DUAL-STAGE CONVERTER FOR CHARGING OF ELECTRIC VEHICLES

Final Report

EE 665: POWER ELECTRONICS SYSTEMS FOR ELECTRIC VEHICLES

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Team Members

- Muhafiz Bilal Khan - 244102111 (Simulated the model in SIMULINK. Edited MATLAB figures in VISIO. Made LaTeX file for report submission.)
- Pramod Vipparthi - 244102112 (Simulated the model in SIMULINK. Made circuit diagrams and waveforms in VISIO.)

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1 Introduction

The application of EV's is increasing day by day in the transport sector[1]. It can also be integrated with renewables for energy management in smart grids[2][3]. To perform the battery charging process, slow or fast chargers can be used. The EV battery charging requires conversion of ac grid voltage to dc voltage of an optimal value for which passive or active converters can be used[4].

In this context, an off board charger which is typically fast was modelled in this report. The charger consisted of two stages. The first stage was ac to dc conversion. The second stage was a bidirectional three level voltage source dc to dc converter which operates similar to an interleaved converter. The resulting frequency in the coupled filter was twice that of the switching frequency due to interleaving behaviour.

The EV charger can also be used to mitigate power quality problems[5]. The whole model can operate in V2G or G2V mode of operation depending on the direction of the current in the battery. During G2V mode of operation, the power flow is from grid to battery of vehicle whereas during V2G mode of operation, the battery supplies the grid in case of excessive power.

2 Architecture of the model simulated

The schematic of the model is shown in figure 1. The model has two stages viz

1. AC-DC conversion stage
2. DC-DC conversion stage

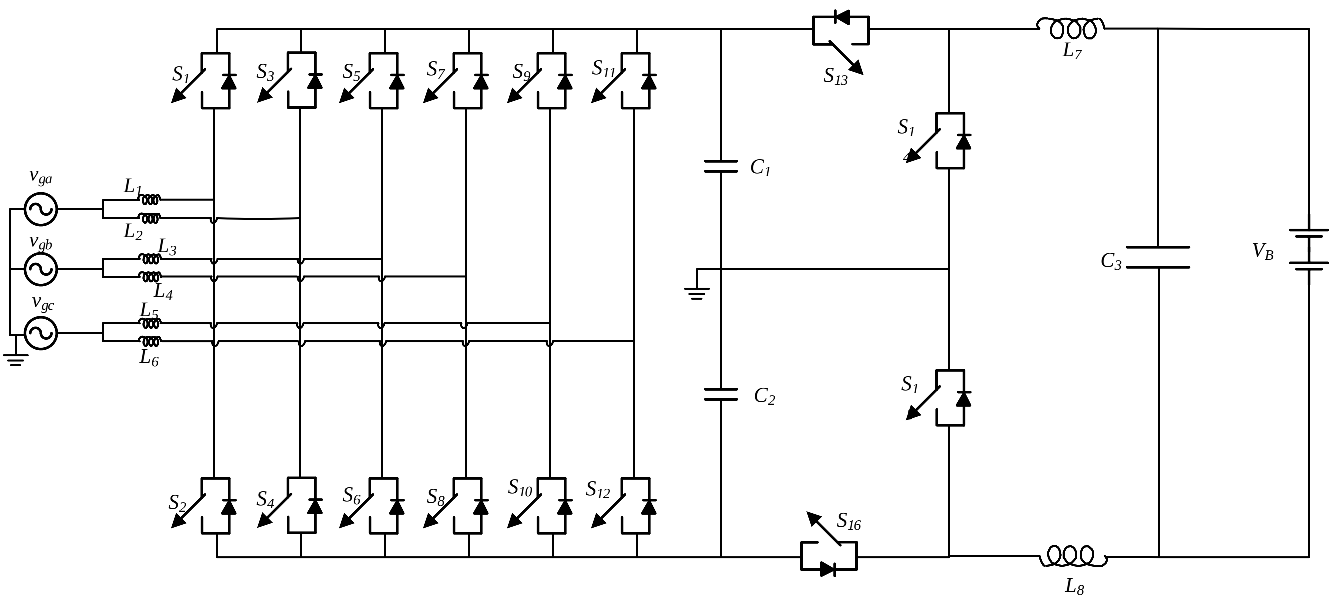

Figure 1: Schematic of three phase EV battery charger

2.1 AC-DC conversion stage

This stage is composed of parallel of two three phase controlled ac to dc converters. It has a total of six legs with each leg having two IGBT's i,e, a total of 12 IGBT's. The use of IGBT's in parallel to a feedback diode allows for bidirectional flow of current. So this converter allows bidirectional flow of power. The 12 pulse ac to dc converter has an advantage that of lower harmonic distortion, smoother dc output, improved effeciency, enhanced power quality etc. But the model becomes complex and is expensive. This acts like an interleaved converter. So the ripple in grid current is smaller than that of a traditional ac to dc converter and the ripple frequency is twice that of the switching frequency. The schematic for this converter is shown below.

