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Implementation of Efficient Electric Vehicle Fast Charging System Using Dual Active Bridge Converter

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Abstract— The paper presents the electric vehicle charging model with fast DC charging technology based on the mathematical modelling and theoretical studies. The problem in this study is to model the fast charging system in order to describe the control and stability of DC bus voltage. The research direction in this study is to design a novel charger in reality. A novel 200 kW fast charger was designed for modeling of fast charging system. The proposed fast charger consists of two portions such as an AC-DC converter and a DC-DC converter using dual active bridge (DAB) technique performing a charging function. The parameters of consumable devices used in the model are mentioned for performance specifications. The main section is a design of transformer that used in the DC-DC converter in order to obtain isolation between the AC system and electric vehicle. This leads to achieve the improvements in the power quality on the AC grid. The performances of the proposed fast charger system were verified through simulations results. The modeling and simulations are performed in MATLAB/SIMULINK and all results confirm the feasibility of proposed design for experimental studies. The recommendation of the system was also given based on the comparison of recent works which were met the objectives of the studies.

Keywords: Electric vehicle, fast charging system, AC/DC converter, Dual active bridge, Isolation transformer.

1. Introduction

The automotive industry has recently encountered a significant turning point due to the environmental impact of internal combustion engine vehicles (ICEVs). Electric vehicles (EVs) are emerging as appealing alternatives to ICEVs because of their environmental benefits and the rising cost of oil. Consequently, the development and commercialization of a charging infrastructure for EVs have become a priority in many countries. This charging infrastructure includes an operating system, customer information system, and charging system. Of these components, the charging system is the most crucial and fundamental part of the infrastructure [1][2].

The charging system can be categorized into slow chargers and fast chargers based on charging time and method. A slow charger typically delivers approximately 3–4 kW of power to the EV, requiring about 6–7 hours for a full charge. This makes slow chargers suitable for overnight charging using a household AC power supply. In contrast, a fast charger supplies over 36 kW (80 A) of power to the EV, reducing charging time to less than 0.5 hours. These fast chargers, also known as Level III or off-board chargers, are often installed in public locations. The development and validation of fast chargers have been pursued in many developed countries. However, large charging stations can negatively affect power quality in the electricity distribution system. These adverse effects may

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manifest as voltage distortions and current harmonics. Poor power quality, including low power factor, has already been an issue in many countries. Implementing appropriate filter technology can help mitigate these problems, although the impact on the AC grid at peak charging power will persist [3][4].

In this work, a novel 200 kW fast charger system is described. The charger system improves the power quality using suitable filter and isolation transformer. It is capable of charging a lithium-ion battery in an EV within a voltage up to 1000 V by supplying a current of maximum 200 A. 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 can provide efficient control and reduced impact on power quality of the system.

The paper is organized as follows. Section II mentions the Consumable Devices of Fast Charging System for Electric Vehicles. Section III presents the Operation and Control of Dual Active Bridge Converter. Section IV offers the Dual Active Bridge Converter. Section V expresses the Modeling of Fast Charging System Using DAB. Section V presents the results and discussions on this study. Finally, section VI concludes the analysis and design of the proposed system.

2. Consumable Devices of Fast Charging System for Electric Vehicles

The source for Electric Vehicle Charging Stations (EVCS) is a three-phase AC supply from the grid. A centralized conversion from AC to DC is achieved using an inverter, which is interfaced with LC filters and a transformer. Appropriate DC bus capacitances are placed on the DC side to stabilize the DC bus voltage during sudden and high load demands. The primary component of the EVCS is the DC bus, to which all the EVs are connected for charging. Since the EVs connected to the DC bus may have different voltage and current ratings, a decentralized DC-DC conversion scheme is implemented to meet their individual requirements. The key driving force behind the centralized AC-DC and decentralized DC-DC converters is the control strategies, which are discussed briefly in the following sections. These control systems primarily ensure proper switching of power electronic devices in these converters[5].

