Reduction of Switching Transients in Constant Current (CC)/Constant Voltage (CV) Mode of Electric Vehicles Battery Charging

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Master of Engineering
in
Power Systems

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Declaration

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Abstract

Optimum charging of electric vehicles is of great interest today. Researchers have worked upon different charge methodology for switching from constant current mode (CCM) to constant voltage mode (CVM). But, major problem occurs while transition are the switching transients. Therefore, a suitable methodology for switching from CCM to CVM while charging the lithium-ion battery is to be implemented. Among the various methods used today, Schmitt trigger switching is the most reliable and efficient method for charging the lithium-ion battery. Therefore, this work adopts CCM/CVM mode of charging with Schmitt trigger switching. This helps in reducing switching losses and increasing the response time of the battery. For implementing the proposed scheme, a hardware for the boost converter is designed and the controlling for the same is obtained using Opal-RT. PI controller for CCM and CVM is designed to regulate the output and generate the desired duty cycle.

Tuning of the PI controller for CCM and CVM is obtained using loop shaping method. Switching between the two modes i.e. CCM and CVM is done using Schmitt trigger. The band limit of Schmitt trigger is set according to the capacitor ripple voltage. The controlling parameter i.e. the duty cycle generated is applied to the IGBT switches using digital I/Os. The input parameters voltage and current are feedback using analog I/Os. Thus, the real-time results for battery charging i.e. voltage and current can be obtained accordingly.

Keywords- Boost converter, CC/CV mode of charging, PI Controller, State of Charge (SOC), Schmitt trigger, Opal-RT.

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List of Symbols

Symbols	Definitions
I_{fc}	Full charging current
V_{min}	Minimum voltage
R_p	Parasitc resistance
C_p	Parasitic capacitance
V_{int}	Internal voltage
V_{bat}	Battery voltage
$I_{charging}$	Charging current
V_R	Voltage drop across resistance
R_{ESR}	Equivalent series resistance
C_{Cell}	Capacitance of battery cell
V_{ref}	Reference voltage
D	Duty cycle
V_{ref}^{oc}	Open circuit reference voltage
V_o	Output voltage
ΔI_L	Inductor ripple current
L	Inductor
C	Capacitor
Δv	Capacitor ripple voltage
f_s	Switching frequency
f	Sampling frequency
R	Resistance
$\hat{d}$	Duty cycle perturbation

$\hat{V}_{\text{in}}$	Duty cycle perturbation on input voltage
$\hat{V}_{\text{o}}$	Duty cycle perturbation on output voltage
$\hat{i}_{\text{L}}$	Duty cycle perturbation on inductor current
Q	Quality factor
w_o	Pole in the left half plane
w_z	Zero in the righ half plane
I_L	Inductor Current
G_{vd}	Control to output transfer function during constant voltage mode
G_{id}	Control to output transfer function during constant current mode

List of Abbreviations

CC	Constant Current
CV	Constant Voltage
CCM	Constant Current Mode
CVM	Constant Voltage Mode
SOC	State Of Charge
EVs	Electric Vehicles
PI	Proportional Integral Controller
MOS	Metal Oxide Semiconductor
OCV	Open Circuit Voltage
PV	Photo Voltaic
UTL	Upper Threshold Limit
LTL	Lower Threshold Limit

Chapter 1

Introduction

1.1 Overview

The world is moving towards electric vehicles as an alternate source of fuel vehicles, thereby reducing the effect of global warming. Also, fuel vehicles are consuming more than 50% of the fuel resources thereby resulting in the production of a large amount of greenhouse gases. If the consumption of non-renewable resources continues to be consumed at the same rate than the day is not far when these will become extinct. Therefore, there is a great need for redevelopment of the transportation sector to have less dependency of human being on fossil fuels. Hence, electric vehicles need to be driven by clean, energy-efficient sources such as a battery so that the dependency on non-renewable energy sources minimizes. Therefore, many countries across the world are actively participating and taking interest in the renovation of the transport sector and moving towards electric vehicles. Thus, with the advancement in the technology transportation sector are fully focused towards the development of the electric vehicles [1] But, limitations with the electric vehicles are the short-driving range and large charging time of the battery. Therefore, efficient and fast battery charging with low charging losses is very important and is the main area the researchers are working upon.

The rapid increase in the price of fuel, have lead to shift from fuel vehicles toward electric vehicles (EVs) which require battery as storage device. However, in case of plug-in hybrid vehicle the battery is charged through the grid or renewable energy sources such as photovoltaic, wind. Depending upon the application, the parameters and dimensions of the battery vary for micro-grid applications, industrial application, EVs, communication system. With the varying dimensions of the battery, the type of the charger also vary. Batteries available in the market are the Lead-acid battery, Lithium-ion battery [2], Nickel-cadmium battery. Among the various alternatives, lithium-ion batteries are most commonly used in EVs because of its large energy and power density, long life-cycle, low memory effect and stable terminal voltage [1]. Lithium-ion batteries finds increasing application in mobile phone's, laptops, EVs. Charging methodology

for Lithium-ion battery can have a serious impact on the battery lifetime.

Good energy efficient electric vehicles are the most preferred means of transportation. There are mainly two type of electric vehicles currently available in the market, purely electric vehicles and plug-in hybrid electric vehicles. Purely electric vehicles completely depends upon the charged condition of the battery. It mainly consists of an electric motor for driving the vehicle and a battery for giving power to the motor. But, for efficient working of the vehicle proper charging and discharging of the battery is required. Battery charging for EVs can be either ON board or OFF board depending upon the type of vehicle. Whereas, Plug-in hybrid electric vehicles work on both fuel and battery. Thus, vast awareness and acceptance of EVs have led to decrease the pollution level in the environment [3].

Hence, electric vehicles need to be driven by clean, energy-efficient sources such as battery so that the dependency on non-renewable energy sources minimizes. Therefore, many countries across the world are actively participating and taking interest in the renovation of transport sector and moving towards electric vehicles. Thus, with the advancement in the technology transportation sector are fully focused towards the development of electric vehicles. But, existing limitations with the electric vehicles are its short-driving range and large charging time of the battery. Therefore, efficient and fast battery charging with low charging losses is very important and is one of the main area researchers are working upon [4].

1.2 Importance of Charging

Efficient charging is very important for increasing the lifetime of the battery. As the charging cycle of a battery depends on the method by which the battery is charged. Hence, to increase the battery efficiency optimum method of charging is employed. Charging voltage or charging current applied to the battery must be based on the present temperature of the battery. This helps not letting the battery to get overcharged or undercharged. Hence, optimum charging method is important for efficient battery charging [5]. Since, charging methodology defers for different type of batteries. Therefore, there is a need to know the charge methodology for Lithium ion, Lead acid & Nickel-cadmium batteries.

1.3 Types of Charging

Battery charging of EVs can be either ON board or OFF board depending on the type of vehicle. Whereas, Plug-in hybrid vehicles worked on both fuel and battery. Thus, vast awareness and acceptance of EVs have led to decreases the pollution level in the enviornment. There are various methods for charging EVs battery. These are as follows:

1. Constant current mode (CCM) charging
2. Constant voltage mode (CVM) charging
3. Reflex charging
4. Pulse charging
5. CCM/CVM charging.

1.4 Issues During Charging

- In CCM charging a constant current is passed through battery no matter what is the battery state of charge or temperature. However, major drawback is that it leads to over-charging of the battery which results in large battery losses. Hence, these are only best suited for Lead-acid batteries [6]
- In CVM charging constant input voltage across the battery is maintained throughout the charging process. This results in high initial current due to large potential difference between the terminal voltage and internal voltage of the battery. But, drawback of this charging scheme is that it results in high initial battery losses thus producing switching transients [7].
- In reflex charging as shown in Fig. 1.1, charging of the battery is done in a cyclic manner. A positive pulse is applied to a battery for about 90% of the total charging time and then with a negative pulse for about 7% of the remaining time, further a small rest period of 3% is applied across the battery. However, the major drawback is that, a dissipative component like resistance for discharging the battery is used with a corresponding negative current, resulting in large system losses [8].

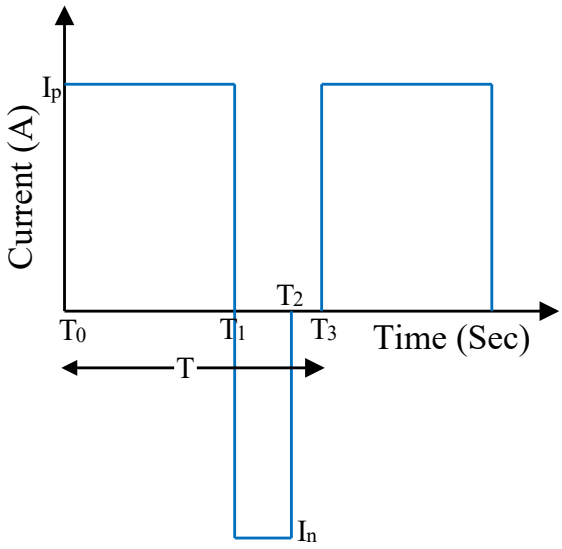

Fig. 1.1: Reflex charging

- In pulse charging as shown in Fig. 1.2, the rate of charging can be varied by varying the width of the pulse. In this, a constant positive pulse is applied for small duration and remains off otherwise. The major drawback is that, there is no specific method to determine the off period i.e. when no pulses are applied [9].

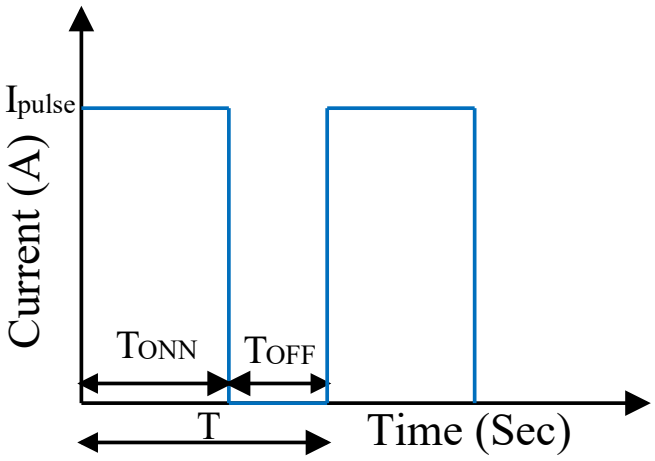

Fig. 1.2: Pulse charging

1.5 CCM/CVM Charging

Among the various method used today CCM/CVM is the most optimum used technique for charging the lithium-ion battery. It starts with a preconditioning phase, to check whether the battery is deeply discharged or to see whether the voltage across the battery is below the minimum charging limit V_{min}.

If such condition exist then a small charging current is passed till the battery terminal voltage reaches V_{min}. When the battery terminal voltage reaches V_{min} a fixed charging current I_{cc} is applied till the battery voltage reaches rated voltage. This phase is called as the current regulation phase. The constant voltage applied during the precondition should be (1/10th) of the full charging current (I_{fc}).

