"Development and Implementation of Bidirectional Voltage Source Based Converter for HVDC Applications"

Major Project Report

Submitted in partial fulfillment of the requirements for the

Degree of

MASTER OF TECHNOLOGY

IN

ELECTRICAL ENGINEERING

(Electrical Power Systems)

By

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Undertaking for Originality of the Work

I, **Cheta M. Dhrangadharia**, Roll No. **12MEEE08**, give undertaking that the Major Project entitled "Development and Implementation of Bidirectional Voltage Source Based Converter for HVDC Applications" submitted by me, towards the partial fulfillment of the requirements for the degree of Master of Technology in **Electrical Engineering (Electrical Power Systems)** of Nirma University, Ahmedabad, is the original work carried out by me and I give assurance that no attempt of plagiarism has been made. I understand that in the event of any similarity found subsequently with any published work or any dissertation work elsewhere; it will result in severe disciplinary action.

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This is to certify that the Major Project Report entitled "Development and Implementation of Bidirectional Voltage Source Based Converter for HVDC Applications" submitted by **Ms. Cheta M. Dhrangadharia (12MEEE08)** towards the partial fulfillment of the requirements for the award of degree in Master of Technology (Electrical Engineering) in the field of Electrical Power Systems of Nirma University is the record of work carried out by her under our supervision and guidance. The work submitted has in our opinion reached a level required for being accepted for examination. The results embodied in this major project work to the best of our knowledge have not been submitted to any other University or Institution for award of any degree or diploma.

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Abstract

Nowadays, huge wind farms are built far out in the sea, which is beneficial from power generation point of view but not that lucrative when it comes to connection of the power source to the AC grid.

HVDC transmission based on Voltage Source Converter (VSC) technology which uses IGBTs and extruded DC cables is the most recent HVDC technology used for low power transmission which easily connects wind farms and solar farms to the grid. It operates with high frequency PWM in order to get high speed control of both active and reactive power. With PWM, it is possible to create any phase angle or amplitude (up to a certain limit) by changing the PWM pattern, which can be done almost instantaneously. Continuous and independent control of active and reactive powers is possible with VSCs used for power transmission (or voltage support combined with an energy storage source). Though LCC-HVDC can handle more power, it needs commutation voltage supplied by a synchronous compensator/STATCOM to the SCRs.

This project involves the simulation and analysis of the bidirectional operation of VSC under static as well as dynamic conditions of R and RL loading and its hardware modelling indicating the boost operation of such a converter with unity power factor at the input.

Abbreviations

HVDC .... High Voltage Direct Current
VSC .... Voltage Source Converter
CSC .... Current Source Converter
LCC .... Line Commutated Converter
PWM .... Pulse Width Modulation
SPWM .... Sinusoidal Pulse Width Modulation
IGBT .... Insulated Gate Bipolar Transistor
pf .... Power Factor

Nomenclature

P .... Real Power
Q .... Reactive Power
S .... Apparent Power
V_{dc}/V_d .... DC Link Voltage
I_{dc}/I_d .... DC Link Current
V_{conv} .... Converter AC Voltage
V_{ac}/V_S .... AC System Voltage
I_{ac} .... AC Supply Current
V_a/V_{in} .... Input Voltage of Phase-A
I_a/I_{in} .... Input Current of Phase-A
V_{ref} .... Reference Voltage
I_{ref} .... Reference Current
L .... Boost Inductance
C_{dc} .... DC Link Capacitance
τ .... Time Constant

Contents

List of Figures

List of Tables

Chapter 1

Introduction

The continuing technological developments in the area of power semiconductor devices, digital electronics, adaptive control and DC protection equipments have increased the pace of application of DC transmission. The major contribution of these developments is to reduce the cost of converter stations while improving the reliability and performance.

The first VSC based HVDC link was commissioned at Hellsjon in Sweden in 1997 with a modest rating of 3 MW. Since then, 8 projects have been commissioned, the last one in 2006 at Estlink as part of the Baltic ring in European Union that allows power exchange between the Baltic countries (Estonia, Latvia and Lithuania) and the Nordel grid. All projects so far have been executed by ABB, who call this technology HVDC Light. Siemens labels it as HVDC PLUS where PLUS stands for 'Power Link Universal Systems' and Alstom Grid markets it as HVDC MaxSine.

Since a long time, diode rectifiers or uncontrolled rectifiers were used for AC to DC conversion, but the problem with those rectifiers was that it injected significant amount of current harmonics in the supply and would result in poor power factor at the supply side, which would eventually lead to increased line losses. On the other hand, controlled rectifiers based on VSC technology offer distinct advantages like unity power factor at the input and reduced THD in input line current. Reversal of power flow is also possible with such systems.

VSC based HVDC link can be viewed as two STATCOMs, at two terminals that are interconnected by a DC link. While SVC was an offshoot of the conventional (LCC) HVDC technology using thyristor valves, VSC-HVDC is an extension of the emerging FACTS controllers based on VSC. In essence, the impact of a VSC on the AC system can be approximated to be as the sum of a conventional CSC and SVC in parallel, but with the added flexibility of secure commutation.[7]

1.1 Background of the Project

In recent times, huge wind farms are built far out in the sea, which is beneficial from power generation point of view but not that lucrative when it comes to connection of the power source to the AC grid. HVDC transmission based on Voltage Source Converter (VSC) technology which uses IGBTs and extruded DC cables is the most recent HVDC technology used for low power transmission which easily connects wind farms and solar farms to the grid.

The main requirement in a power transmission system is the precise control of active and reactive power flow to maintain the system voltage stability. The VSC operating with the specified control strategy can perform independent control of active/reactive power at both ends. This ability of VSC makes it suitable for connection to weak AC networks or even dead networks i.e. without local voltage sources. Furthermore, in case of VSC, the reactive power flow can be bidirectional depending on the AC network operating conditions.

1.2 Scope of the Project

The main scope of this project is to build a VSC-HVDC system model and study its operational performance using a simulation software. The operational performance of the complete system is to be studied with regard to the active and reactive power variation on sending and receiving ends, DC voltage control and short time overload

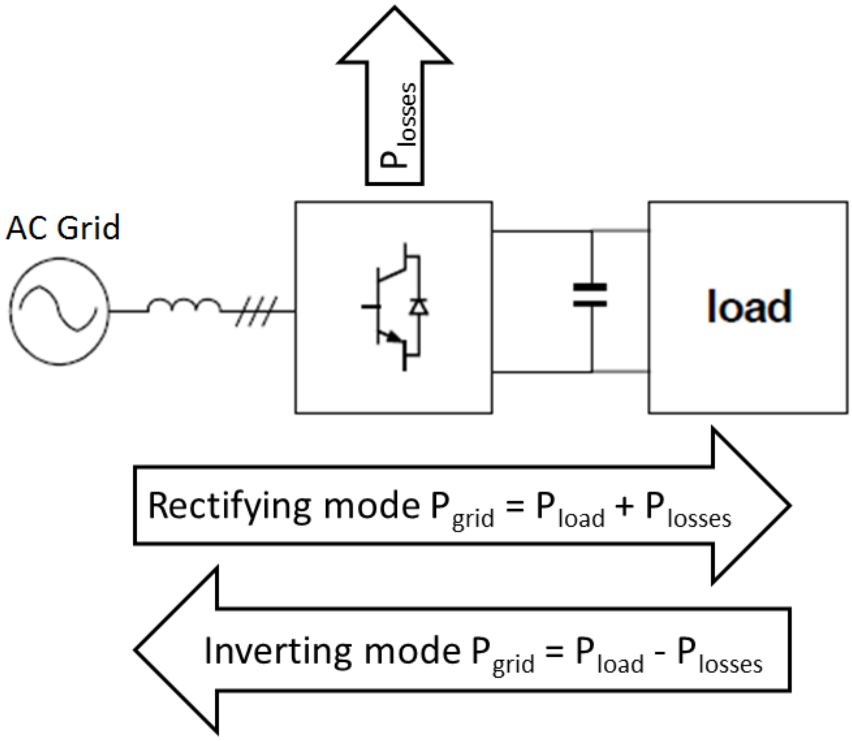


Figure 1.1: System description

capacity. Representation of the same through a prototype hardware model is also included.

1.3 Literature Survey

- **HVDC and FACTS Controllers: Applications of Static Converters in Power Systems by Vijay K. Sood:**[11]
  This book focuses on the technical advances and developments that have taken place in the past ten years or so in the fields of High Voltage DC transmission and Flexible AC transmission systems. Various control techniques related to voltage source converters along with the theoretical concepts are described in this book. The practical implementation of VSCs is also given.

- **Power Electronics: Circuits, Devices and Applications by Muhammad H. Rashid:**[8]

  This book covers the basics of emerging areas in power electronics and a broad range of topics such as power switching devices, conversion methods, analysis and techniques, and applications. Its unique approach covers the characteristics of semiconductor devices first, then discusses the applications of these devices for power conversions. It also describes various switching techniques possible.

- **A Two-Level 24-Pulse Voltage Source Converter Based HVDC System for Active and Reactive Power Control by D. Madhan Mohan, Bhim Singh and B. K. Panigrahi:**[6]

  In this paper, a two-level voltage source converter based HVDC system operating at fundamental frequency switching has been proposed for a 24-pulse converter HVDC system and it has been successfully tested for an independent control of active and reactive powers. A control algorithm has been developed for the power flow between the two stations. The converter has been successfully operated in all four quadrants of active and reactive powers with the proposed control.

- **PWM Regenerative Rectifiers: State of the Art by Jose R. Rodriguez et al:**[10]

  This paper has reviewed the most important topologies and control schemes used to obtain AC to DC conversion with bidirectional power flow and very high power factor. Topologies for single- and three-phase power supplies are considered with their corresponding control strategies. This paper shows that PWM regenerative rectifiers are a highly developed and mature technology with a wide industrial acceptance.

- **Topologies for VSC Transmission by B. R. Andersen, L. Xu, P. J. Horton and P. Cartwright:**[2]

  This paper discusses the various topologies that are possible for a VSC-HVDC system and their advantages and disadvantages. It also discusses the various applications where the topologies prove to be useful.

- **Simulation, Design and Practical Realization of Single Phase PWM Boost Rectifier by D. V. Garasiya, Santosh C. Vora and P. N. Kapil:**[4] A PWM boost rectifier system using IGBTs is reported in this paper. This rectifier provides the desirable boost in DC output voltage and still maintains a unity power factor at the input side with low % THD (< 5 %). PWM method is used for switching of the IGBTs. Firing scheme, required phase shifting circuit for boosting the output voltage and open loop control for this topology is explained. Simulation and experimental results are verified for the same.

1.4 Thesis Outline

This thesis entitled "Development and Implementation of Bidirectional Voltage Source Based Converter for HVDC Applications" is organized into the following 9 chapters.

- **Chapter 2 Voltage Source Converter:** This chapter starts off by presenting a comparison between VSC based HVDC systems and the conventional HVDC systems. Further, the operating principle of a VSC-HVDC system is explained and its primary area of applications is presented.

- **Chapter 3 Power Control in VSC System:** This chapter provides an insight into the control of active and reactive power in VSC systems and its capability curve.

- **Chapter 4 VSC-HVDC Topologies:** It gives the various topologies possible for such systems, followed by a comparison between them and the topology chosen for the project work. Towards the end of this chapter, the PWM boost rectifier topology and its operation is discussed.

- **Chapter 5 Control Techniques:** This chapter discusses the various PWM control techniques and also the control of the capacitor voltage through AC current control and AC voltage control.

- **Chapter 6 Simulation and Results:** This chapter presents various calculations needed for the simulation of the proposed system. It also provides the open loop simulation of the system and closed loop simulation under static as well as dynamic conditions of R and RL loading. At the end of the chapter, simulation of the prototype hardware system is presented at a scaled down level.

- **Chapter 7 Hardware Design:** This chapter involves the physical implementation of the simulation done to validate the project.

- **Chapter 8 Controller and Programming:** This chapter discusses the controller used and its features, along with programming for the closed loop system implementation.

- **Chapter 9 Conclusion and Future Work:** In the end, the project is concluded and any further scope for work on the project is discussed.

Chapter 2

Voltage Source Converter

Generally, an HVDC system consists of two converter stations with a DC line in between. Depending on the control, the converter stations can operate as rectifiers converting AC to DC or as inverters converting DC to AC. Most existing HVDC converters are based on components in the valve that can be switched to a conducting state, but must remain conducting until the polarity in the connected network shifts. This converter principle is called Current Source Converter (CSC) or Line Commutated Converter (LCC), which is technically more exact than the more general term "Classic". The first LCC-HVDC was established in 1954. Worldwide there have been delivered more than 100 LCC transmissions and several more are under construction.

The newer technique is based on semiconductors in the converter that are capable of not only turning on to a conducting state on a control signal, but also are able to stop conducting on the removal of the control signal. For this type of converter, the term is Voltage Source Converter (VSC). VSC transmission systems have been in operation since 1997.

VSC converter stations have fewer components than LCC converter stations. They occupy much less space and demand much less systems studies than LCC systems; VSC-HVDC has a very simple structure, since it consists of only a few main parts. Due to this simple structure, VSC-HVDC is a very flexible technology.

Almost all HVDC systems built until now are point-to-point transmissions, connecting or paralleling AC transmission systems, where the main reasons for choosing an HVDC solution has been one or more of these: long (submarine) cable, connection of asynchronous systems (including different frequency systems) or just a very long transmission distance.

There are fundamental differences in principle between VSC and LCC; thus control principles are different. The difference can be illustrated by the power flow control during reversal of the power flow. In LCC, a reversal of the active power flow is made by reversing the polarity. The reactive power must be supplied externally and is usually done in steps with switched filters and other capacitive elements. In VSC, the active power flow is changed by changing the direction of the DC current. The reactive power is controlled independently of the active power and like in AC, VSC does not need communication between stations during normal operation.[5] Each converter can operate as a rectifier or inverter at variable frequency and to absorb or deliver reactive power to the AC grid. Four quadrant operation is possible for each power converter, thus a bidirectional active power flow is possible.

The polarity reversal in LCC gives other stresses in HVDC cables. Thus oil impregnated mass cables must be used for LCC. In VSC, the high voltage stresses on the insulation systems allows the use of extruded HVDC cables.
A comparison between VSC-HVDC and Classic HVDC is presented in table I.

2.1 VSC-HVDC System

A basic VSC-HVDC system comprises of two converter stations built with VSC topologies (figure 2.1). The simplest VSC topology is the conventional two-level three-phase bridge shown in figure 2.2.[3]

Typically, many series-connected IGBTs are used for each semiconductor shown (figure 2.2) in order to deliver a higher blocking voltage capability for the converter, and therefore increase the DC bus voltage level of the HVDC system. It should be noted that an antiparallel diode is also needed in order to ensure the four-quadrant

Table I: Comparison of VSC-HVDC and Conventional HVDC

VSC-HVDC	Conventional HVDC
Power ratings: 50-1100 MW.	Power ratings: up to 6400 MW.
IGBT based converters.	Thyristor based converters.
Footprint (for 550 MW) - 120x50x11m.	Footprint (for 600 MW) - 220x120x22m.
Gate turn-off - Forced commutation up to 2 kHz.	No gate turn-off - Line commutation at 50/60 Hz.
High speed switching devices.	Most economical way to transmit power for long distances.
Ensures reactive power compensation.	Does not provide reactive power compensation.
Suitable both for land and submarine cable connections.	Long submarine cable connections.
No minimum DC power flow required.	Minimum DC power flow is 5-10 % of rated power.
Fault ride-through and black start capability.	No fault ride-through and no black start capability.

operation of the converter. The DC bus capacitor provides the required storage of the energy so that the power flow can be controlled and offers filtering for the DC harmonics. Each phase leg of the converter is connected through a reactor to the AC system. Filters are also included on the AC side to further reduce the harmonic content flowing into the AC system. The VSC-HVDC system can also be built with other VSC topologies.