2.1 LCL Filter

The primary reason for implementing the filter circuit is to attenuate harmonics, which reduce the power factor and interfere with the proper operation of the inverter by appearing as undesirable circuit components. Simple low pass filters attenuate harmonics but removing 3rd and 5th order harmonics is challenging because the fundamental component can also be filtered out. The main purpose of using LCL filters is to eliminate current harmonics that may arise between the inverter and the grid. Typically, L filters are installed between the grid and the inverter, except for applications above several kW, where they become too expensive, occupy large space, and exhibit poor system dynamics. Therefore, LCL filters are used instead. As 3rd order low-pass filters, LCL filters offer better harmonic attenuation and a smaller filter size [4].

2.2 Control Systems

The section of control systems are crucial for the modeling and operation of any system. They monitor the system’s performance at various points and adjust input parameters to ensure the output meets the required set values.

2.3 Converter Control System

The control system used for converters is a cascaded control system operating in the dq frame, followed by a PWM generator that sends gating pulses to the switches in the converter to maintain a constant DC bus voltage. Each PI control block within the system has specific functions, which are labeled accordingly as shown in the accompanying Figure.1 [5].

3. Operation and Control of Dual Active Bridge Converter

Figure.1 illustrates the block representation of the proposed converter along with its controller. The operation of the proposed converter is similar to that of a typical dual active bridge converter circuit. A DC source is supplied to the dual active bridge converter, and the output is connected to the battery for charging applications. In this setup, the output current must be maintained at a constant level to ensure proper battery charging. The controlled output current is a function of the input DC voltage. The controller detects variations in the output current and maintains a constant output current by adjusting the phase of the secondary side of the bridge relative to the primary side. The DC input to the circuit is 1000V, and the MOSFET switches used in the converter operate at a frequency of 50 kHz with a duty cycle of 50%.

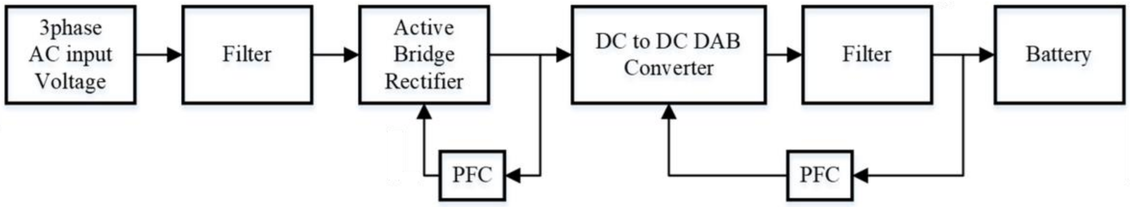

Figure 1. Block Diagram of fast charging system using DAB converter

4. Dual Active Bridge Converter

The dual active bridge converter circuit consists of eight MOSFET switches, a high-frequency transformer, an energy transfer element (an inductor), and DC-link capacitors. This configuration allows for a bi-directional, controllable, high-power DC-to-DC conversion. Essentially, the converter functions as a standard full bridge with a programmable rectifier. Due to the symmetry of the primary and secondary bridges, this converter can regulate power flow in both directions.

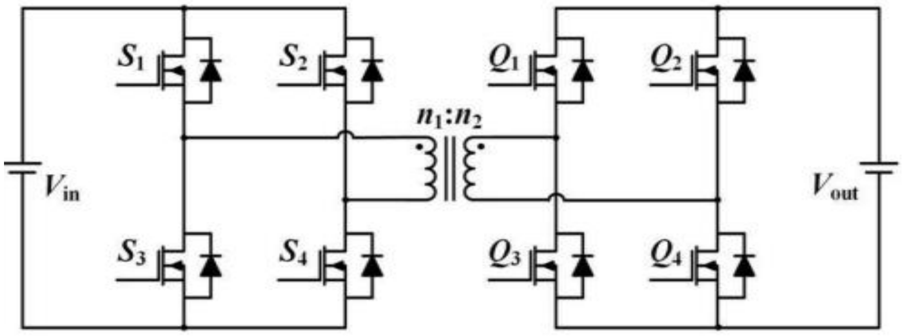

Figure 2. Schematic for Dual active bridge converter

The converter comprises two bridges: the primary bridge and the secondary bridge. The primary side bridge functions as an inverter, while the secondary side bridge functions as a rectifier. The high-frequency transformer connected to both bridges provides isolation. In a dual active bridge converter, both the primary and secondary bridges are simultaneously controlled, with all switches operating at a 50% duty cycle. The diagonal switches turn on and off simultaneously, creating a square wave output for each bridge.