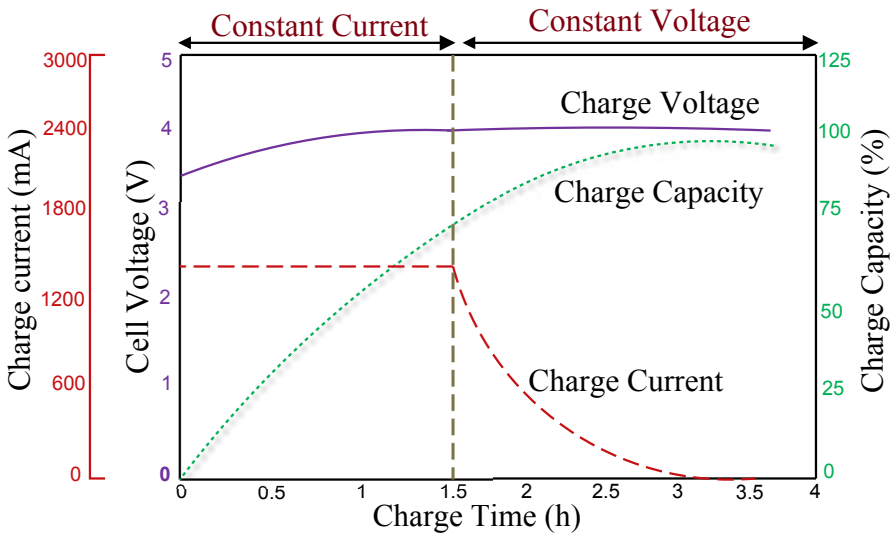

Fig. 1.3: CCM/CVM Charge Characteristic

This is done so as to avoid excessive heating of the battery. Fig. 1.3 shows the charge characteristics of CCM/CVM mode of charging the lithium-ion battery. A challenging task for CCM/CVM mode of charging is to have smooth transition between the two modes of operation. To implement smooth switching, battery voltage is observed and is compared with the predefined value. But, due to parasitic component and internal resistance of the battery, the voltage across the battery terminal contains switching frequency ripple apart from DC. This results in large switching transients.

Hence, the transition between the two modes is a decisive feature for optimum charging, so as to prevent overheating and overcharging of the battery [10].

1.6 Switching Techniques Issues

There are various switching techniques used by the researchers for transition from CCM to CVM. These are as follows:

1.6.1 Magnetically Coupled Feedback Clamped Circuit

In this the transition between the two loop is done using feedback clamped circuit. A gate timer signal is used for driving the gate circuit. But, major problem face is in the coordination between the error signal generated by the comparator and signal from the timer logic circuit [11]. If coordination between the two mismatches, the system results in production of large transients during switching.

1.6.2 Diode Clamping Network

In this a diode is used for transition between the two charging modes, thereby controlling the operation of metal oxide semiconductor (MOS) device. But, drawback is lengthening the duration of CVM, which increases floating time leading to the condition of overcharging of the battery.

1.6.3 Toggle Switching

In this, a toggle switch is used for switching between the two modes based on the threshold value being set. However, major problem arises is in the production of oscillation at the instant of switching because of ripple in the output voltage. Thus, switch move ON and OFF to and fro continuously thereby affecting the charging efficiency of the battery.

1.6.4 Integrated Resistance Compensator

In this, the integrated resistance compensator is used for smooth switching and rapid charging of the battery. Disadvantage of this method is, module of the system becomes larger. Also, large number of resistance connected across the battery results in the production of switching losses.

Among the various method mentioned above, major problem being faced is the switching transients. These switching transients result in production of oscillations which cause toggle switch to oscillate continuously from ON to OFF. Thus, the charging efficiency of the battery diminishes, thereby decreasing battery lifetime. Fig. 1.4 shows the output of toggle switch at the instant of switching.

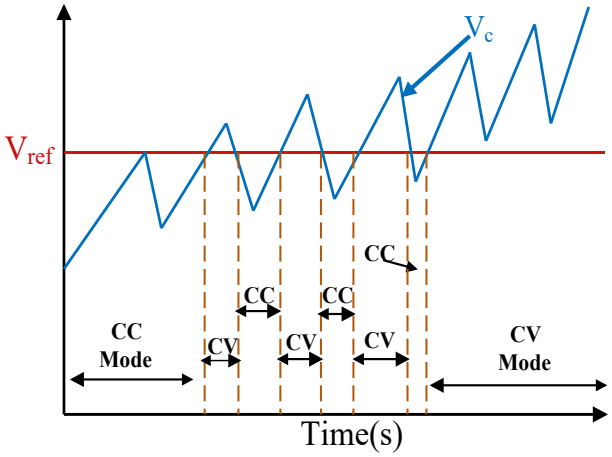

Fig. 1.4: Output of toggle switch.

1.7 Schmitt Trigger Switching

Hence, the scope of this work is to design an optimum battery charging methodology, which minimizes the switching transients during transition between the two modes. Therefore, a novel technique using Schmitt trigger is proposed, which eliminates the oscillations during transition between the two modes. This results in smooth switching from CCM to CVM [12]. In the proposed scheme the band limit of Schmitt trigger is set according to the capacitor ripple voltage.

If the input to the Schmitt trigger is within the band, output is high and the corresponding charging mode i.e. CCM will operate. As soon as the upper limit of Schmitt trigger is reached system switches to CVM. Thus, the process results in smooth switching during the instant of transition [5].

Fig. 1.5 shows the behavior of the voltage and current using Schmitt trigger.

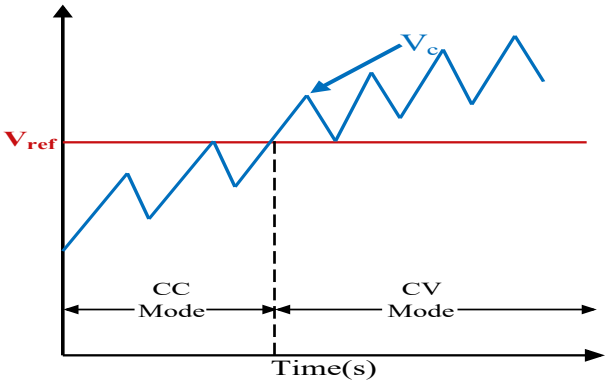

Fig. 1.5: Output of Schmitt trigger.

Fig. 1.6 shows the optimal battery charging scheme for charging the Li-ion battery. The input to the boost converter is obtained either through battery or through PV panel. Output voltage and current flowing through the battery is sensed and is applied to the PI controller. Duty cycle generated by the controller is applied to the IGBT switch. Thus, the process results in producing the desired output. Thereby, resulting in minimizing the switching losses, and increasing the charging efficiency of the battery.

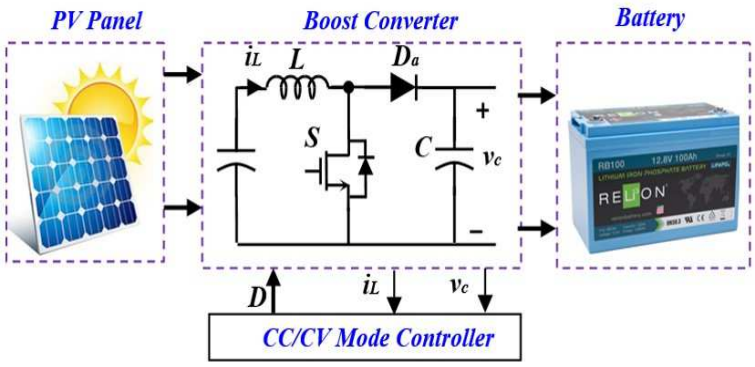

Fig. 1.6: Optimal battery charging.

1.8 Literature Review

Major problem which arises in CCM/CVM mode of charging is during the transition from CCM to CVM.

- Hussein *et al.* [2] has explained the charging algorithms for nickel cadmium and lithium-ion batteries. For charging the Nickel-cadmium battery, initially voltage is sensed across

the battery. Corresponding to the sensed voltage derivative is calculated and variation in battery current for charging is provided. Whereas, in lithium-ion battery firstly the battery temperature is sensed to avoid overheating or overcharging of the battery. Charging of the battery is initiated by measuring the open circuit voltage (OCV) of the battery. If the value is below the predefined level, than the period is called as trickle charging period. If the predefined level is reached the battery is charged initially with a constant current and when upper limit is reached battery is switched to constant voltage mode.

- Singh *et al*. [11] proposes a feedback-clamped two-way battery charging using CCM and CVM. In this the gate timer signal is used for driving the gate circuit. But, major problem is the coordination between the error signal generated by the comparator and signal from the timer logic circuit. If coordination between the two mismatches, the system results in the production of large transients during switching.

- Chen *et al*. [13] uses a diode for transition between the two feedback loop control charging mode i.e. CCM and CVM. Charging of a battery in CCM or CVM depends on the duty cycle applied to the mosfet. Since series connected diode is used for transition between the two modes. Hence, the major problem being faced is in the calculation of the desired switching voltage across the diode. Thus, false calculation results in abrupt switching condition leading to overcharge or undercharge condition in the battery.

- Lin *et al*. [14] uses integrated resistance compensator for smooth switching and rapid charging of the battery. The smooth transition from CCM to CVM is implemented using external parasitic resistance for the lithium-ion battery. Disadvantage of this method is, module of the system become larger. Also, large number of resistance connected across the battery results in the production of switching losses.

- Yang *et al*. [15] proposes a CC/CV charging method for lithium-ion battery. Smooth transition between the two modes is done using a diode clamping network. However, the major drawback is the production of switching transients during transition, because of the false clamping of the diode network.

- Jhung *et al*. [16] proposed adaptive fast charging strategy which can increase the charge speed of CC/CV charging. The objective of fast charging can be achieved by proper designing of the circuit-components in the charging circuit. In this paper in order to

increase the efficiency continuous monitoring of the output voltage is needed which becomes difficult, thus results in the production of an inaccurate output.

- Yang *et al.* [17], for instance uses a toggle switch for switching from constant current to constant voltage, thus resulting in the production of oscillations at the instance of switching. So, it's necessary to switch the battery charger into constant voltage mode with a decreasing current and to terminate the charging sequence when the battery voltage reaches a desired value.

- Lai *et al.* [18] introduces digital controlled technique of battery charging using constant current/constant voltage mode. The switching between the two mode is done using duty cycle limit controller. Initially the battery is charged with a constant current and when the desired value of voltage is reached the duty cycle is limited such that it switches to constant voltage mode. However, the major drawback is that limiting the duty cycle through the switch results in false switching. Thus, resulting in the production of switching transients at the instant of transition.

