DESIGN AND CONTROL OF FAULT TOLERANT BIDIRECTIONAL INTERLEAVED CONVERTER FOR BATTERY CHARGING APPLICATIONS

A DISSERTATION

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Submitted by

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CANDIDATE'S DECLARATION

I, Abhishek Chawla, Roll No. 2K21/PES/03 student of MTech (Power Electronics & Systems), hereby declare that the project Dissertation titled **"Design and Control of Fault Tolerant Bidirectional Interleaved Converter for Battery Charging Applications"** which is submitted by me to the Department of Electrical Engineering, Delhi Technological university, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

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CERTIFICATE

I hereby certify that the project Dissertation titled **"Design and Control of Fault Tolerant Bidirectional Interleaved Converter for Battery Charging Applications"** which is submitted by Abhishek Chawla, Roll No. 2K21/PES/03, Department of Electrical Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the student under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

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DR. MAYANK KUMAR
(SUPERVISOR)

ABSTRACT

Most industrialized countries are aiming towards cleaner modes of transportation, and Electric Vehicles (EVs) are top contenders for the same. EVs are largely seen as the future of the transportations business. Although the topic is a great deal of research, this research focuses on improving the reliability of the system by making it fault tolerant. DC-DC converters are one of the most important and challenging subsystems in charging systems. The reliability of the system has always been an issue because of the failures of the semiconductor switches. The study presents the design and control of a 1kW fault-tolerant bidirectional interleaved converter for battery charging applications. It also proposes an algorithm for detection of fault in any of the switches and uses a 3-phase bidirectional interleaved non- isolated converter. The converter's working is simulated based on two configurations that conducts using all legs at once and redundant leg-based topology so that the converter functions like the prior fault condition. The algorithm makes use of the digitally implemented circuit and hence does-not affect the cost of the system much. A modified PI control integrated with fault detection control scheme is implemented to charge the battery in constant current mode and ensure minimum ripples in output voltage and current. While discharging, voltage mode control is implemented using the PI control. The fault-tolerant capability ensures the continuous operation of the converter even after a fault and made it suitable for EVs battery charging applications.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATION

S. No.	Abbreviated Name	Full Name
1.	EV	Electric Vehicle
2.	ICE	Internal Combustion Engine
3.	BEV	Battery Electric Vehicles
4.	G2V	Grid to Vehicle
5.	V2G	Vehicle to Grid
8.	OBC	On-Board Charger
9.	CC	Constant Current
10.	CV	Constant Voltage
11.	CC-CV	Constant Current -Constant Voltage
12.	CTC	Constant Trickle Charging
13.	DCFC	DC Fast Charging
14.	PI	Proportional Integrator
15.	PWM	Pulse Width Modulation
16.	SoC	State of Charge
17.	HESS	Hybrid Energy Storage Systems
18.	BIC	Bidirectional Interleaved Converters
19.	ANN	Artificial Neural Network
20.	OCF	Open Circuit Fault
21.	SCF	Short Circuit Fault
22.	CCM	Continuous Conduction Mode
23.	DCM	Discontinuous Conduction Mode
24.	MUX	Multiplexer
25	Li-ion	Lithium ions

LIST OF SYMBOLS

S. No.	Symbols	Description
1.	V_{in}	Input Voltage to the Converter
2.	V_{out}	Output Voltage across Battery
3.	n	Number of Phases
4.	f_{sw}	Switching Frequency
5.	D	Duty Cycle of the Converter
6.	C_i	Input Capacitance
7.	C_o	Output Capacitance
8.	I_{out}	Output Current of the Converter
9.	L	Inductance of each Phase
10.	i_{pp}	Peak to Peak current across the inductor
11.	$\Delta V_{in}, \Delta V_{out}$	Ripples in input and output voltage
12.	$V_{sw(MAX)}$	Maximum Voltage across switch
13.	$I_{sw(MAX)}$	Maximum Current across switch
14.	m	Floor value of nD
15.	S_1, S_3, S_5	Upper switches of interleaved converter
16.	S_2, S_4, S_6	Lower switches of interleaved converter
17.	K_p	Controller's Proportional Gain
18.	K_i	Controller's Integral Gain

CHAPTER 1

LITERATURE OVERVIEW

1.1Introduction To Electric Vehicles

With the increasing energy demand of the world, there is a global movement going on to bring cleaner and greener technologies. At present, conventional resources are used to meet the demand of the world out of which fossil fuels provide 70%-80% of the primary energy required by the world. It not only results in severe consequences like the prolongation of the rise in atmospheric carbon dioxide, climate change, rapid depletion of the conventional resources and increasing hazardous effects of the pollution in urban areas but is disastrous to both the environment and people. Therefore, a paradigm shift is required, and different technologies should be looked upon to minimize the pollution in urban cities as most of the population resides there. Electric Vehicles (EVs) / Battery Electric Vehicles (BEVs) are one of the technologies that do not emit greenhouse gases and are not dependent on fossil fuels. They also help in mitigating noise pollution as they are basically noiseless compared to conventional vehicles which uses Internal Combustion Engines (ICE) [1]-[3]. Not only this, the running cost and the maintenance cost of the EVs is low as compared to the ICE. EVs also have the advantage of serving as energy storage devices for vehicle-to-grid (V2G) applications [4]-[5]. The main concept behind vehicle-to-grid (V2G) technology is to use automobiles as energy storage systems and supply electricity to the grid to help the grid during voltage and frequency dips [6]-[7]. Although renewable energy sources generate a considerable amount of electricity, but these are not reliable as solar energy can't be generated during the nights or windy days. In order to store the energy and to promote EVs, the development of secondary batteries, particularly lead acid and Lithium ions (Li-ion) batteries are rapidly accelerating at the moment.

Li-ion batteries have many benefits, including their high-power density, high operating voltage, lack of memory effect and ease of usage with EVs and power systems [8]. Along with this, Li-ion batteries have high recycling and renewable qualities when compared to other types of batteries. In order to adapt these changes and for user convenience, quick charging of these batteries is necessary. With higher charging current, charging time to fully charge the battery reduces. Therefore, a chain of efficient charging systems along with proper infrastructure is required that charges the battery within minimum time. To support this, government of India has taken initiative that all the two-wheelers with engines under 150cc that must be sold after March 31, 2025, and all three-wheelers sold after March 31, 2023, be EVs in order to achieve the government of India's 2030 goal of making India a fully EVs nation.

1.2 Charging Levels In EV

EV charging is possible at three different power levels generally known as level 1, level 2, and level 3 charging. Level 3 Charging is also known as DC Fast Charging. These charging levels are based on the amount of time battery takes to get fully charged. The higher the charging level the higher amount of power in can transfer to battery in less amount of time [9]-[11]. Along with this, a proper control is required to charge the battery. Generally, the modes are classified as constant-voltage (CV) mode, constant-current (CC) mode, constant-current constant-voltage (CC-CV) mode and constant trickle charging (CTC) mode [3]. Fig.1.1 represents the different regions where battery is charged in constant-current mode and in constant-voltage mode.

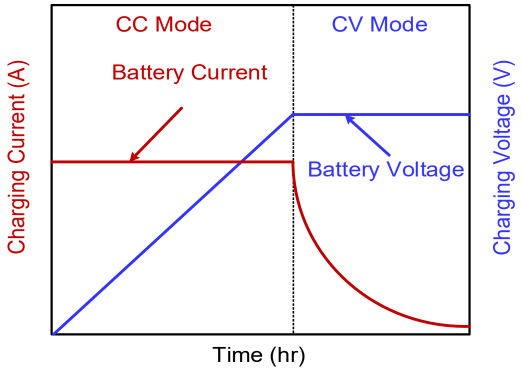


Fig.1.1 CC-CV modes during battery charging.

1.2.1 Level 1 Charging

Level 1 charging is the simplest charging method. It draws electricity of typically around 1.9 kW while charging from an AC source, 120 Volts connected at a typical uptown and/or commercial electrical socket capable of passing a current of amount which is 15-20 amps. Portable Level 1 chargers, also known as On-Board Chargers (OBCs), are used with electric cars. Fig.1.2. shows the components used in

Level 1 charger [12-13]. An EV with a range of 60–80 miles require a full charge in the range of 10–14 hours, which is a significant amount by level 1 charging standards.

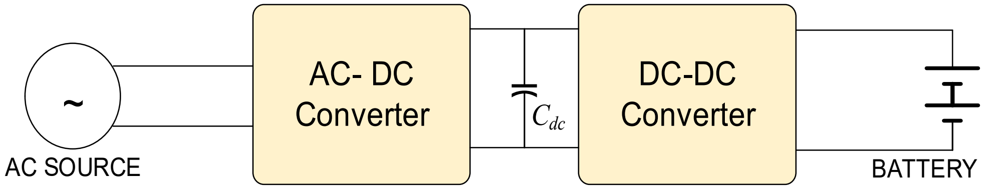


Fig.1.2 Components of a Charger

1.2.2 Level 2 Charging

Level 2 charging uses three to four times the current of a Level 1 charging and operates at a higher voltage, typically 240V. As a result, most Level 2 units charge the EV's battery pack at a pace that is around six to eight times faster than Level 1 configurations and provide 12-32 miles of driving range for each hour of charging. It is connected to the AC grid for 4-6 hours and charges the battery fully in it. However, Level 2 charging rates can vary quite a bit. A typical 240-volt, 24-amp unit has a constant output capacity of around 6.0 kW. However, 80 amps, or 19.2 kW, the fastest Level 2 charging rate, is more than three times quicker. Although the majority of currently available vehicles only utilize up to 30 amps for 3.3 to 6.6W charging, a J1772 connector used by electric cars may potentially provide current of up to 80 amps (19.2 kW). Level 2 charging equipment can be put at a person's home, place of employment, as well as in public areas like malls, railway stations, and other places [14]. Since adding Level 2 charging capabilities at home adds to the cost, several states and cities in India offer financial incentives to help with the costs.

1.2.3 Level 3 Charging

Level 3 charging, also known as the DC Fast Charging (DCFC), is the quickest charging method. It can recharge an EV at a rate of 3 to 20 miles of range per minute. Level 3 charging employs direct current (DC), when compared to Level 1 and Level 2 charging, which use alternating current (AC). Compared to Level 1 & 2 charging, the voltage is also significantly higher, typically in the range of 400V to 800V. The charger is installed externally and has a maximum power level of 90 kW. The car's battery gets charged up to 80% of its rated capacity by the DC source in 30 minutes at the rate higher than 1C [3-4], where 1C represents charge rate of the battery. The connectors used in

DC fast charging are the CCS, CHAdeMO and Tesla. CCS fast-charging connection uses the same J1772 socket for Level 1 and Level 2 charging in addition to two additional pins for DC fast-charging [15]. CHAdeMO is the other kind of fast-charging connector which allows you to charge up to 400kW**.**

Table 1.1 Comparison of different charging levels in EV

Charging Level	**Power Ratings**	**Voltage Ratings**	**Current Ratings**	**Charging Time**
Level 1	Up to 1.9kW	120V @ AC	15-20A	10-12 hours
Level 2	Up to 19.2kW	240V @ AC	Up to 80A	4-6 hours
Level 3	Up to 90kW	400-800V @DC	Up to 300 A @ 480V	Less than 1 hour

1.3 Fault Tolerant Converters

DC-DC converters are widely employed to efficiently convert DC voltages from one level to another. A single failure in one of the converter's components can result in a flaw in the entire system therefore, the system reliability of these converters is extremely important. In the case of EVs, DC-DC converters finds its applications in charging (G2V) an d discharging (V2G mode) of the battery [6]. The DC-DC converters must be able to run continuously in some essential procedures, even when a fault occurs. Faults can be caused by defects that the system develops because of both internal and external factors. A lot of research has been going on in the field of fault diagnosis and fault tolerant control scheme and it is reported in the literature that about 30-35% of faults occurred in the power converters are because of the semiconductor switch faults. Short circuits and open circuits faults in the system are the main reliability issues of the converter, and they appear may be because of internal or/and external defects [16]. The faults are typically caused by issues with grounding, or a fast rise in system temperature. The most critical switch fault is SCF, which results in extreme high current that can turn the complete power converter off. Although the OCF is not as severe as the SCF, the effect of this fault cannot be ignored. If it is not diagnosed quickly enough, additional switches and circuit components can become over stressed and fail. Therefore, detection of fault is as important as making the converter tolerant from these faults [17-19]. The various configurations used to make a converter fault tolerant are based on:

1. Free of Additional Hardware
- Phase shift Adjustment
- Bypassing the Faulty Module
2. Based on Additional Hardware
- Bypassing the Faulty Module
- Inclusion of Redundant Leg
- Inclusion of Additional discrete components

Gating signal adjustment is introduced in phase shift adjustment. Once the defect has been identified, the switching pattern must be changed to eliminate the gating signal connected to the defective switch. Additionally, the active switches' phase shift between the gating signals is adjusted. This reconstruction scheme is typically used in converter topologies that use the phase shift modulation technique. input parallel output-series (IPOS) converters, interleaved DC-DC converters, and parallel-connected SAB converters are the ones on which the approach works well.

The bypass of faulty module is one of the simplest methods that can be executed in multi- module converters. Initially, the converter conducts through its active modules and in case of fault it conducts through its redundant leg and maintain the conversion ratio constant. Also, all the elements that were initially part of the construction are needed to carry out the bypass function.

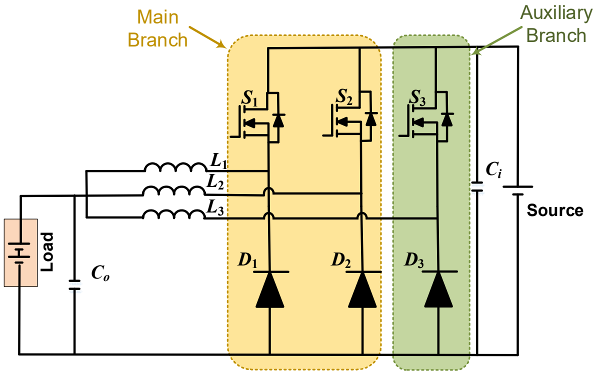


Fig.1.3 Redundant leg based Interleaved buck converter

Based on additional hardware, the bypass of faulty modules includes additional components such as solid-state relays or thyristors. If the converter has a modular structure, components either directly replace the defective element or bypass the defective element. The replacement can happen either at the device level (IGBTs, TRIACs, and MOSFETs) or at the leg level, depending on the topology of the DC-DC converter. Reconfigurable switch-based converters reconfigure the converters after the fault and let the converter operate prior to fault condition. These converters make use of the minimum switches to reconfigure the converter whereas redundant Leg based converters shut down the faulty leg and start conducting through the redundant leg [20]. Fig.1.3. Represents the redundant leg based two phase interleaved buck converter.