In the accompanying figure, the switching waveform of a conventional dual active bridge converter is depicted. Switches S1, S2, S3, and S4 are part of the primary side circuit, while Q1, Q2, Q3, and Q4 belong to the secondary side circuit. At any given time, four switches are turned on, operating in four intervals as follows:

Interval 1: S1, S2, Q2, and Q3 are triggered.
Interval 2: S1, S4, Q1, and Q4 are triggered.
Interval 3: S2, S3, Q1, and Q4 are triggered.
Interval 4: Q2, Q3, S2, and S3 are triggered.

There is a phase difference between the triggering pulses from the primary to the secondary side, typically maintained in the range of 0 to 30 degrees.

5. Modeling of Fast Charging System Using DAB

The mathematical modelling of the proposed circuit structure is given in the following equations. The main idea of this mathematical expressions is to effectively calculate the suitable consumable devices for designing the physical circuit in real world applications. The abbreviations in those equations are also expressed in this section. The performance specifications of the numerical analysis could be expressed based on the MATLABSIMULINK model for confirmation.

$$N_p = \frac{V_i \times 10^8}{4 \times f \times B_{\max} \times A_c} \tag{1}$$

$$\frac{N_p}{N_s} = \frac{V_p}{V_s} \tag{2}$$

$$V_L = V_i \frac{N_s}{N_p} - V_0 \tag{3}$$

$$I_{ripple} = 0.2A \tag{4}$$

$$L = \frac{V_L D T_s}{I_{ripple}} \tag{5}$$

$$V_{ripple} = 1\% of\, 24 = 0.24V \tag{6}$$

$$C = \frac{I_{ripple} D T_s}{V_{ripple}} \tag{7}$$

$$C_{dc} = \frac{3 X_n T}{(1.8 V_m)^2 - (1.4 V_m)^2} \tag{8}$$

$$L_{inv} = \frac{V_{grid}^2}{S_{rated} THD 2\pi f_{sw}} \sqrt{\frac{\pi^2}{18}\left[\frac{3}{2} - \frac{\sqrt[4]{3}}{\pi} m_a + \frac{8}{9} m_a^2\right]} \tag{9}$$

$$C_f \le \frac{0.05 S_{rated}}{2\pi f_{grid} V_{grid}^2} \tag{10}$$

$$L_{grid} = \frac{RAF + 1}{RAF C_f \, 2\pi \, f_{sw}^2} \tag{11}$$

Abbreviations:
V_i : Input Voltage
V_o : Output Voltage
D : Duty Cycle
V_{ripple} : Voltage Ripple
C : Capacitance
A_c : Area of cross section
V_L : Voltage across the inductor
I_{ripple} : Window factor
T_s : Switching Time
B_{max} : Maximum permeability
L_{inv} : rectifier-side inductance
C_f : filter capacitance
V_{grid} : Grid Voltage
f_{gird} : grid voltage fundamental frequency
S_{rated} : rated power
THD : total harmonic distortion
f_{sw} : switching frequency
m_a : rectifier modulation index
RAF : ripple attenuation factors of the rectifier-side current
Cdc : DC Capacitance
Vm : peak value of the phase voltage

XnT : energy changes rating for capacitor

Table 1. Battery and Component Parameters

No.	Parameter	Unit
1	Input Voltage(AC)	400V
2	Frequency	50Hz
3	L_{grid}	0.0965mH
4	C_f	99μF
5	L_{inv}	0.165mH
6	C_{dc}	22.2mF
7	L_{dc}	1mH
8	Battery Nominal Voltage	400V
9	Battery Nominal Capacity	78Ah
10	Duty Cycle (D)	50%
11	Switching Frequency	50kHz

For the modeling of fast charging system Matlab/Simulink software is used. The designed fast charging system consists of EMI filter, AC/DC converter and dual active bridge (DAB) bidirectional converter. The main function of EMI filter is to reduce the harmonic distortion at the system. The AC/DC converter convert the input AC to desired DC voltage. The DAB converter performs the isolation function and produce the specific DC voltage level which is suitable for fast charging to the battery. Figure.3 illustrates the Simulink model for fast charging system using DAB.