2.2 VSC Operating Principle

VSCs utilize self-commutating switches (e.g. IGBTs, MOSFETs) which can be turned-on or off at will. The relative ease with which the switches can be controlled and its suitability for high frequency switching, has made these devices a better choice over thyristors. Commutation in a force-commutated VSC valve can occur

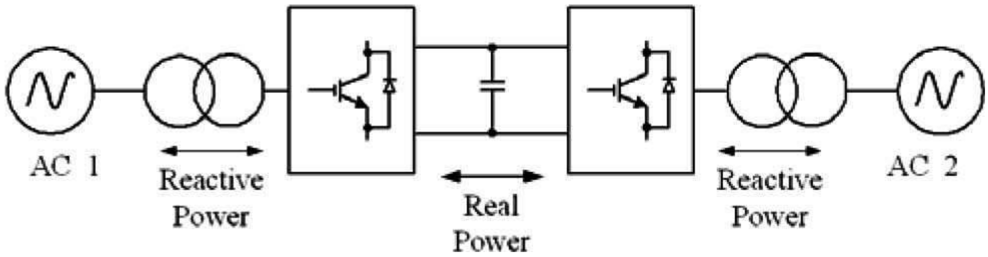


Figure 2.1: HVDC system based on VSC technology built with IGBTs

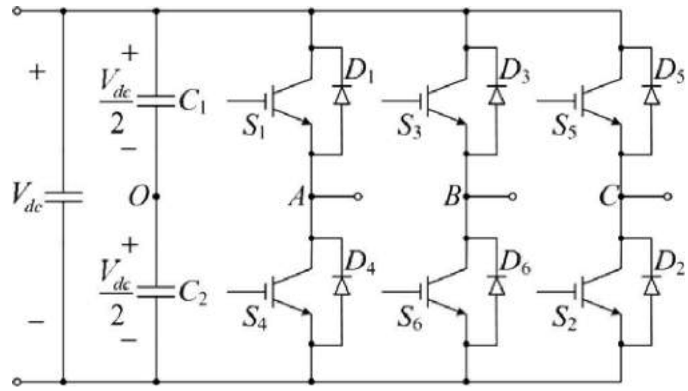


Figure 2.2: Conventional three-phase two-level VSC topology

many times per cycle which allows the voltage/current in a VSC to be modulated to produce a nearly sinusoidal output and control the power factor as well.

In figure 2.3, the operating principles of a VSC are evident. The DC voltage V_d is monitored and compared to a reference value V_{ref} to generate an error signal which controls the PWM controller. When the DC current I_d is positive, the VSC acts as a rectifier; the DC capacitor is discharged as it feeds the DC load, and the control system will modify the firing angle to import power from the AC system. When the DC current I_d is negative, the VSC acts as an inverter; the DC capacitor is charged from the DC source, and the control system will modify the firing angle to export power to the AC system.[11]

The VSC can also modulate the firing of the valves to control the reactive power so that a unity power factor (or any other value, for that matter) can be obtained.

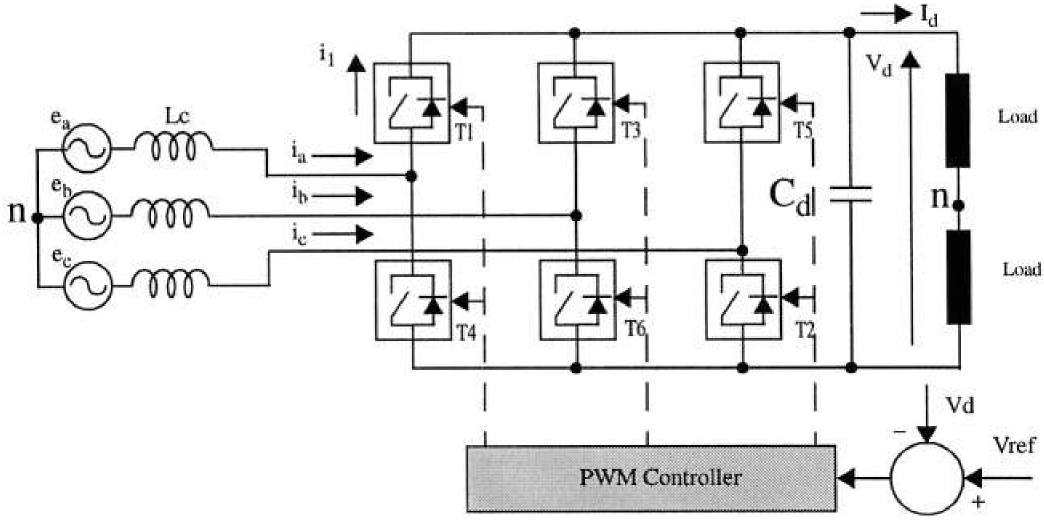


Figure 2.3: VSC operating principle

The PWM controller generates a voltage V_{gen} with the same frequency as the AC system voltage V_S. By altering the amplitude of V_{gen} and its phasor relationship with V_S, the converter can be made to operate in all four quadrants i.e. rectifier/inverter operation with lagging/leading power factor. The phasor relationships for such an operation are illustrated in figure 2.4. Under rectifier operation, the circuit works like a Boost converter, and under inverter operation it works as a Buck converter.

2.3 VSC Transmission Applications

VSC transmission can be used in all the applications for which LCC-HVDC are currently used. The reactive power control capability of a VSC transmission scheme means that it is better suited to applications with passive or very weak AC networks, than an LCC HVDC solution.[1]
The applications of VSC based HVDC transmission include:

a. Interconnection to a small isolated network.

b. Interconnection between weak power systems.

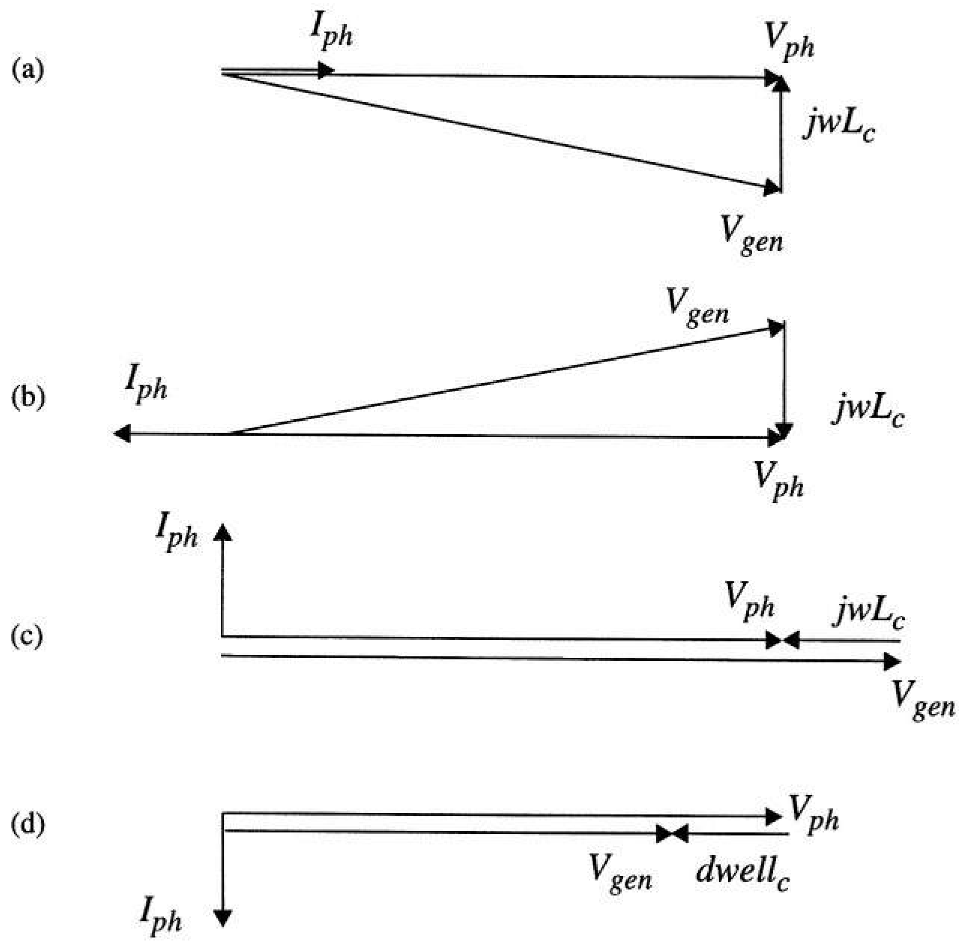


Figure 2.4: Four quadrant operation of the VSC. (a) Rectifier operation at unity power factor, (b) Inverter operation at unity power factor, (c) Purely reactive with leading current, and (d) Purely reactive with lagging current

c. Reinforcement of weak AC tie-lines for stability improvement.

d. Connection of distant loads (offshore oil and gas platforms).

e. Connection of remote wind parks.

f. Power transfer from offshore wind power plants and supply to offshore platforms (in addition to asynchronous and cable transmission).

Chapter 3

Power Control in VSC System

The VSC-HVDC system allows full independent control of both the active and the reactive power flow within the operating range of the system. The active power can be continuously controlled from full power export to full power import. Normally each station controls its reactive power flow independently of the other station. However, the flow of active power to the DC network must be balanced, which means that the active power leaving the DC network must be equal to the active power coming into the DC network, minus the losses in the VSC-HVDC system (refer figure 1.1). A difference in power would imply that the DC voltage in the system would rapidly increase or decrease, as the DC capacitors change their voltage with increased or decreased charge.

A VSC-HVDC transmission system can transmit active power in either of the two directions with the same control setup and with the same main circuit configuration. This means that an active power transfer can be quickly reversed without any change of control mode, and without any filter switching or converter blocking. The power reversal is obtained by changing the direction of the DC current and not by changing the polarity of the DC voltage as for HVDC Classic. The speed of the reversal is determined by the network. The converter could reverse to full power in milliseconds if needed. The reactive power controller operates simultaneously and independently, in order to keep the reactive power exchange unaffected during power reversal.

The voltage source converter (VSC) can be considered equivalent to a synchronous generator without inertia. The exchange of active and reactive power between a VSC and the AC grid is controlled by the phase angle and amplitude of the VSC output voltage in relation to the voltage of the AC grid. At the fundamental frequency, the active and reactive powers are defined by the following relationships, assuming that the reactor between the converter and the AC system is ideal (i.e. lossless):

$$P = \frac{V_s \sin\delta}{X_L} V_r \tag{3.1}$$

$$Q = \frac{V_s \cos\delta - V_r}{X_L} V_r \tag{3.2}$$

where δ is the phase angle between the voltage phasors V_s and V_r at the fundamental frequency.

Figure 3.1 illustrates the control of active power through the converter line inductance by the variation of the phase angle. When the phase angle of the converter AC voltage V_{conv} leads the AC system voltage V_L, the VSC injects active power in the AC system, indicating **Inverter** mode of operation. Conversely, when the converter AC voltage V_{conv} lags behind the AC system voltage V_L, the VSC absorbs active power from the AC system, indicating **Rectifier** mode of operation.[1]

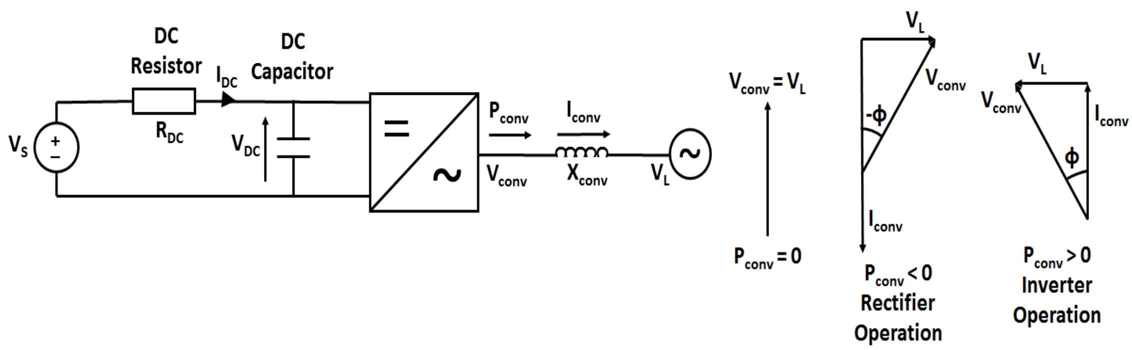


Figure 3.1: Active power control

Similarly, figure 3.2 illustrates the control of reactive power. When the amplitude of the converter AC voltage V_{conv} is larger than the AC system voltage V_L, the VSC injects reactive power in the AC system, i.e. it acts as a shunt **Capacitor**. Conversely, when the converter AC voltage V_{conv} is lower than the AC system voltage V_L, the VSC absorbs reactive power from the AC system, i.e. it acts as a shunt **Inductor**.

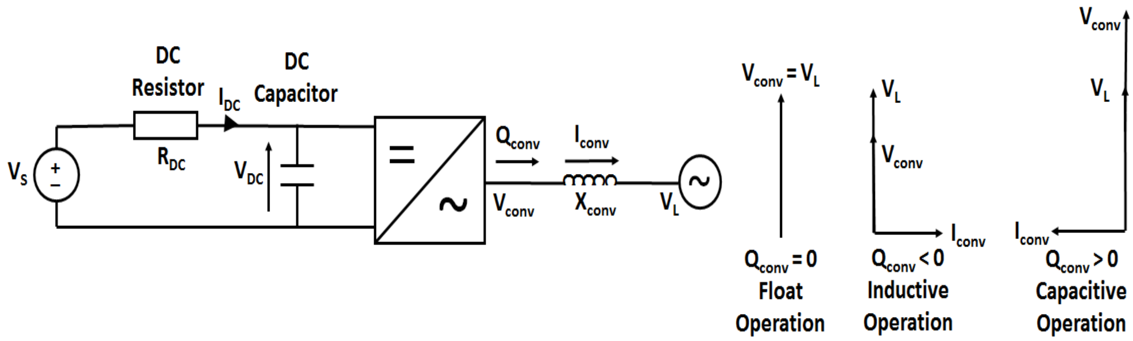


Figure 3.2: Reactive power control

3.1 Active and Reactive Power Capability

VSCs are capable of operating in all four quadrants on the active power (P) and reactive power (Q) plane as shown in figure 3.3. It allows for the fast control of active and reactive powers independent of each other. Depending upon the requirements, the VSC can be operated to supply or absorb reactive power from the grid. The figure has been drawn for 3 different AC network voltages, to illustrate the dependence of the capability on the AC voltage.[1]

The maximum current capability of the VSC valve dictates the MVA capability at a given AC voltage. Assuming that the IGBT and the diode have the same current capability, the MVA capability at a given AC voltage can be assumed to be described by a circle.

In the example shown in figure 3.3, the active power capability of the VSC transmission scheme exceeds the desired capability at all AC voltages within the range of V_{min} to V_{max}. Since the generation of reactive power requires the converter voltage

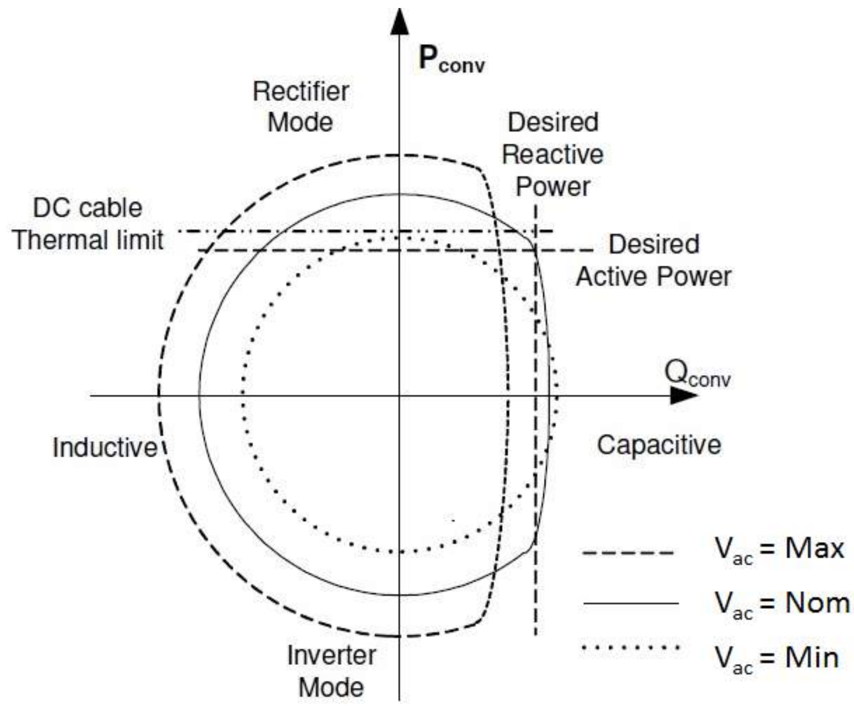


Figure 3.3: Capability curve of a VSC on active power and reactive power plane

amplitude to be higher than the AC network voltage, the capacitive power capability falls with increasing AC voltage. In figure 3.3, the capacitive power capability is lower than the desired output at the maximum AC network voltage. In practice this is likely to be acceptable, since generation of reactive power is unlikely to be required when the AC network voltage is already higher than the nominal value. When specifying the required reactive power capability, it is necessary to state explicitly the AC voltage and active power exchange at which the reactive power capability is required.