All these converters require a fault detection scheme that can detect the fault and apply the redundant control as fault detection is one of the crucial step in making the converter fault tolerant. It gives us thorough information on the damages that different types of defects can do, as well as the seriousness of the type of faults appeared [21]. It provides us with precise details regarding the highest withstand capacity of each converter component and greatly aids in the design of the converters within their safe working ranges.

1.4 Fault Diagnostic Algorithms

Over a period of time, many techniques have been developed and reported in literature that deals with a specific fault in the system. The faults in EV chargers range from switch level fault, leg level fault, module level fault, measurement level fault, network level fault and system level fault but the basic being switch level fault [22]. Fig.1.4. represents the classification of switch level fault diagnostic algorithms.

Signal processing-based algorithms are one of the simplest algorithms that are implemented in the literature. These algorithms make use of the control variables such as inductor current and capacitor voltage to generate a fault alarm system.. Some of the techniques that were used in the literature to detect an open circuit fault are analysis of the duty cycle and inductor current slope, examination of the current waveform and variations at various converter locations, monitoring of the voltage of the capacitors, measurement of the converter's primary voltage and analysis of its behaviour. Some of these techniques apply to many converters while some are limited to isolated or non-isolated. Some have the ability to detect multiple faults while some can detect a single one. Unfortunately, signal processing diagnostic algorithms may not always be successful because false fault alarms may be set off when the converter is required to operate under extremely dynamic conditions with significant switching frequencies or load level oscillations, producing false diagnostic results [20].

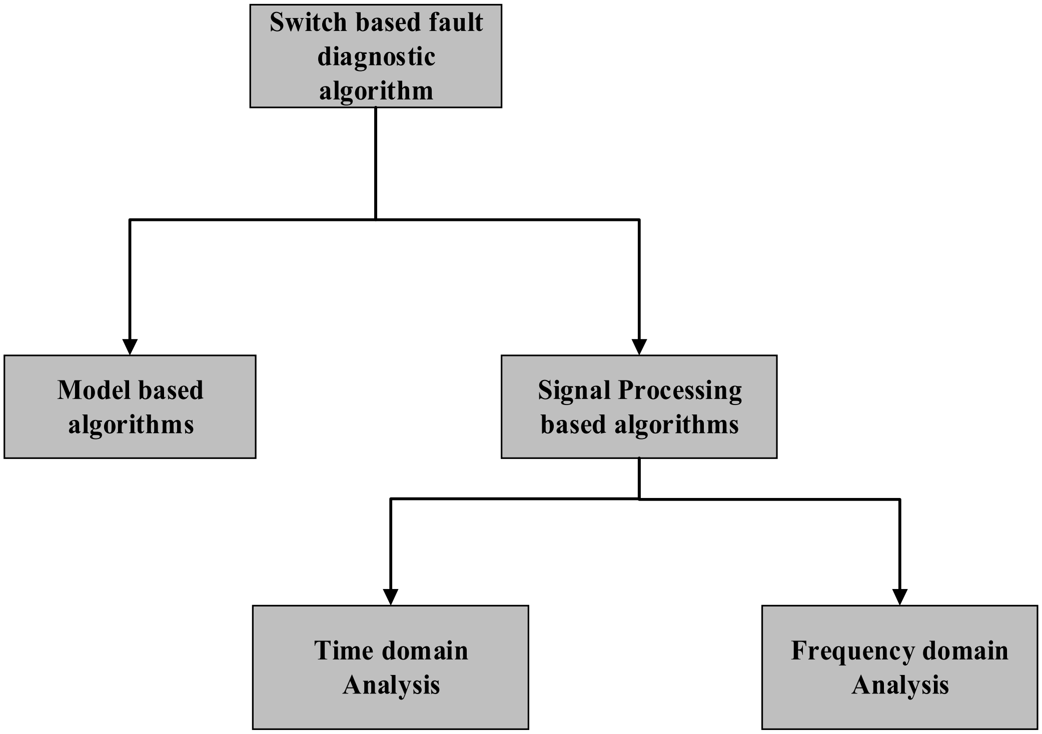


Fig.1.4 Classification of switch level fault diagnostic algorithm

Model-based fault diagnostic techniques have gained a lot of attention in the recent few years. When determining SCF or OCF, these algorithms are efficient and adaptable regardless of converter parameters (load level, switching frequency, input and output current, voltage across load etc.). As these typically rely on parity equations, state observers, or residual generation utilizing parameter evaluation, the stability against non-linearity, such as load transients or noise, is also improved. These techniques make use of the artificial intelligence (A.I) based techniques such as ANN (artificial neural network), fuzzy logic control and other supervised and non-supervised machine learning techniques. Basically, these model-based techniques compare a observed response of a parameter with the predetermined response. The model is trained extensively and thus these techniques prove to be more accurate than the signal processing-based techniques [20].

1.5 Motivation

This study's primary objective is to build and simulate a fault-tolerant bidirectional converter for electric car on-board battery charging systems that can operate at high efficiency and over a broad range of battery voltages. The initial design would be an interleaved bidirectional boost buck converter. The main objective is to increase converter reliability in order to support V2G mode and reduce output voltage and current ripples to prevent battery degradation and limit battery life. Additionally, a failure detection technique based on signal processing has been developed. It is compatible with closed loop control and works along with closed loop control and works with normal configuration and redundant leg-based configuration.

1.6 Outline Of Thesis

The thesis comprises of 6 chapters. The synopsis for each chapter is as follows:

1. Chapter 1 covers the fundamentals of EVs and various EV charging levels. Additionally, it covers the classification of fault tolerant converters and their significance. There is also discussion of various signal processing and model-based approaches for locating faults in the converter.
2 Chapter 2 covers the bidirectional converter and its various applications. Additionally, it discusses interleaving and the various constraints in selecting the converter for EV charging.
3 Chapter 3 covers the mathematical analysis of the bidirectional converter and the various steps involved in designing the converter.
4 Chapter 4 covers the closed loop control of the bidirectional interleaved converter. It discusses the effect of switch faults, primarily open circuit fault on the system and the need of fault tolerant converters.
5 Chapter 5 discusses the fault tolerant operation of the converter. A signal processing-based fault tolerant control scheme applicable to the non-isolated interleaved converter is proposed and simulated in MATLAB/SIMULINK.
6 The major conclusion of the work is provided in this chapter, along with suggestions for additional research.

CHAPTER 2

BIDIRECTIONAL INTERLEAVED BUCK-BOOST CONVERTER

2.1 Introduction

This chapter provides information about the bidirectional interleaved converters (BIC) used in fields such as EVs, hybrid energy storage systems (HESS), dc microgrids and many other applications. These converters can interface with different voltages at input and output side and can transfer power in both directions. Interleaved converters serve many benefits, and these can be combined with bidirectional converters to make it suitable for battery charging applications.

2.2. Interleaved Converters

A parallel group of converters is known as interleaved converters. Fig.2.1. represents a two-phase interleaved buck converter, each phase having their own power MOSFETs and inductors. A phase is the collective name for these parts. These phases share input and output capacitors and are connected in parallel [23]. Individual phases are active at regular intervals during steady-state operation, and the space interval is provided by ø as follows where *n* represents the total number of phases.

$$\phi = \frac{360^\circ}{n} \tag{2.1}$$

The Pulse Width Modulation (PWM) signals sent to the power MOSFETs is shown in Fig.2.2. These signals are phase shifted with each other. It is assumed that the duty cycle for the converter is 50%. Interleaving in converter causes ripple cancellation within the circuit which makes it suitablefor charging circuit. Besides these, interleaving increases the efficiency of the converter and reduces the size of the components and usually done in order to get low ripples in the output voltage and current and where there is requirement of high power and high current [9,24].

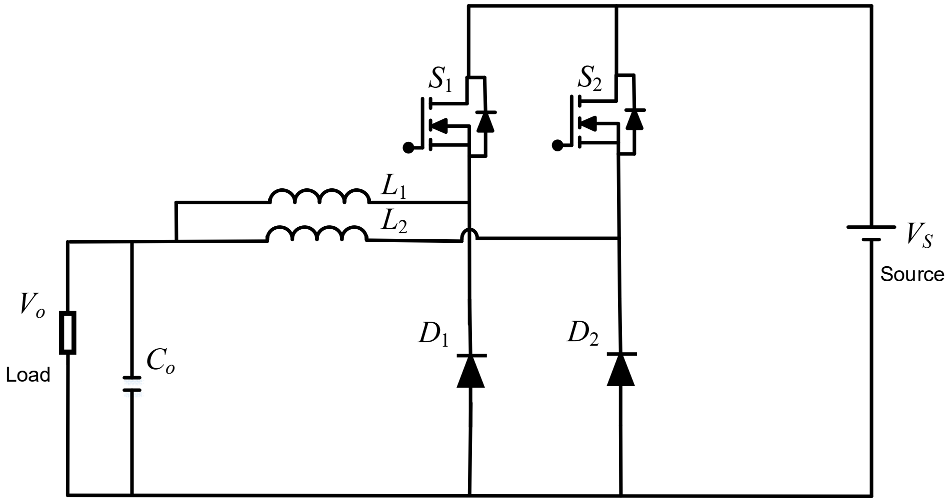


Fig.2.1 Two phase interleaved converter

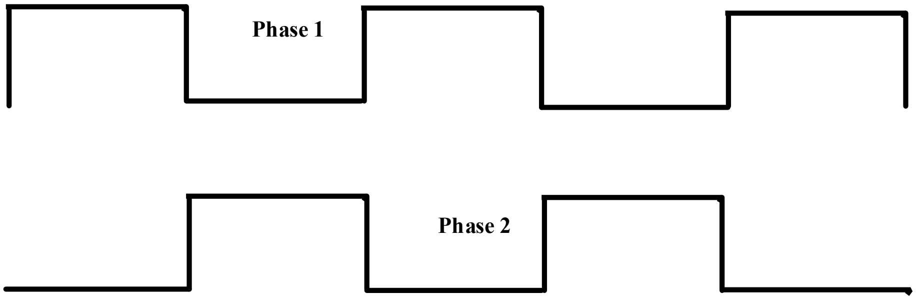


Fig.2.2 Phase shifted PWM signals.

Generally, the converter operates in one of the two conduction modes as follows:

i. Continuous conduction mode (CCM)
ii. Discontinuous conduction mode (DCM)

As the name suggests, in continuous current conduction mode the current through the inductor never falls back to zero whereas in discontinuous current conduction mode the current through the inductor falls to zero. Fig.2.3. shows the difference between CCM and DCM. The reverse current that flows during the rectifying diode's reverse recovery period causes losses in CCM. In low-voltage switching DC-DC conversion, the rectifying diode's reverse voltage and current are both low, hence CCM is often used with output ripple voltage and harmonics reduction as the top priority. The inductance of the inductor used in CCM is greater than that of DCM thereby increasing the size along with the cost. Also, the switching losses in CCM are higher than that of in DCM thereby affecting the efficiency of converter but the allowable power of the switching device is low when compared to that in DCM thereby reducing the size and overall cost [25].

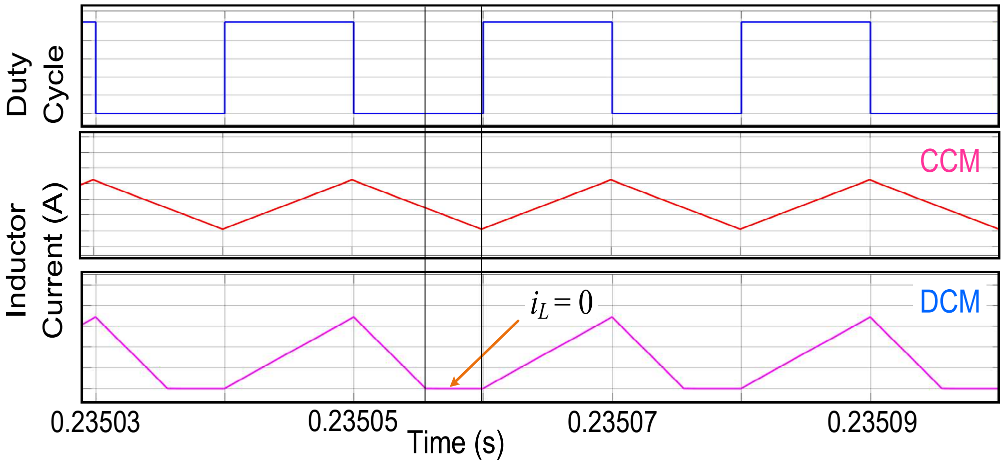


Fig.2.3 Continuous Current Mode vs Discontinuous Current Mode

2.3. Bidirectional Buck-Boost Converter

Bidirectional buck-boost converter is one of the simplest converters that can be formed by replacing the power diode in the buck converter/ boost converter with a power MOSFET. The circuit diagram of non-isolated bi-directional converter is given in Fig.2.4. The converter can transfer power in both directions. The bidirectional conversion is carried out by two switches and are regulated with the help of controllers. When Switch S1 is operated it can work in buck mode to charge the battery and when switch S2 is operated it can transfer power from battery to the source. Further analysis of the converter can be done by analysing the converter in its different modes [26-30].

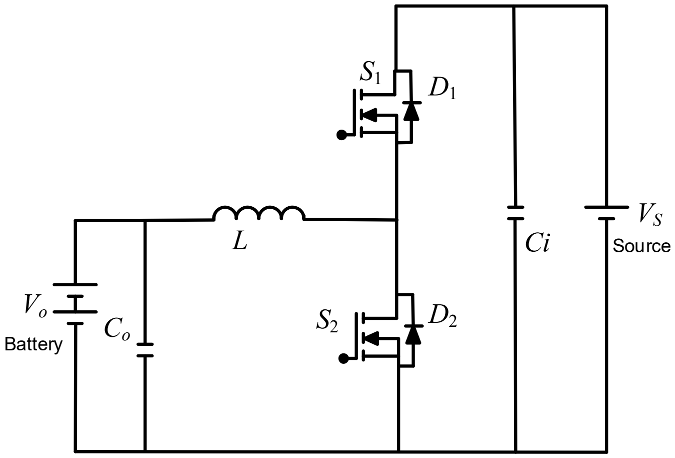


Fig.2.4 Bidirectional Buck Boost Converter

2.3.1 Operation of Converter during Charging

The charging mode, which is also known as forward power flow mode, is the first functioning mode. Fig.2.5. represents the operation of converter in forward power flow mode. When the battery receives power from an active dc source or from a dc bus, this mode is activated. Switch S1 will be switched on in this mode, and switch S2 will be off. The battery will receive electricity from the active dc source or dc bus through S1 for charging purposes. When the S1 is turned ON, the input current increases and passes via the MOSFET switch S1 and inductor L. The inductor current decreases until the next cycle after turning off S1. The battery is being charged in the meantime using the energy that the inductor L has stored.