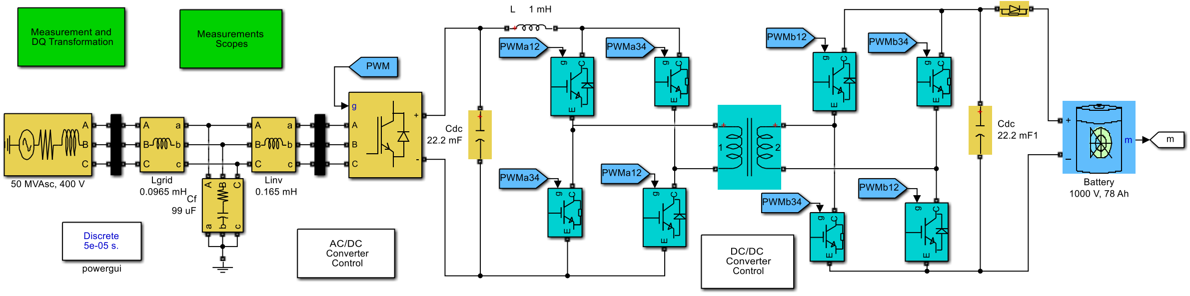

Figure 3. Simulink Model for Fast Charging System Using DAB

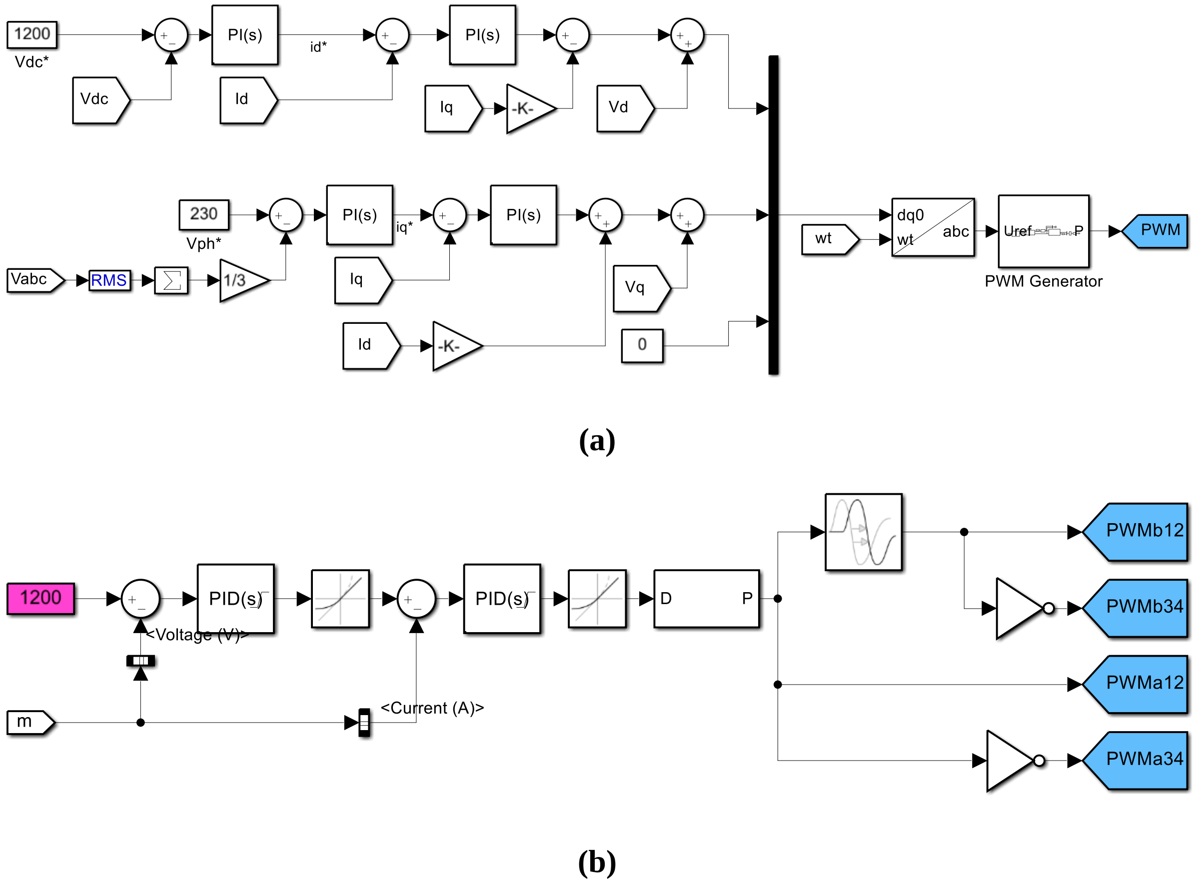

Figure 4. Controllers for Fast Charging: (a) AC/DC Converter Control and (b) DC/DC Converter Control for DAB

There are two controllers in fast charging system as; (i) AC/DC converter controller and (ii) DAB controller as shown in Figure.5. 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.