The DC cable may impose a restriction on the maximum DC current amplitude between the VSC transmission terminals. This limitation will typically be just above the desired power transfer capability, and the VSC control system will ensure that this limit is not exceeded. For clarity, the DC cable limit in figure 3.3 is shown significantly higher than the desired power transfer capability.

Figures 3.4, 3.5 and 3.6 show the flow of real power in the proposed system.

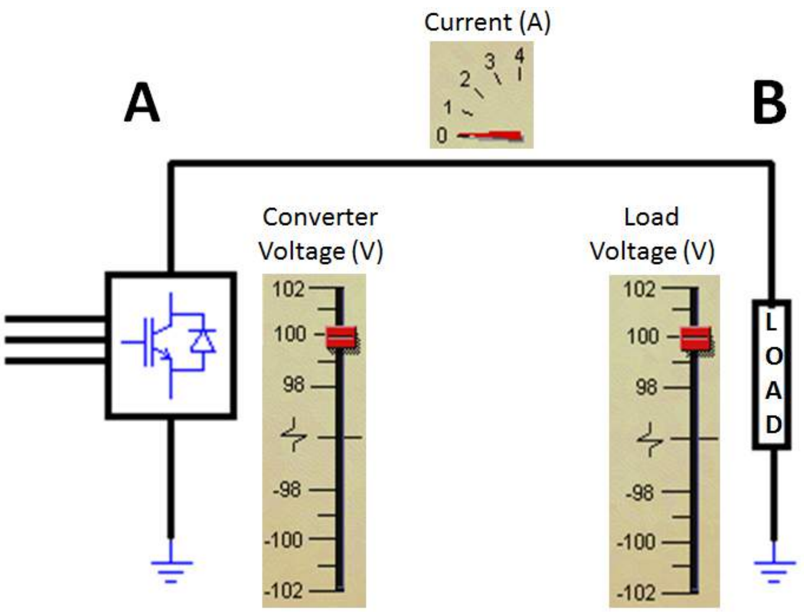


Figure 3.4: VSC-HVDC system with no power transfer

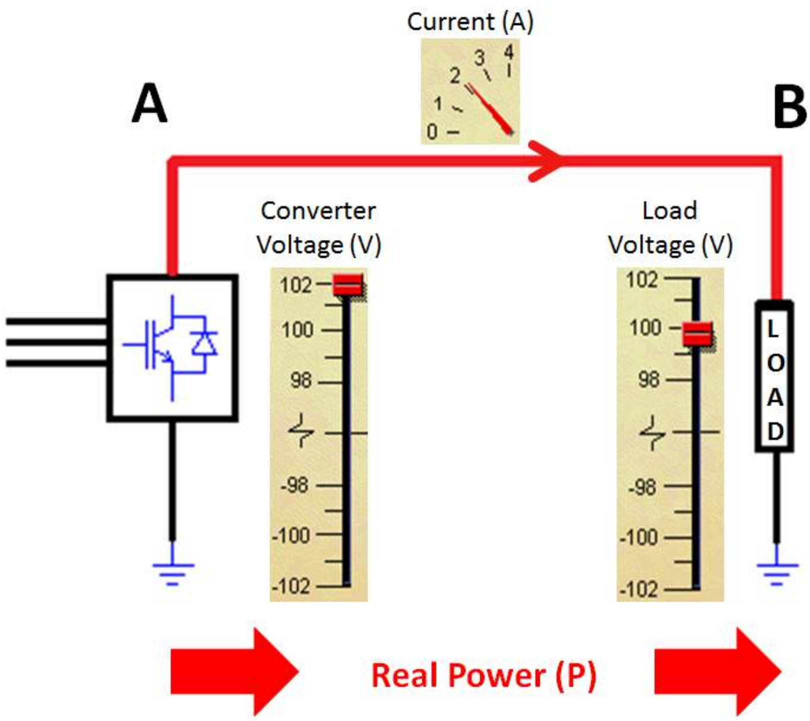


Figure 3.5: System with normal power flow

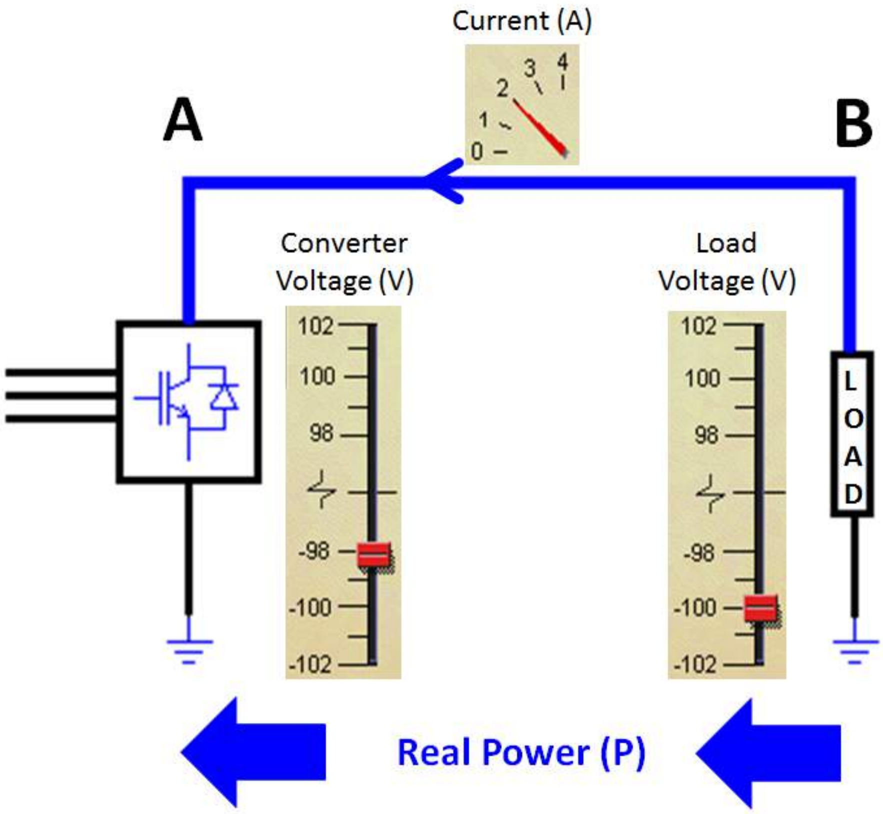


Figure 3.6: System with reverse power flow

Chapter 4

VSC-HVDC Topologies

The basic, unrefined AC output waveform of a VSC is determined by the topology of the converter. Three main categories of topology suitable for DC power transmission exist.[2] These are:

a. Two-level topology

b. Multilevel diode-clamped topology

c. Multilevel floating capacitor topology

4.1 Two-level VSC

The two-level topology has been widely used in many applications at a wide range of power levels. A number of two-level transmission VSCs have also been built with ratings up to 60 MW. The schematic of one phase of a two-level converter is given in figure 4.1. As shown, it is capable of generating the two voltage levels, $+V_{dc}$ and $-V_{dc}$. In order to improve the quality of the output, PWM can be used to produce an output waveform with a dominant fundamental component with the compromise that significant high-order harmonics are also produced.

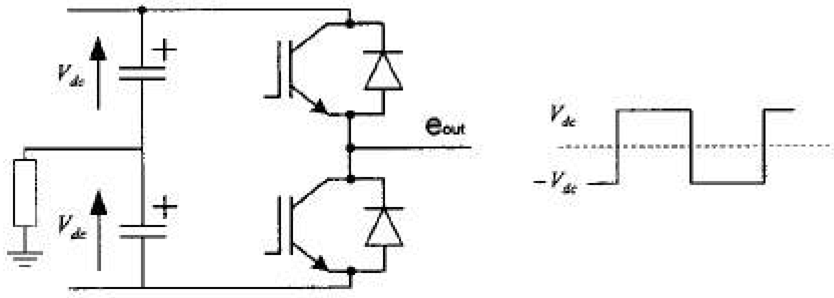


Figure 4.1: One phase of a two-level VSC[2]

The advantages of the two-level topology are:

- simple circuitry
- small DC capacitors
- semiconductor switches have the same rating

The disadvantages of the two-level topology are:

- large blocking voltage of semiconductor switches
- crude basic AC waveforms
- high converter switching loss due to high switching frequency used

4.2 Multilevel Diode-Clamped Topology

By using a number of DC capacitors in series and additional diodes, a multilevel diode-clamped converter can be formed. Figure 4.2 shows one phase of a three-level circuit and the three output voltage levels, i.e. $+V_{dc}$, 0, -V_{dc}. For a three-phase unit, the DC capacitors are usually shared by the phases. Again, PWM can be used to improve the output waveform quality.

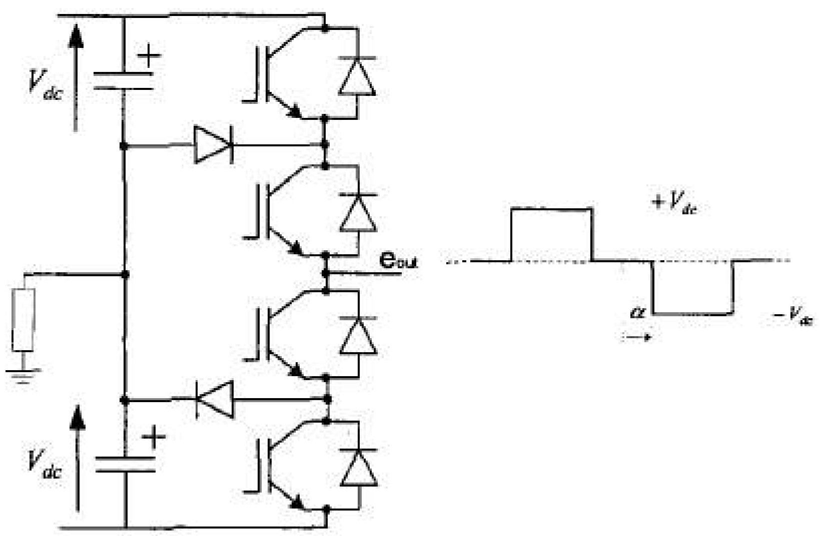


Figure 4.2: One phase of a three-level diode-clamped VSC[2]

The advantages of the diode-clamped topology are:

- reasonably small DC capacitors
- lower switch blocking voltage
- good basic AC waveforms
- relatively low converter switching loss

The disadvantages are:

- inherent difficulty in keeping DC capacitor voltages constant
- complex circuitry for large number of levels; the number of diodes added increases rapidly with the number of levels
- semiconductor switches have different duties

4.3 Multilevel Floating Capacitor Topology

The multilevel floating capacitor topology produces the same AC waveform as the multilevel diode-clamped topology. This topology has no additional diodes but has additional DC capacitors known as floating capacitors. One phase of a three-level floating-capacitor converter is shown in figure 4.3. For a three-phase unit, the main DC capacitors are shared by the three phases but the floating capacitors, marked C_f, are not.

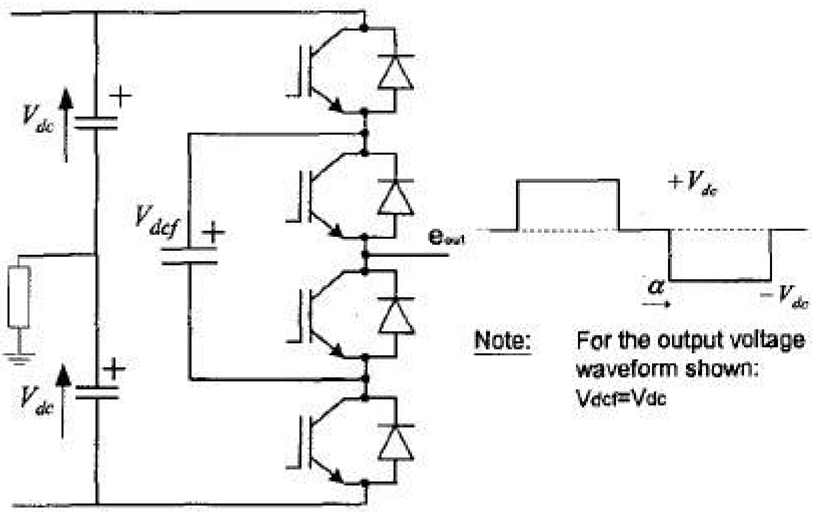


Figure 4.3: Three-level floating capacitor topology[2]

The advantages of the multilevel floating-capacitor topology are:

- semiconductor switches have the same duty
- lower switch blocking voltage
- good basic AC waveform
- low converter switching loss

4.4 Comparison of Topologies

Table II summarises the findings of the study comparing the three topologies. Only the issues concerning the deliverable VSC scheme are considered, as other technical issues are ultimately reflected in the system cost or converter loss elements.

Table II: Comparison of VSC Topologies

Comparison for VSCs Rated at 300 MW	Capital Cost	Losses	Converter Size
Two-Level	1	1	1
Three-Level Diode Clamped	1.05	0.70	1.45
Four-Level Capacitor Clamped	1.10	0.53	2.30

Every VSC transmission application will have a range of requirements that emphasise different strengths or weaknesses of each converter topology. For our application, we will be considering the two-level voltage source PWM converter which offers advantages like DC voltage control, AC current phase and shape control, as well as enables bidirectional power flow.

4.5 Basic Theory of Boost Rectifier

The three phase full bridge AC to DC converter consists of three legs with two switches and two antiparallel diodes as shown in figure 4.4. A lot of flexibility is offered via the six switches: all desirable current and voltage waveforms can be achieved by using different PWM methods. In a three-phase rectifier, the input AC voltages are defined and the output DC voltage is dependent on the input quantities as well as the switching pattern of the rectifier.

Each phase can be switched to the positive or negative terminal of the DC-bus

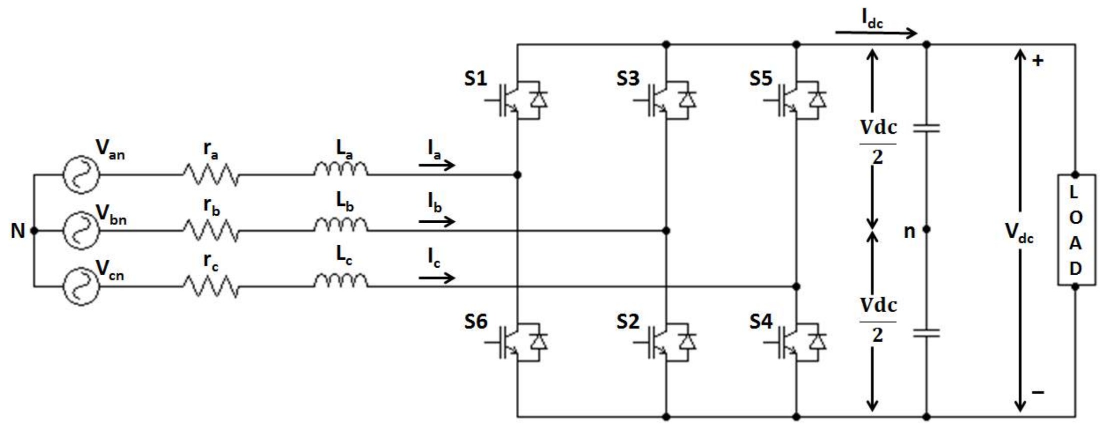


Figure 4.4: Three-phase PWM rectifier

by using the six switches. The current waveform depends on the switching pattern; a high switching frequency will result in a smooth sinusoidal current waveform, but also in higher switching losses. A low switching frequency will result in a choppy current waveform with a high harmonic distortion but also in lesser switching losses.

Another advantage of the proposed topology in figure 4.4 is the possibility to control the power factor. By changing the power factor, the amount and the direction of the power flow can be controlled.

Figure 4.5 shows the power circuit of the phase controlled single-phase PWM rectifier in bridge configuration, which uses four IGBTs with antiparallel diodes to produce a controlled DC voltage V_{dc}. Using a bipolar PWM switching strategy, this converter may have two conduction states:

- S1 and S2 in the ON state and S3 and S4 in the OFF state; or
- S3 and S4 in the ON state and S1 and S2 in the OFF state.

In this topology, the output voltage V_{dc} must be higher than the peak value of the AC source voltage V_S in order to ensure proper control of the input current.