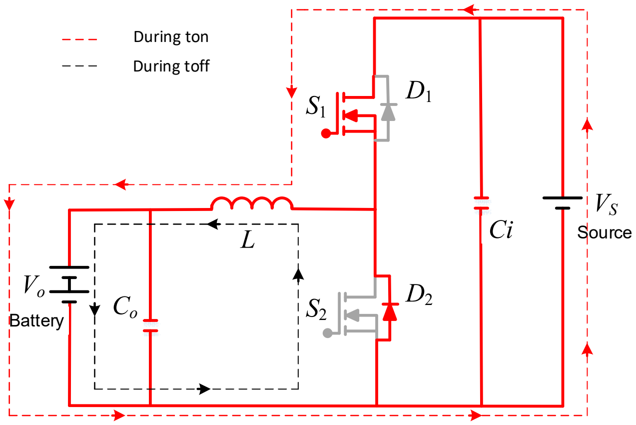


Fig.2.5 Converter operation during charging

2.3.2 Operation of Converter during Discharging

Fig.2.6. illustrates the operation of converter during discharging mode function. The second working mode is also known as reverse power flow mode. When the battery supply power to an active dc source or from a dc bus, this mode is activated. Switch S2 will be switched on in this mode, and switch S1 will be off. The battery will supply electricity to the active dc source or dc bus through S2. When the S2 is turned ON, the input current increases and passes via the MOSFET switch S2 and inductor L and charges the inductor. When the switch S2 is turned off, the inductor supplies the stored energy to the dc source via diode D1. In this way, bidirectional flow of power takes place.

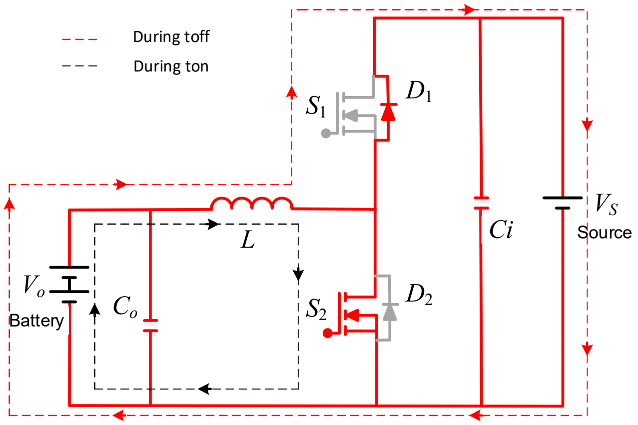


Fig.2.6 Converter operation during discharging

2.4. Design consideration for constraints under EV Charging

The research work mainly focuses on the application of fault tolerant converters in EVs. The converter finds its application in on board charger, regenerative braking and dual bus power system for vehicles having loads at different voltages. The various constraints in selecting the topology are discussed below.

1. Efficiency

Interleaved bidirectional non- isolated converters are the ones with very high efficiency. Single-phase converters have all the output power flowing through a single inductor and two MOSFETs. So as the current increases, the losses associated with it increases as the conduction losses in the system dominates the switching losses and thereby efficiency of system reduces. In order to cope up interleaved bidirectional converter is used. Fig.2.7. shows that upto 200A current 5 phases and less than that can be used to achieve an efficiency of more than 90% [31]. Isolated converters make use of the transformer and thereby efficiency of the system drops. Also, at high current the conduction losses increases and thus efficiency can never be over 90%.

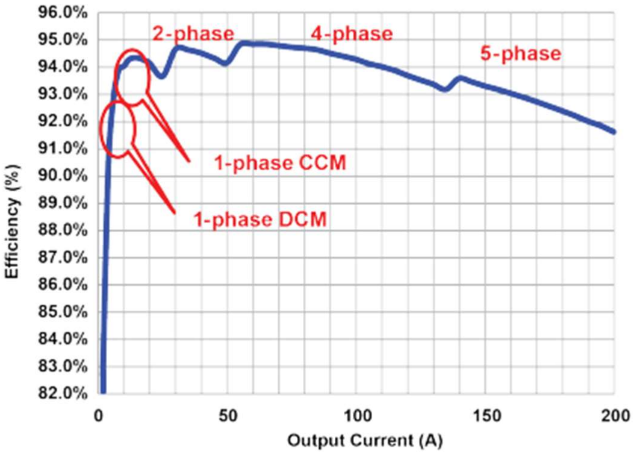


Fig.2.7 Efficiency of n phase system with increasing current

2. Better Transient Response

Interleaved converters offer better transient response as the phase inductors are parallel with one another which further reduces the overall equivalent inductance of the system seen at the output node. The inductance is reduced by a factor of n, where n represents the total phase of the converter. Undershoots in the system are reduced as the charge from the inductances can quickly be transferred to the output capacitance. In the very same fashion, overshoots in the system are reduced as less charge is stored in the inductors and is supplied to the output capacitors [31].

3. Light Weight and Less Space

For applications like EV, the space and weight of the converter is an essential parameter as it contributes to the efficiency of the system in indirect ways. Isolated converters make use of the transformer which increases the size and weight of the charger [30,31]. Also, since it's a single phase it requires proper space for thermal management otherwise the elements could heat up and turn the charger down. Bidirectional Interleaved converter shares the current and thus thermal management of this is better as losses are less. Also, for applications like dual bus power systems in vehicles, this comes out as the best option**.** Fig.2.8. shows the dual bus power system for 12V loads and 48 V loads.

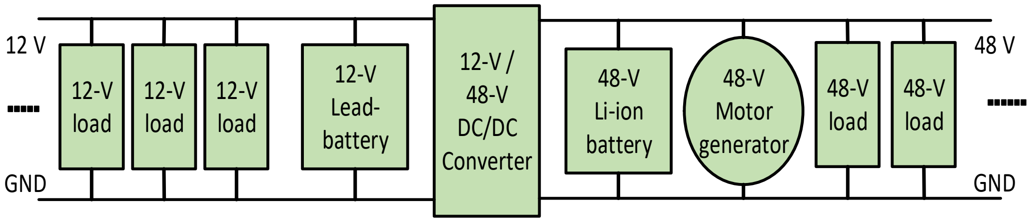


Fig.2.8 Dual bus power system for 12V loads and 48 V loads.

4. Effect of Ripples

High content of ripple in the output current of the dc-dc converter can degrade the life of the battery. Not only this, it causes the heating of the battery as internal resistance of the battery varies and generally increases with time. Interleaved dc-dc converters minimize these ripples. A two-phase interleaved converter operating at 50% duty cycle and phase shifted by 180º ideally produces pure dc current and no ripples. But practically there are ripples although very few because of the internal resistance of the components in the converter. Therefore, for battery charging application, it is one of the suitable converters.

5. Cost

Cost plays an important role in selecting the converter for the system. A balanced has to be made in between the quality and the amount spent on the converter. If a converter works well but is too expensive, one cannot incorporate that in on board chargers. Therefore, to minimize the cost and to provide effective solution the following converter is used.

CHAPTER 3

MATHEMATICAL ANALYSIS OF BIDIRECTIONAL BUCK-BOOST CONVERTER

3.1 Introduction

The mathematical analysis of the converter can be done by doing the state space averaging of it. State space averaging is a technique that approximates the switching converter as a continuous linear system. The effective output filter corner frequency needs to be substantially lower than the switching frequency. The analysis of the converter can be done by analyzing the configurations in which it operates.

3.2 Steady State Analysis of Bidirectional DC-DC Converter

The analysis of the bidirectional converter can be done by analyzing the different regions in which it operates. The converter is analyzed over a switching cycle, and it can be observed, there are always two subintervals, ton and toff, regardless of the operating mode, whether it be battery charging mode or discharging mode. Fig.3.1. shows bidirectional dc-dc converter.

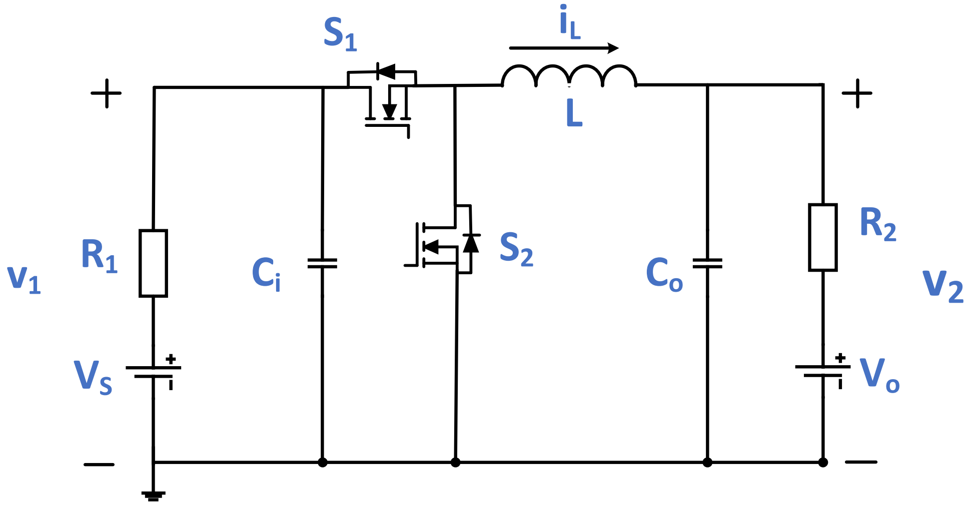


Fig.3.1 Bidirectional DC-DC Converter

The converter equivalent circuit is shown in Figure.3.2. for the first subinterval when switch S1 is on and S2 is off. Inductor current iL, low side capacitor voltage v2, and high side capacitor voltage v1 are the three energy storage elements. The capacitor current is given by (3.1) and the voltage across the inductor L is given by (3.3).

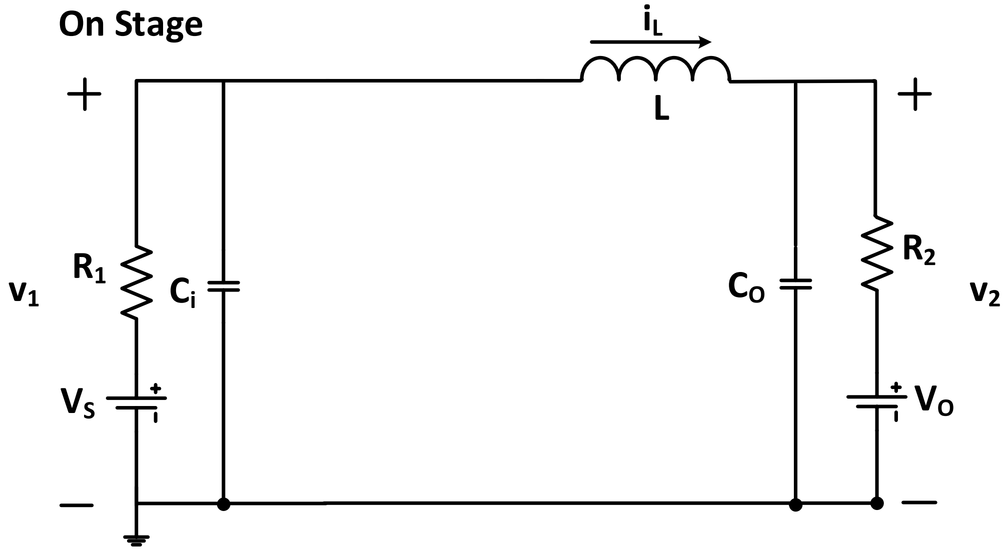


Fig3.2 Converter during interval ton when Q1 is ON

$$\frac{dv_1}{dt} = -\left(\frac{i_L}{C_i} + \frac{v_1 - V_S}{R_1 C_i}\right) \tag{3.1}$$

$$\frac{dv_2}{dt} = \frac{i_L}{C_O} - \frac{v_2 - V_O}{R_2 C_O} \tag{3.2}$$

$$\frac{di_L}{dt} = \frac{v_1}{L} - \frac{v_2}{L} \tag{3.3}$$

The converter equivalent circuit is shown in Figure.3.3. during the second subinterval when the switches S1 is off and S2 is on.

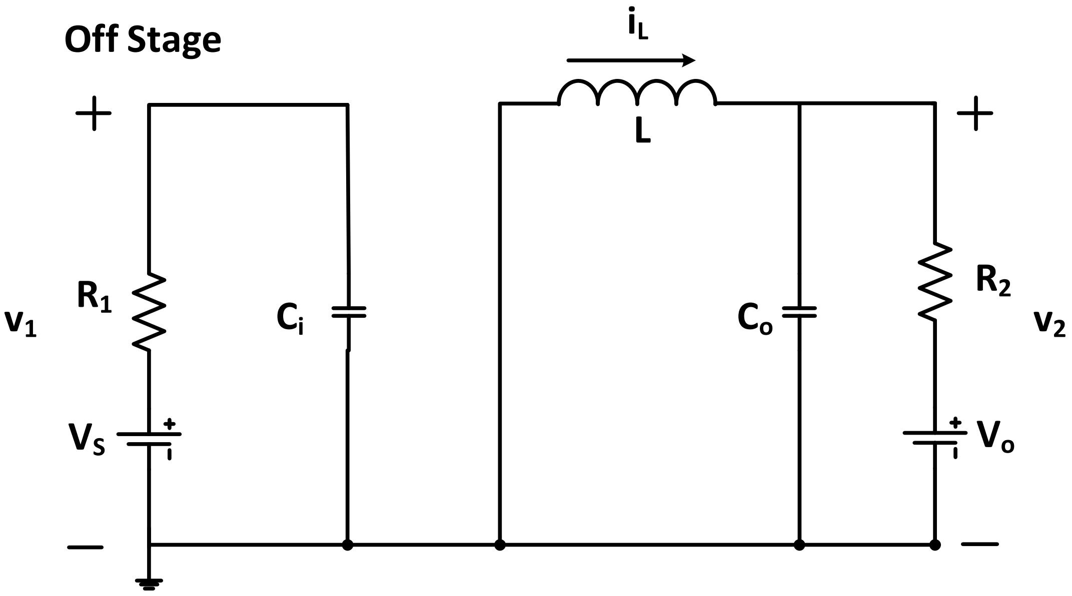


Fig3.3 Converter during interval toff when Q1 is OFF.

$$\frac{dv_1}{dt} = -\frac{v_1 - V_S}{R_1 C_i} \tag{3.4}$$

$$\frac{dv_2}{dt} = \frac{i_L}{C_O} - \frac{v_2 - V_O}{R_2 C_O} \tag{3.5}$$

$$\frac{di_L}{dt} = -\frac{v_2}{L} \tag{3.6}$$

State Space equations are derived as follows:

$$\frac{d\overline{v_1}}{dt} = -D\left(\frac{\overline{i_L}}{C_i} + \frac{\overline{v_1} - V_S}{R_1 C_i}\right) - D'\,\frac{\overline{v_1} - V_S}{R_1 C_i} \tag{3.7}$$

$$\frac{d\overline{v_2}}{dt} = \frac{\overline{i_L}}{C_O} - \frac{\overline{v_2} - V_O}{R_2 C_O} \tag{3.8}$$

$$L\frac{d\overline{i_L}}{dt} = D\left(\overline{v_1} - \overline{v_2}\right) + D'\left(-\overline{v_2}\right) \tag{3.9}$$

The average state space model can be represented as:

$$0 = A.\begin{bmatrix} I_L \\ v_1 \\ v_2 \end{bmatrix} + B.\begin{bmatrix} V_O \\ V_S \end{bmatrix} \tag{3.10}$$

Where

$$A = \begin{bmatrix} 0 & \frac{D}{L} & -\frac{1}{L_1} \\ -\frac{D}{C_i} & \frac{-1}{R_1 C_i} & 0 \\ \frac{1}{C_o} & 0 & \frac{-1}{R_2 C_o} \end{bmatrix} \text{ and } B = \begin{bmatrix} 0 & 0 \\ 0 & \frac{1}{R_1 C_i} \\ \frac{1}{R_2 C_o} & 0 \end{bmatrix}$$

3.3 Parameter Design of Bidirectional Converter

The various steps involved in designing a bidirectional buck-boost converter are as follows. To ensure that each phase share equal amount of current, the nonidealities are not considered while designing the parameters of the system.