6. Result and Discussion

In order to investigate the performance of the designed fast charging system, the measurements are carried out for the voltages, currents and powers. Figure.6 shows the AC input voltage and current at the supply terminal. With the use of EMI 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.

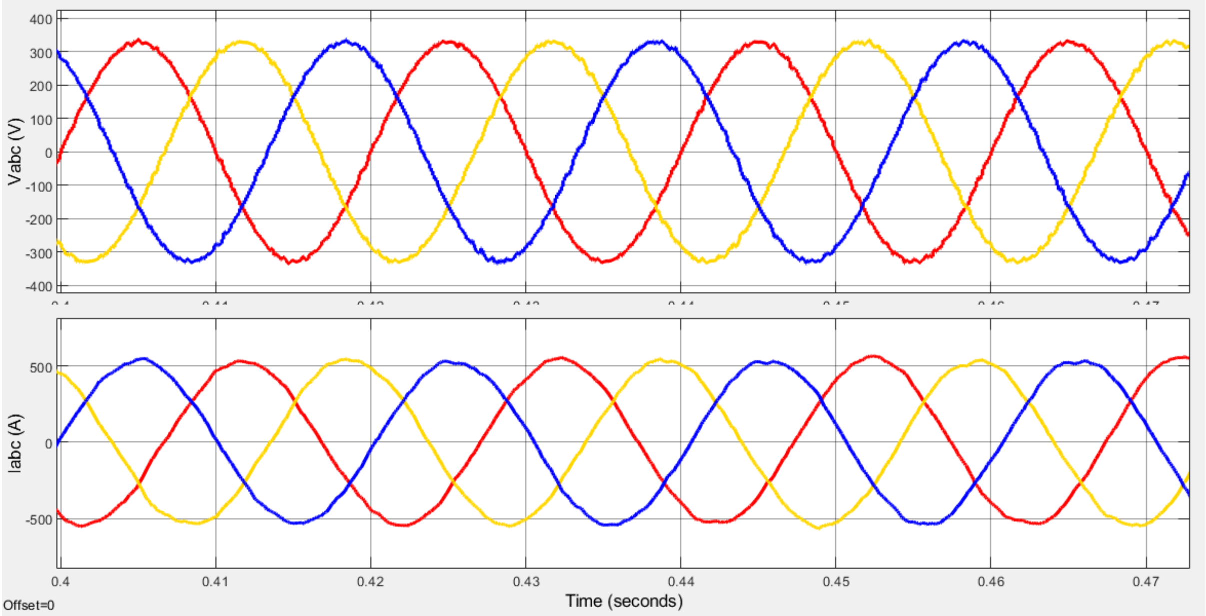

Figure 5. AC Voltage and Current Waveform at Supply

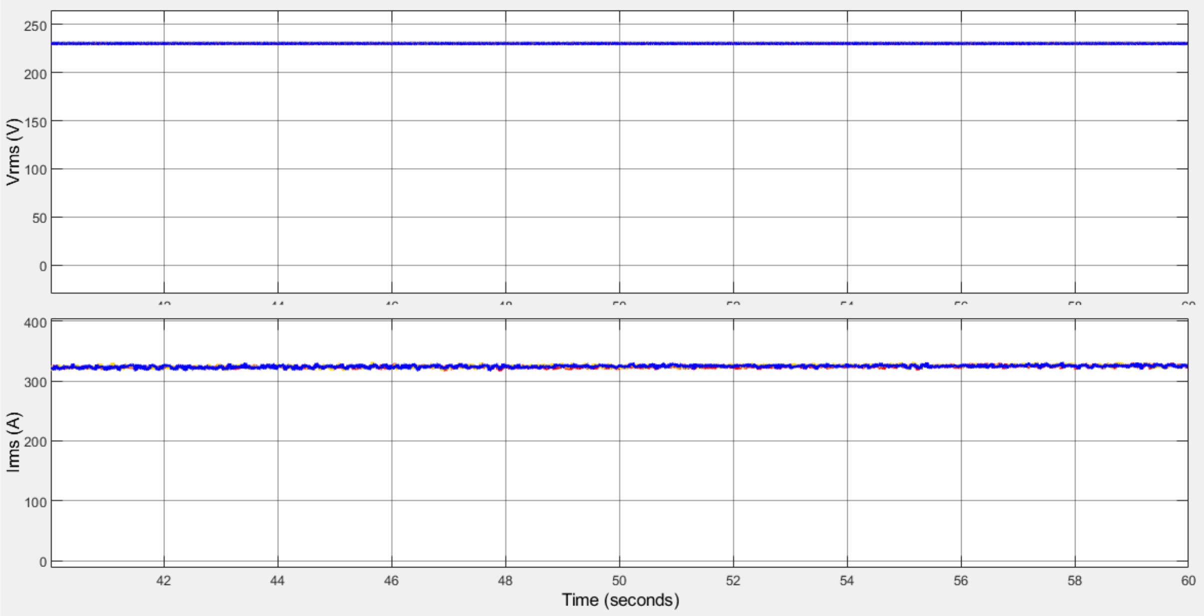

Figure 6. RMS Voltage and Current at Supply

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 320 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 20 kVAR. Thus, power factor is about 0.996 (lagging) and is acceptable.