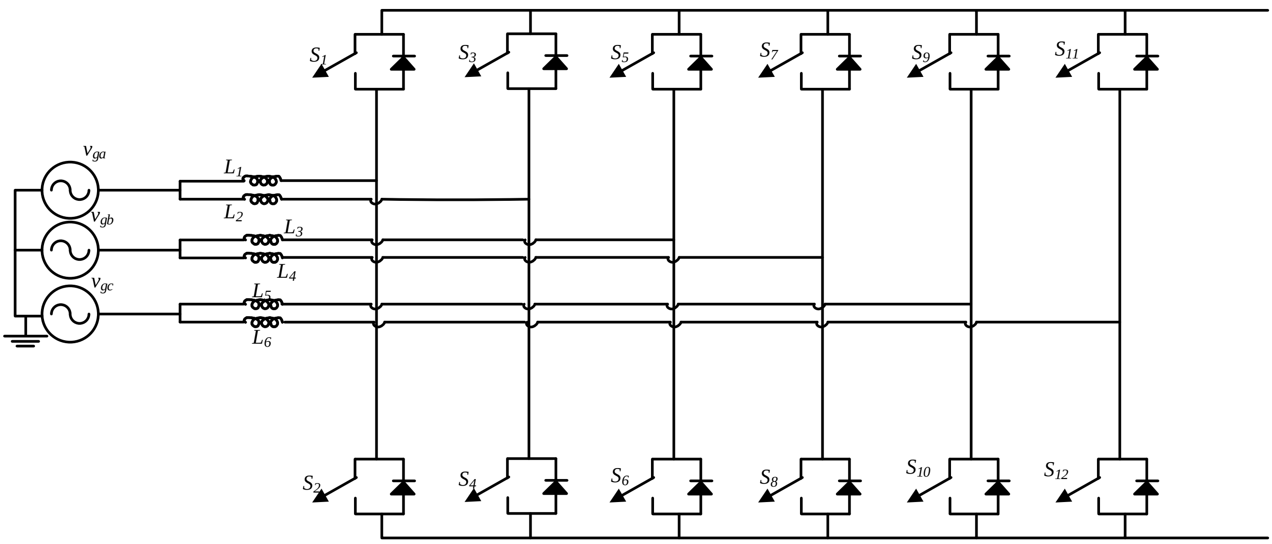

Figure 2: 12 Pulse bidirectional AC-DC converter

2.2 DC-DC conversion stage

This stage includes a bidirectional three level voltage source converter. it has four switches and is coupled with ac-dc stage through dc link split capacitors and has a second order LC filter. The converter operates as as buck converter in G2V mode and as a boost converter in V2G mode of operation. During the G2V operation, the antiparallel diodes of IGBTs S14 and S15 are used. During V2G operation, the antiparallel diodes of IGBTs S13 and S16 are used. This acts like an interleaved converter. So the ripple frequency of current through inductors is twice that of the switching frequency. Moreover, the overall ripple gets reduced. The schematic of this converter is given as.

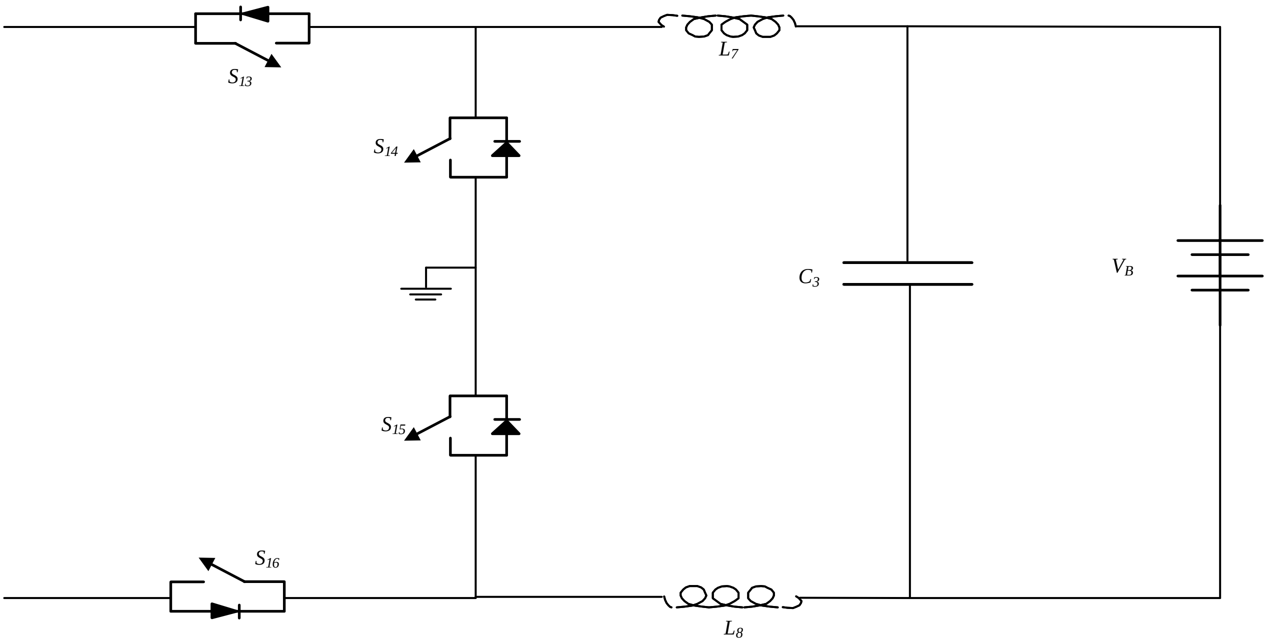

Figure 3: Bidirectional three level voltage source converter

3 Modelling of Converter in Open Loop in SIMULINK

3.1 Discussion

The system was simulated in SIMULINK. The model consisted of a 12 pulse ac-dc converter. The ac to dc stage consists of two parallel three-phase ac-dc converters. Each phase of the three phase source was connected to the two legs via an inductor. The pulses for the converters was generated using SPWM with the reference being three pase sinusoidal voltages having a phase shift of 120° with each other. The carrier of the two parallel converters was a triangular wave with a phase shift of 180°. The ac-dc stage was coupled with the dc-dc stage using split capacitors.