1. Selecting the rated power, input and output voltage and switching frequency.
2. Phase Shift between legs of converter can be calculated as

$$\phi = \frac{360°}{n} \tag{3.11}$$

3. Calculation of Duty and the Output Current and per phase Inductor Current. For other mode, duty would be 1-D for same voltages at both the end.

$$D = \frac{V_{out}}{V_{in}} \tag{3.12}$$

$$I_{out} = \sum_{i=1}^{n} i_{Li} \tag{3.13}$$

4. Per phase Inductance of converter is calculated as

$$L = \frac{V_{out}(1-D)}{I_{PP} \times f_{sw}} \tag{3.14}$$

5. Calculation of Output and Input Capacitance

$$C_{out} = \frac{I_{pp}}{8 \times f_{sw} \times \Delta V_{out}} \tag{3.15}$$

$$C_{in} = \frac{I_{phaseMAX} \times D \times n(1-D)}{f_{sw} \times \Delta V_{in}} \tag{3.16}$$

6. Calculating the voltage and current stress across the switch .

$$V_{sw(\max)} = V_{in} \tag{3.17}$$

$$I_{sw(\max)} = i_{L(\max)} \tag{3.18}$$

7. The ripple in output current can be calculated as:

$$\Delta I_{out} = \frac{V_{in}}{L \times f_{sw}} \left(1 - \frac{m}{nD}\right)\left(1 + m - nD\right) \tag{3.19}$$

Using the above steps one can design the bidirectional interleaved converter having n healthy legs.

CHAPTER 4

CLOSED LOOP CONTROL OF BIDIRECTIONAL INTERLEAVED BUCK-BOOST CONVERTER

4.1. Introduction to PI Control

A proportional and integral (PI) controller is used for the system that determines equal sharing of current among all the phases of converter under healthy condition. During discharging mode, a voltage mode control is being implemented with the help of a PI controller. An ideal controller must have zero settling time, steady state error, and low peak overshoot [32-33]. Fig.4.1. shows the representation of the PI controller. The control signal U can be written as follows:

$$U = K_p + K_i \int \Delta dt \tag{4.1}$$

Where

K_p = controller's proportional gain,

K_i = controller's integral gain,

$$E = RV\text{-}MV \tag{4.2}$$

E = the error or deviation of actual measured value (MV) from the reference value (RV).

The transfer function of PI controller is given by:

$$C\ (s) = K_p + \frac{K_i}{S} \tag{4.3}$$

The following advantages are served by the PI controller:

1. Proportional action boosts loop gain and reduces system sensitivity to changes in system parameters.
2. The steady-state error is eliminated or reduced by the integral action.
3. The integral time can be altered to change the "Integral" action.
4. Both the integral and proportional components of the control action are impacted by changes in the value of K_p.

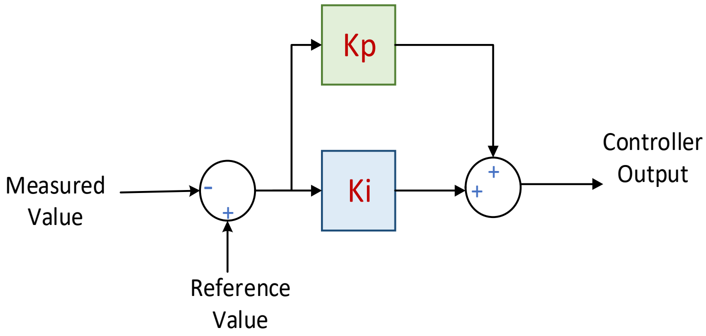


Fig.4.1 Block diagram of PI controller

4.2 Converter Operation under Healthy Condition

Under normal circumstances, it is anticipated that all of the phases have the same parameters. Ideally, all the phases should share equal amount of current but because of the non-idealities in the system, some phase may have greater current than the other branch. To guarantee equitable distribution of current throughout the phases, the primary converter is managed to operate using a closed-loop system. The closed loop system uses a PI controller for each phase followed by a pulse modulation generator to regulate the inductor currents and produce duty cycle. Each phase gets the exact same duty cycle generated by the closed loop current system but are phase-shifted with each other by 120º.

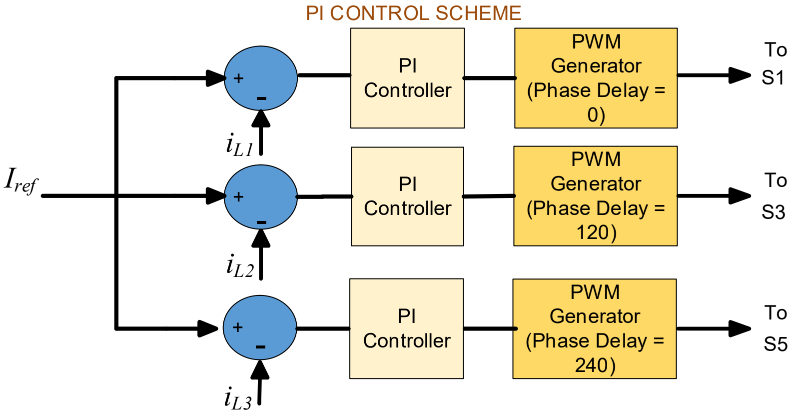


Fig.4.2 PI control scheme for three phase interleaved converter

Fig.4.2. shows the closed loop control for constant current charging of the battery. The output current of the converter is the sum of all the three phase currents. Fig.4.3. shows the inductor current for different phases and these current being phase shifted with each other. The ripple frequency in the output current is *n* times the

switching frequency of the converter. Also, because of the interleaving the size of the output capacitor and inductors along with the ripples are reduced approximately by *n* times. The effectiveness of the PI control can be seen in Fig.4.5. as the inductor current of a phase becomes stable within no time with the variation of the input voltage.

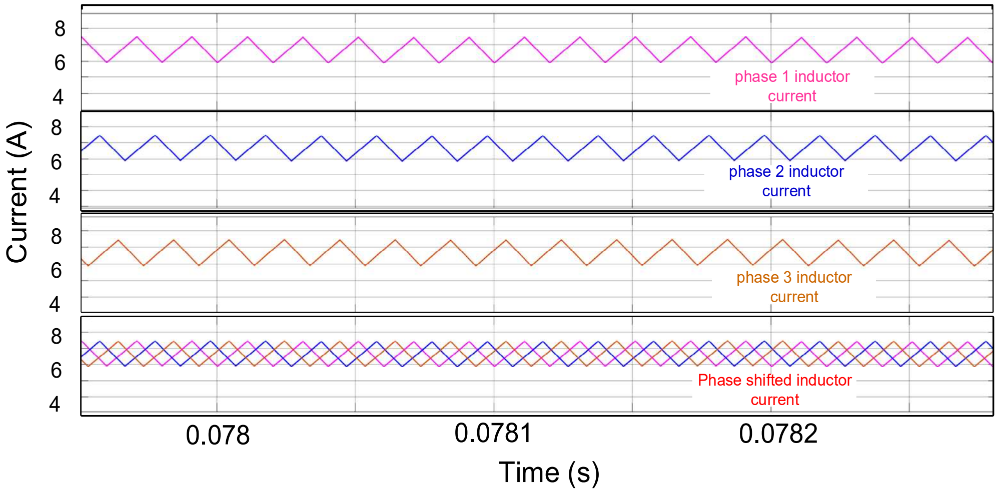


Fig.4.3 Inductor Current for different phases

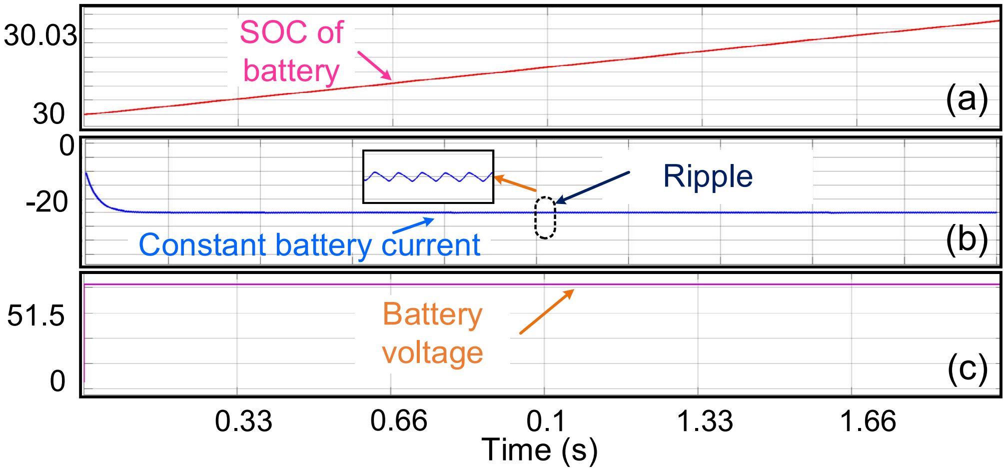


Fig 4.4 (a) SoC of battery, (b) battery current, (c) battery voltage during charging

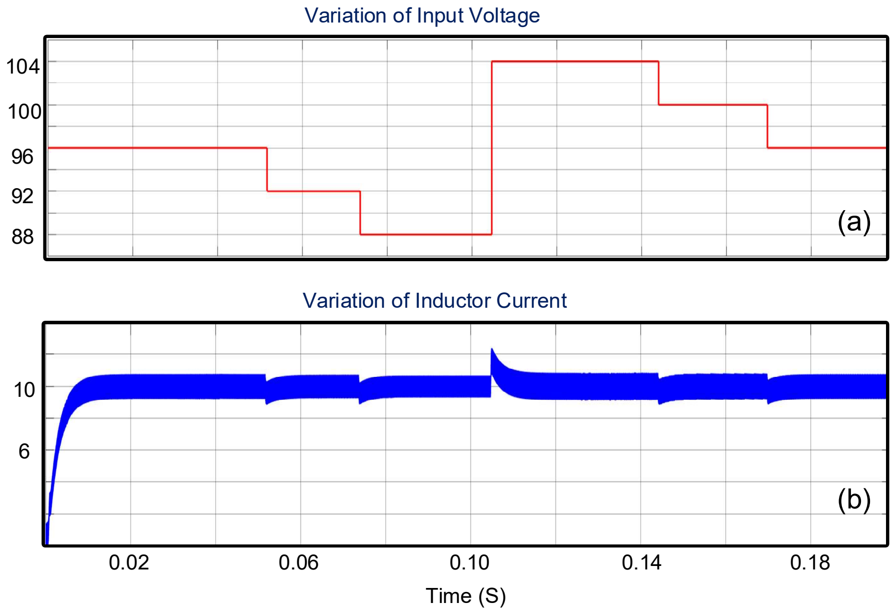


Fig.4.5 Variation in input voltage (b)Variation of phase inductor current corresponding to input voltage

During discharging mode, the battery supplies current to the load being fed at the other side of the converter. Fig.4.6. shows that SoC of battery being depleted along with its current and voltage. A closed loop voltage PI control is being applied to maintain the voltage constant. Fig.4.7. depicts inductor currents are negative specifying the reverse flow of current and are phase shifted to ensure minimum ripple in the load current.

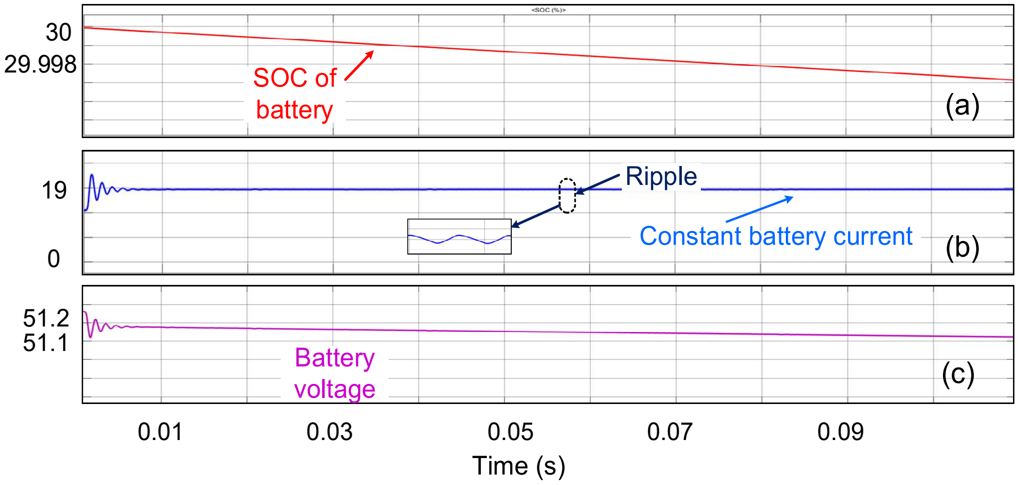


Fig.4.6 (a) SoC of battery, (b) battery current, (c) battery voltage during discharging