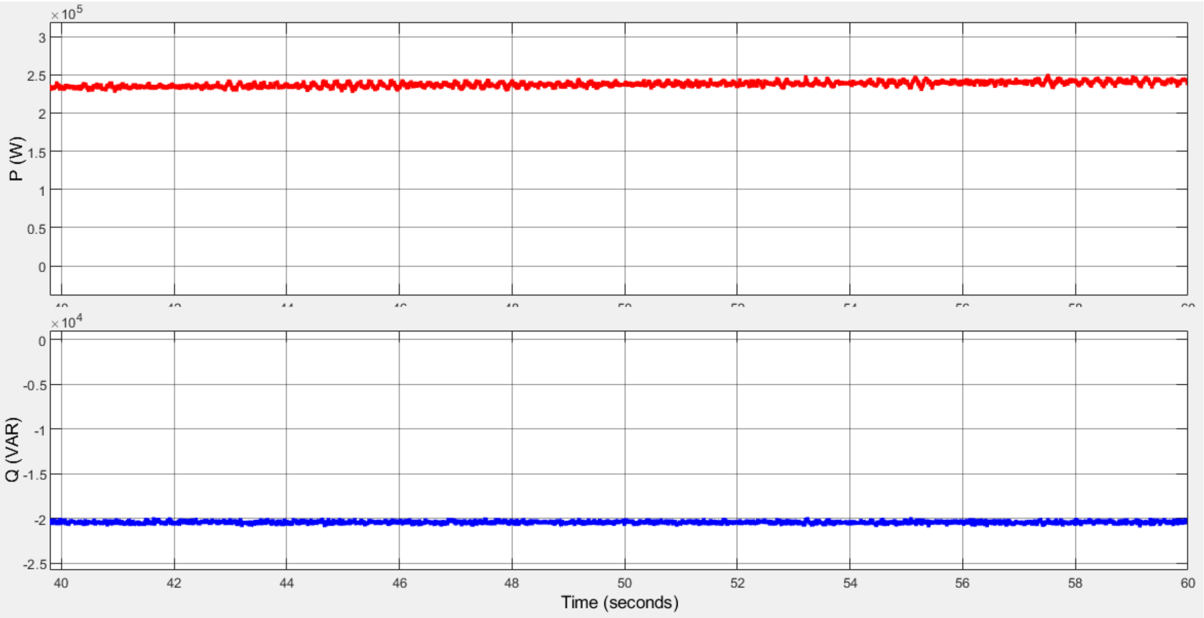

Figure 7. Active and Reactive Power at Supply

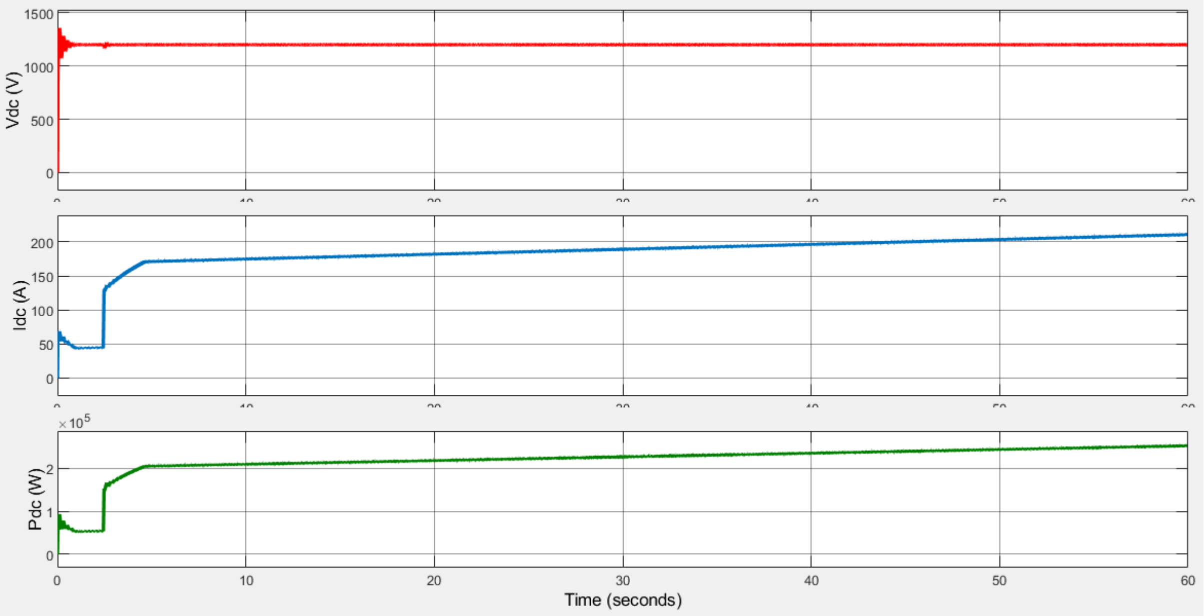

Figure 8. DC Voltage, Current and Power at DAB Input

The DC voltage and current at AC/DC converter output i.e., DCB converter input is shown in Figure.8. Since the reference DC voltage is set at 1200 V for AC/DC converter, the DC voltage is constant at about 1200 V. The DC current is about 190 A and thus the corresponding converter output power is about 230 kW.