This dc-dc stage was a bidirectional three-level dc-dc converter. This converter acts as both buck and boost converter depending on which switches are turned on and off. The battery was connected across the terminals of this stage. The switching pulses for this stage was generated by comparing a constant value of duty ratio with two repeating triangular signals. Each comparison generated switching pulses for one pair of switches depending on the mode of operation of this stage. This stage consists of a pair of inductors.

The SIMULINK model was simulated with a discrete solver with a sampling rate of 10^{-6}. The method used was Runge-Kutta method.

3.2 Parameters

Parameter	Value
Grid voltage	400 V
Grid frequency	50 Hz
$DC-link\ Capacitors$	2.6 mF
Input Inductors	2 mH
Output Inductors	130 μH
Battery Voltage	350 V

Table 1: Simulation Parameters in Open loop

3.3 Simulation Results

3.3.1 Waveforms

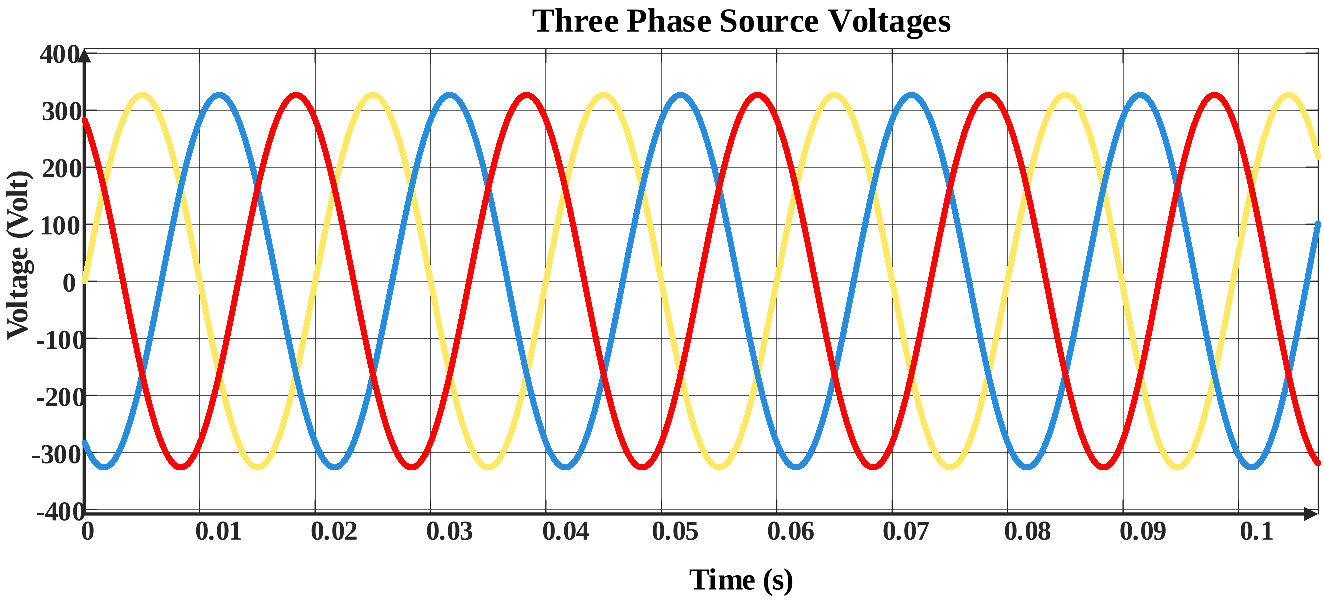

Figure 4: Three Phase Source Voltage

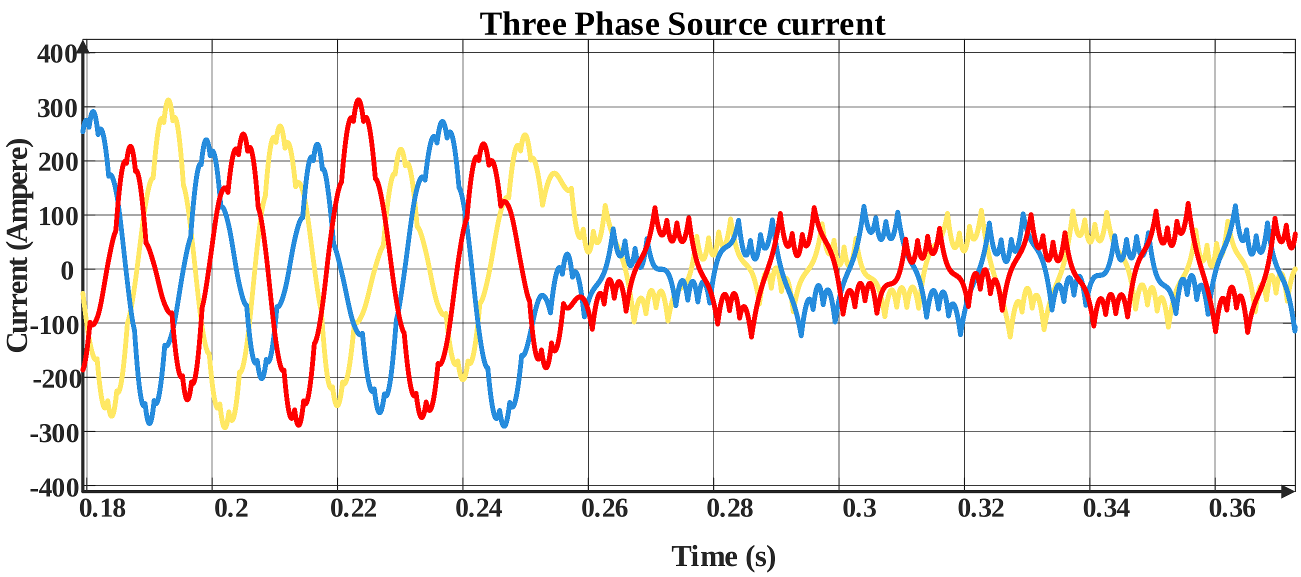

Figure 5: Three Phase Source current

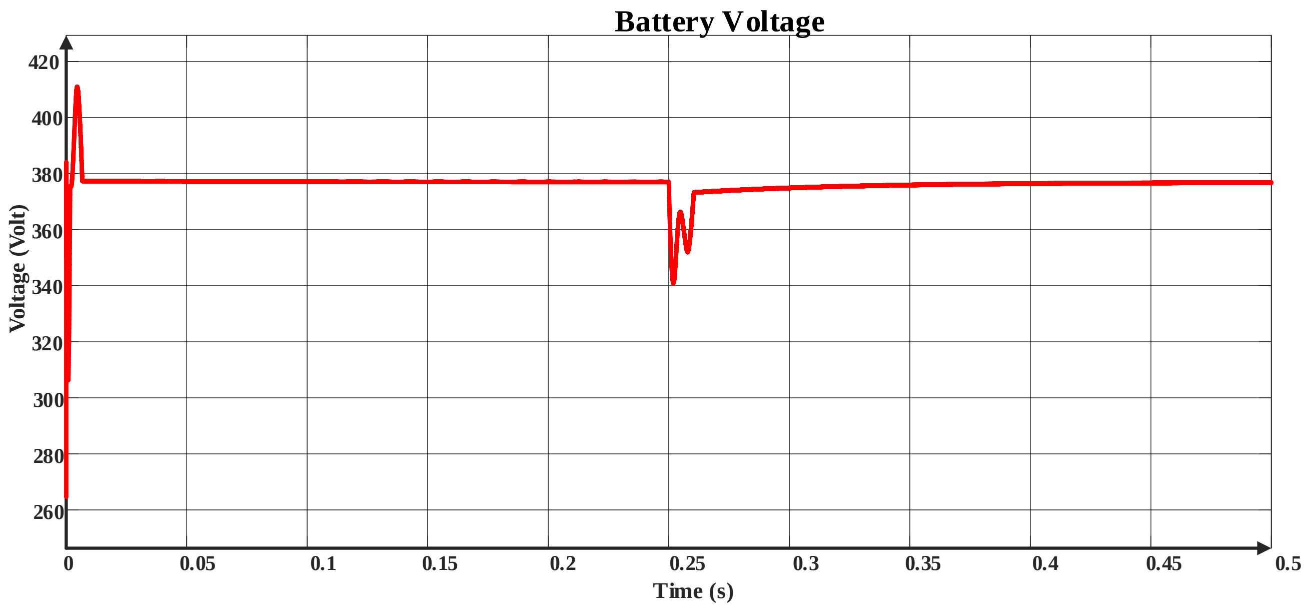

Figure 6: Battery Voltage

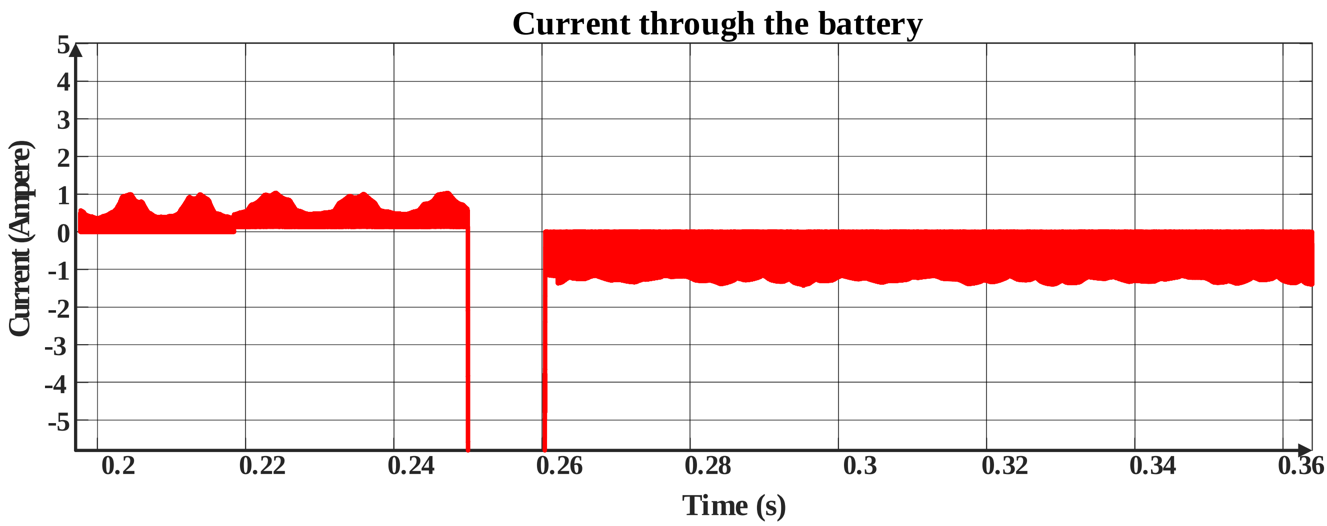

Figure 7: Current through the battery

3.3.2 Observation

On observing the above waveforms of currents, the source current had a %THD of 17.45% when operated in G2V mode and a %THD of 57.52% when operated in C2G mode. Moreover, the current during G2V mode is positive whereas the current during C2G mode is negative.