The PWM rectifier basically operates as a boost chopper (often called a Boost Rectifier) with bipolar voltage (AC) at the input, but unipolar voltage (DC) at the

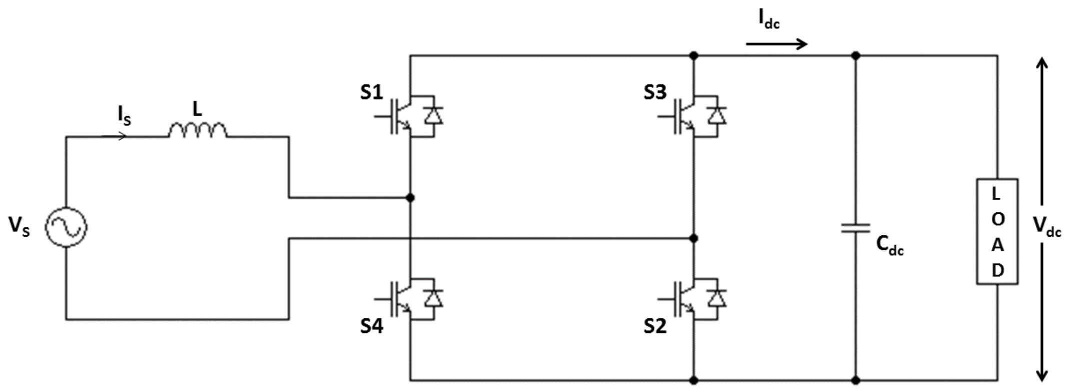


Figure 4.5: Single-phase PWM rectifier

output.

To satisfy the condition that the output voltage V_{dc} be higher than the input AC voltage peak, the line inductor (L) must be switched ON and OFF several times with appropriate duty cycle. During ON period of the duty cycle, the inductor is charged to voltage $v_L = L\frac{di_s}{dt}$ and during OFF period of the duty cycle, this voltage is added in quadrature to the supply voltage to give the converter input voltage (V_{conv}).

4.6 Switching Pattern of Single-Phase Rectifier

To perform the boost rectifier operation, there are four switching conditions that are possible. For positive half cycle, switching condition 1 and 2 occur, while for negative half cycle, switching conditions 3 and 4 occur. These conditions are explained below.

4.6.1 Switching Condition-1

S1 = ON, S2 = OFF, S3 = ON, S4 = OFF:

The red arrow line in figure 4.6 indicates the flow of current. In this condition, the inductor is charged to a voltage of $v_L = L\frac{di_s}{dt}$.

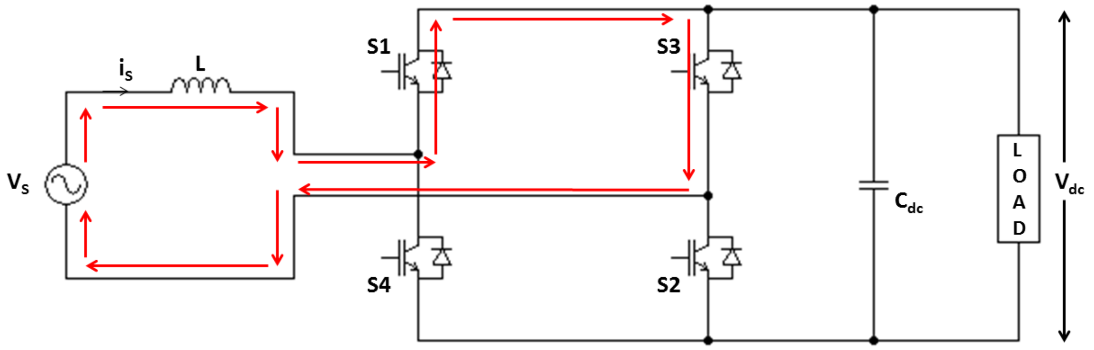


Figure 4.6: Switching condition-1

4.6.2 Switching Condition-2

S1 = ON, S2 = ON, S3 = OFF, S4 = OFF:

In this condition, the voltage at the converter is the sum of the supply voltage and voltage across the inductor.

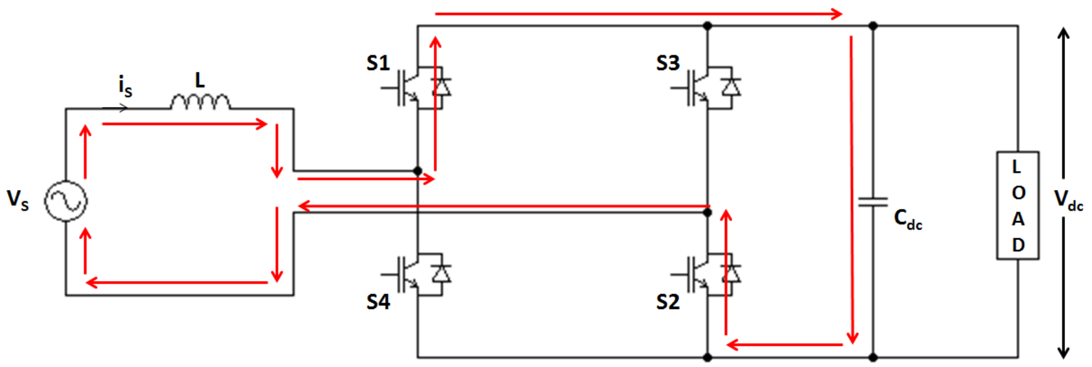


Figure 4.7: Switching condition-2

4.6.3 Switching Condition-3

S1 = OFF, S2 = ON, S3 = OFF, S4 = ON:

In this condition, the inductor is charged again to a voltage of $v_L = L\frac{di_s}{dt}$.

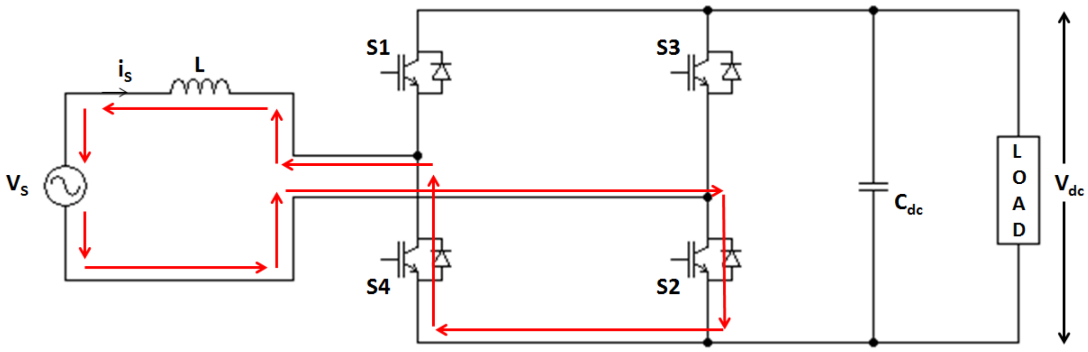


Figure 4.8: Switching condition-3

4.6.4 Switching Condition-4

S1 = OFF, S2 = OFF, S3 = ON, S4 = ON:

In this condition, the voltage at the converter is the sum of the supply voltage and voltage across the inductor.

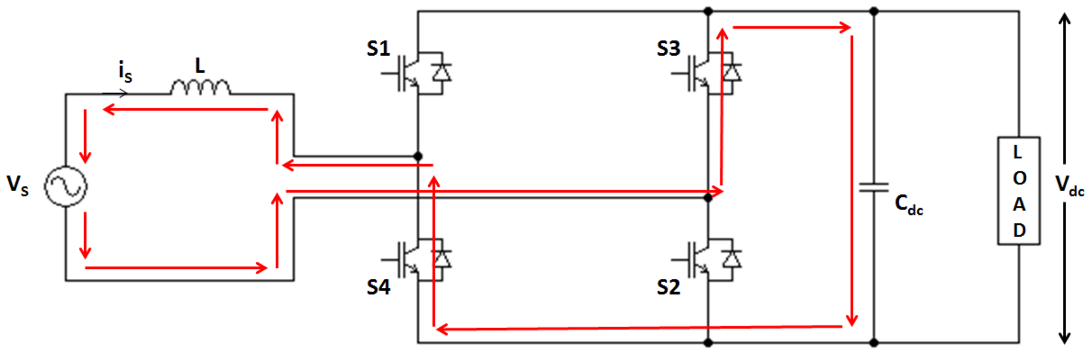


Figure 4.9: Switching condition-4

Chapter 5

Control Techniques

5.1 Pulse Width Modulation (PWM) Control

The appearance of high switching frequency transistors like IGBTs has enabled the use of advanced PWM technology, i.e., the AC voltage is obtained by very fast switching between two given voltages. By almost instantaneous change of PWM pattern, the creation of any phase angle or amplitude is enabled. Herewith, PWM gives the possibility of separate control of active and reactive power, which makes this technology very good for power transmission.

The control of the output voltage of inverters is often necessary (1) to cope with the variations in the input voltage, (2) to regulate voltage of inverters, and (3) to satisfy the constant voltage and frequency control requirements. There are various techniques to vary the inverter gain. The most efficient method of controlling the gain (and in turn, output voltage) is to incorporate PWM control within the inverters.[8] The commonly used techniques are:

- Single pulse width modulation
- Multiple pulse width modulation
- Sinusoidal pulse width modulation

- Modified sinusoidal pulse width modulation
- Phase-displacement control

5.1.1 Single Pulse Width Modulation

In single pulse width modulation control, there is only one pulse per half-cycle and the width of the pulse is varied to control the inverter output voltage. The gating signals are generated by comparing a rectangular reference signal of amplitude A_r with a triangular carrier wave of amplitude A_c. The frequency of the reference signal determines the fundamental frequency of output voltage.

5.1.2 Multiple/Uniform Pulse Width Modulation

The harmonic content can be reduced by using several pulses in each half-cycle of output voltage. The generation of gating signals for turning-on and off of transistors is done by comparing a rectangular reference signal with a triangular carrier wave. The frequency of reference signal sets the output frequency f_o, and the carrier frequency f_c determines the number of pulses per half-cycle p. The modulation index controls the output voltage.

5.1.3 Sinusoidal Pulse Width Modulation

Instead of maintaining the width of all pulses the same as in the case of multiple pulse modulation, the width of each pulse is varied in proportion to the amplitude of a sine wave. The distortion factor and the lower order harmonics are reduced significantly. The gating signals are generated by comparing a sinusoidal reference signal with a triangular carrier wave of frequency f_c. This sinusoidal pulse width modulation (SPWM) is commonly used in industrial applications. The frequency of reference signal f_r determines the inverter output frequency f_o; and its peak amplitude A_r controls the modulation index M, and then in turn, the rms output voltage V_o.

5.1.4 Modified Sinusoidal Pulse Width Modulation

The SPWM technique can be modified so that the carrier wave is applied during the first and last 60° intervals per half-cycle (e.g., 0° to 60° and 120° to 180°). Thus, the fundamental component is increased and its harmonic characteristics are improved. It reduces the number of switchings of power devices and also reduces switching losses.

5.1.5 Phase-Displacement Control

Voltage control can be obtained by using multiple inverters and summing the output voltages of individual inverters. A single-phase full-bridge inverter can be seen as the sum of two half-bridge inverters. A 180° phase displacement produces an output voltage displaced by 180°.

5.1.6 Advanced Modulation Techniques

The other techniques that offer improved performances are:

- Trapezoidal modulation
- Staircase modulation
- Stepped modulation
- Harmonic injection modulation
- Delta modulation/Hysteresis modulation
- 60° PWM
- Space vector modulation

5.2 Control of DC Capacitor Voltage

The DC capacitor voltage of the VSC can be modulated by a PWM controller as a function of either AC current or voltage. The version with AC current control is simpler and more stable than the version with AC voltage control.[11]

5.2.1 VSC with AC Current Control

The VSC with AC current control method is shown in figure 5.1. The objective here is to force the phase currents to follow a sinusoidal current reference template I_{ref}. The amplitude of the current reference template is made a function of the DC capacitor voltage V_d and the desired DC voltage V_{ref}, i.e.

$$I_{max} = K(V_{ref} - V_d) \tag{5.1}$$

where K is the gain of a PI controller, and equal to $K_p + K_i/s$.

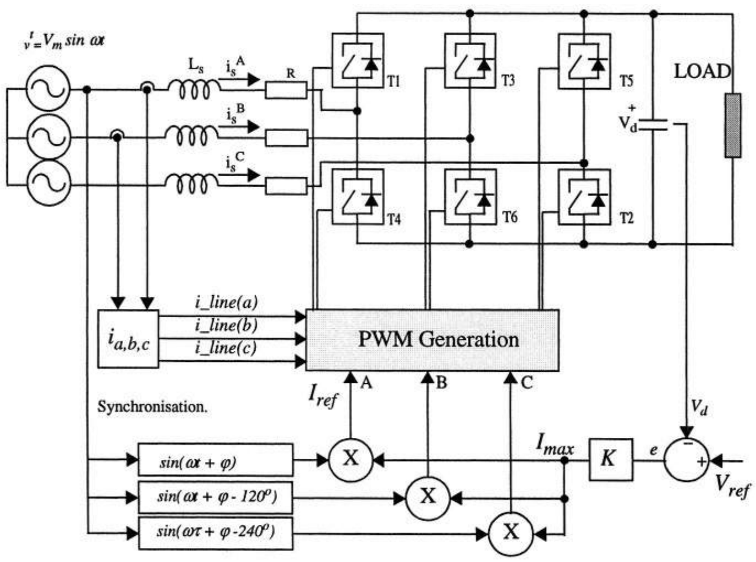


Figure 5.1: Voltage-source current-controlled rectifier[11]

The desired sinusoidal current waveform template is obtained as

$$I_{ref} = I_{max} \sin(\omega t + \phi) \tag{5.2}$$

where ω is same as the supply frequency and ϕ is the desired phase shift. Therefore, synchronization with the supply voltage(s) is necessary to obtain a correct version of $\sin(\omega t + \phi)$. A measure of the instantaneous phase currents is necessary to generate an error between them and the reference current template, and this error is minimized by means of the closed feedback loop.

5.2.2 VSC with AC Voltage Control

Figure 5.2 shows the VSC with AC voltage control. In this circuit, the generated voltage V_{gen} is able to be controlled both in amplitude and phase with the source voltage V_S. An advantage of this method is that this method does not require the input AC currents to be monitored.

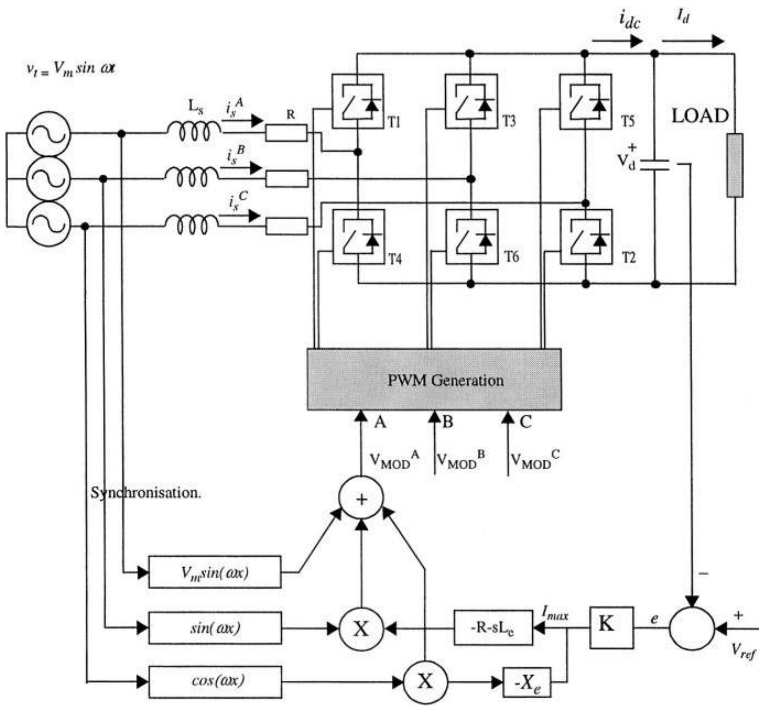


Figure 5.2: Voltage-source voltage-controlled rectifier[11]

A modulation technique to generate the firing pulses for the VSC switches is necessary. One of the most common methods is the Sinusoidal Pulse Width Modulation (SPWM) technique which uses a triangular carrier wave, as shown in figure 5.3. SPWM technique together with AC voltage control will be used for achieving the desired control for our application.

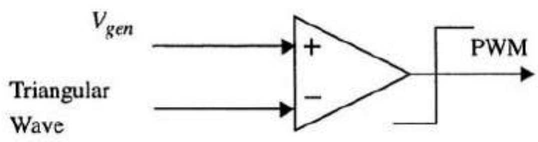


Figure 5.3: Sinusoidal PWM implementation

Chapter 6

Simulation and Results

6.1 Calculations

The system is considered to be rated at 100 MVA, 100 MW. The following are the calculations involved for various parameters of the system:

- Here, $P_o = 100$ MW.

