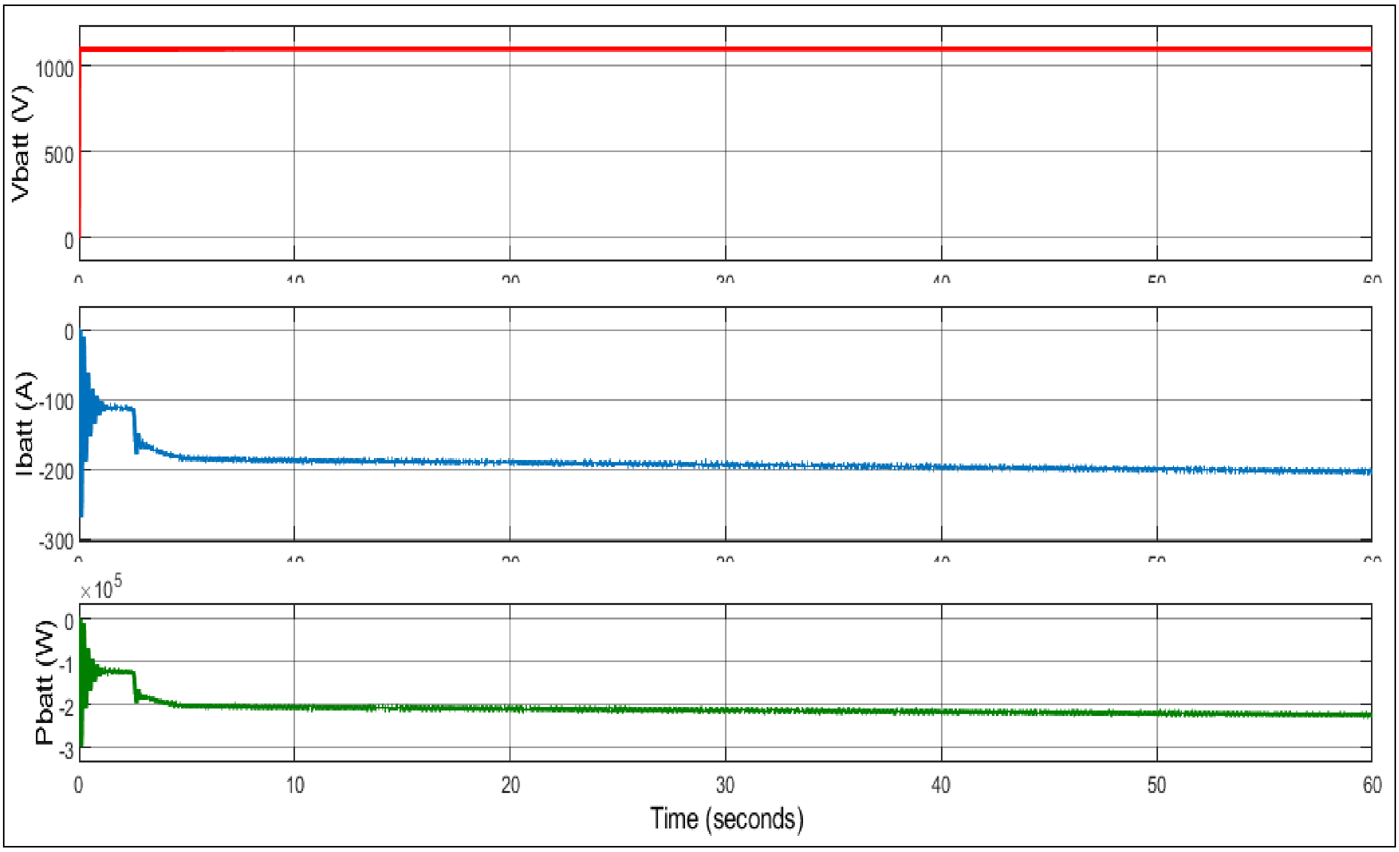

Fig 9: Voltage, Current and Power at Battery

Battery SoC condition during charging is shown at figure 10. In the simulation, the battery inertial state of charge is set at 50 %. During charging, the SoC is increased with time. During simulation time 60 seconds (1 minute), the battery SoC is increased from 50 % to 55.4 %. Thus, 5.4 % increase in 1 minute. For fully charge of empty battery, the time taken is about 18 minutes. Therefore, the TPS modulation is suitable for fast charging of EV battery.