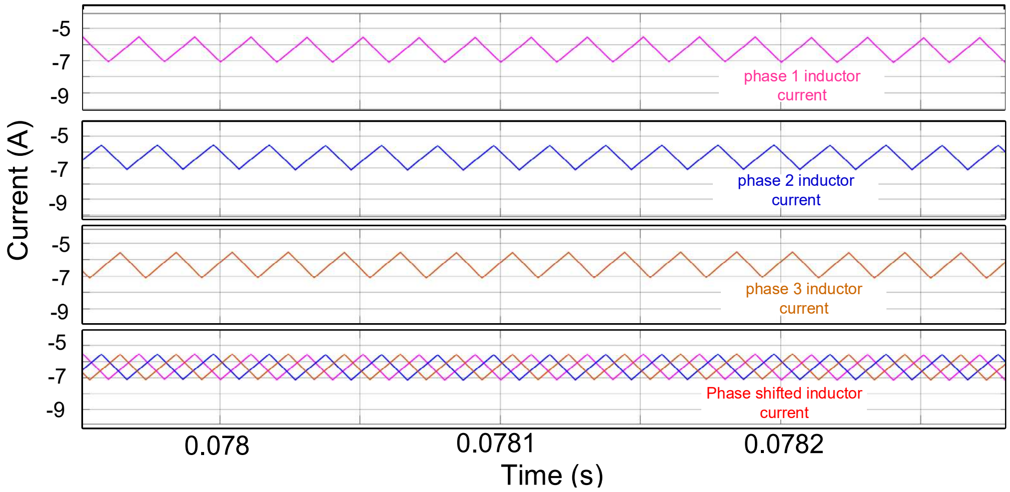


Fig.4.7 Inductor Current during discharging mode

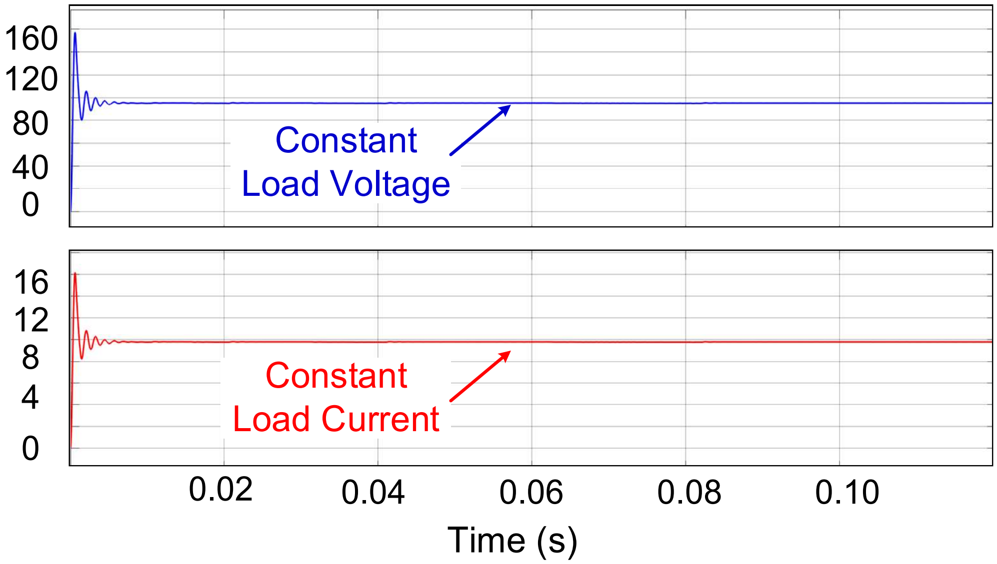


Fig.4.8 Load Voltage and Load Current under no fault

4.3 Converter Operation under Faulty Condition

No current will flow through a power switch once it experiences an open circuit fault, preventing any energy transfer across the phase connected to that switch. After a fault, the phase current will rapidly fall linearly until it is zero. The converter's input and output current ripples both grow when the frequency of the input and output current ripple falls.Fig.4.9. shows an open circuit fault in phase 1 of the converter at t=0.1sec.

Fig.4.10. shows that during charging it can be seen that the charging current reduces and the ripples in the current rises rapidly. The ripple content rises to nearly

1.5A from 0.4A after the fault. These ripples affect the battery in much worse way as they decrease its life and causes unnecessary heating leading to additional losses and more space requirement for thermal management.

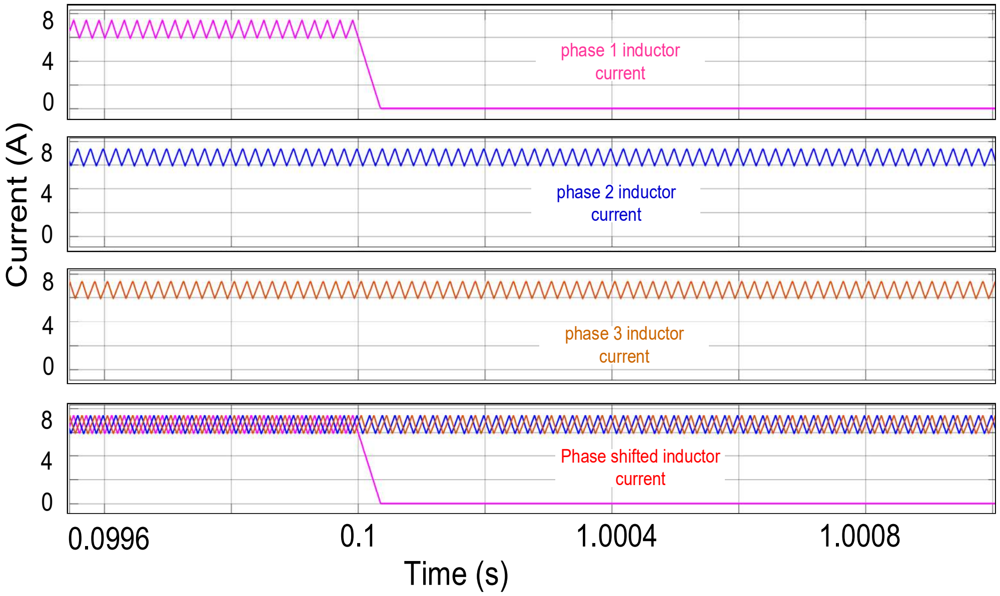


Fig.4.9 Effect of fault on different phases of converter.

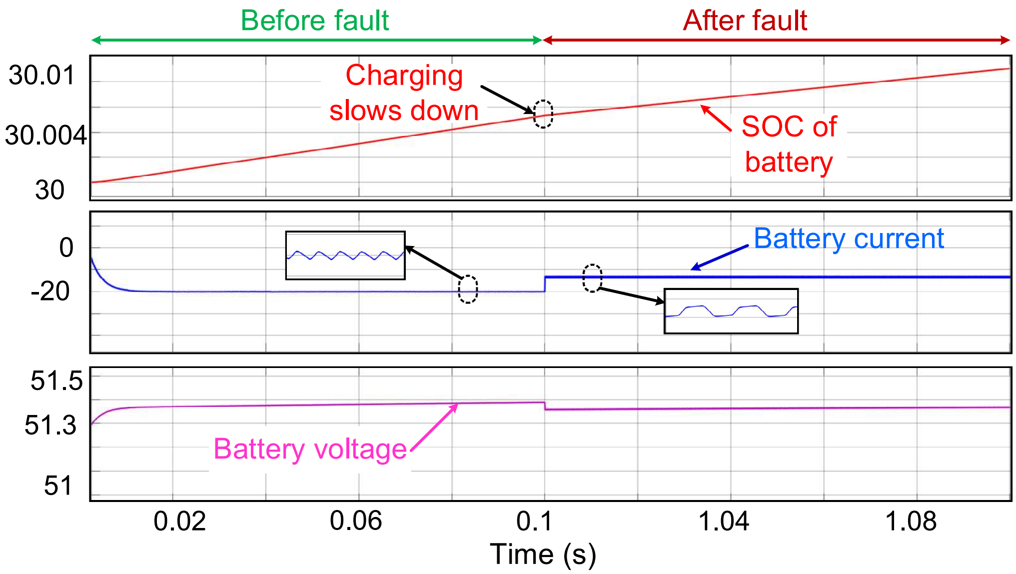


Fig.4.10 Effect of fault on battery parameters during charging

Fig.4.11. shows that during discharging mode, the current through remaining phases increases to meet the requirement of the load but the ripple content in the load current increases as one phase is shut down. The voltage control manages to stabilize

the load voltage within no time after experiencing an fault in the system. Fig.4.12. shows the load voltage and load current after experiencing an fault.

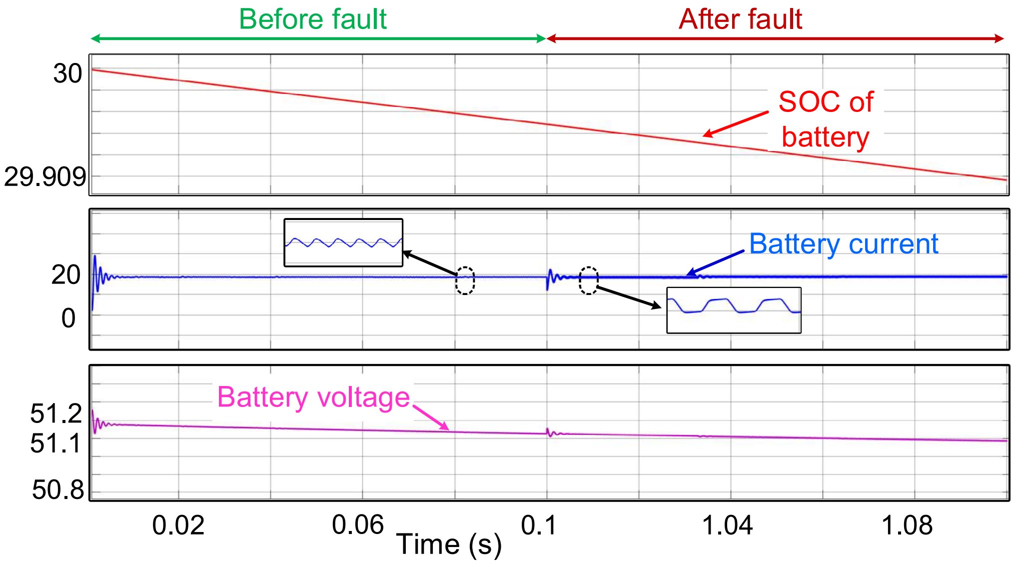


Fig.4.11 Effect of fault on battery parameters during discharging

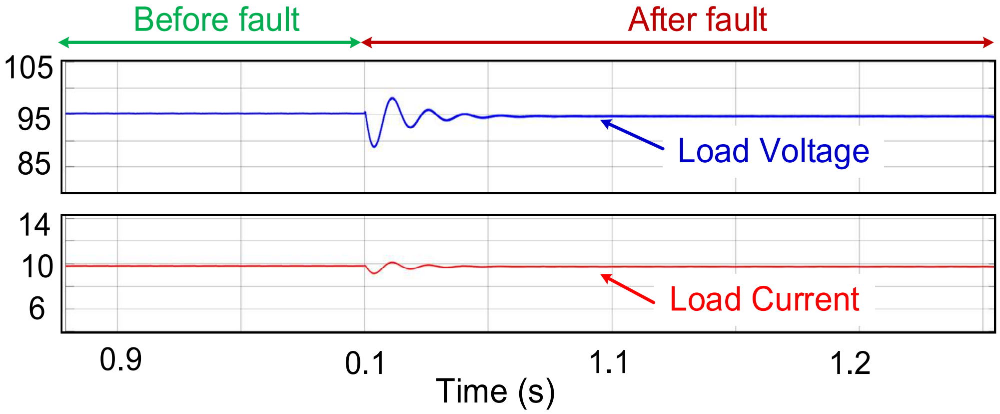


Fig.4.12 Effect of fault on load voltage and load current

With this increased ripple content and non- constant current, the converter is not suitable for constant current battery charging and for loads fed from battery. Therefore, a control structure comprising fault analysis and diagnosis must be applied to make it suitable for battery charging applications. Along with it, ripple minimization technique is discussed that can be applied to it. The next chapter discusses the scheme and configurations that can be applied to the converter.

CHAPTER 5

FAULT TOLERANT CONTROL OF BIDIRECTIONAL INTERLEAVED BUCK-BOOST CONVERTER

5.1 Introduction

DC-DC converter must work in normal condition, even after an open-circuit defect. The ability of a converter to still power the load despite having open-circuit defects in its power switches was also confirmed in literature [9], [20-22],[34-35].Interleaved converters possess the ability to work with a switch fault in any of the respective phases, but with degraded condition. The input current and output capacitor current changes are the most obvious impacts. In order not to degrade the performance of the converter the fault detection and tolerant scheme has been used based on converter configuration.

5.2 Redundant Leg based Fault Tolerant Operation

5.2.1 Configuration and Closed Loop Control

A 3-phase interleaved converter can be used as a two-phase interleaved (main) converter along with a redundant leg. The converter operates through its main branch and in case of fault the redundant leg activates. Fig.5.1. shows a redundant leg based interleaved bidirectional converter.

During charging/ buck mode, a slight modification is done in closed loop PI controller as 2:1 multiplexer (MUX) is used before that selects either the inductor current of the main branch or the auxiliary branch in case of occurrence of fault in the system. The system works parallel with the fault detection technique. Only upper switches are controlled as these are responsible for charging/buck operation. The fault detection technique determines the control signal given to the MUX. The MUX shifts to the auxiliary leg's inductor current as soon as the defect is discovered, maintaining equal current distribution among the phases while not impacting the converter's constant current output. The modified closed loop control is shown in Fig.5.2.

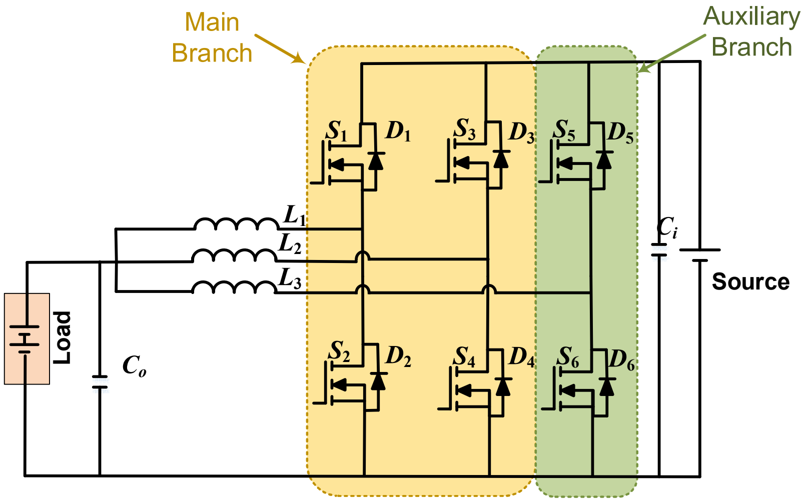


Fig.5.1 Redundant leg based interleaved bidirectional converter

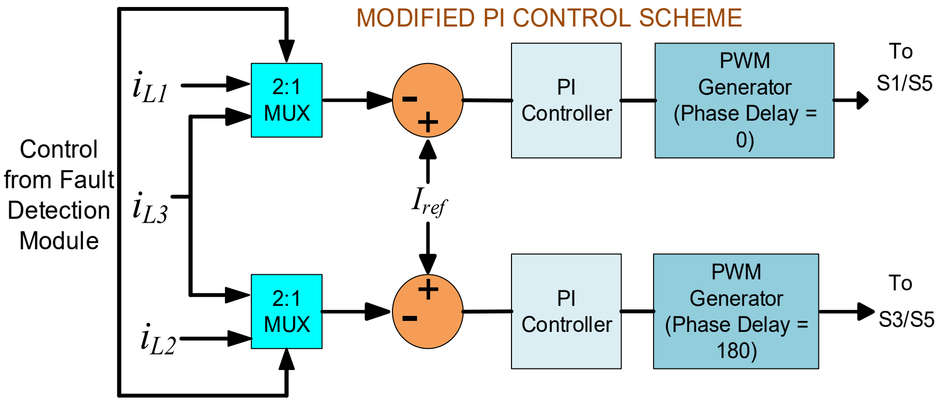


Fig.5.2 Modified PI control Scheme

5.2.2 Fault Detection and Tolerant Scheme

The first step being fault diagnosis. It can be done by finding the defect in the switch and activating the alarm signal. The second step is to isolate the defective phase and then different controlling techniques can be applied to avoid degrading the converter's power ratings.