4 Closed Loop Control of Dual-Stage Converter

4.1 Overview

The EV fast battery charger consists of a dual-stage power conversion system:

- **AC-DC Stage:** Interfaces the charger with the power grid and regulates the DC-link voltage while ensuring sinusoidal grid currents.
- **DC-DC Stage:** Manages the charging current to the battery using a bidirectional converter.

4.2 AC-DC Stage Control

4.2.1 Grid Current Reference

The current reference is based on power theory, modeling the charger as an equivalent conductance:

$$i_g^{abc*}(t) = G_{EV}(t) \cdot v_{PLL\_s}^{abc}(t) \tag{1}$$

To provide reactive power support, the reference is extended as:

$$i_g^{abc*}(t) = G_{EV}(t) \cdot v_{PLL\_s}^{abc}(t) + \frac{Q^*}{V_G^{abc2}(t)} \cdot v_{PLL\_c}^{abc}(t) \tag{2}$$

4.2.2 Predictive Current Control

Using the inductor voltage relation, we predict the required converter output voltage:

$$v_{cv\_AC\_a1}[k] = v_{ga}[k] - \frac{L_1}{T_s}\left(i_{L1a}^*[k] - i_{L1a}[k]\right) \tag{3}$$

4.2.3 Interleaved Switching

Two converters operate with a 180° phase shift in PWM carriers, doubling the ripple frequency and improving filtering.

4.3 DC-DC Stage Control

4.3.1 Battery Charging Current Control

Using the inductor model, the required output voltage is:

$$v_{cv\_DC1}[k] = v_{bat}[k] + \frac{L_7}{T_s}\left(i_{L7}^*[k] - i_{L7}[k]\right) \tag{4}$$

4.3.2 Interleaved PWM

Two interleaved carriers are used to produce a ripple frequency of 40 kHz, enhancing current quality during charging.

4.4 Summary

Stage	Control Objective	Strategy
AC-DC	Sinusoidal current, DC voltage	Power theory + predictive control
DC-DC	Battery current regulation	Inductor-based predictive control
Both	Reduced ripple	Interleaved PWM

Table 2: Summary of control algorithm

The above discussed control scheme is taken from [6].

4.5 Block Diagram and Simulation Parameters for Closed Loop Contro

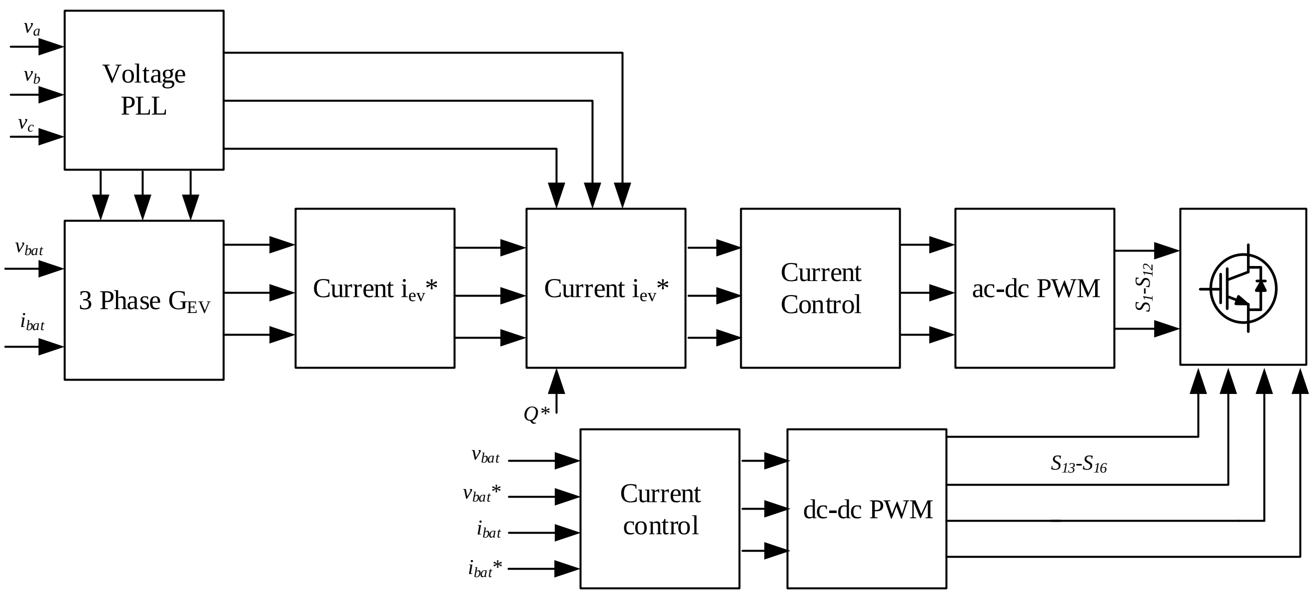

Figure 8: Block diagram of the digital algorithm

Parameter	Value
Grid voltage	400 *V*
Grid frequency	50 *Hz*
DC − link Capacitors	2.6 *mF*
Input Inductors	2 *mH*
Output Inductors	130 μH
Battery Voltage	350 *V*

Table 3: Simulation Parameters in Closed loop Control

5 Simulation

The simulation of the dual-stage converter was modelled in SIMULINK. The control scheme was executed in the same manner as shown in figure 8.