- Tran *et al.* [19] uses an output inductor between the boost converter and the lithium-ion battery for reducing output ripple, but it results in large charging time of the battery which may results in instability. Thus, proper tuning of the PI controller is necessary otherwise it will result in the production of the false output. To make CCM to operate satisfactorily balance of this mode need to be realized by proper detection of the initial and present state of the battery i.e. continuous monitoring of SOC of the battery is required

- Liu *et al.* [20] implemented multi mode battery charging technique using adaptive control scheme. In this the transition between CCM and CVM is done using a switch. Also resistance is used in parallel with the battery so as to limit the initial current. However, the major drawback is that resistance connected across the battery results in large initial losses. Thus, resulting in depleting the lifetime of the battery.

- Hwang *et al.* [21] uses a comparator for switching between the two modes. Terminal voltage across the battery is compared with the reference voltage for switching between the two modes. But, because of the gradually decreasing charging current, terminal voltage across the battery becomes smaller than the predefined voltage. However, this condition causes oscillating back to CCM.

- Zheng *et al.* [22] uses a battery-equalization scheme for charging the battery. In, this inductors are used as an energy storing device and the anti-parallel diode connected across the switch is used as a free-wheeling path for the inductor current. This, paper uses a cascade control strategy for charging of the lithium-ion battery using CC/CV mode. In this the main aim is to balance voltage corresponding to the state of charge (SOC) of the battery.

- Akagi *et al*. [23] uses bi-directional DC/DC converter for charging the lithium-ion battery. In this an open loop feed forward method is used for controlling the switching of converter operation for lithium-ion battery charging. Researcher mainly tries to maintain the efficiency of the converter output so that the minimum losses occur while charging or discharging the battery.

- Wang *et al*. [24] uses primary side regulation based CCM/CVM mode flyback converter for optimizing the battery charging process. The battery charging process is done in three continuous process i.e. the start-up state, current regulation phase and voltage regulation phase. But, major problem occur is load resistance is used for transition from CCM to CVM, which results in shortening the battery lifetime.

1.9 Research Gap

With the rapid increase in population and correspondingly decreasing rate of fuel the demand of electric vehicles is increasing day by day. Therefore, there is a great need to shift from fuel vehicles towards electric vehicles. But, major problem being faced in electric vehicles is the charging of the battery. Switching transients at the instant of transition from CC to CV have cause gap in the efficient charging of the battery. This gap leads to decrease the charging efficiency and lifetime of the battery. Therefore, the gap can efficiently be fulfilled by using optimum switching technique [12]. However, switching from CCM to CVM using Schmitt trigger is less studied in literature. Generally, the transition between the two modes is done using toggle switch, where the major problem of large switching transients occurs at the instant of transition. So, an optimum technique is adopted. The Schmitt trigger helps in reducing the switching transients, thereby resulting in the production of smooth transition.

Hence, in proposed scheme Schmitt trigger switching is implemented for transition from CCM to CVM. The band limit of Schmitt trigger is set according to the capacitor ripple voltage.

The charge methodology initially operate in the CCM till the input to Schmitt trigger is within the band limit. As the input to the Schmitt trigger goes beyond the limit, the controller switches to CVM. Thus, resulting in the production of smooth transition from CCM to CVM. Hence, the proposed methodology results in increasing the charge efficiency of the battery.

1.10 Motivation

Consequently, focus of researchers is on the charging of EVs battery using either CC mode or CV mode or both CC/CV mode. But the main problem being observed by researchers, is the transients occurring while switching from CCM to CVM. Since, researchers have used toggle switch for switching between the two modes, which results in the occurrence of discontinuity at the point of switching. Also, another problem being faced is the occurrence of ripple in the output voltage while charging the battery. As per the best knowledge of author, none of existing researcher has applied the Schmitt trigger for switching from CCM to CVM.

Thus, intent of the work is to search for optimum solution of charging the lithium-ion battery. Schmitt trigger being used for switching produces continuous pulses while switching from CCM to CVM. This results in smooth transition, thereby increasing the battery life time.

1.11 Contribution

Hence, the major contributions of this paper are summarized below.

- Unlike conventionally used toggle switching, the proposed Schmitt trigger switching is used for transition from CC to CV.
- The proposed scheme intends to reduce the switching transients, thereby producing smooth transition from CC to CV.
- A battery charging model using CC/CV mode is designed and the controlling of each mode is done using PI controller.
- Tuning of the PI controller is done using loop shaping method for individual mode.
- Also, hardware for the same is designed and the results are obtained using Opal-RT.

1.12 Organization of the Dissertation

The work carried out in this project has been coordinated in 5 chapters.

Chapter 1 includes Introduction and Literature Review. Chapter 2 deals with the study of system framework.

Chapter 3 deals with the designing of the boost converter, mathematical modeling, problem formulation .

Chapter 4 Results and Discussion.

Chapter 5 deals with Conclusion and References

Chapter 2

System Framework

As various types of batteries are available in the market. Among all the lithium-ion batteries are most commonly applied in EVs because of large energy density, long-life, stable-operating condition. Fig. 2.1 shows circuit for Lithium ion battery.

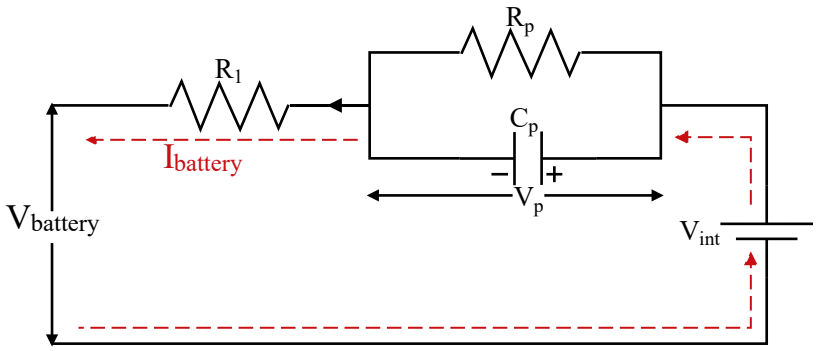

Fig. 2.1: Lithium ion battery model.

R_p & C_p are the parasitic resistance and capacitance of the battery respectively, V_{int} is the internal voltage of the battery. R_1 the internal battery resistance. The parallel RC network shown in Fig. 2.1 describes the transient condition of the battery when the battery is excited [16]. Hence, during this condition there will be some losses occurring across the internal resistance of the battery. Therefore, voltage across the battery is not same as that of the internal battery voltage.

Fig. 2.2 shows equivalent circuit of the battery

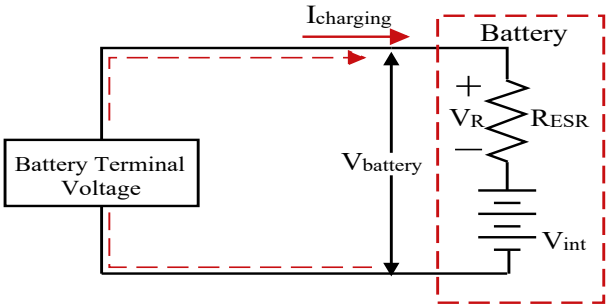

Fig. 2.2: Equivalent circuit of a battery.

$$V_{\text{R}} = I_{\text{charging}} * R_{\text{ESR}} \tag{2.1}$$

Therefore,

$$V_{\text{battery}} = V_{\text{R}} + V_{\text{int}} \tag{2.2}$$

Hence,

$$V_{\text{battery}} = V_{\text{int}} + I_{\text{charging}} * R_{\text{ESR}} \tag{2.3}$$

Also, the cell charge battery voltage is given as,

$$V_{\text{battery}} = \frac{1}{C_{\text{Cell}}} \int I_{\text{charging}} dt + V_{\text{int}} + I_{\text{charging}} * R_{\text{ESR}} \tag{2.4}$$

The maximum cut-off voltage of the lithium-ion battery $V_{\text{battery cutoff}}$ can be calculated using equation (2.4) as,

$$\Delta t = \frac{1}{I}(V_{\text{battery cutoff}} - V_{\text{int}} - V) * C \tag{2.5}$$

Hence, equation (2.5) represents the charge time taken by the battery. Here, V_{int} is the initial battery voltage before charging, R_{ESR} is the equivalent series resistance of the battery. The switching instant voltage for transition from CCM to CVM is calculated according to (2.4). When the terminal voltage across the battery reaches to around 98% of the rated voltage, transition from CCM to CVM is applied.

2.1 Battery Charging Schematic

The schematic circuit of battery charging is shown in Fig. 2.3. The source used for battery charging is obtained directly from the grid and is then stepped down using isolation transformer. Output of the transformer is then rectified to obtain the desired DC voltage. The DC voltage generated is then passed on to the converter. There are different kinds of converter available like buck converter, boost converter, and buck boost converter [16]. But, the most commonly used is the boost converter. This paper adopts DC/DC boost converter to form control circuit for battery charging.

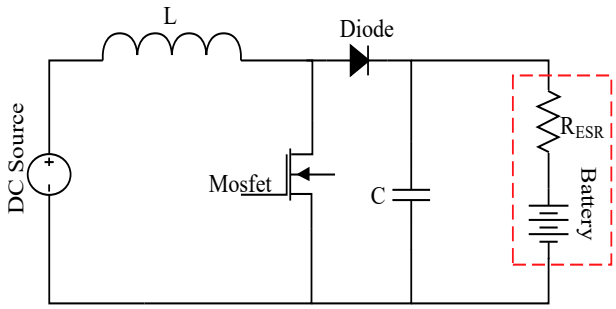

Fig. 2.3: Boost converter connected to battery.

The boost converter connected to a battery is shown in Fig. 2.3. PI controller is used for controlling the output of boost converter for charging the battery using CCM/CVM. The controller helps in producing the stability, there by reducing the steady state error.

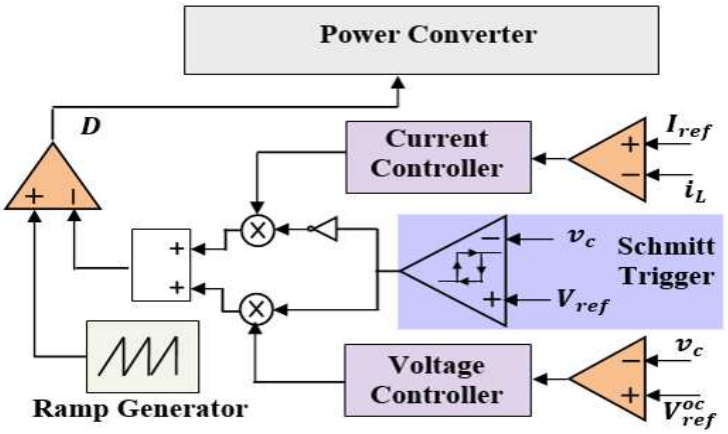

Fig. 2.4: Switching Scheme for optimal battery charging.

Switching mechanism of the boost converter using CCM/CVM mode is clearly shown in Fig. 2.4. Initially the battery is charged in CCM. In this, the battery current is compared with the reference current. Error signal generated is passed through PI controller to generate controlling signal i.e. the duty cycle. Similarly, in CVM battery voltage is compared with the reference voltage. Error signal generated is passed through PI controller [19]. Now, the switching action from CCM to CVM is done using Schmitt trigger as shown in Fig. 2.4.