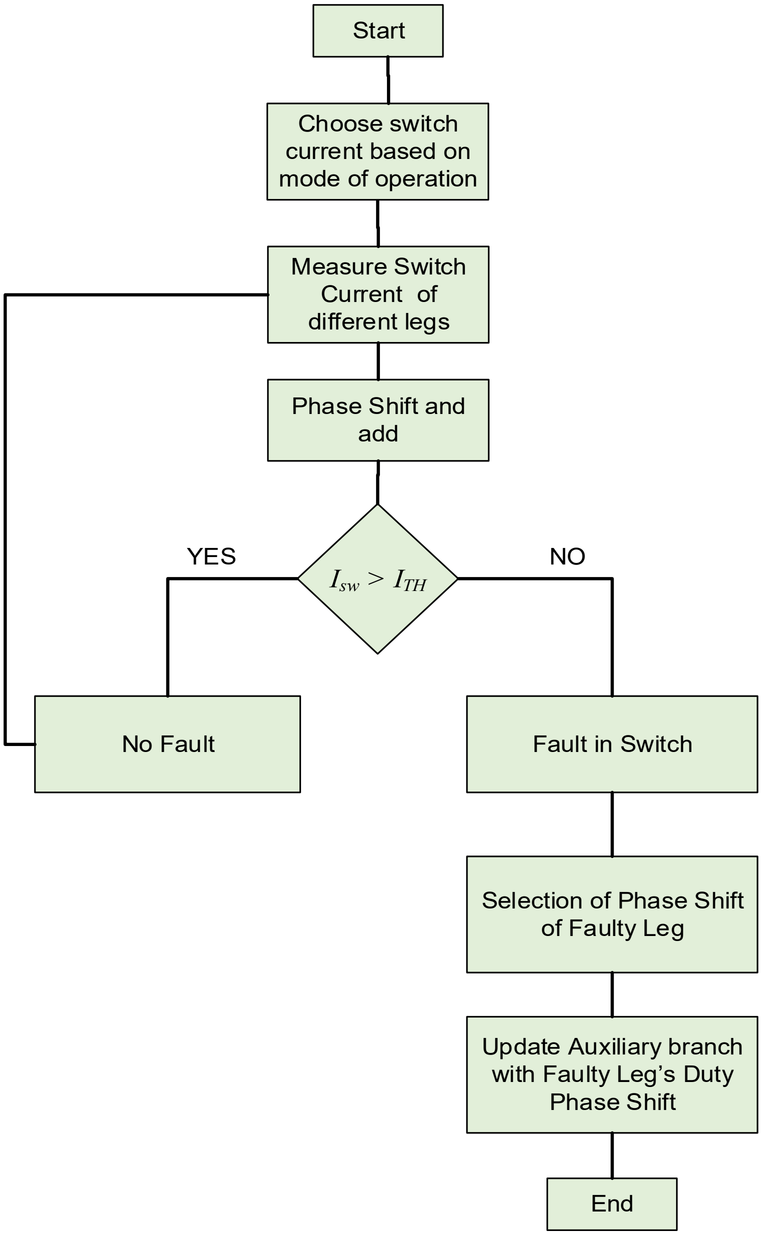


Fig.5.3 Flow chart of fault tolerant control scheme for redundant leg based converter.

Consider the scenario in which phase 1 experiences an open-circuit fault. The phase current is detected and sent through the ADC. These are then passed through a phase shifter, followed by addition and passage through a magnitude comparator. This procedure is repeated for two distinct legs. In the event of an open circuit fault (phase current less than threshold current) the magnitude of the respective leg becomes zero as soon as the fault occurs. To break the connection in the occurrence of a short circuit problem, a fuse is fitted.

The short circuit fault is treated as an open circuit fault. These signals are passed through an OR gate, which produces output 1 if any of the legs fail. In addition, these two signals control the mux between the PI controller to select the respective leg current or the auxiliary leg current. The output of the OR gate is the control signal of the final multiplexer, which transmits the faulted leg's duty cycle to the redundant leg. Fig.5.4. represents the block diagram of the scheme. Similarly, the entire procedure can be followed in case of fault in 2nd phase. The phase shift operation followed by summing of current varies with the duty cycle of the converter. For the following system parameters, D> 0.5 is considered.

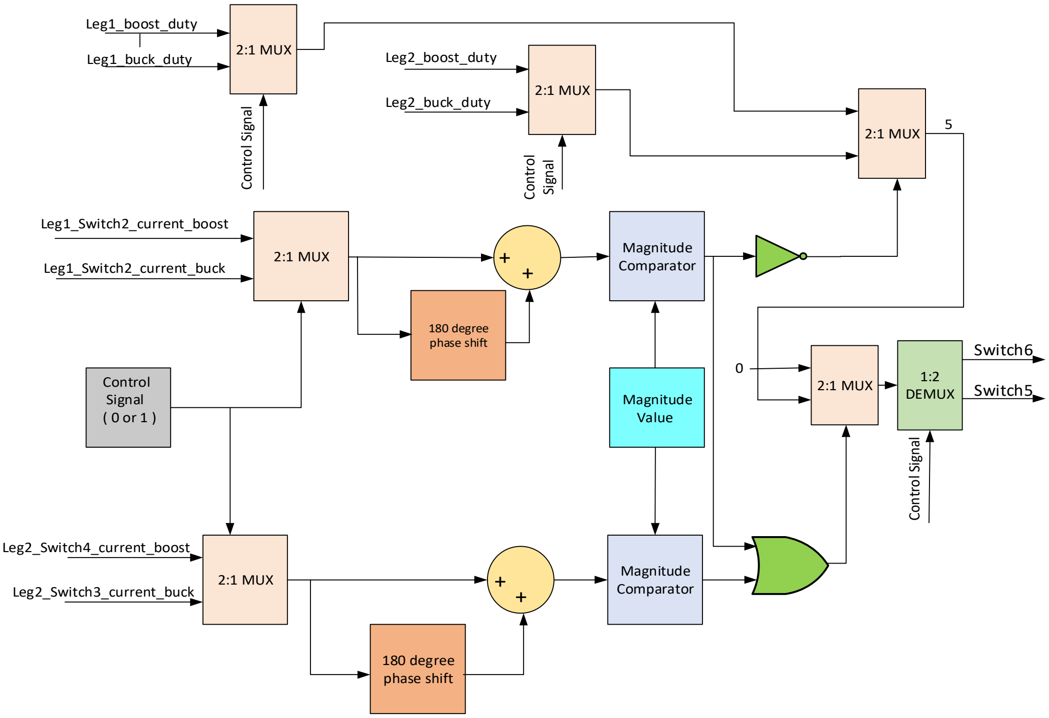


Fig.5.4 Block diagram of scheme for redundant leg interleaved bidirectional converter.

The effect on varying the threshold value of current I_{TH} can be seen on the fault detection time. The higher the value of threshold current the lower is the fault detection time however, higher values of threshold current can lead to false triggering of the detection system. Therefore, a balance should be made in between the threshold value of the current and the time for detecting the fault and taking appropriate action. In the following study, gains are adjusted such that the balance between both is maintained.

5.2.3 Simulation Results

MATLAB software is used to model the suggested fault-tolerant control method in 1kW interleaved bidirectional converter with redundant leg. The parameters used in simulating the system are enumerated in Table II. Fig.5.5 shows the inductor current for the different phases with $D > 0.5$. Also, equal current sharing between phases is achieved with the help of PI controller. Fig.5.6. shows an open-circuit fault modelled in second phase of the main branch at $t = 0.1$ sec.

TABLE II: SYSTEM PARAMETERS

PARAMETERS	**VALUE**
Power Ratings	1kW
Switching Frequency	50 kHz
Inductance Per Phase	304 µH
Output Capacitance	100 µF
Input Capacitance	80 µF
Input Voltage	88-104 V / 96 nominal
Battery Nominal Voltage	48 V
Battery Ah ratings	100Ahr
Controller's Proportional Gain (Kp)	0.05
Controller's Integral Gain (Ki)	20

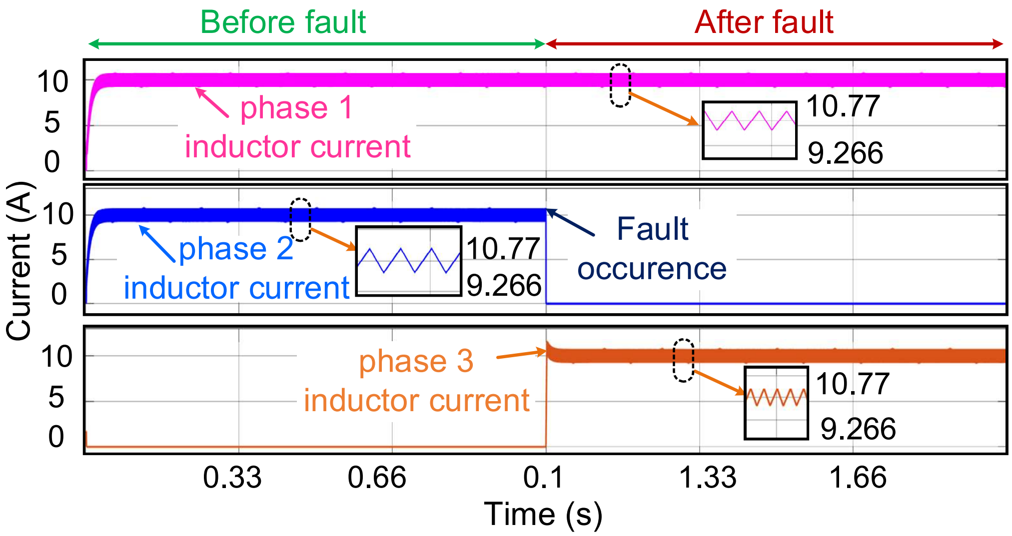


Fig.5.5 Inductor current waveforms of different phases under healthy condition and after fault

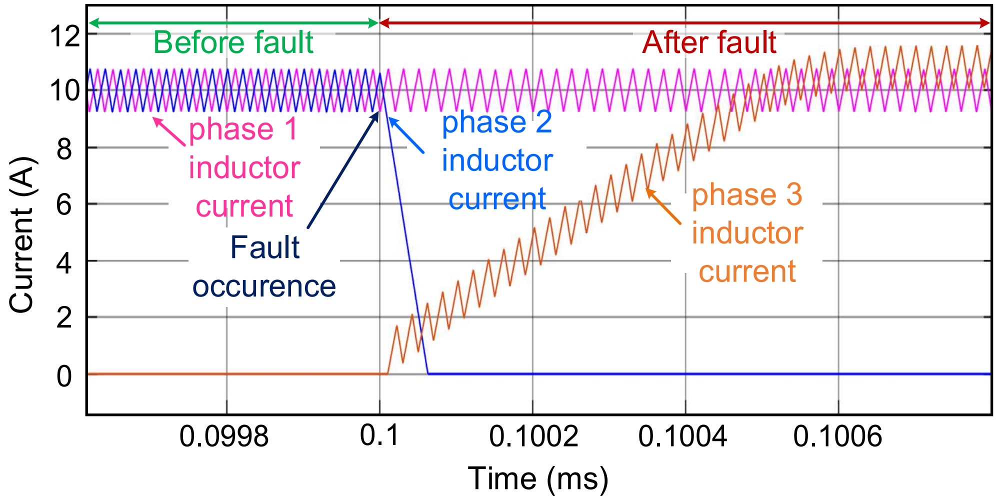
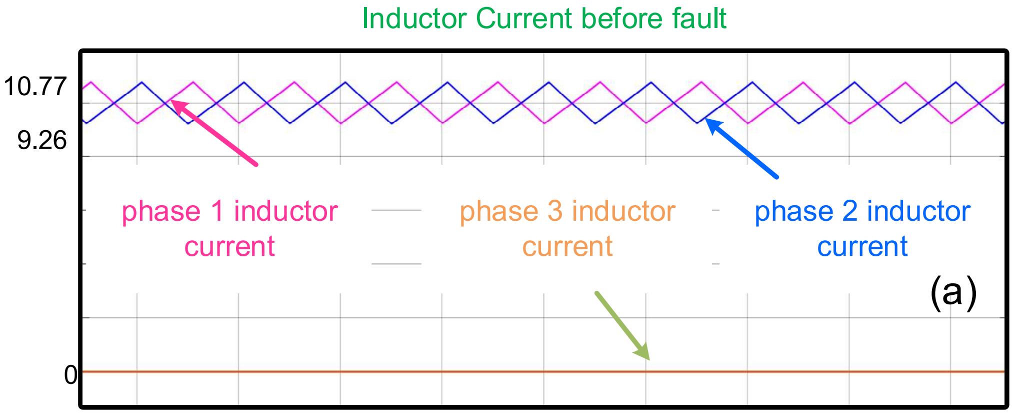


Fig.5.6 Effect of fault on different phases of BIC.



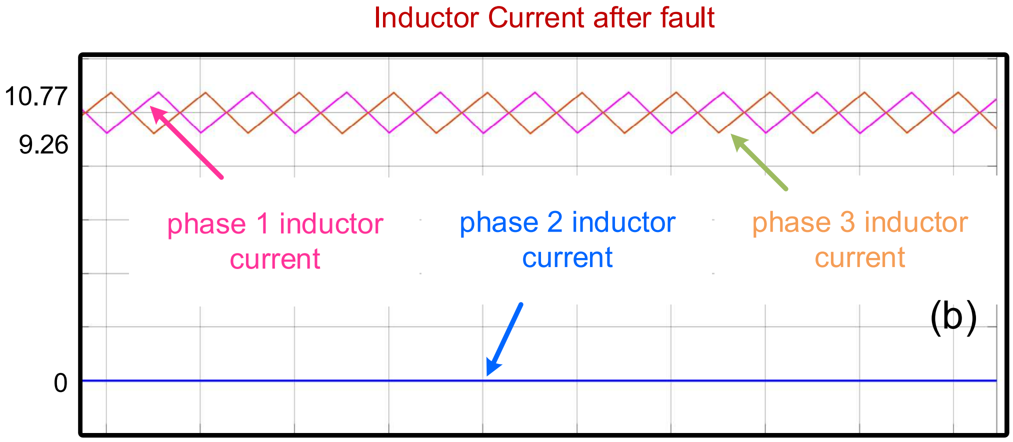


Fig.5.7 (a)inductor current before fault (b) inductor current after fault.