  Let us assume an efficiency of 94 %.

  Considering unity power factor,

  $P_i = \frac{P_o}{\eta} = \frac{100}{0.94} = 106.38$ MW

- **AC Input Voltage:**

  $V_{l-l}^{rms} = 312$ kV

  Frequency, f = 50 Hz

  $V_{ph(primary)}^{peak} = \frac{\sqrt{2}}{\sqrt{3}} 312$ kV $= 254.75$ kV

- **Transformer:**

  Star-Star connected transformer with neutral grounded.

  Turns ratio = 8:1

  Voltage ratio = 312/39 kV

  $V_{ph(secondary)}^{peak} = \frac{\sqrt{2}}{\sqrt{3}} 39$ kV $= 31.8$ kV

- **AC Input Current:**

  $P_i = 3V_{ac}I_{ac} = 106.38$ MW

  or, $I_{ac} = \frac{106.38\times10^6}{3\times39\times10^3} = 0.91$ kA

- **Boost Inductance:**

  Considering 3 % of supply voltage as the drop across inductance,

  $I_{ac}X_L = 0.03 \times 39 \times 10^3 = 1170$ V

  or, $X_L = \frac{1170}{0.91\times10^3} = 1.286\ \Omega$

  or, L = $\frac{1.286}{2\times\pi\times50} = 4.1$ mH

- **Modulation Index:**

  $V_{carrier} = 4$ V (peak-to-peak)

  After voltage sensing,

  $V_{ref} = 3$ V (peak-to-peak)

  Modulation index, m = $\frac{V_{ref}}{V_{carrier}} = \frac{3}{4} = 0.75$

- **DC Link Capacitor:**

  $C_{dc} = \frac{2\times S\times\tau}{V_{dc}^2} = \frac{2\times100\times10^6\times4\times10^{-3}}{(54.5\times10^3)^2} = 269.3\ \mu$F

  where τ is the time constant whose value lies between 4 ms to 10 ms and S is the MVA rating of the system.

  The value of capacitance obtained from above equation is the minimum capacitance needed. The value of capacitance chosen here is 470 μF.

- **Expected DC Output at the Link:**

  $V_{dc} = 1.4V_{ac} = 1.4 \times 39 = 54.6$ kV

6.2 PWM Signals

The PWM method that is used is Sinusoidal PWM where a sine wave and a triangle wave are compared and the resulting pulses after comparison are fed to the IGBTs as shown in figure 6.1.

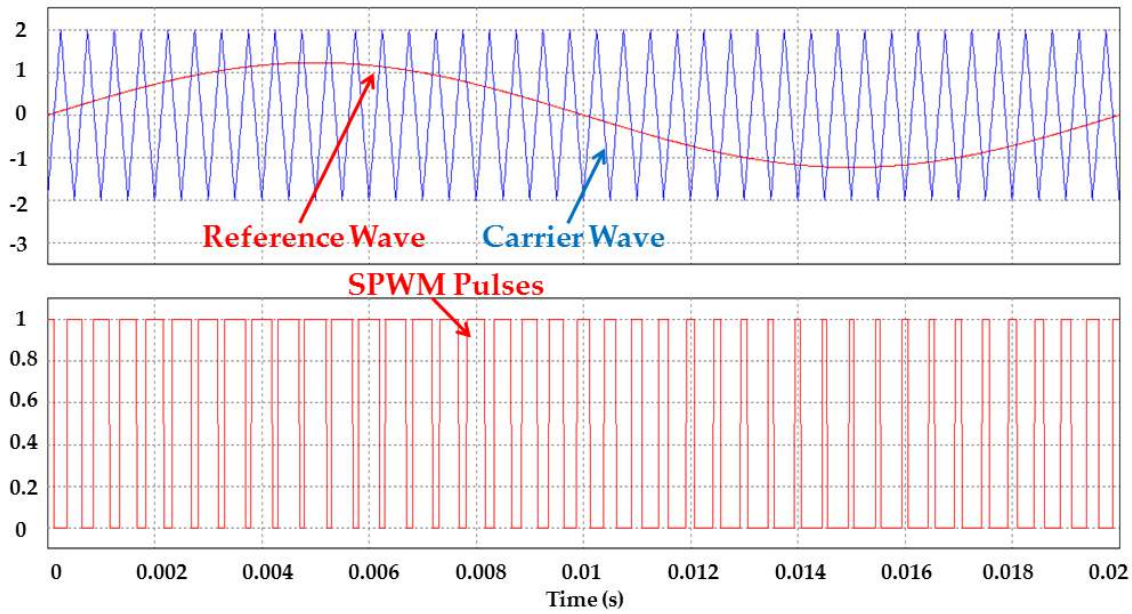


Figure 6.1: Waveform showing SPWM pulses

6.3 Open Loop System

Figure 6.3 shows the DC output waveforms for the open loop system shown in figure 6.2 where the voltage is sensed from the grid/source and given to the SPWM circuit for comparison. Figure 6.4 shows the waveforms of input voltage and current of phase-A which are in phase, indicating unity power factor for an active front end rectifier.

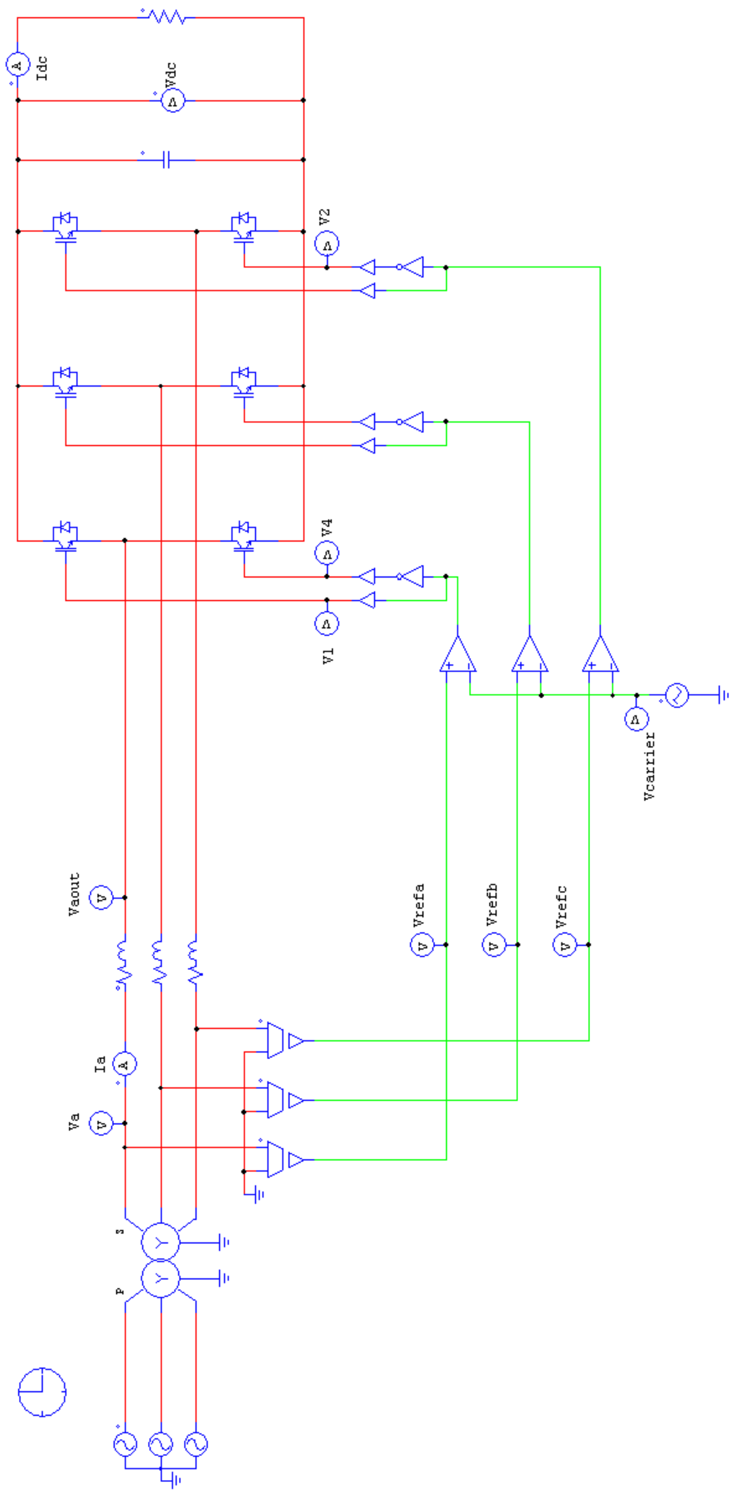


Figure 6.2: Open loop simulation of voltage source rectifier

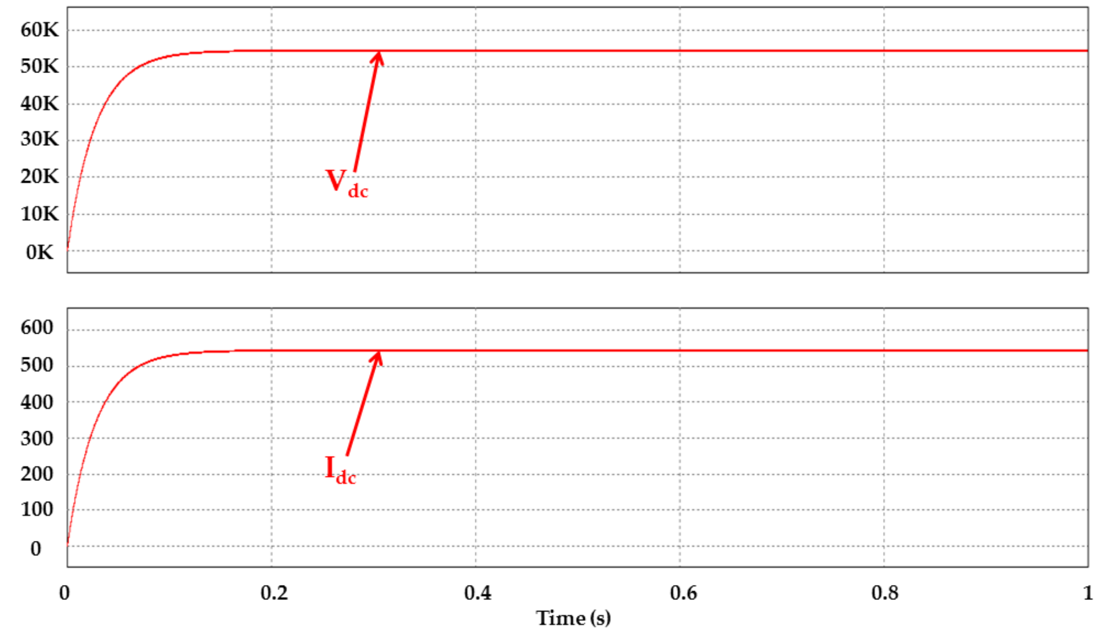


Figure 6.3: DC link voltage and current waveforms for open loop system

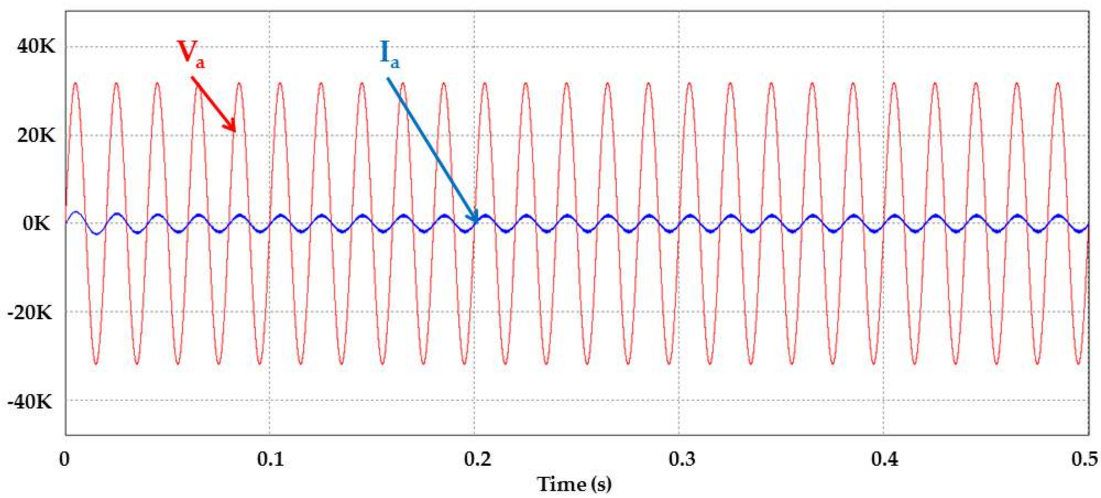


Figure 6.4: Input voltage and current waveforms for open loop system which are in-phase

6.4 Closed Loop System

Figure 6.5 gives the block diagram of the circuit that has been implemented.

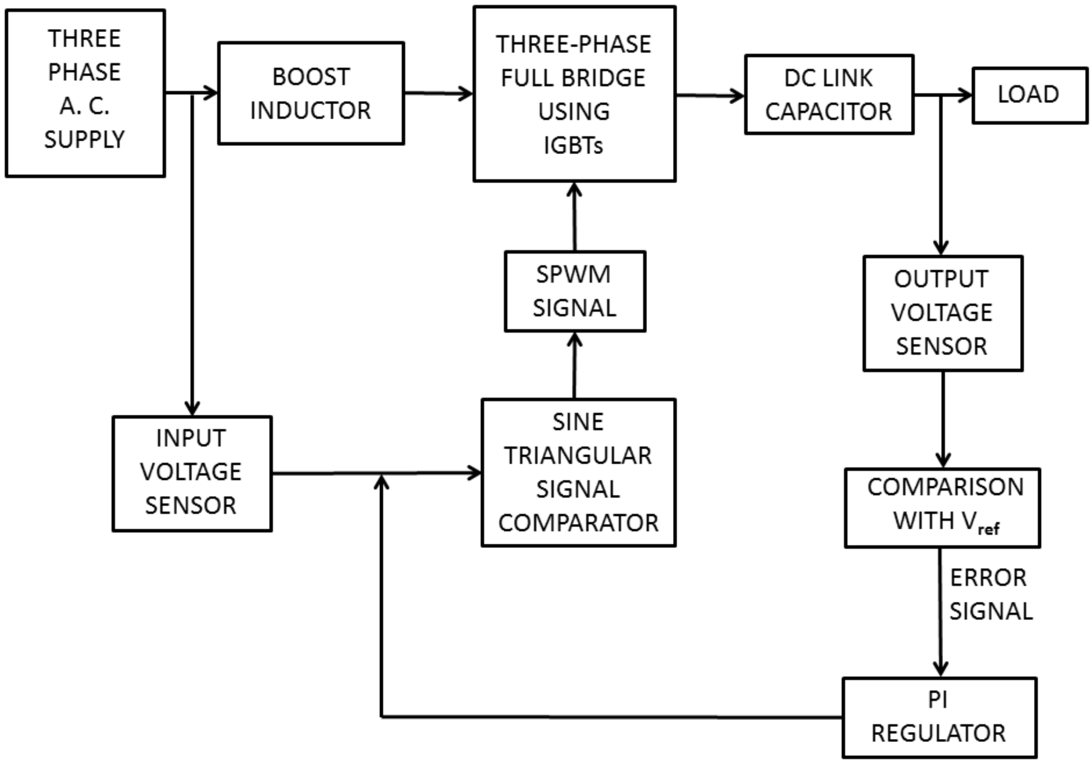


Figure 6.5: Block diagram of the closed loop system implemented

Here, the output DC voltage is sensed and compared with a reference voltage and through a PI regulator, the error signal generated is fed back to the input and accordingly the gating signals to the IGBTs are modified in order to provide a constant DC voltage on the link. This type of control is called **DC Voltage Balance Control**.

6.4.1 Static Condition

The same block diagram of figure 6.5 has been implemented in simulation and the relevant DC waveforms V_{dc} and I_{dc} under static loading conditions are shown in figure 6.6.