The switching action of Schmitt trigger is controlled according to the ripple voltage of the battery. The switching instant of Schmitt trigger is set such that, when voltage of the battery reaches to 98% of the rated voltage it switch on to the CV mode. The charging of the battery is continued to be in this mode until the current across the battery goes below 3% of the rated current [25]. This period is also called as the floating period as the battery is left to float till the battery SOC reaches to 100%.

Calculation of various parameters of boost converter:

Duty cycle D of the boost converter is expressed as,

$$D = 1 - \frac{V_{\text{in}}}{V_{\text{o}}} \tag{2.6}$$

The value of inductor L is calculated as,

$$L = \frac{V_{\text{in}} D}{2\Delta I_{\text{L}} f_{\text{s}}} \tag{2.7}$$

The value of capacitance C is calculated as,

$$C = \frac{V_{\text{o}} D}{2\Delta v R f_{\text{s}}} \tag{2.8}$$

There are two control mode being used for charging of the Lithium-ion battery i.e. CCM and CVM. The controller being used for controlling of these two mode is the PI controller.

Chapter 3

Problem Formulation

3.1 Operation of Schmitt Trigger

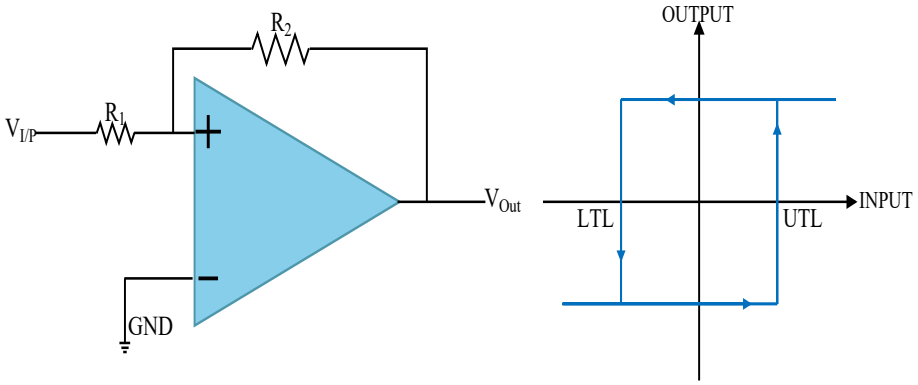

Fig. 3.1: Output of boost converter.

Schmitt trigger is a logic switch which works at two different edge voltage level and creates a output either high or low depending upon band limit [26]. The band limit of Schmitt trigger is set according to the voltage ripple i.e. capacitor ripple voltage. The output produce by the Schmitt trigger depends upon the equations derived below [27].

$$V_{\text{High}} = \frac{R_2}{R_1 + R_2} V_{\text{I/P}} \tag{3.1}$$

$$V_{\text{Low}} = -\frac{R_2}{R_1 + R_2} V_{\text{I/P}} \tag{3.2}$$

Henceforth, if the input applied to Schmitt trigger is within the upper threshold limit (UTL) and lower threshold limit (LTL), the output of Schmitt trigger is high. Else if, the input to Schmitt trigger goes below LTL, the output of Schmitt trigger is low. Thus, this switching technique avoids the production of oscillations at the instant of transition from CCM to CVM.

3.2 Operation of Toggle Switch

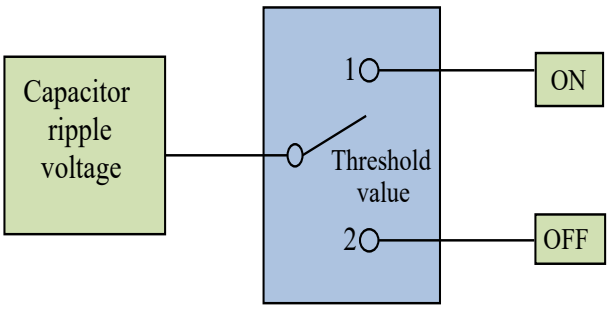

Fig. 3.2: Toggle Switch.

Fig. 3.2 shows the working operation of toggle switch. It is used to switch between two condition in a circuit. Toggle switch is either ON or OFF depends upon the input voltage and threshold voltage. Being easy in operation, toggle switch can be used in a number of different applications, both in commercial and in house hold appliances.

If,

$$V_{\text{ripple}} \leqslant V_{\text{Threshold}} \tag{3.3}$$

From (3.3) if the input to toggle switch is below the threshold value, the output is high i.e. switch is ON and the controller operates in CCM and as the threshold limit is achieved it changes back to lower state i.e. it turns OFF and controller operates in CVM. However, since the input to toggle switch is the capacitor voltage. Since, capacitor voltage has ripples which result in the generation of oscillations at the instant of transition thus switch oscillates. In this way, large transients are created which influences the lifetime and charging state of the battery.

3.3 Modeling of Plant Transfer Function for Constant Voltage Mode

Fig. 3.3 shows the circuit for battery charging during CVM.

Equations for the ideal boost converter are written below [28].

$$sL\hat{i}_{\text{L}}(s) = \hat{V}_{\text{in}}(s) - D^{'}\hat{V}_{\text{o}}(s) + V_{\text{o}}\hat{d}(s) \tag{3.4}$$

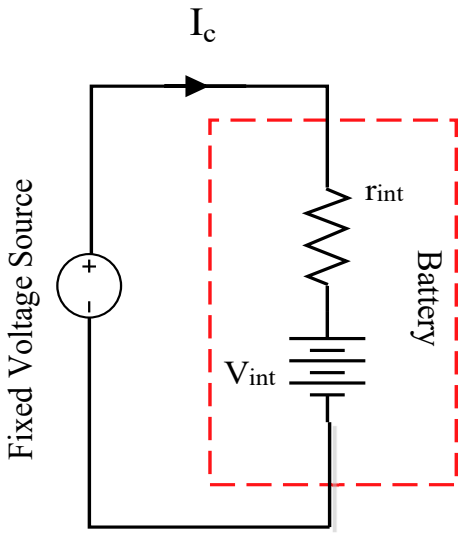

Fig. 3.3: Constant voltage mode.

$$sc\hat{v}_{\mathrm{o}}(s) = D^{'}\hat{i}_{\mathrm{L}}(s) - I_{\mathrm{L}}\hat{d}(s) - \frac{\hat{V}_{\mathrm{o}}}{R}(s) \tag{3.5}$$

Where,

$$D^{'} = 1 - D \tag{3.6}$$

$V_{in}(s)$ is the input voltage, $V_o(s)$ is the output voltage, $\mathrm{I_L}$ is the inductor current, $\hat{d}$ is the perturbation on the output voltage V_o, inductor current I_L, input voltage V_{in} respectively.

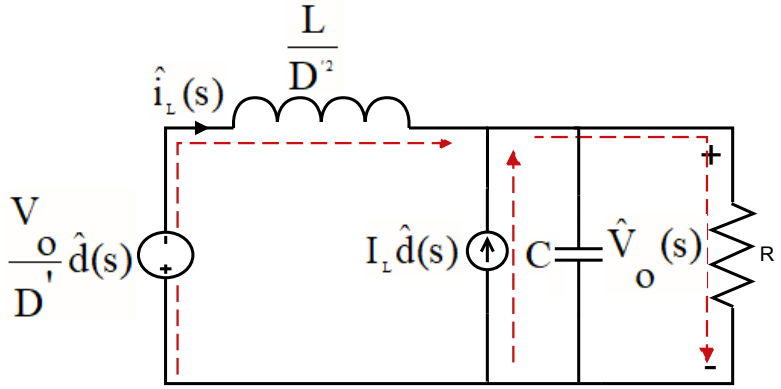

Fig. 3.4: System equivalent circuit for calculating transfer function.

From Fig. 3.4 the transfer function $G_{vd}(s)$ of constant voltage mode boost converter is calculated as follow

$$G_{\mathrm{vd}}(s) = \frac{\hat{v}}{\hat{d}} \tag{3.7}$$

Assuming,

$$\hat{V}_{\mathrm{in}}(s) = 0, in(3.4) \tag{3.8}$$

So, (3.1) can be re written as,

$$\hat{i}_{\mathrm{L}}(s) = \frac{(V_{\mathrm{o}}\hat{d}(s) - D^{'}\hat{V}_{\mathrm{o}}(s))}{sL} \tag{3.9}$$

Now, replacing the value of (3.9) in (3.5)

$$sC\hat{V}_{\mathrm{o}}(s) = D^{'}(\frac{(V_{\mathrm{o}}\hat{d}(s) - D^{'}\hat{V}_{\mathrm{o}}(s))}{sL}) - I_{\mathrm{L}}\hat{d}(s) - \frac{\hat{V}_{\mathrm{o}}}{R}(s) \tag{3.10}$$

Therefore,

$$sC\hat{V}_{\mathrm{o}}(s) = \frac{\hat{D}V_{\mathrm{o}}\hat{d}(s)}{sL} - \frac{\hat{D}^{'2}\hat{V}_{\mathrm{o}}(s)}{sL} - I_{\mathrm{L}}\hat{d}(s) - \frac{\hat{V}_{\mathrm{o}}}{R}(s) \tag{3.11}$$

on rearranging the above equation,

$$(sC + \frac{D^{'2}}{sL} + \frac{1}{R})\hat{V}_{\mathrm{o}}(s) = (\frac{(D^{'}V_{\mathrm{o}} - sLI_{\mathrm{L}})}{sL})\hat{d}(s) \tag{3.12}$$

Now, by using the principle of superposition control to output transfer function G_{vd} can be calculated,

As observed from Fig. 3.4, it contains a $\hat{d}$ dependent voltage and current source. From these two sources, on applying the superposition theorem the transfer function G_{vd} can be written [28].

1. *Case 1*

   Setting current source to zero, Control to output voltage G_{vd1} can be expressed from Fig. 3.5 as,

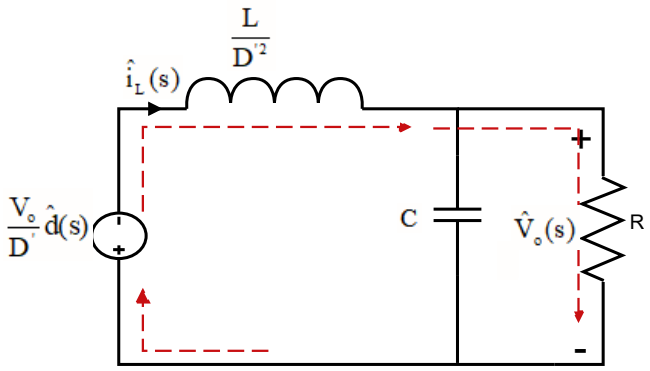

Fig. 3.5: Equivalent circuit when current source is zero.

$$G_{\text{vd1}} = -(\frac{V_{\text{o}}}{D'})\frac{(R||\frac{1}{SC})}{(\frac{sL}{D'^2} + (R||\frac{1}{SC}))} \tag{3.13}$$

2. *Case 2*

Setting voltage source to zero, the circuit obtained is shown in Fig. 3.6.