As soon as the fault occurs in the phase while charging, the current through it becomes zero while the redundant leg starts conducting within some microseconds. The tolerant control is activated in less than one cycle i.e., less than 20µs. Also, it does not impact the current in phase 1 of the system as the current doesn't shoot up and it is maintained constant. Fig.5.7. ensures that the inductor currents are out of phase with each other even before fault and after fault, thereby ensuring the minimum ripple in the output current along with output voltage for longer life of the battery which is attained with the help of modified PI control.

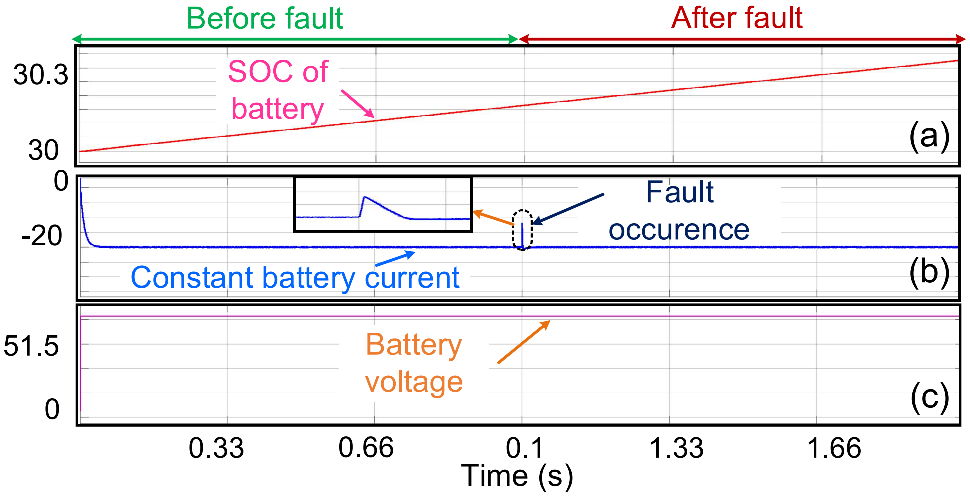


Fig.5.8 (a) SoC of battery, (b) battery current, (c) battery voltage

As the switch experiences an open circuit fault, the redundant leg module activates within one switching cycle and shares equal current among two different phases using modified PI controller. The mux help in selecting between the main branch and auxiliary branch which is controlled by the fault detection signal of the particular phase and thereby not affecting the constant current fed to battery as shown in Fig.5.8. During discharging the converter works in the same fashion and both the legs are out of phase with each other to ensure minimum ripple while feeding the load.

5.3 Three Phase Interleaved Converter Based Fault Tolerant Operation

5.3.1 Converter Configuration and Closed Loop Control

A 3-phase bidirectional converter is used along with conventional PI control for charging and discharging purposes. Unlike redundant leg-based configuration, there is no modification in the closed loop control of the system, just a gain selector is used before for selection of gain in case of fault or in healthy condition. The fault detection system controls the gain selector block. Also, a 2:1 MUX is used before phase shift selector to select the duty cycle of the respective mode i.e. charging or discharging mode to provide the respective phase shift to the legs of the converter. Fig.5.9. gives an overview of the system.

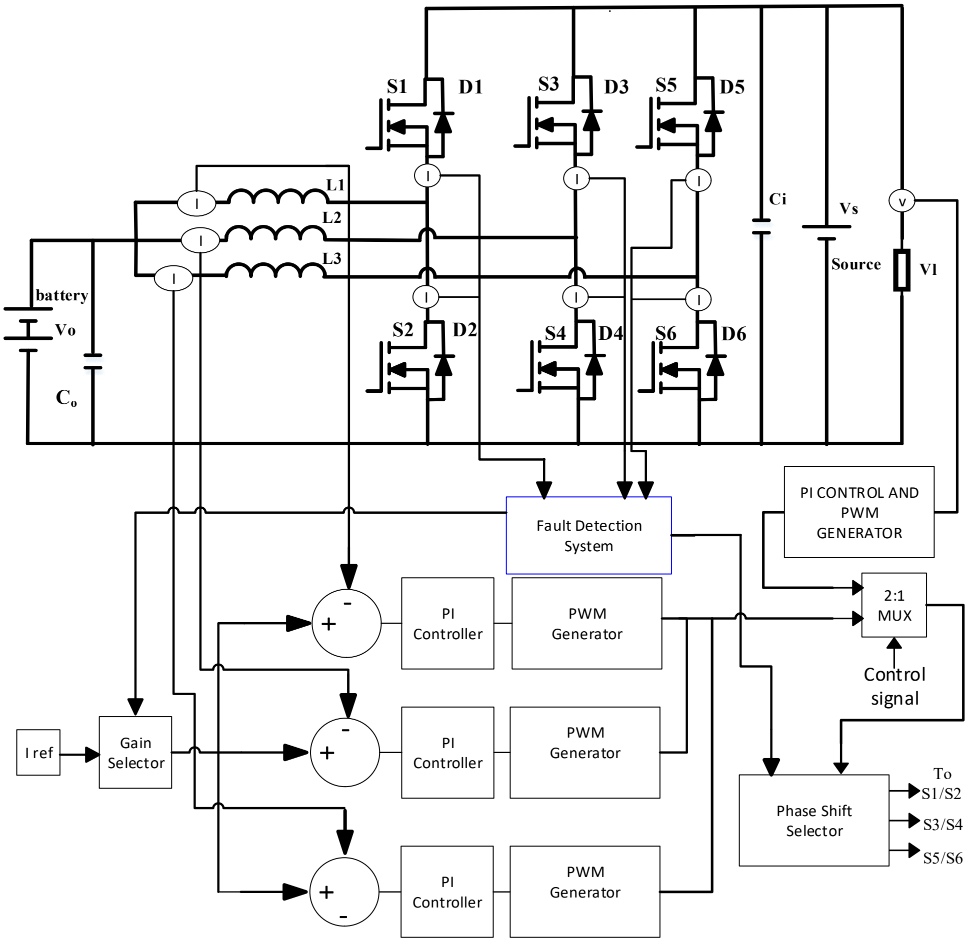


Fig.5.9 Overview of the System

5.3.2 Fault Detection and Tolerant Scheme

The proposed scheme makes use of combinational circuits such as Multiplexer, Phase shifter, Magnitude comparator to detect the fault in the respective leg of the converter. Since switch current waveform contains information that can be harnessed to detect the fault. The flowchart of the scheme is represented in Fig.5.10.

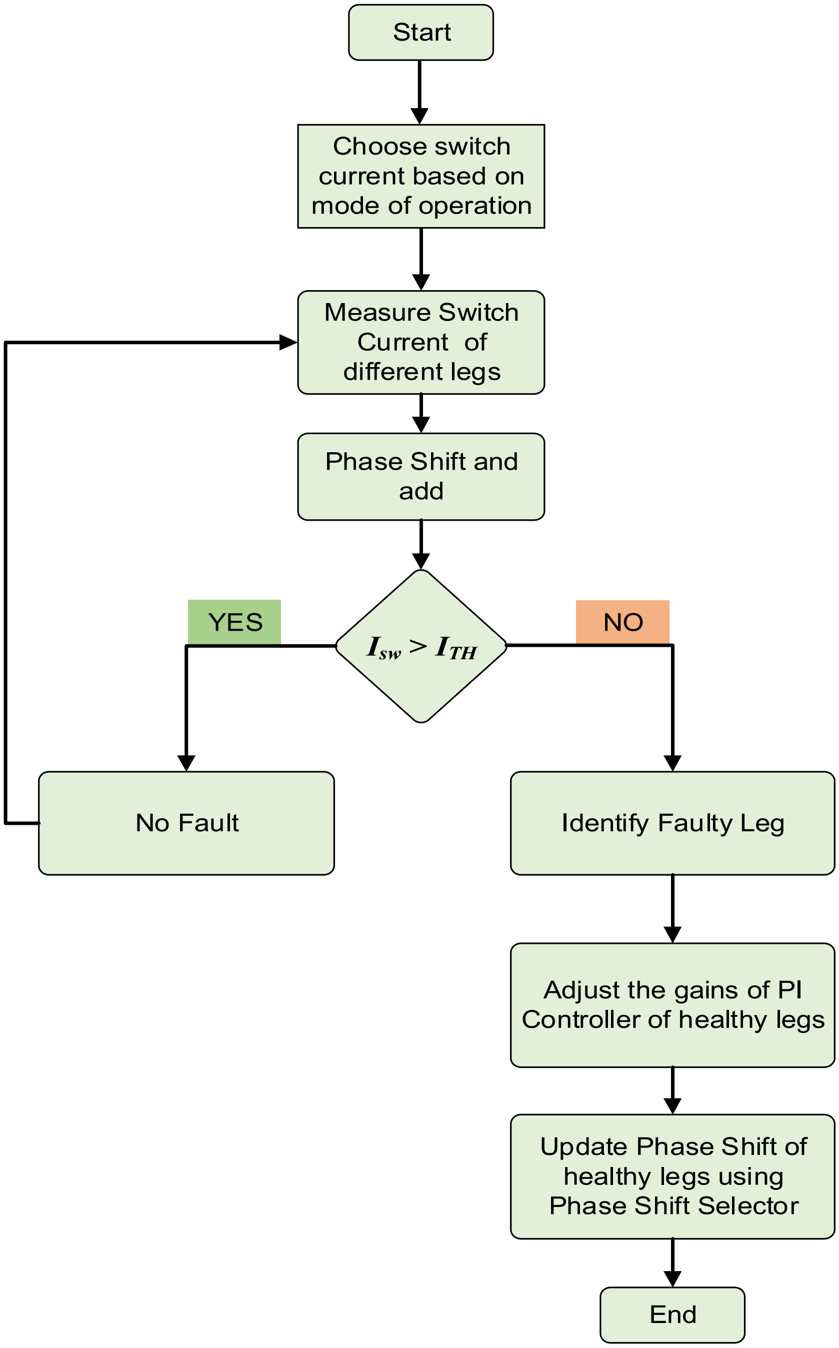


Fig.5.10 Fault tolerant Scheme for Bidirectional Interleaved Converter

Picture a situation where leg 1 develops an open circuit fault. Current Sensors are used to sense the leg’s current and then these are passed through Analog to Digital Converter (ADC). n number of current sensors are used. Each sensor contributes towards detecting a fault in the respective leg. These are then added to and transmitted via a magnitude comparator after passing through a phase shifter. The same process can be repeated for each of the legs. The magnitude of each leg immediately becomes zero in the case of an open circuit failure (phase current falls below the threshold current value). A fuse is provided to sever the connection in the event of a short circuit fault. The alarm signal for the respective leg gets high. The gains are adjusted as these are controlled using the alarm signals of the legs. The phase shifter block updates the phases for the remaining two healthy legs with 0º and 180º in order not to increase the ripple content in the output current.

TABLE III: **PHASE SHIFT UNDER FAULTY CONDITIONS**

Fault in Leg	**Phase of Leg 1**	**Phase of Leg 2**	**Phase of Leg 3**
No Fault	0º	120º	240º
Fault in Leg 1	-	180º	0º
Fault in Leg 2	180º	-	0º
Fault in Leg 3	0º	180º	-

Table III summarizes the phase shift that needs to be updated in case of fault while Fig.5.11. gives an insight how the phase shift controller is designed using the table with the help of digital circuits. The PWM generator generates respective duty cycle for each leg. The phase shifter block controls the phase shift of each leg with the help of fault detection signals. For leg 1, the fault alarm signal of leg 2 controls the 2:1 Mux, for leg 2, fault alarm signal of leg1 and leg 3 act as control signal to the mux whereas for leg 3 fault alarm signal of leg 1 and leg 2 act as controlling signal. They provide the respective phase shift in case of fault occurrence and avoid rise of ripple in the output current. Considering the remaining cases, if the second leg or third leg experiences a problem, the overall process might be used, and the results will be similar to that of one considered here. The suggested research uses a signal-based approach to locate the fault and, like any other standard SP technique, is susceptible to erroneous system triggering in highly dynamic environments. Therefore, a trade-off is to be made between the fault detection time and the reliable operation of the algorithm.

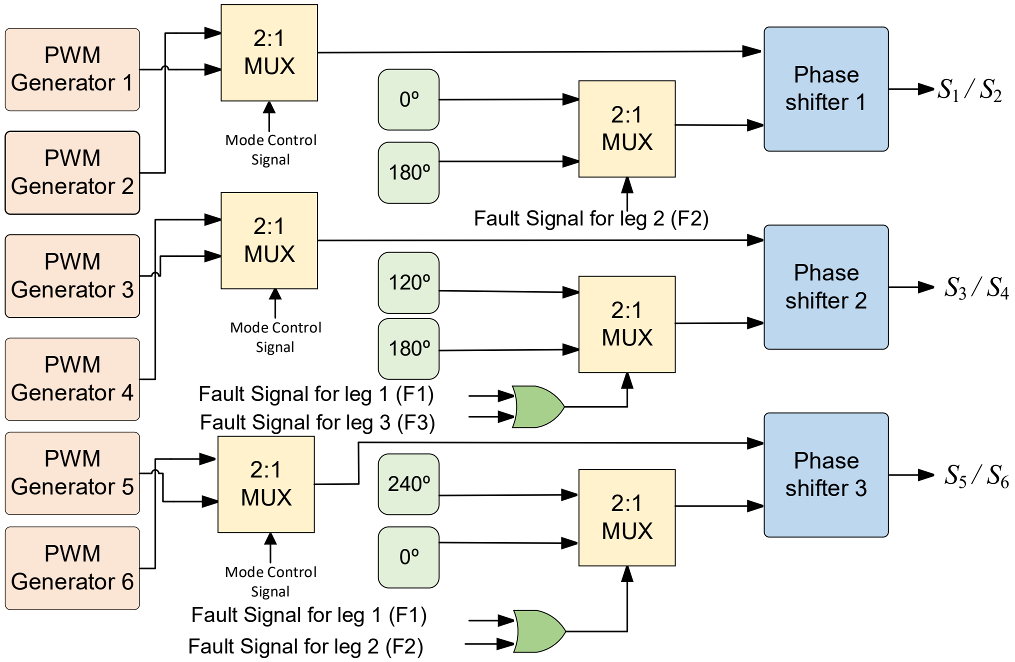


Fig.5.11 Block diagram of Phase shift Selector

5.3.3 Simulation Results

The recommended fault-tolerant control mechanism has been modelled using MATLAB/SIMULINK. Table II (listed in the previous section) were utilized to simulate the system. The inductor current waveform for each of the phases for D>0.33 (overlapping) is shown in Fig.5.12. It makes sure that the inductor currents are phase shifted by 120º before the fault and are out of phase i.e., 180º phase shifted with one another after the fault during charging and discharging mode. The current shoots up to almost 10A per phase to maintain same output current. Moreover, the PI control is used to achieve equitable current distribution across legs. Fig.5.13. manifests an open-circuit switch fault, which is modelled in the converter's first phase at time $t = 0.1$s. The gains of the PI controller are changed in less than one switching cycle, or less than 20 µs, upon the occurrence of the fault, while the current through the faulty leg becomes zero. It also shows the effectiveness of the digitally implemented PI control.