5.1 Simulation Waveforms

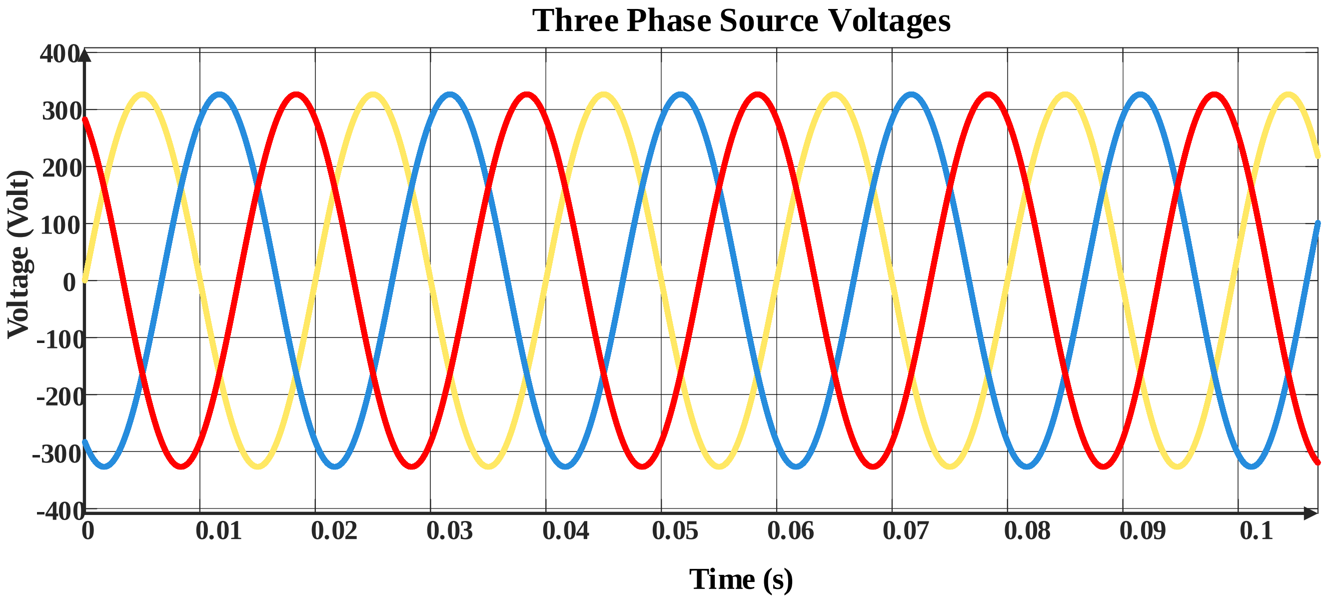

Figure 9: Three Phase Source Voltage

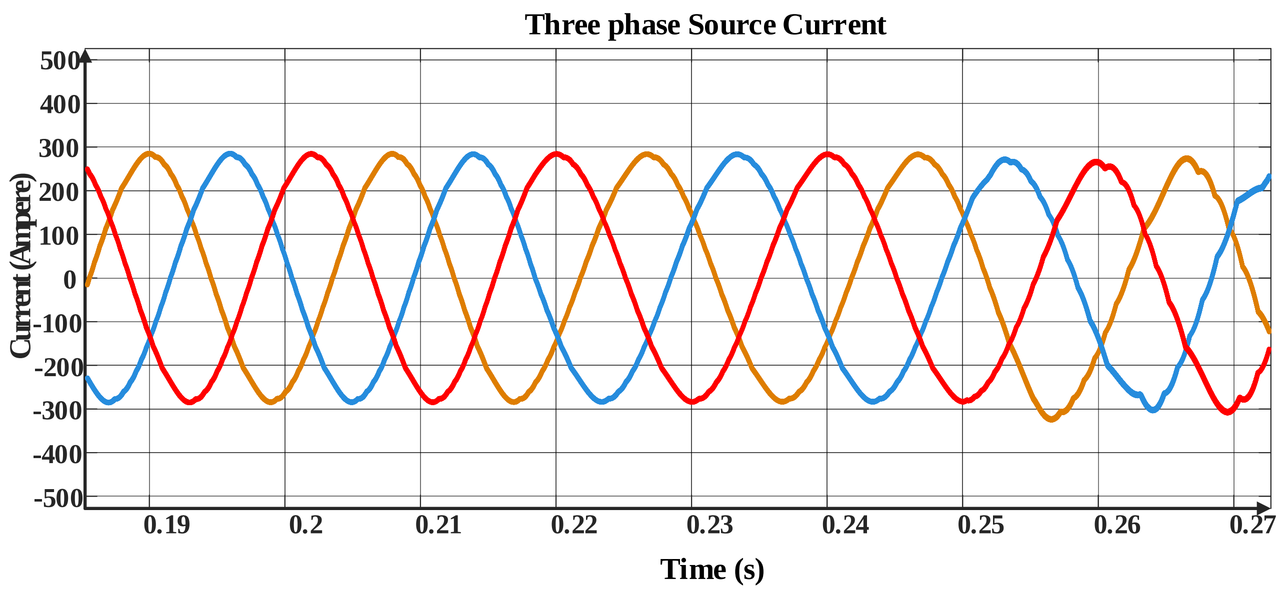

Figure 10: Three Phase Source Current

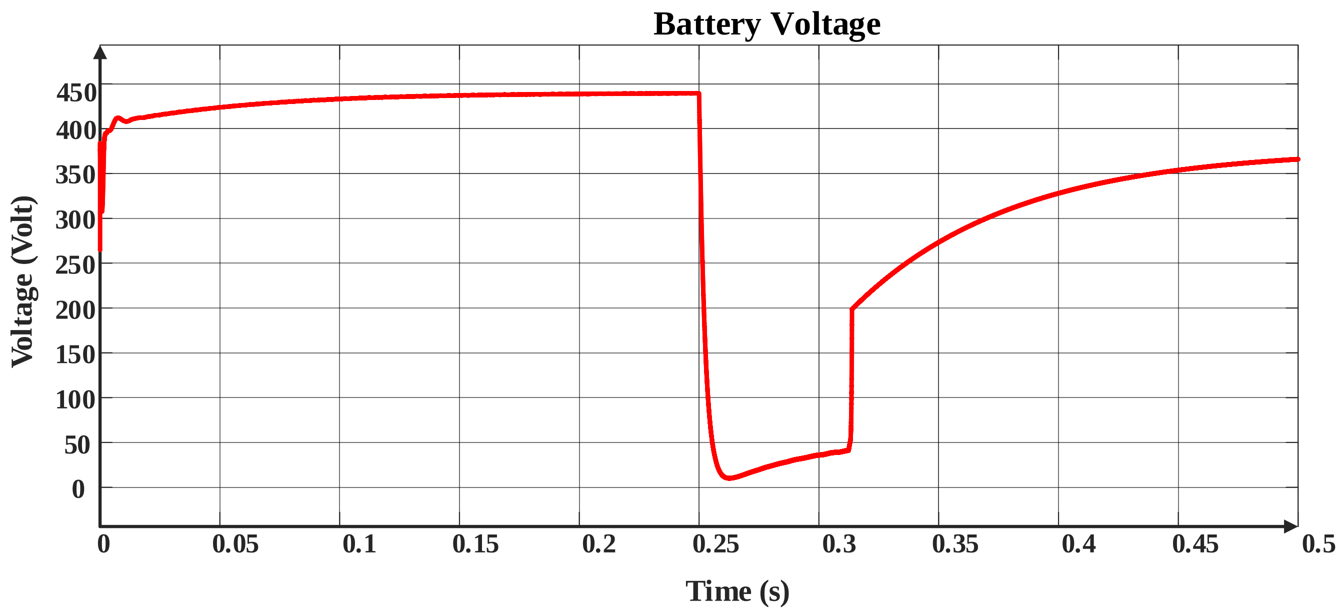

Figure 11: Battery Voltage

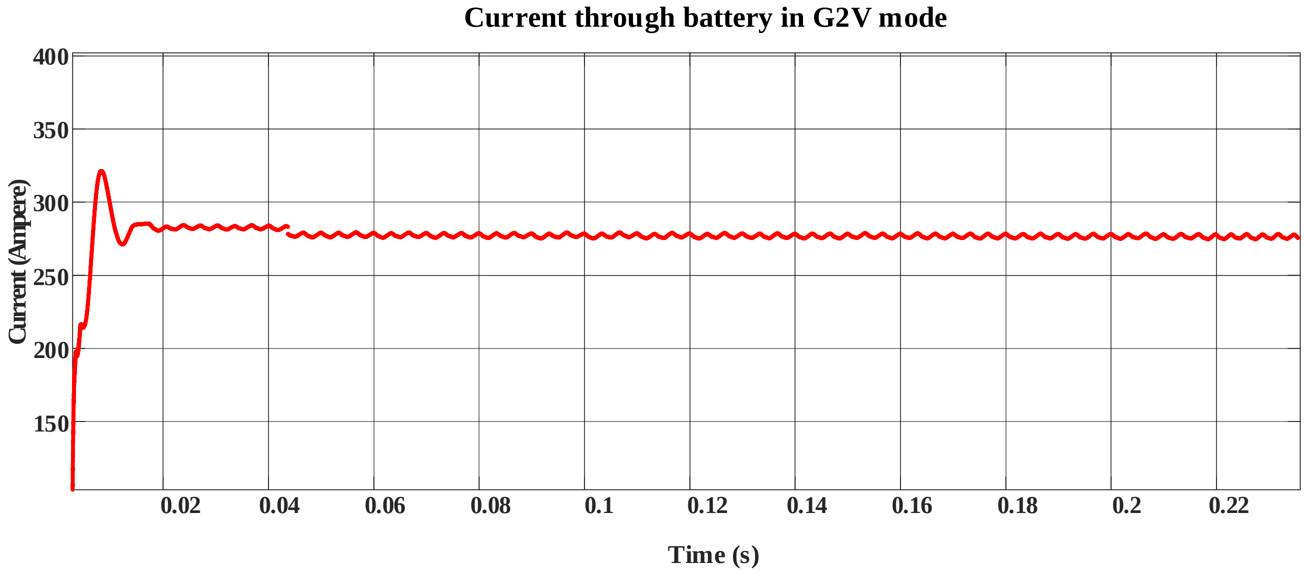

Figure 12: Battery Current in G2V mode

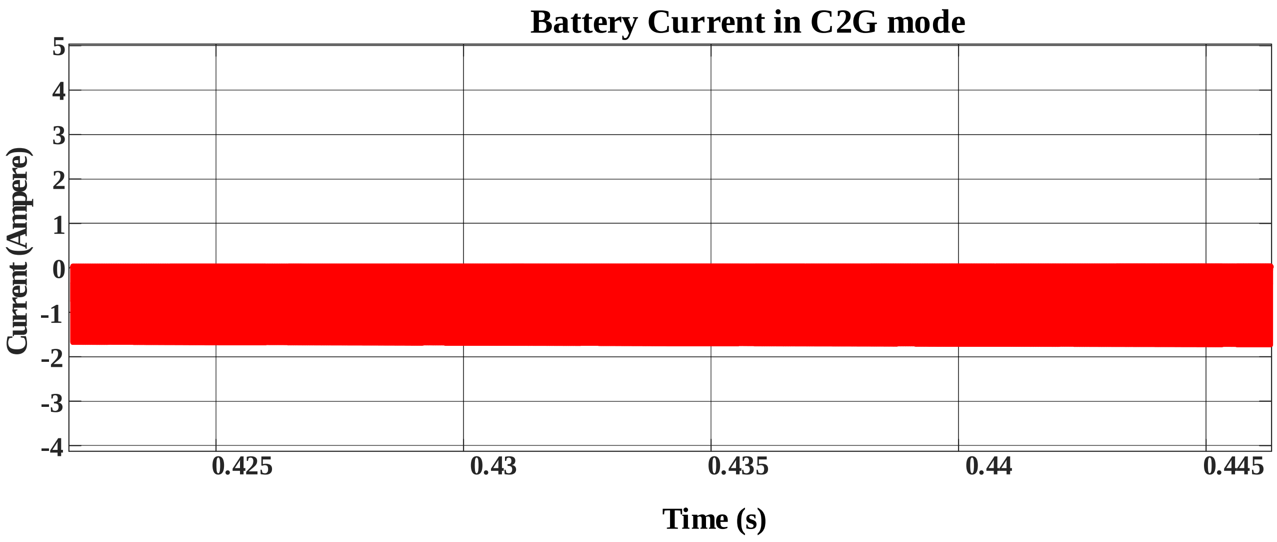

Figure 13: Battery Current in V2G mode

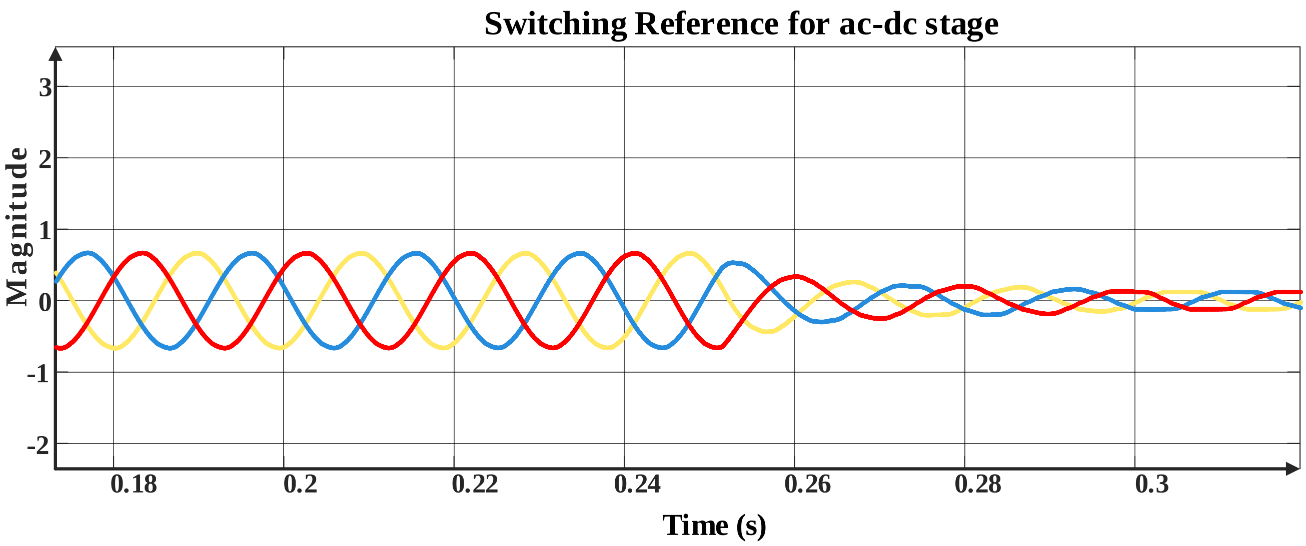

Figure 14: Reference for ac-dc stage

5.2 Predictive Control MATLAB Code

5.2.1 AC-DC stage

```
function D = predictiveControl(v_g, i_g, i_ref, L, Ts, v_dc, KL)
    % v_g: Grid voltage
    % v_c2: Capacitor voltage
    % i_g: Measured current
    % i_ref: Reference current
    % L: Inductance
    % Ts: Sampling time
```

```
    % v_dc: DC-link voltage
    % KL: Inductance correction factor

    % Calculate converter voltage
    v_cv = v_g  - (KL*L/(4*Ts))*(i_ref - i_g);

    % Convert to duty cycle
    D = v_cv/v_dc;
end
```

5.2.2 DC-DC stage

```
function D = predictiveDCDC(V_bat, V_dc, i_bat, i_ref, L, Ts, KL_dc)
    % Calculate converter voltage
    v_cv = V_bat + (KL_dc*L/Ts) * (i_ref - i_bat);

    % Convert to duty cycle
    D = v_cv/V_dc;

    % Limit duty cycle to valid range
    D = max(0, min(1, D));
end
```

5.3 Observation

On observing the above waveforms of currents, the source current had a %THD of 2.28% when operated in G2V mode and a %THD of 8.71% when operated in C2G mode. Moreover, the current during G2V mode is positive whereas the current during C2G mode is negative.

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