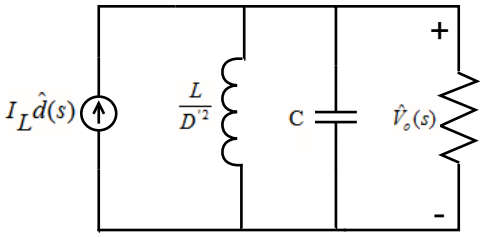

Fig. 3.6: Equivalent model when voltage source is zero.

$$G_{\text{vd2}} = I(\frac{sL}{D'^2}||R||\frac{1}{SC}) \tag{3.14}$$

Thus, the net transfer function is,

$$G_{\text{vd}} = G_{\text{vd1}} + G_{\text{vd2}} \tag{3.15}$$

$$G_{\text{vd}} = -(\frac{V_{\text{o}}}{D'})\frac{(R||\frac{1}{SC})}{(\frac{sL}{D'^2} + (R||\frac{1}{SC}))} + I(\frac{sL}{D'^2}||R||\frac{1}{SC}) \tag{3.16}$$

The above expression can be reduce as,

$$G_{\text{vd}}(s) = (\frac{V_{\text{o}}}{D'})\frac{(1 - sL/D'^2R)}{(1 + s\frac{L}{D'^2R} + s^2\frac{LC}{D'^2})} \tag{3.17}$$

D is the controlling parameter which decides the output of the boost converter and V_o is the battery terminal voltage.

Thus, the equation is of the form

$$G_{\text{vd}} = G_{\text{do}} \frac{(1 - \frac{s}{w_{\text{Z}}})}{(1 + \frac{s}{Qw_{\text{o}}} + (\frac{s}{w_{\text{o}}})^2)} \tag{3.18}$$

where, w_z represent right half plane zero.

$$Q = D^{'} R \sqrt{\frac{C}{L}}, w_{\text{o}} = \frac{D^{'}}{\sqrt{LC}} \tag{3.19}$$

From (3.17) it is observed that, there is a right half-plane zero present. At low frequency it has negligible effect, but at high frequency right half-plane zero has significant effect, which results in phase reversal at high frequency thus producing instability.

3.4 Modeling of Plant Transfer Function for Constant Current Mode

Fig. 3.7 shows the circuit for battery charging during constant current mode. The transfer

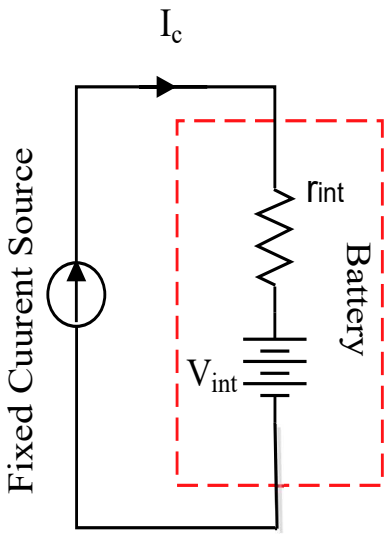

Fig. 3.7: Constant current mode

function of constant current mode boost converter is calculated as follows:

$$G_{\text{id}}(s) = \frac{i}{d} \tag{3.20}$$

Now by referring to (3.4) and (3.5) for calculating control to output transfer function during CCM, Assuming,

$$\hat{V}_{\text{in}}(s) = 0, in(4) \tag{3.21}$$

From (3.4) we can write,

$$\hat{V}_{\text{o}}(s) = \frac{(V_{\text{o}}\hat{d}(s) - sL\hat{i}_{\text{L}}(s))}{D^{'}} \tag{3.22}$$

Replacing the value of $\hat{V_o}$ from (3.22) in (3.5)

$$(sC + \frac{1}{R})(\frac{(-sL\hat{i}_{\text{L}}(s) + V_{\text{o}}\hat{d}(s))}{D^{'}}) = D^{'}\hat{i}_{\text{L}}(s) - I_{\text{L}}\hat{d}(s) \tag{3.23}$$

on rearranging (3.23)

$$(\frac{V_{\text{o}}}{D^{'}}(sC + \frac{1}{R}) + I_{\text{L}})\hat{d}(s) = (D^{'} + \frac{sL}{D^{'}}(sC + \frac{1}{R}))\hat{i}_{\text{L}}(s) \tag{3.24}$$

Similarly, by using the superposition theorem value of G_{id} can be calculated as,

$$G_{\text{id}} = (\frac{V_{\text{o}} + I_{\text{L}}D^{'}R}{D^{'2}R})\frac{(1 + (\frac{V_{\text{o}}RC}{V_{\text{o}} + I_{\text{L}}D^{'}R})s)}{s^2(\frac{LC}{D^{'2}}) + s(\frac{L}{RD^{'2}}) + 1} \tag{3.25}$$

(3.17) and (3.25) are the required plant transfer function. Using these two equations controller value for CCM and CVM is designed by programming the same using MATLAB. The

bode plot for individual mode controller i.e. CCM and CVM is designed and the value of proportional(K_p) and integral(K_i) controller is obtained correspondingly [29].

3.5 Stability Analysis

To analyze the stability, a PI controller need to be designed to reduce its effect and thus producing stability. Tuning of the PI controller is done using loop shaping technique. Hence, the designing of individual loop PI controller is obtained utilizing equation (3.17) and (3.25). The tuning of the controller is done using PID tool in MATLAB. Fig. 3.8 shows the Bode plot for

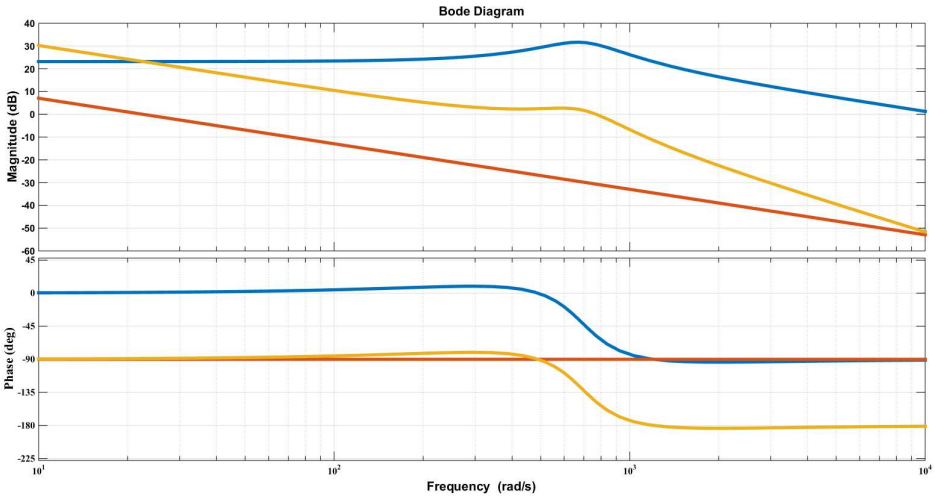

Fig. 3.8: Control to output plot during CI mode using PI controller

open loop transfer function (G_{id}), controller H_i and loop gain ($G_{id}H_i$) of the CC mode. From the plot ($G_{id}H_i$) it is observed that phase margin is positive and gain margin is infinity.

Chapter 4

Results and Discussion

The proposed methodology for charging the Li-ion battery using CC/CV mode was implemented using Schmitt Trigger as a switching technique.

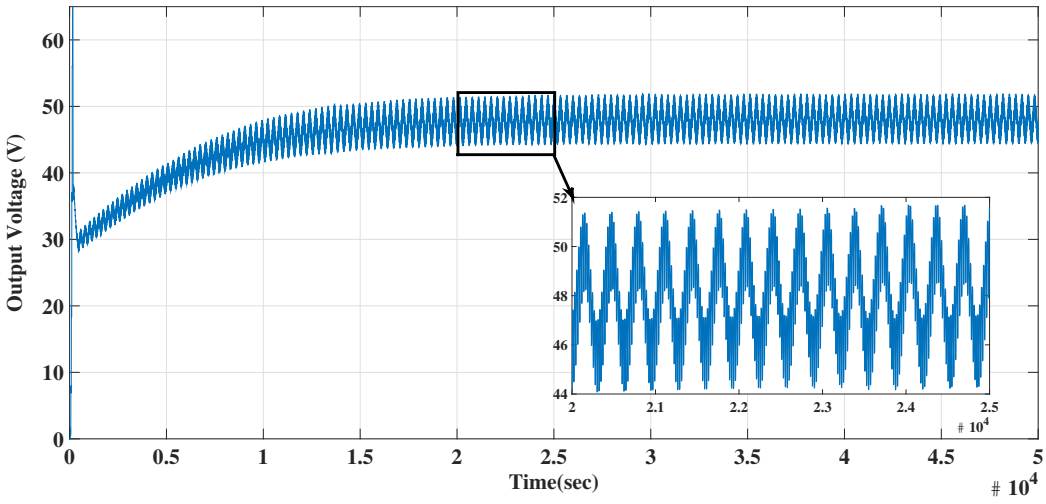

Fig. 4.1: Output of boost converter.

Table 4.1: System parameters for simulation design

Parameters used		
Sr. No.	Parameters	Value
1	Inductance (L)	0.415mH
2	Capacitance (C)	200 μF
3	r_{int}	20 Ω
4	V_{in}	24 V
5	f_s	20 KHz
6	ΔI	25%
7	ΔV	5%

Fig. 4.1 demonstrates the output of boost converter as indicated by the parameter planned in

Table. 4.1 As it is obviously seen there are large transients in the output voltage which brings about the production of system unstability. Additionally, battery efficency is very influenced if directly connected over the load end.

So, an appropriate controller for delivering desired output with minimum ripples should be composed, thereby creating less switching transients for battery charging. Thus, the principle focal point of this work is to design the desired control technique accordingly producing less transients while charging the battery.