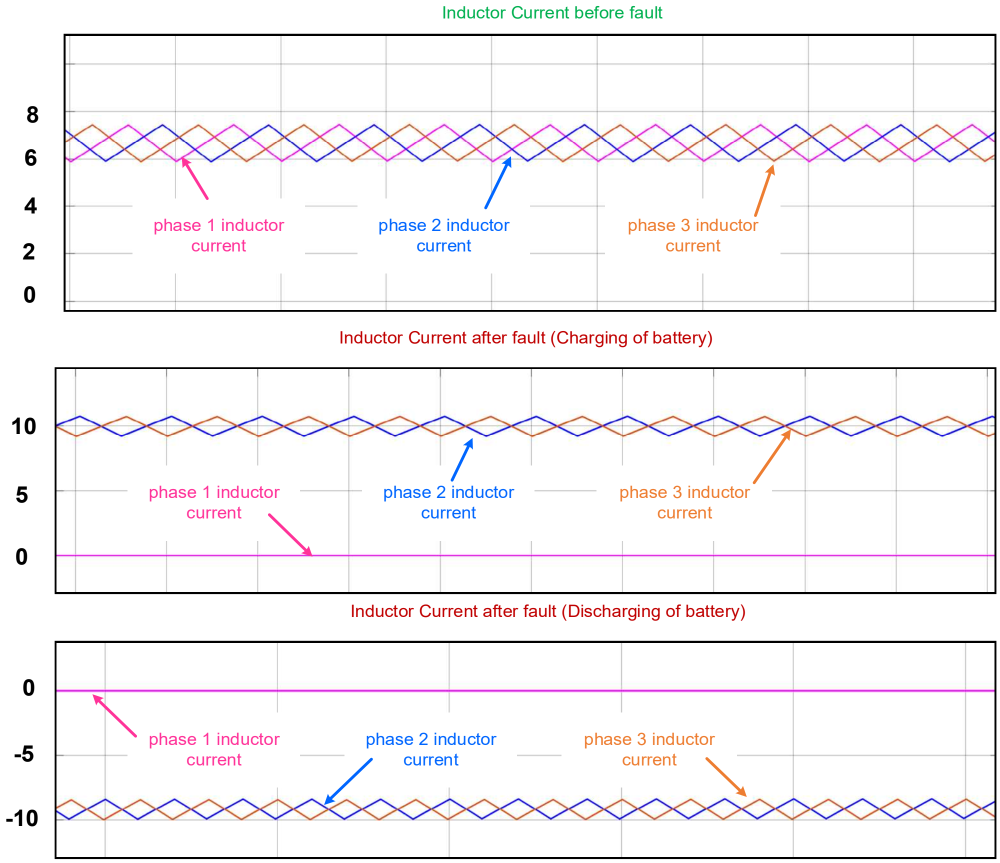


Fig.5.12 Inductor Current of different phases before and after fault during charging and discharging

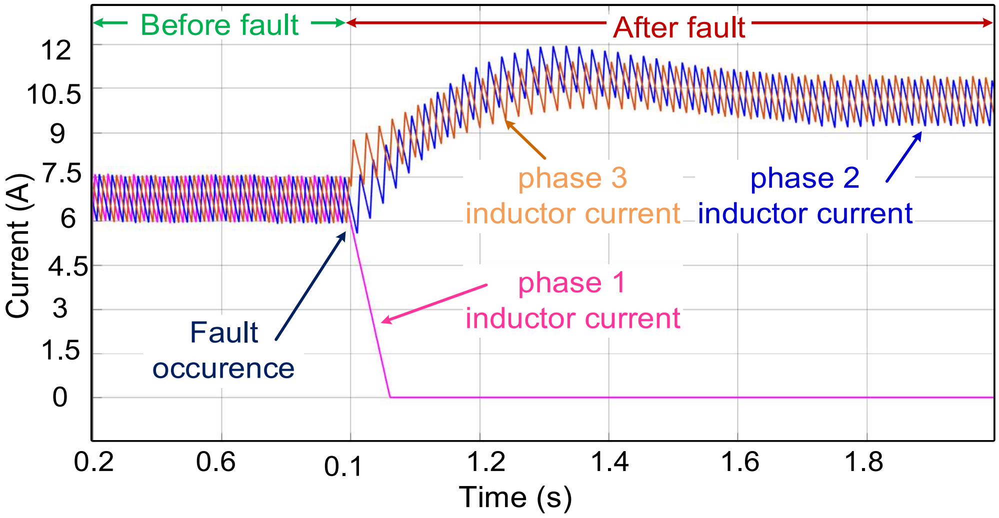


Fig.5.13 Effect of open circuit fault

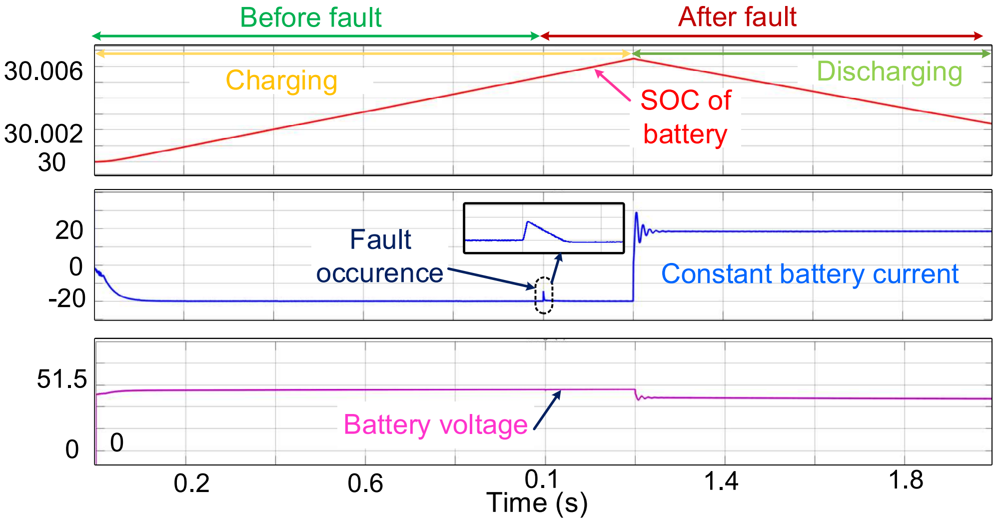


Fig.5.14 Battery parameters during mode switch and before and fault

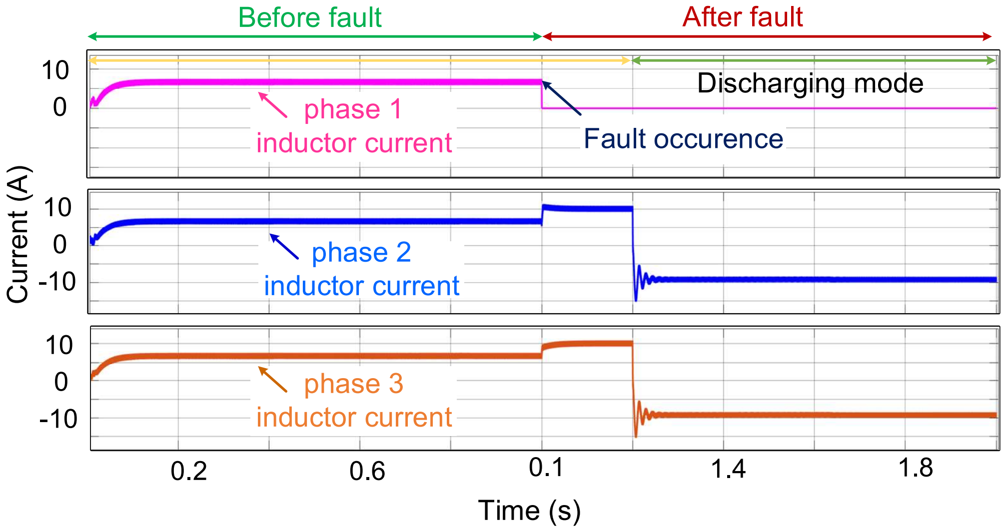


Fig5.15 Inductor current of different phase during charging and discharging mode before and after fault

Fig.5.14. depicts the battery being charged at a steady 20A current. Even after shutdown of one leg of the converter at t =0.1sec, the current is maintained constant with only a little dip in battery current for some milliseconds. Since the battery has a 40 Ah capacity, it will take roughly 2 hours to fully charge. At t=0.12 sec, the mode is switched and battery started supplying current to the load. The inductor current switches from positive to negative in case of mode switch as seen in Fig 5.15. With a small variation for some microseconds, the voltage and current stabilizes as seen in Fig.5.16.

The fault activation signal by the scheme is shown in Fig.5.17. Since being a signal processing-based scheme, it shows false triggering during startup but works fine once the system is stable. Also, it can work under dynamic conditions.

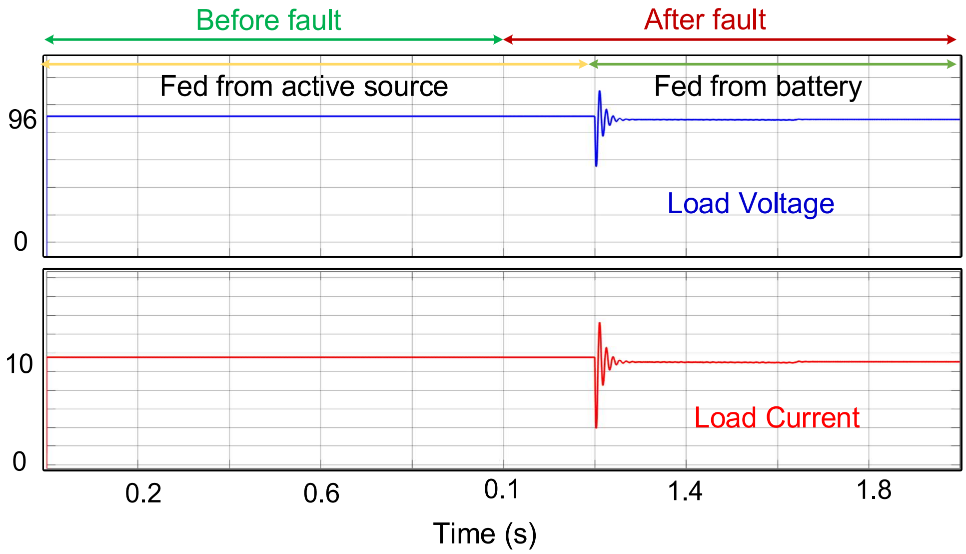


Fig.5.16 Load Voltage and Load Current during mode switch and before and after fault

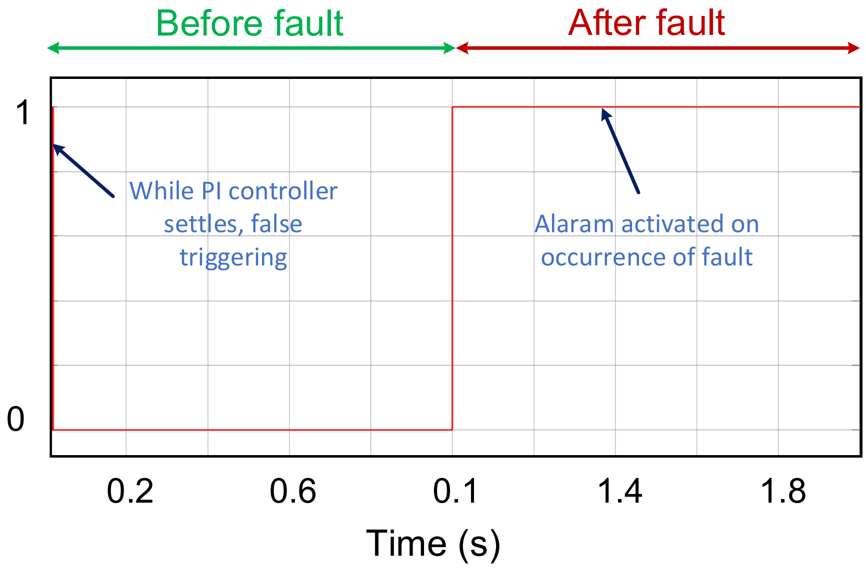


Fig.5.17 Fault Activation Signal

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

6.1. Conclusion

` DC-DC converter utilization is becoming more and more significant. DC-DC converters were mostly used in industrial settings up until recently. However, given that most of the generation will own EVs, these converters may soon be totally integrated into our home appliances. The smooth operation of these converters, as well as the battery or any other load attached to them, may be compromised by flaws, which shorten their lifespan and compromise both the converters and the load. Finding the causes of these flaws and taking corrective measures to reduce their effects are therefore of utmost importance.

In this dissertation, fault detection and fault tolerant technique was applied to open-circuit failures in the power switches of interleaved non-isolated bidirectional DC-DC converter. numerous different DC-DC converter topologies can also use the strategy to detect fault and apply tolerant control based on the hardware. Closed loop control and fault detection and tolerant control were integrated to offer constant current to the battery in case of charging mode while voltage control along with fault tolerant control in order to offer constant voltage to the load. A digitally implemented phase shift correction circuit works hand in hand to offer minimum ripple in the output current of the converter even after a fault. This study demonstrated the efficacy of fault tolerant techniques in various converter configurations. Additionally, it was demonstrated that using a phase shift correction technique in combination with other techniques improves outcomes and can be one of the solutions for compact level 1 on board chargers.

6.2. Future Scope

Since the above scheme has been implemented in software only, hardware can be built for the same. Fault tolerant converters have great potential to grow, and these are currently in the early stages of development. These converters can be used not just in EVs but also in other applications where reliability is the main concern. Increasing power ratings and efficiency along with an increase in the number of legs of the interleaved converter can be one of the areas where researchers can work.

Researchers can work towards building new fault detection and tolerant algorithms that can detect faults in less than half switching cycle leading to better dynamic behaviour of the converter and less stress over the components.

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