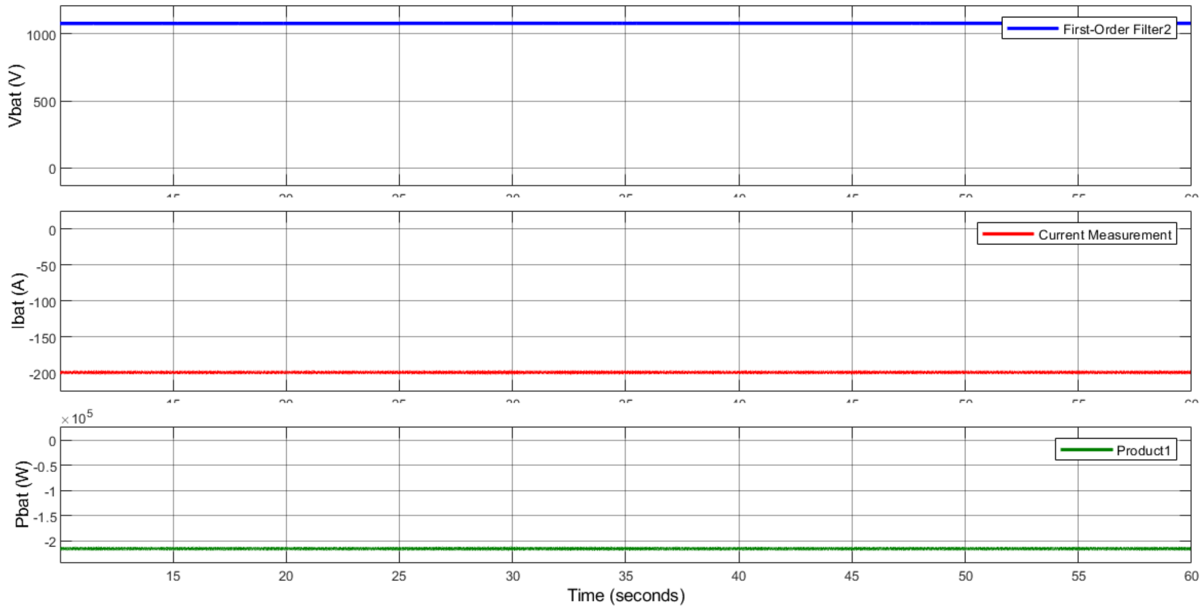

Figure 9. Voltage, Current and Power at Battery

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. 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.

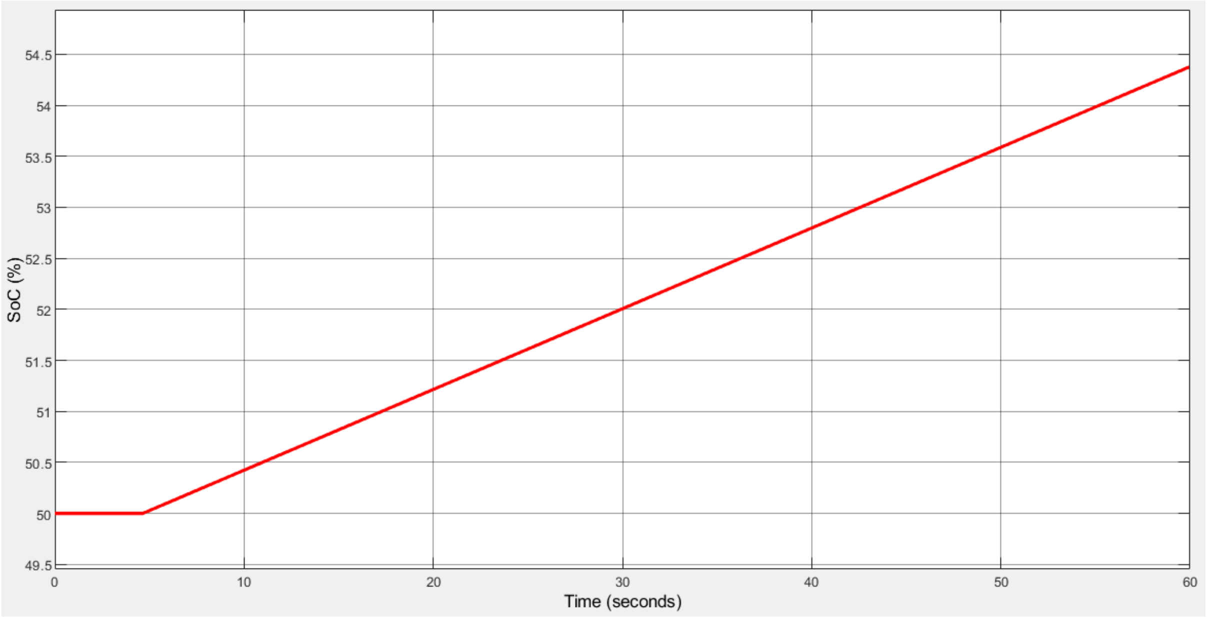

Figure 10. Battery SoC Condition During Charging

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 54.38 %. Thus, 4.38 % increase in 1 minute. For fully charge of empty battery, the time taken is about 23 minutes. Therefore, the design charger is suitable for fast charging of EV battery.

7. Conclusion

With the increase in fuel price and environmental pollution problems, the electric vehicles applications become more and more widespread all over the world. The main drawback in use of electric vehicle is its long charging time. In order to overcome these problems, much research is carried out for fast charging of electric vehicles. In this paper, the design and modeling of fast charging system for electric vehicle using DAB converter is described. The DAB converter can provide the fast charging as well as the isolation of the charging system. It can also perform bidirectional power flow and thus is suitable for vehicle to grid and grid to vehicle application. The modeling and simulations are done using MATLAB/SIMULINK. According to the simulation results, the designed fast charging system take about 23 minutes for fully charging of empty battery. For further study, the practical construction of prototype and testing is recommended for real world applications.

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