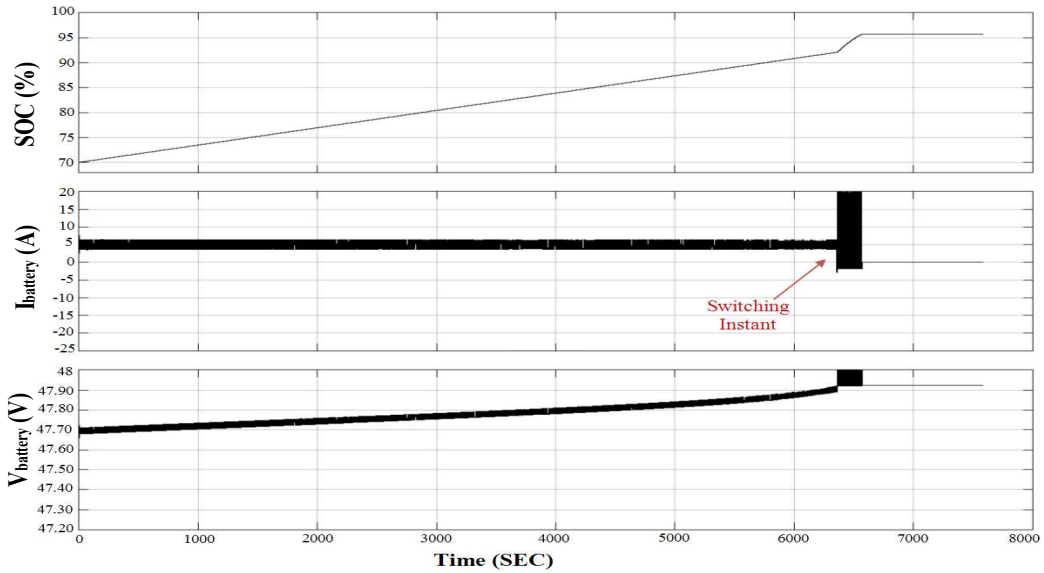

Fig. 4.2: Output of toggle switch

Fig. 4.2 demonstrates the real-time simulations result utilizing toggle Switch. It is seen, at the instant of switching, continious oscillations are produced while moving from CCM to CVM. These oscillations happen on account of ripple in the capacitor voltage, which results in consistently turning ON and OFF of the toggle switch. This results to rise in current making the system unstable. Hence, continious oscillations results in the execution of the battery. Henceforth, brings about large system unstability.

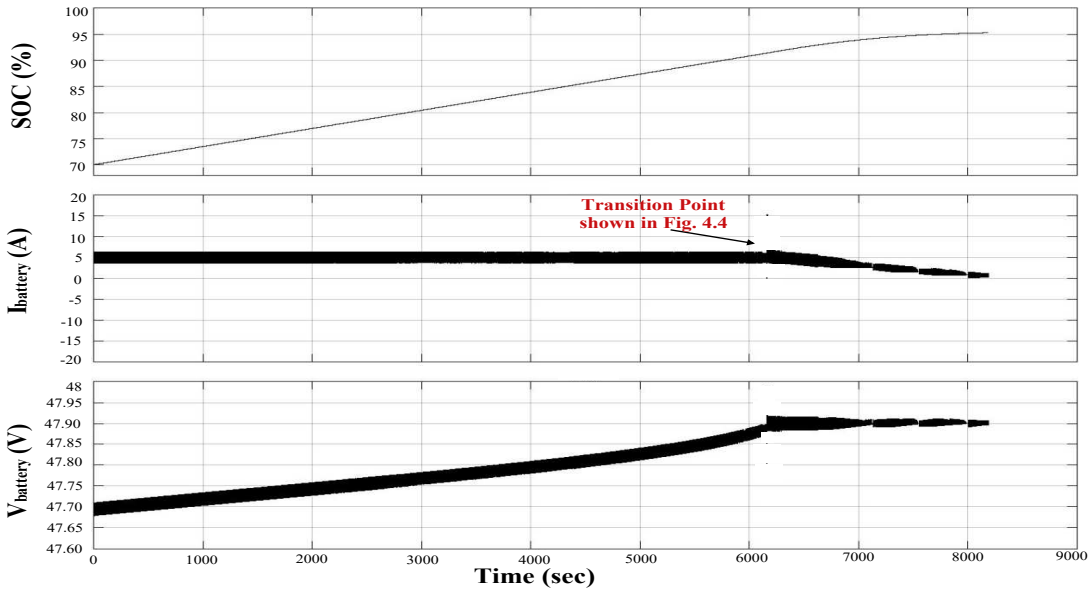

Fig. 4.3: Output using Schmitt trigger.

Fig. 4.3 demonstrates the reponse during switching for the proposed scheme utilizing 44V-33Ah Li-ion battery. At first, the output of Schmitt trigger is set such that the controller works in a CC mode. Results demonstrate that battery charges with a constant current till the terminal voltage of the battery accomplishes 98% of the rated voltage. Now, when the output of Schmitt trigger reaches to UTL, the controller changes from CCM to CVM, until the point when the current drop downs to 0.1% of the evaluated current. Consequently, the outcomes demonstrate switching ripples are decreased extensively and a smooth change is observes while moving from CC to CV.

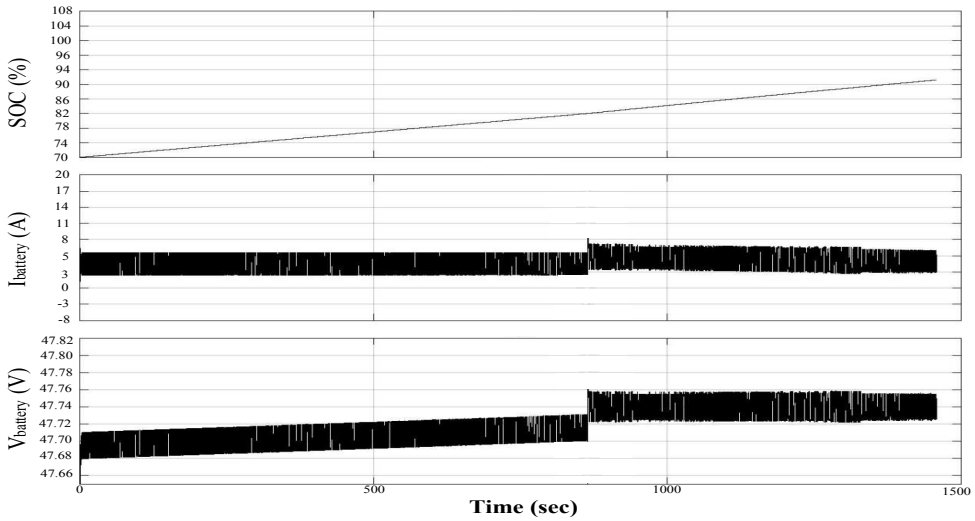

Fig. 4.4: Switching response using Schmitt trigger.

From Fig. 4.4 it is clearly seen that smooth progress happens from CCM to CVM. Subsequently, the event of transition at the instant of switching has been diminished fundamentally. Therefore, Schmitt trigger switching in contrast with toggle switching or diode switching have brought about the generation of less transients during transition from CCM to CVM.

4.1 Hardware implementation

To verify the proposed scheme hardware for the same is composed and the results are acquired using Opal-RT as a controller. For implementing the proposed schme, four Lead-acid batteries of 26Ah capacity and 14V nominal voltage are connected in series to produce the aggregate nominal voltage of around 46V for testing the hardware. All the passive components utilized for the designing are considered as lossless. Variable DC supply is utilized for applying the input voltage to the DC-DC boost converter.

The hardware design of the DC-DC boost converter consist of,

- Power switch.
- Led indication is used for protection, i.e overvoltage and under voltage protection.
- An ammeter for displaying current flowing through the battery.
- 2 pole MCB for turning on the input voltage.
- Two DC ports to connect the input and output terminals.
- 2 pole MCB for turning ON the battery voltage.
- Battery voltage display meter.
- Test point for seeing analog signals on DSO.
- PWM signal port from Opal-RT.

The parameters used for designing are shown in Table. 4.2.

The performance of charger is verified for 44-V-26-Ah Lead-Acid battery using hardware. Based on the parameters listed in Table 4.2, the proposed charger circuit of power rating 1.2kW is implemented. Thus, battery charging is performed using real time system hardware via Opal-RT.

Table 4.2: System parameters for hardware design

Parameters used		
Symbols	Quantity or Device	Attributes
V_s	Input voltage	24V
V_o	Output voltage	48V μF
r_{int}	Internal resistance of battery	20 Ω
L	Inductance	5mH/20A
C_{in}	Input filter capacitance	2200mfd/450V
C_{out}	Output filter capacitance	2200mfd/450V
S/W	IGBT	SKM100GB12T
I_{sensor}	Current sensor	LA25P
V_{sensor}	Voltage sensor	LV25P
Battery	Four lead acid battery	12V, 26Ah
f_s	Switching frequency	2KHz
f	sampling frquency	20KHz
ΔI	Ripple in current	25%
ΔV	Ripple in voltage	5%
K_{p1}	Proportional gain in CCM	0.03
K_{i1}	Integral gain in CCM	5.5679
K_{p2}	Proportional gain in CCM	0.01
K_{i2}	Integral gain in CCM	7.4357

The battery charging is done under the condition that battery is charged to around 80%.

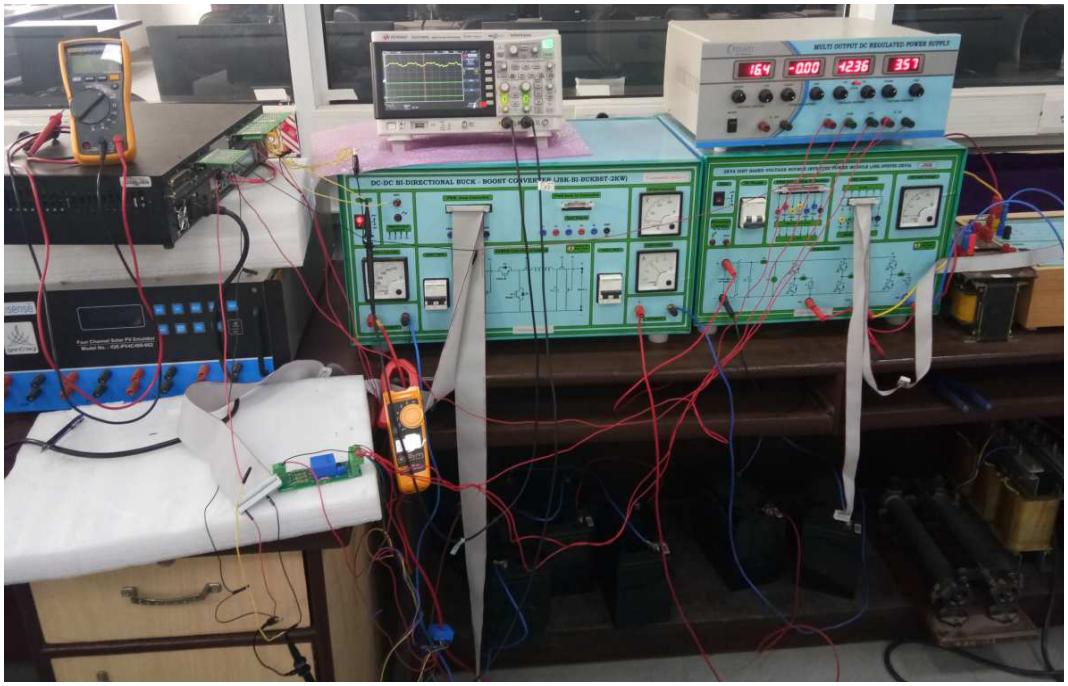

Fig. 4.5: Hardware circuit for CC/CV mode battery charging.