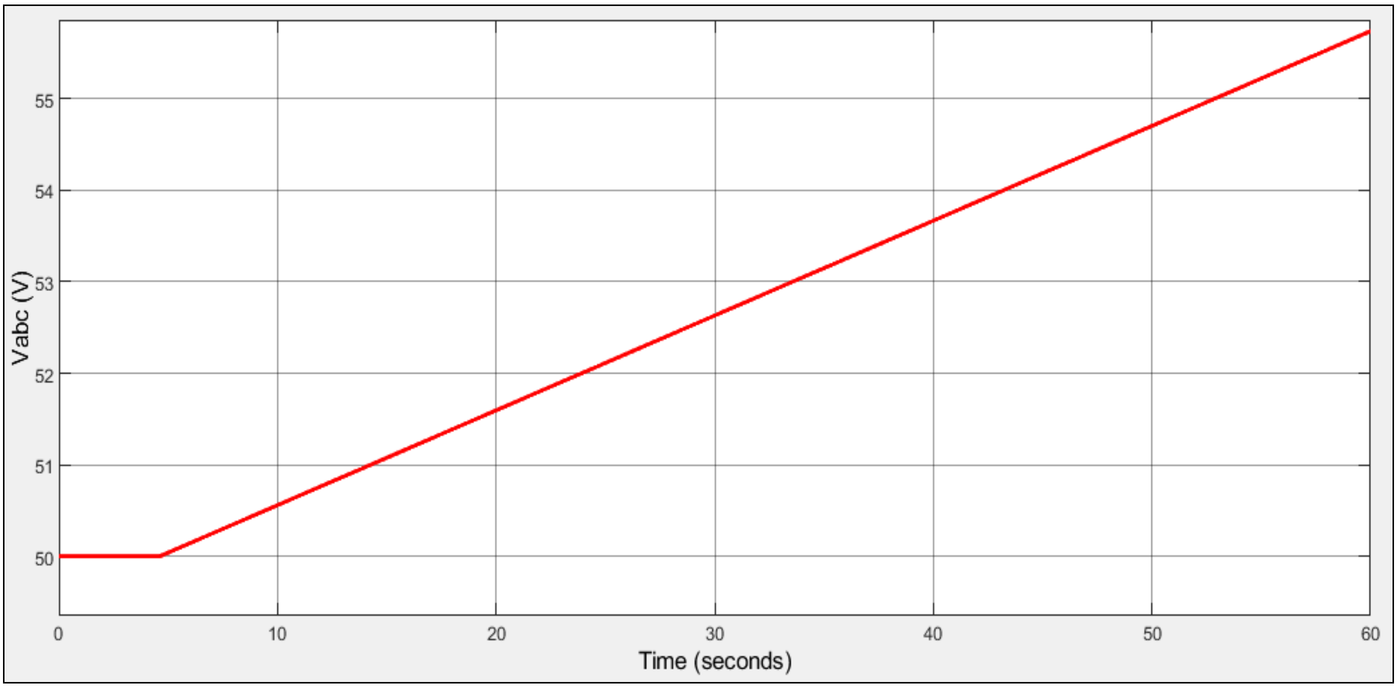

Fig 10: Battery SOC Condition During Charging

V. CONCLUSION

With rising fuel prices and increasing environmental concerns, electric vehicles are becoming more widespread across the globe. However, a significant drawback of electric vehicles is their lengthy charging time. To address this issue, extensive research has been conducted on fast charging solutions for electric vehicle. This paper presents the design and modeling of a fast-charging system using a triple phase shift modulated DAB converter. Compared to other conventional phase shift modulation techniques, the proposed system offers improved power quality, particularly in harmonic reduction, and reduces reactive power consumption, thereby shortening charging time. The modeling and simulations were carried out using MATLAB/SIMULINK, and according to the results, the designed fast charging system can fully charge an empty battery in approximately 18 minutes. For future work, the operation of the DAB converter with other modulation schemes should be explored to further enhance the performance of fast charging systems for electric vehicles.

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