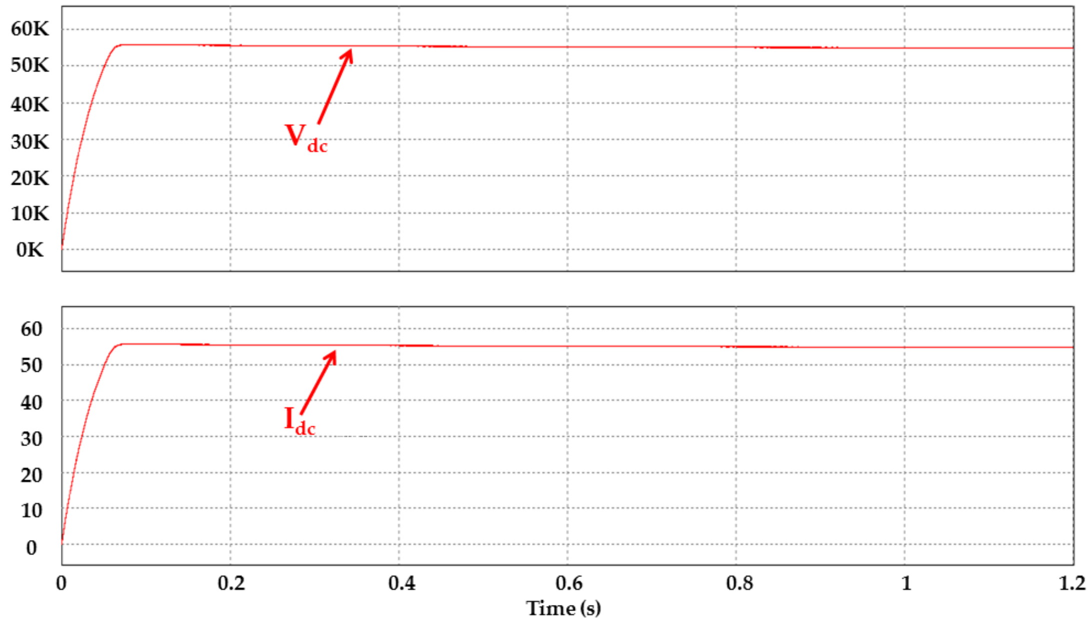


Figure 6.6: DC link voltage and current waveforms for closed loop system under static loading condition

6.4.2 Dynamic Condition with R Load Switching

Figure 6.9 shows the circuit for a three-phase closed loop system with switching of R load and figure 6.7 shows the waveforms of V_{dc} and I_a when R = 1000 Ω and a resistor of 500 Ω is inserted at time t = 0.5 sec and a resistor of 250 Ω is inserted at time t = 0.7 sec and the loading is restored to 1000 Ω at t = 0.9 sec.

After the PI senses the changes in the loading, it tries to maintain the DC voltage to a constant value and accordingly, an offset equal to the error is introduced in the reference voltage and the output voltage after multiplying is shown in figure 6.8, which is given to the comparator. Figure 6.10 shows the input voltage and current of phase-A which are in-phase, indicating a unity power factor operation.

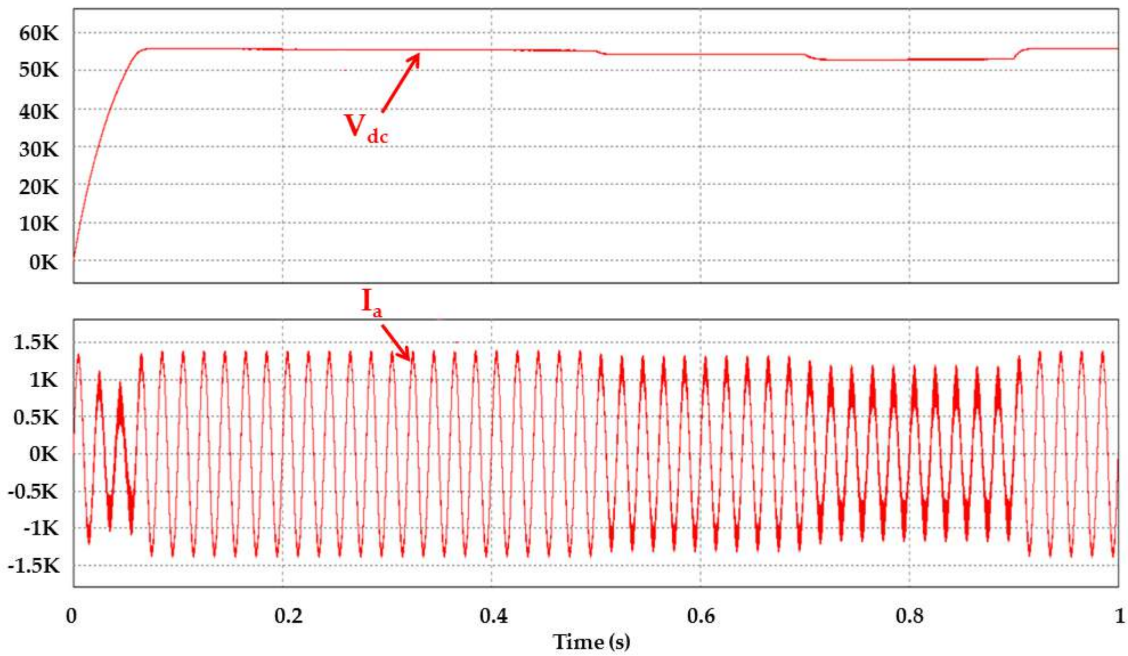


Figure 6.7: V_{dc} and I_a for closed loop system under dynamic conditions with R load switching at t = 0.5 sec and t = 0.7 sec

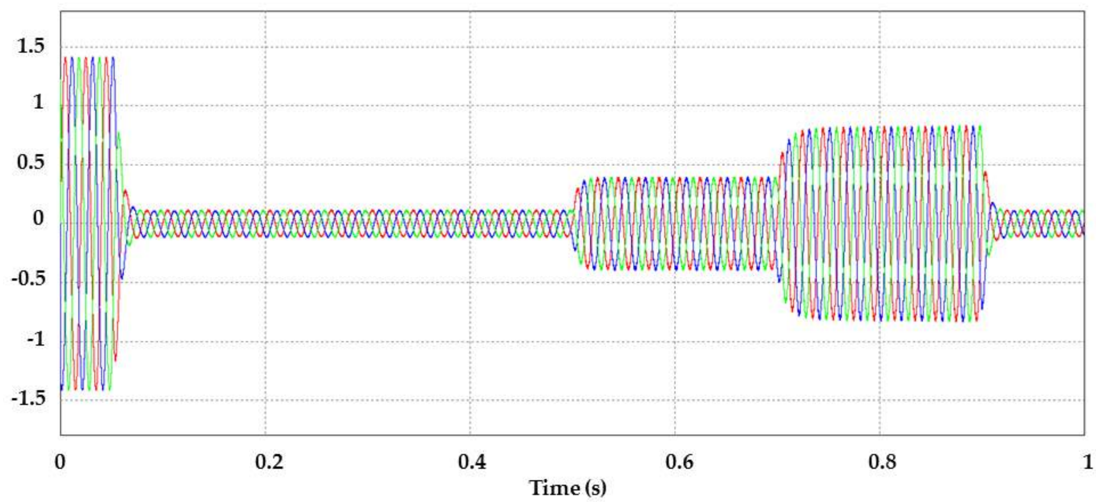


Figure 6.8: Changes in the reference voltages considering the error produced by the switching of R load at t = 0.5 sec and t = 0.7 sec

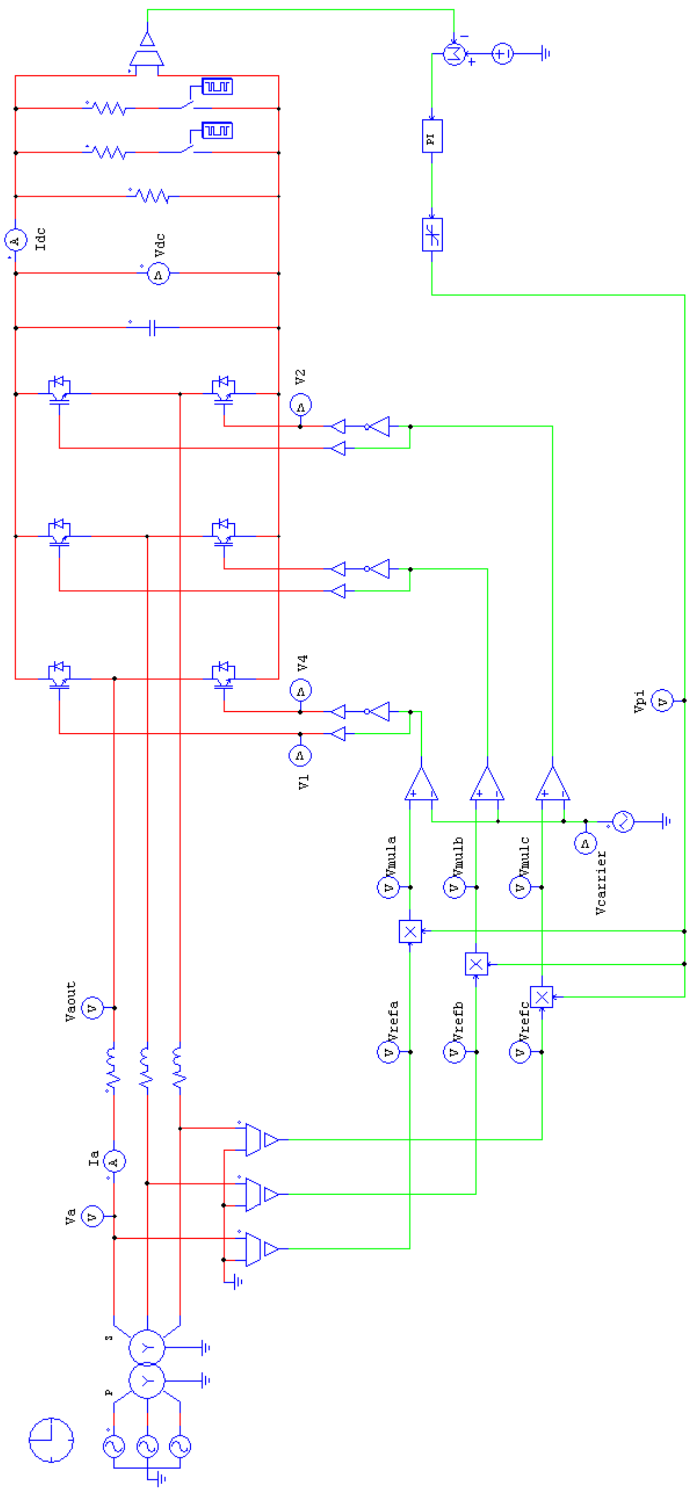


Figure 6.9: Closed loop simulation of voltage source rectifier with switching of R load

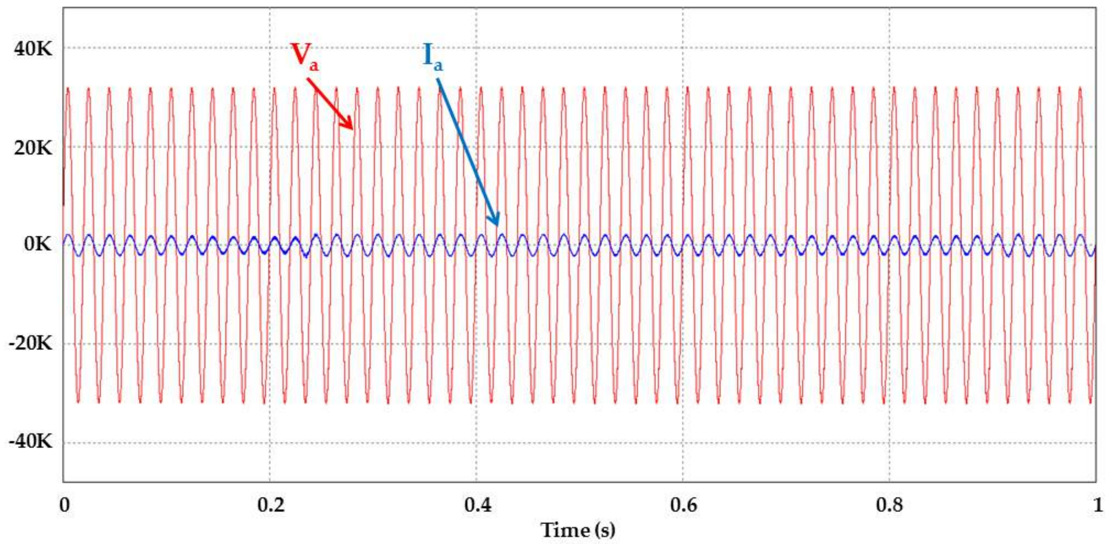


Figure 6.10: Input voltage and current waveforms for closed loop system with R load showing unity power factor

6.4.3 Dynamic Condition with RL Load Switching

Following are the simulation results with a resistive load of 1000 Ω and an inductive load of 0.45 H and a load of R = 500 Ω, L = 0.225 H is inserted at t = 0.5 sec and R = 250 Ω, L = 0.1125 H at t = 0.7 sec. The DC link voltage, V_{dc} and input current of phase-A, I_a is shown in figure 6.11.

As the DC voltage is less than the reference voltage, with reduced value of load, the PI controller will command to increase the input gating signal for compensation of DC bus voltage drop.

The phase-A of supply voltage and input current is shown in figure 6.12.

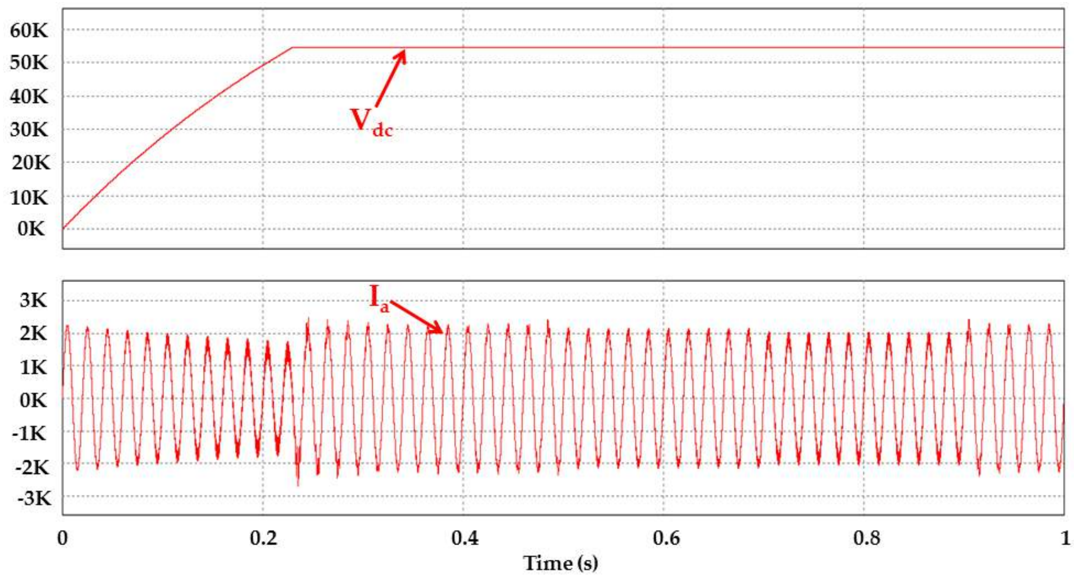


Figure 6.11: V_{dc} and I_a for closed loop system with RL load switching at t = 0.5 sec and t = 0.7 sec

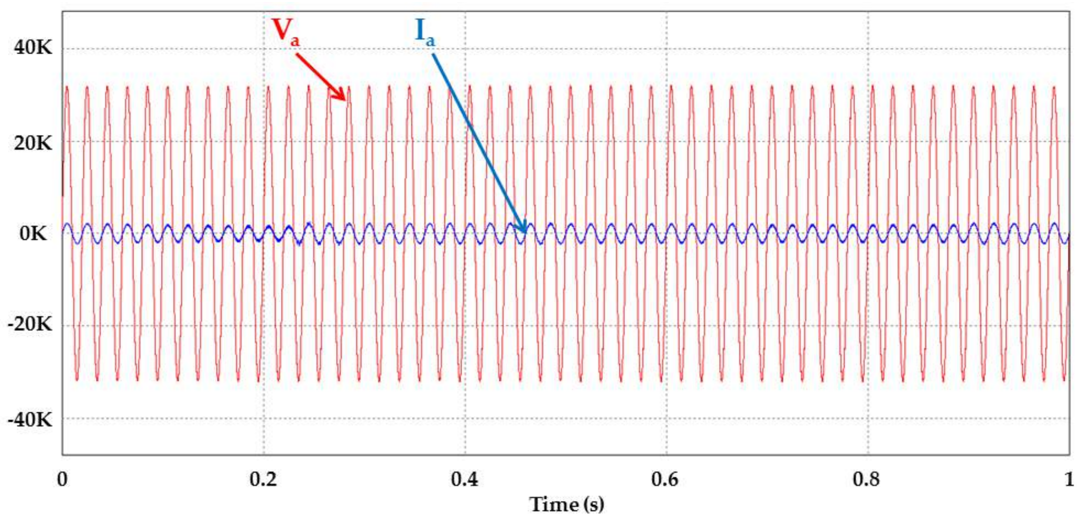


Figure 6.12: Input voltage and current waveforms for closed loop system with RL load which are in-phase

6.5 Simulation for Prototype Hardware System

The three-phase system that has been implemented in the software is now simulated at a scaled-down single-phase level. The single-phase system is implemented in the hardware as well.