Fig. 4.5 demonstrates the hardware model for CC/CV mode electric vehicles battery charging created in the laboratory. The control structure for the proposed scheme is introduced in Fig. 2.4 and the experimental result performed is shown in Fig. 4.9 and Fig. 4.10. So as to compare the proposed scheme with the generally used scheme, battery voltage and current using toggle switch is shown in Fig. 4.7 and Fig. 4.8. Also, sensors are required for detecting the voltage and current. In this manner, two sensors are utilized as a part of this experiment circuit. LA25P current sensor is utilized for detecting the input current for the controller.

Likewise, the LV25P voltage sensor is being utilized for input voltage for the controller. Additionally, a simulator system is required for producing the PWM pulses for the IGBT switch. In this manner, a real-time simulator OP4510 Opal-RT is utilized for applying PWM pulses to the IGBT switch. Four 26Ah limit and 11V nominal voltage battery are connected across the DC-DC boost converter. Results are obtained using Opwrite block of Opal-RT. Duty cycle generated is applied utilizing 40Pin connector and can be seen utilizing DSO.

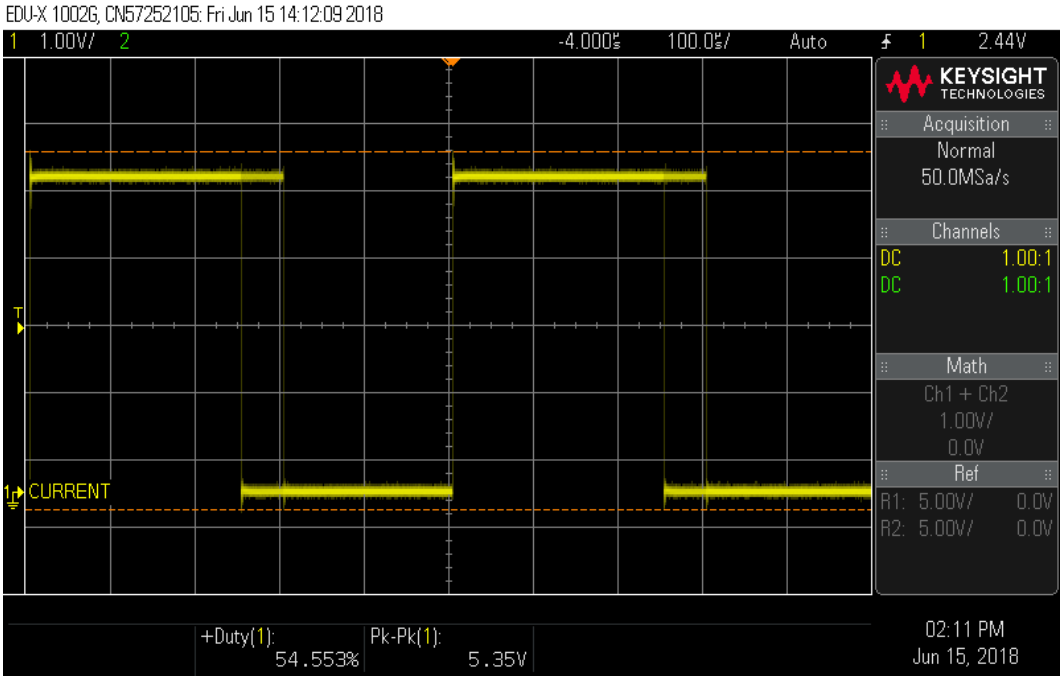

Fig. 4.6: Pulses applied to the IGBT using Opal-RT.

Fig. 4.6 shows the Duty cycle applied to the IGBT switch using Opal-RT.

4.1.1 Experimental result using Toggle switching

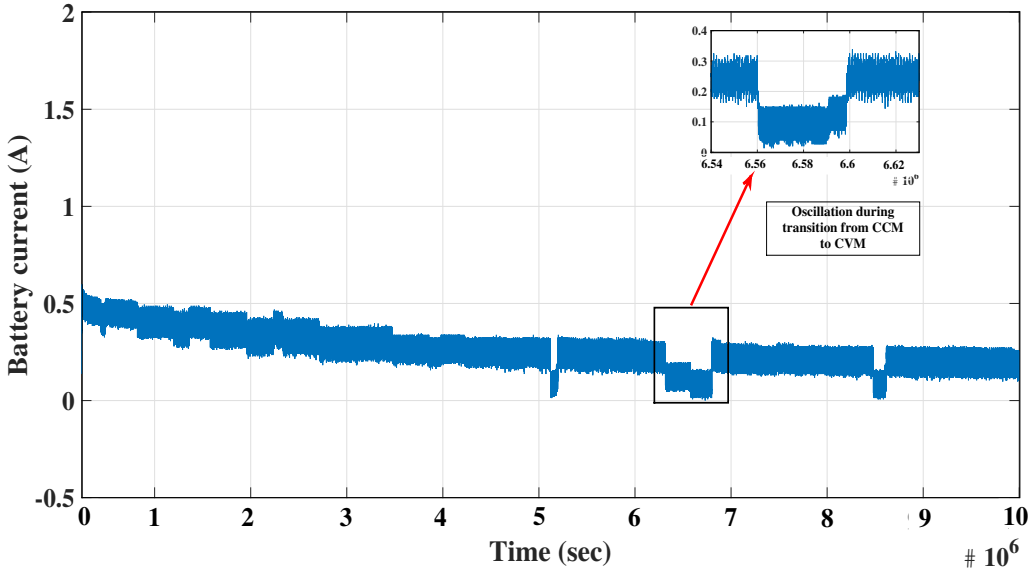

Fig. 4.7: charging current through battery using toggle switch.

Fig. 4.7 demonstrates the experimental results of the charging current moving through the battery using toggle switch. Firstly, the battery is charged with a constant current until the

threshold value of the toggle switch is reached. As the threshold value of the toggle switch achieves the controller switches to CVM. But, because of ripple in the capacitor voltage, the system keeps on oscillating back and fro amongst CCM and CVM at the instant of transition. This outcomes in diminishing the charge productivity and lifetime of the battery.

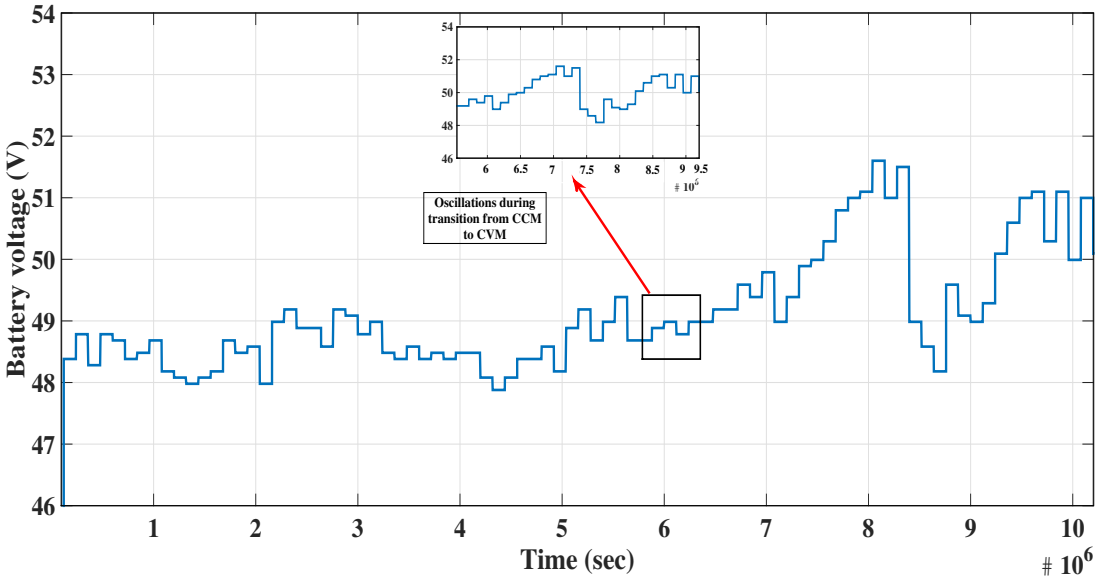

Fig. 4.8: Charging voltage across battery using toggle switch.

Fig. 4.8 demonstrates the experimental results of the charging voltage across the battery using toggle switch. Firstly, the battery is charged with a constant current until the threshold value of the toggle switch is reached. As the threshold value of the toggle switch achieves the controller switches to CVM. From Fig. 4.8 it is clearly shown that due to the production of oscillations at the instant of transitions large disturbance is produce in the voltage. Hence, the production of these large transients results in decreasing the lifetime of the battery.

4.1.2 Experimental result using Schmitt trigger switching

Fig. 4.9 demonstrates the experimental results of the charging current flowing through the battery utilizing Schmitt trigger switching. The battery is at first charged with a constant current till the UTL of Schmitt trigger is reached. As the Schmitt trigger goes above UTL, the controller changes to constant voltage mode. The controller keeps on staying in this mode until the point when current goes beneath 1% of the rated current. Subsequently, at the instant of transition from CCM to CVM, it is observed that switching transients has been limited extensively.

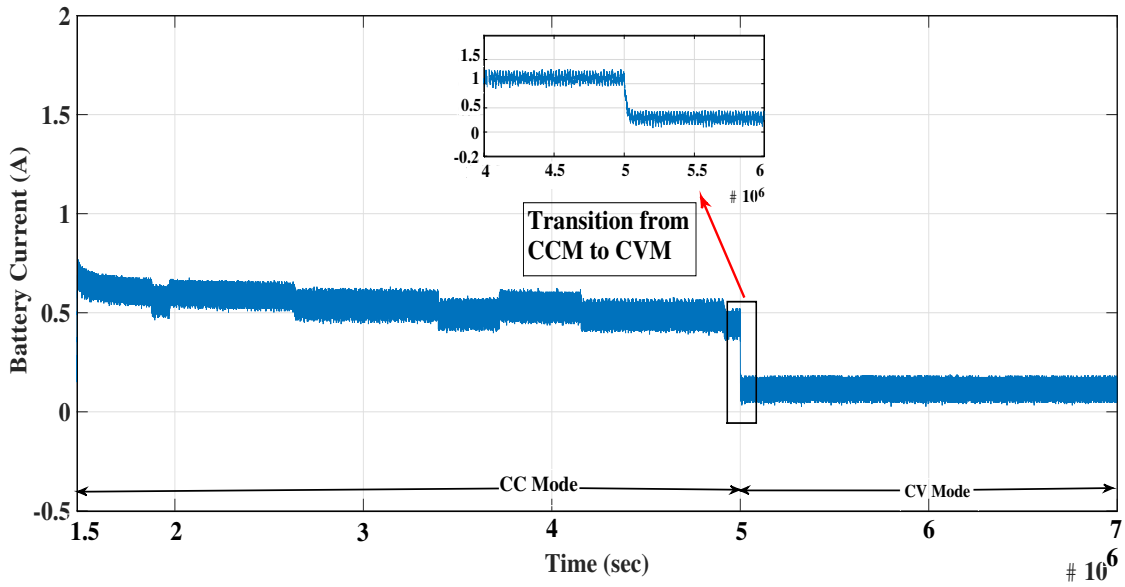

Fig. 4.9: Charging current through battery using Schmitt trigger.

Thus, the use of Schmitt trigger avoids the production of oscillations at the moment of transition, thereby expanding the charge productivity and lifetime of the battery.

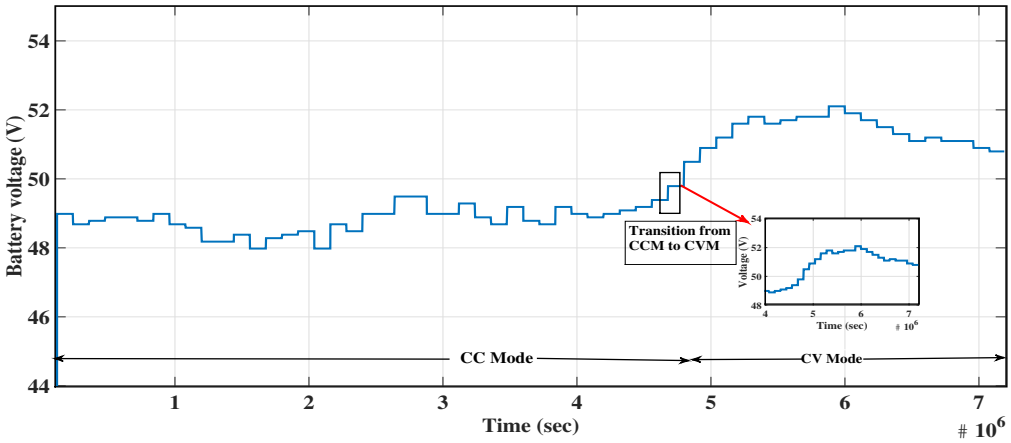

Fig. 4.10: Charging voltage across battery using Schmitt trigger.

Fig. 4.10demonstrates the hardware results of charging voltage over the battery during CCM and CVM utilizing Schmitt trigger switching. The battery is at first charged to around 47.5V. From Fig. 4.10 it can be clearly seen, battery voltage increments gradually during the constant current mode. As the battery voltage stretched around 98% of the evaluated voltage, the controller changes from CCM to CVM. Thus, a smooth transition is observed while switching from CC to CV. Thus, Schmitt trigger helps in reducing switching lossess, thereby expanding the charging productivity and lifetime of the battery. Subsequently, the issue of switching back to CCM has been wiped out totally.

Chapter 5

Conclusion

In this work, a novel charging strategy for battery charging is adopted to limit the switching transients. Battery charging is finished utilizing CCM/CVM procedure. With a specific end goal to reduce the switching transients and to have a smooth transition between the two modes, transition from CCM to CVM is done using Schmitt trigger. Keeping in mind the end goal to reduced switching transients during transition, a controller is designed for CCM and CVM. Tuning of the controller is obtained utilizing loop shaping strategy. The proposed methodology is initially actualized in Matlab simulation environment utilizing Opal-RT. In the wake of getting the desired outcome, a hardware for the same is designed. Firstly, the hardware designing of the DC-DC boost converter is done corresponding to the values calculated as mentioned in Table. 4.2

Further, the outcomes are experimentally verified utilizing Opal-RT as a controller. The pulses for IGBT switch is generated using Opal-RT and is applied using 40pin cable. Also, correlation of the current strategy i.e toggle switch and Schmitt trigger clearly portrays, oscillations produces during transition from CCM to CVM have been disposed of.

References

[1] T. S. Mundra and A. Kumar, "An innovative battery charger for safe charging of nimh/nicd batteries," *IEEE Transactions on Consumer Electronics*, vol. 53, no. 3, pp. 1044–1052, Aug 2007.

[2] A. Hussein and I. Batarseh, "A review of charging algorithms for nickel and lithium battery chargers," *IEEE Transactions on Vehicular Technology*, vol. 60, no. 3, pp. 830–838, March 2011.

[3] V. Torres, J. Sanguesa, F. Martinez, P. Garrido, and J. Barja, "Enhancing the charging process of electric vehicles at residential homes," *IEEE Access*, vol. 6, pp. 22 875–22 888, Feb 2018.

[4] D. H. Tran and W. Choi, "Design of a high-efficiency wireless power transfer system with intermediate coils for the on-board chargers of electric vehicles," *IEEE Transactions on Power Electronics*, vol. 33, no. 1, pp. 175–187, Nov 2018.

[5] V. Vu, V. Doan, V. Pham, and W. Choi, "A new method to implement the constant current-constant voltage charge of the inductive power transfer system for electric vehicle applications," in *Transportation Electrification Asia-Pacific (ITEC Asia-Pacific), 2016 IEEE Conference and Expo*, Mar 2016, pp. 449–453.

[6] R. Shi, S. Semsar, and P. W. Lehn, "Constant current fast charging of electric vehicles via dc grid using dual inverter drive," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 2, pp. 422–432, Aug 2017.

[7] H. Tanaka, F. Ikeda, T. Tanaka, H. Yamada, and M. Okamoto, "Novel reactive power control strategy based on constant dc-capacitor voltage control for reducing the capacity of smart charger for electric vehicles on single-phase three-wire distribution feeders," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 4, no. 2, pp. 481–488, Aug 2016.

[8] L. R. Chen, N. Y. Chu, C. S. Wang, and R. H. Liang, "Design of a reflex-based bidirectional converter with the energy recovery function," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 8, pp. 3022–3029, Feb 2008.

[9] L. R. Chen, "Design of duty-varied voltage pulse charger for improving li-ion battery-charging response," *IEEE Transactions on Industrial Electronics*, vol. 56, no. 2, pp. 480–487, Feb 2009.

[10] R. Mai, Y. Chen, Y. Li, Y. Zhang, G. Cao, and Z. He, "Inductive power transfer for massive electric bicycles charging based on hybrid topology switching with a single inverter," *IEEE Transactions on Power Electronics*, vol. 32, no. 8, pp. 5897–5906, Nov 2017.

[11] R. K. Singh and S. Mishra, "A magnetically coupled feedback-clamped optimal bidirectional battery charger," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 2, pp. 422–432, Feb 2013.

[12] J. M. Bosque, H. Valderrama Blavi, F. Flores-Bahamonde, E. Vidal-Idiarte, and L. Martínez-Salamero, "Using low-cost microcontrollers to implement variable hysteresis-width comparators for switching power converters," *IET Power Electronics*, vol. 32, no. 9, pp. 7045–7055, 2017.

[13] M. Chen and G. A. R. Mora, "Accurate, compact, and power-efficient li-ion battery charger circuit," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 53, no. 11, pp. 1180–1184, Nov 2006.

[14] C. H. Lin, C. Y. Hsieh, and K. H. Chen, "A li-ion battery charger with smooth control circuit and built-in resistance compensator for achieving stable and fast charging," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 57, no. 2, pp. 506–517, March 2010.

[15] S. Yang, J. Liu, and C. Wang, "A single-chip 60-v bulk charger for series li-ion batteries with smooth charge-mode transition," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 59, no. 7, pp. 1588–1597, Oct 2012.

[16] R. J. Wai and S. J. Jhung, "Design of energy-saving adaptive fast-charging control strategy for li-fe-po4 battery module," *IET Power Electronics*, vol. 5, no. 9, pp. 1684–1693, November 2012.

[17] S. H. Yang, J. W. Liu, Y. H. Wu, D. S. Wang, and C. C. Wang, "A high voltage battery charger with smooth charge mode transition in bcd process," in *Circuits and Systems (ISCAS), 2011 IEEE International Symposium on*, November 2011, pp. 813–816.

[18] B. Y. Chen and Y. S. Lai, "New digital-controlled technique for battery charger with constant current and voltage control without current feedback," *IEEE transactions on industrial electronics*, vol. 59, no. 3, pp. 1545–1553, Sep 2012.

[19] V. L.Tran, N.T.Tran, S. H. Yu, Y. Park, and W. Choi, "Design of a nonisolated fuel cell boost charger for lithium polymer batteries with a low output ripple," *IEEE Transactions on Energy Conversion*, vol. 30, no. 2, pp. 605–614, June 2015.

[20] P. J. Liu and L. H. Chien, "A high-efficiency integrated multimode battery charger with an adaptive supply voltage control scheme," *IEEE Transactions on Power Electronics*, vol. 33, no. 8, pp. 6869–6876, Sep 2018.

[21] Y. Hwang, S. Wang, F. Yang, and J. Chen, "New compact cmos li-ion battery charger using charge-pump technique for portable applications," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 54, no. 4, pp. 705–712, Nov 2007.

[22] X. Zheng, X. Liu, Y. He, and G. Zeng, "Active vehicle battery equalization scheme in the condition of constant-voltage/current charging and discharging," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 5, pp. 3714–3723, Sep 2017.

[23] N. M. L. Tan, T. Abe, and H. Akagi, "Design and performance of a bidirectional isolated dc–dc converter for a battery energy storage system," *IEEE Transactions on Power Electronics*, vol. 27, no. 3, pp. 1237–1248, May 2012.

[24] Z. Wang, X. Lai, and Q. Wu, "A psr cc/cv flyback converter with accurate cc control and optimized cv regulation strategy," *IEEE Transactions on Power Electronics*, vol. 32, no. 9, pp. 7045–7055, April 2017.

[25] V. L. Tran, H. N. Vu, D. D. Tran, and W. Choi, "Design and implementation of a high-efficiency multiple output charger based on the time-division multiple control technique," *IEEE Transactions on Power Electronics*, vol. 32, no. 2, pp. 1210–1219, Aug 2017.

[26] B. Gu, J. S. Lai, N. Kees, and C. Zheng, "Hybrid-switching full-bridge dc–dc converter with minimal voltage stress of bridge rectifier, reduced circulating losses, and filter requirement for electric vehicle battery chargers," *IEEE Transactions on Power Electronics*, vol. 28, no. 3, pp. 1132–1144, Feb 2013.

[27] S. Kulasekaran and R. Ayyanar, "Analysis, design, and experimental results of the semidual-active-bridge converter," *IEEE Transactions on Power Electronics*, vol. 29, no. 10, pp. 5136–5147, Aug 2014.

[28] R. W. Erickson and D. Maksimovic, *Fundamentals of power electronics*. Springer Science & Business Media, 2007.

[29] N. Li, F. Gao, T. Yang, L. Zhang, Q. Zhang, and G. Ding, "An integrated electric vehicle power conversion system using modular multilevel converter," in *Energy Conversion Congress and Exposition (ECCE), 2015 IEEE*, vol. 30, no. 8, Dec 2015, pp. 5044–5051.

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