The values of the different parameters are as follows:

- Output Power $P_o = 1$ kW
- Input AC Voltage = 100 V
- Input AC Current (rms) = 3.625 A
- DC Link Voltage $V_{dc} = 145$ V

The output DC voltage and current waveforms, as well as the input AC voltage and current waveforms are as shown in figure 6.13 and 6.14 respectively.

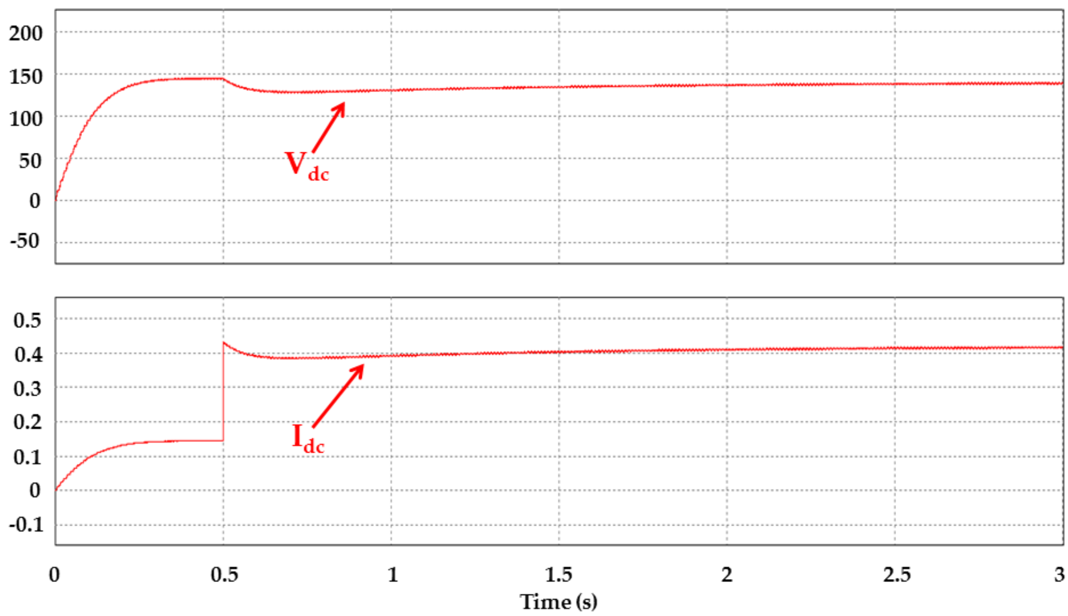


Figure 6.13: DC link voltage and current waveforms for hardware model

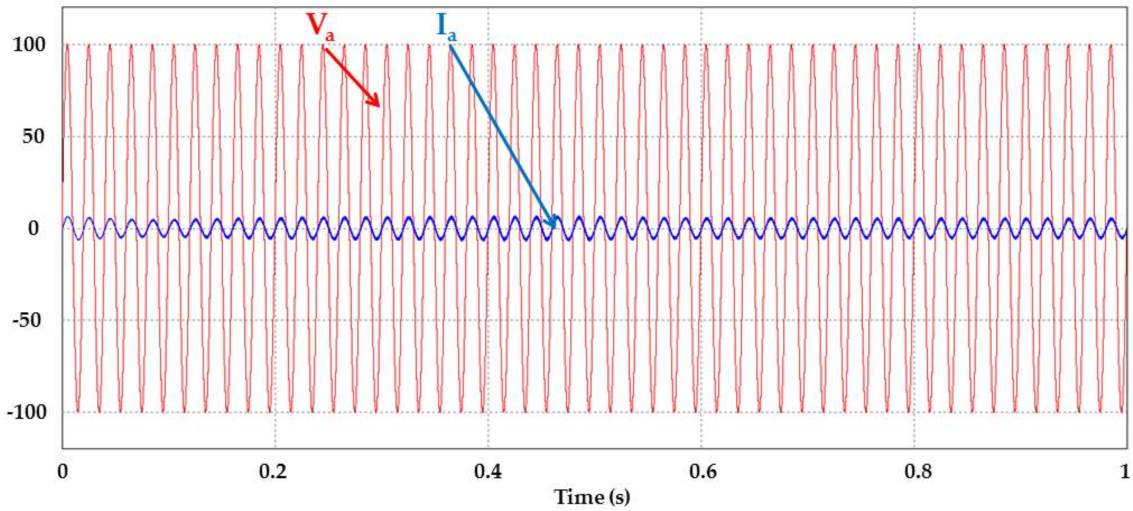


Figure 6.14: Input AC voltage and current waveforms indicating unity power factor

Chapter 7

Hardware Design

7.1 Control Circuit

The gate driver IC used is IR2110 which is a high voltage, high speed power MOSFET and IGBT driver with independent high and low side referenced output channels. The floating channel can be used to drive an IGBT in the high side configuration which operates up to 500 V. It has a gate drive supply range from 10 to 20 V and a separate logic supply range from 5 to 20 V.[9]

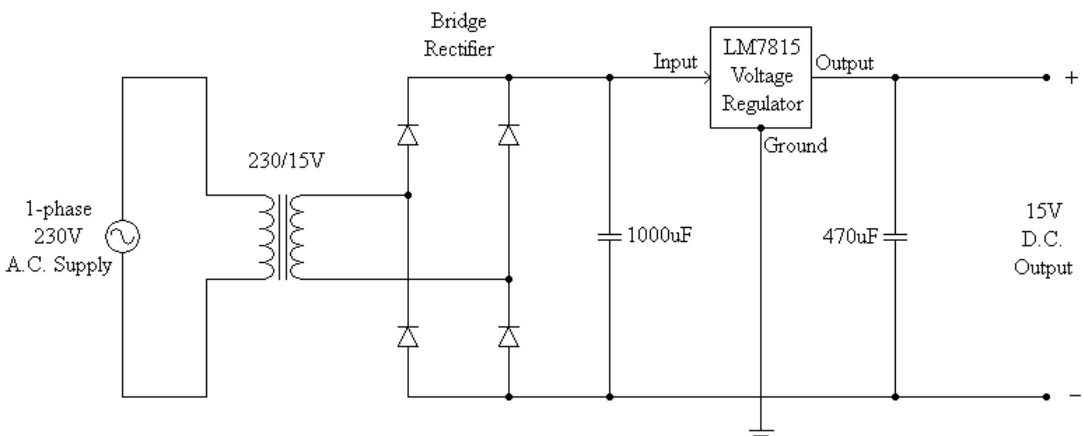


Figure 7.1: Power circuit for gate driver

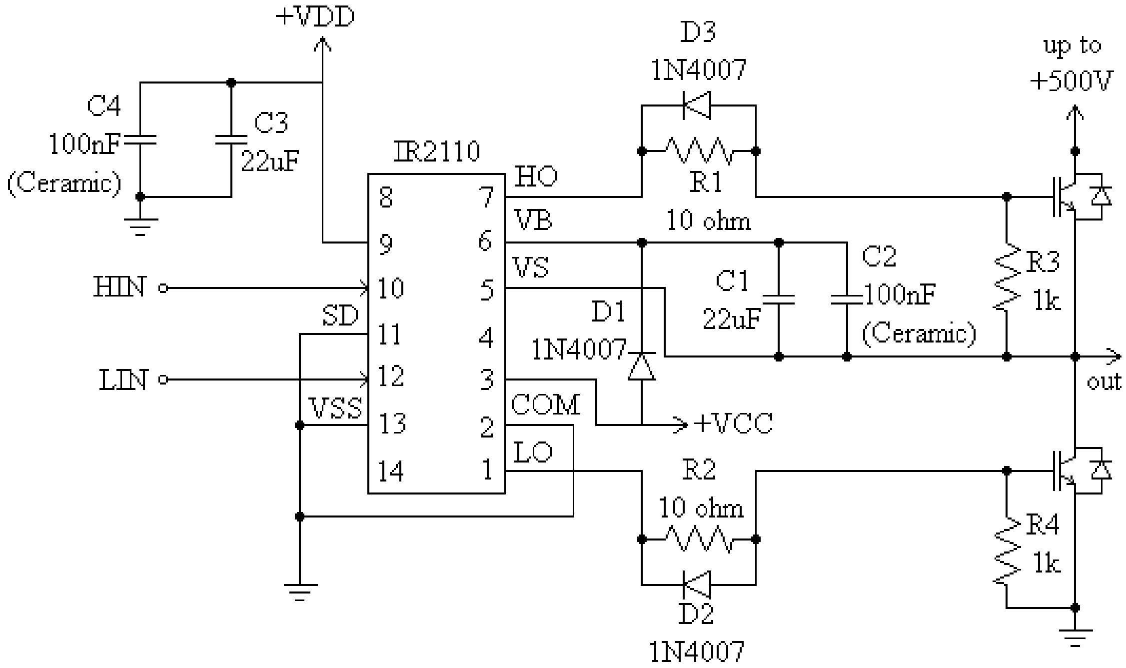


Figure 7.2: Gate driver circuit

The circuit diagram for the power supply and the gate driver fabricated is shown in figure 7.1 and 7.2 respectively. In the power supply circuit of figure 7.1, 230 V A.C. supply from the mains is stepped down to 15 V A.C. through a transformer which is then rectified with the help of a diode bridge rectifier and filtered through a 1000 μF capacitor. The unregulated output of the rectifier is then fed to the voltage regulator IC LM7815 to obtain a regulated 15 V D.C. supply.

In figure 7.2, D1, C1 and C2 along with the IR2110 form the bootstrap circuitry, while D2 and D3 discharge the gate capacitances of the IGBT quickly, bypassing the gate resistors, reducing the turn-off time. R1 and R2 are the gate current-limiting resistors.

Figure 7.3 shows the gate driver card made and figure 7.4 shows the output pulses obtained at the high and low side channels which are complementary.

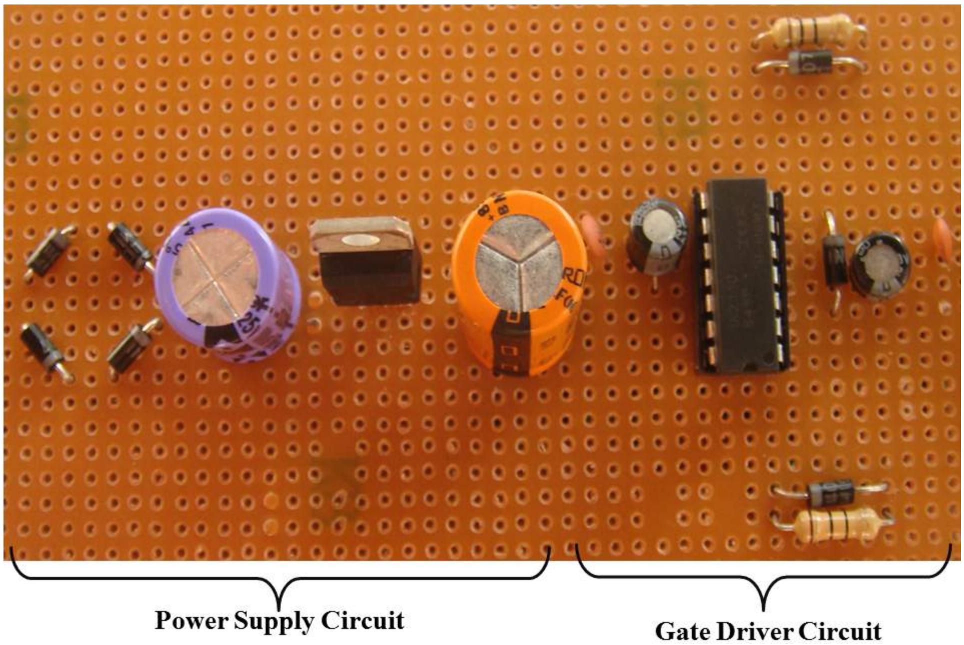


Figure 7.3: Gate driver card

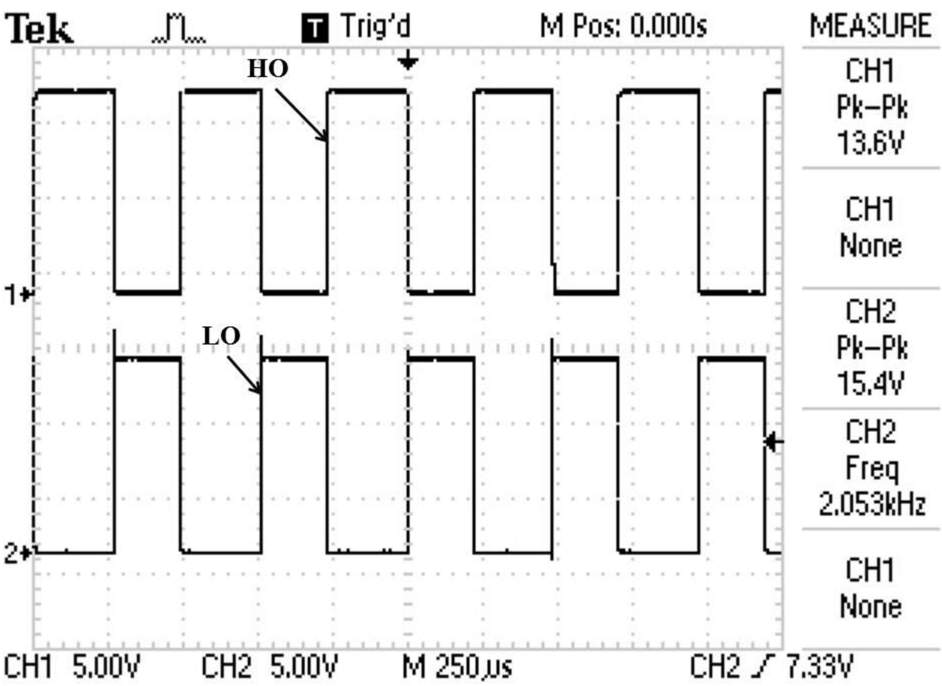


Figure 7.4: High and low side gate pulses

7.2 Power Circuit

Figure 7.5 shows the single-phase H-bridge topology that has been fabricated. The power circuit is mainly made up of the IGBTs and a snubber circuit.

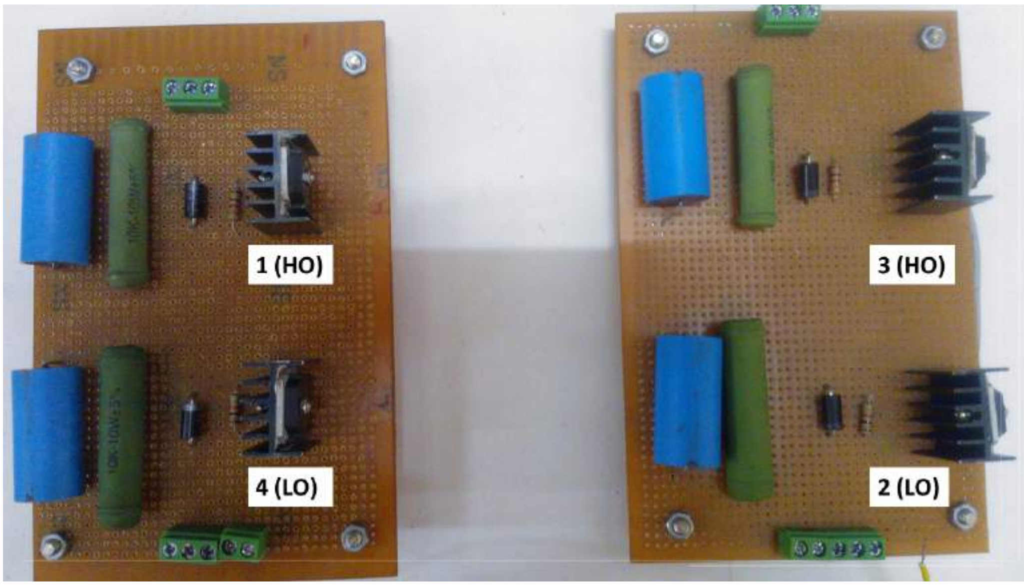


Figure 7.5: Single-phase full bridge

The IGBT chosen for the purpose is FGA25N120ANTD manufactured by Fairchild which has an in-built antiparallel diode across the IGBT. It has a collector-emitter voltage of 1200 V and a gate-emitter voltage of ±20 V. It has a collector current rating of 50 A at a temperature of 25° C and 25 A at 100° C.

Snubber circuit is a supplementary circuit used in the converter circuit to reduce stress put on the power semiconductor. The ultimate goal of the snubber circuit is to improve the transient waveform. It suppresses over-current or over-voltage or improves dv/dt and di/dt to ease the transient waveform to reduce stress on the device.

An RCD snubber circuit is connected across each IGBT as shown in figure 7.6. This snubber suppresses over-voltage at turn-off to reduce the switching losses. The snubber capacitor is completely discharged at turn-on, and it is fully recharged at

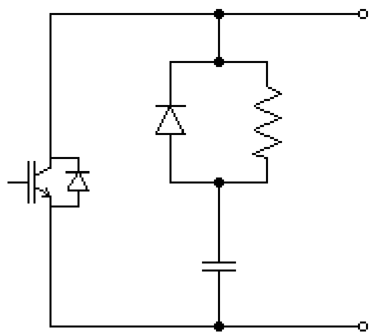


Figure 7.6: RCD snubber circuit

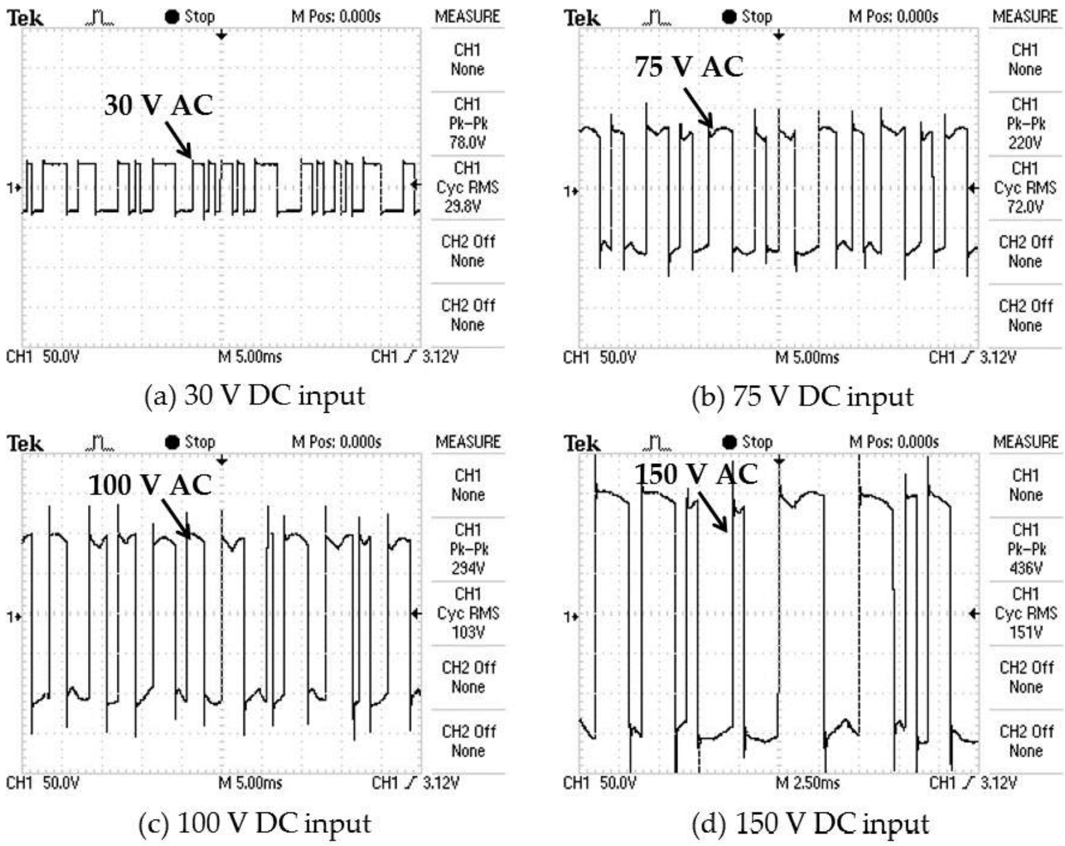
turn-off. This circuit reduces IGBT dv/dt during turn-off. As such, soft switching is possible, and IGBT loss is reduced. The resistor chosen is 10 kΩ, 10 W, the capacitor is 100 nF, 2000 V and the diode is 1N5408.

7.3 Inverter Mode of Operation

The power circuit was fired with the IR2110 and was tested for various voltage levels up to 150 V. The AC voltage output waveforms are as shown in figure 7.7.

7.4 Rectifier Mode of Operation

For the rectifier mode of operation, IR2110 was unable to drive the IGBTs and also resulted in the heating of the components. Since we just needed the testing of the power circuit, the IGBTs were fired from TLP250 for the rectifier mode of operation and the various waveforms were observed. Figure 7.8 shows the input AC current and output DC voltage of the rectifier.



(a) 30 V DC input

(b) 75 V DC input

(c) 100 V DC input

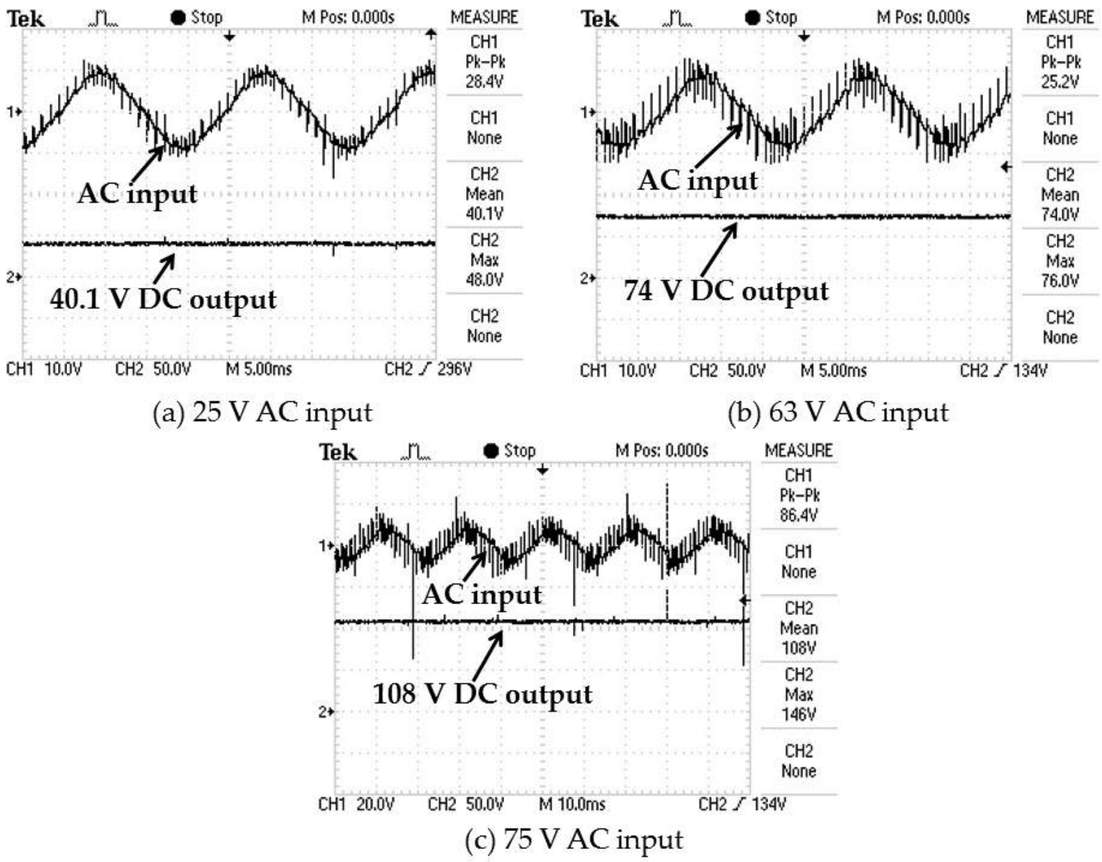
(d) 150 V DC input

Figure 7.7: Output AC voltage waveforms in inverter mode. (a), (b) and (c) Scale: X-axis: 1 unit = 5.00 ms, Y-axis: 1 unit = 50.0 V; (d) Scale: X-axis: 1 unit = 2.50 ms, Y-axis: 1 unit = 50.0 V

Figure 7.9 shows the DC voltage output of the rectifier at various voltage levels.

Figure 7.10 shows the AC input current waveform in the rectifier mode of operation, while figure 7.11 shows the AC input current and voltage waveforms which are in phase indicating a unity power factor at the input side at 85 V and 100 V.

Figure 7.12 shows the complete hardware setup with the power circuit, control circuit, boost inductor, and the controller.

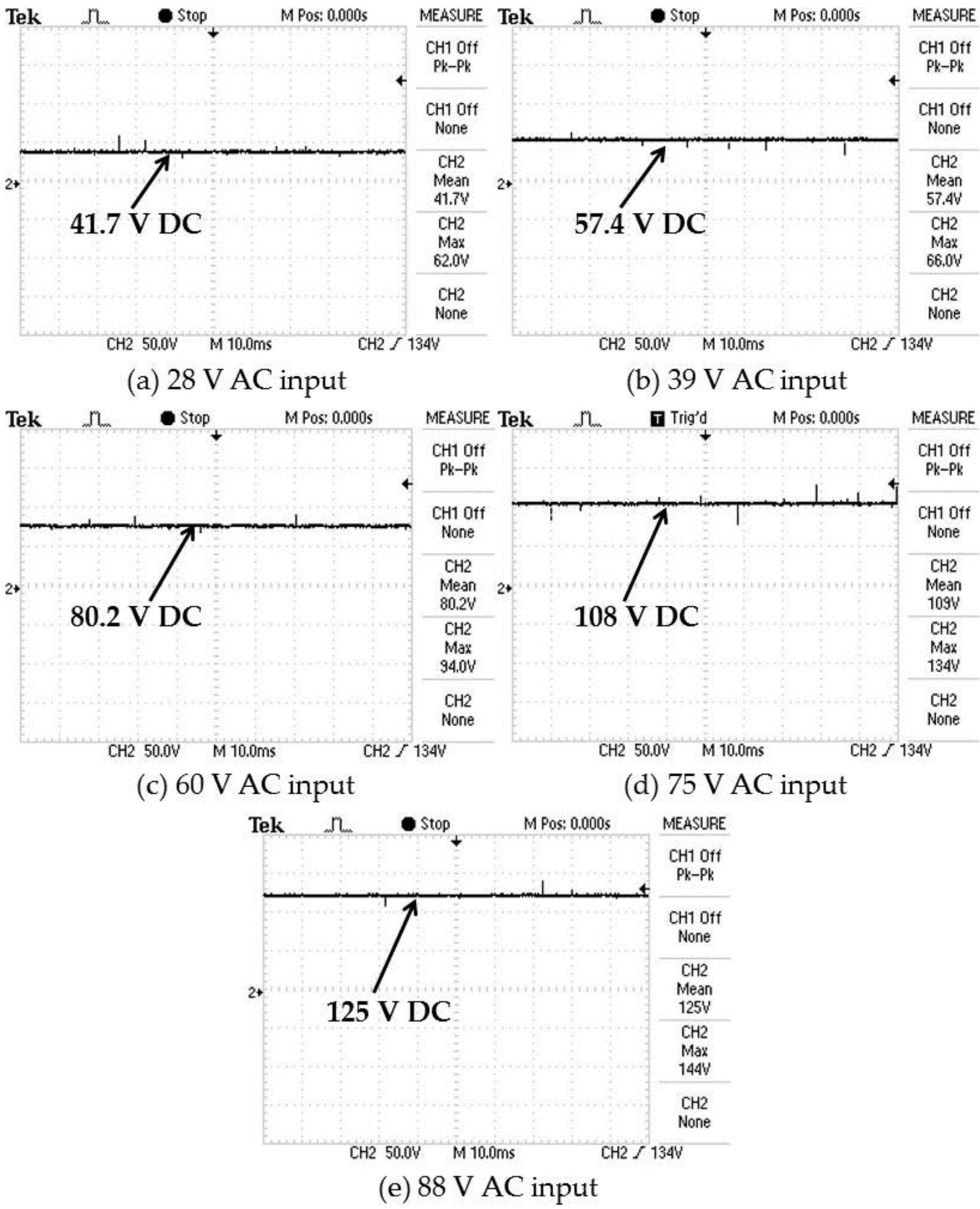


(a) 25 V AC input

(b) 63 V AC input

(c) 75 V AC input

Figure 7.8: Input AC current and output DC voltage waveforms in rectifier mode. (a) and (b) Scale: X-axis: 1 unit = 5.00 ms, Y-axis: CH-1: 1 unit = 10.0 V, CH-2: 1 unit = 50.0 V; (c) Scale: X-axis: 1 unit = 10.0 ms, Y-axis: CH-1: 1 unit = 20.0 V, CH-2: 1 unit = 50.0 V



(a) 28 V AC input

(b) 39 V AC input

(c) 60 V AC input

(d) 75 V AC input

(e) 88 V AC input

Figure 7.9: Output DC voltage waveforms in rectifier mode. Scale: X-axis: 1 unit = 10.0 ms, Y-axis: 1 unit = 50.0 V

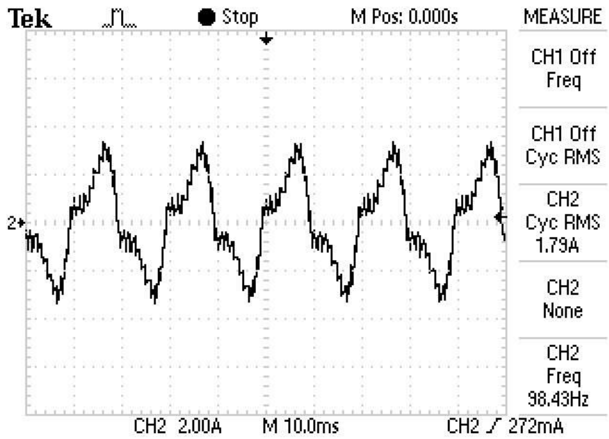
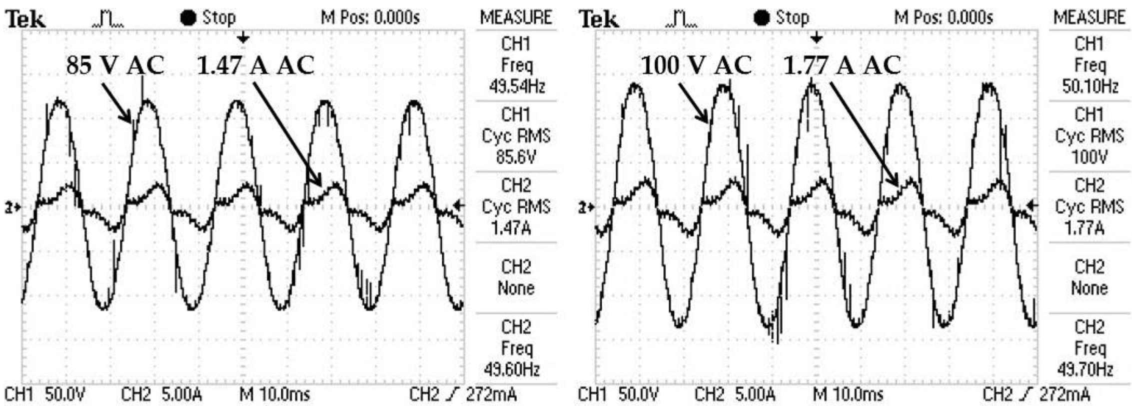


Figure 7.10: Input AC current waveform in rectifier mode. Scale: X-axis: 1 unit = 10.0 ms, Y-axis: 1 unit = 2.00 A



(a) 85 V AC input

(a) 100 V AC input

Figure 7.11: Input AC current and voltage waveforms in rectifier mode. Scale: X-axis: 1 unit = 10.0 ms, Y-axis: CH-1: 1 unit = 50.0 V, CH-2: 1 unit = 5.00 A

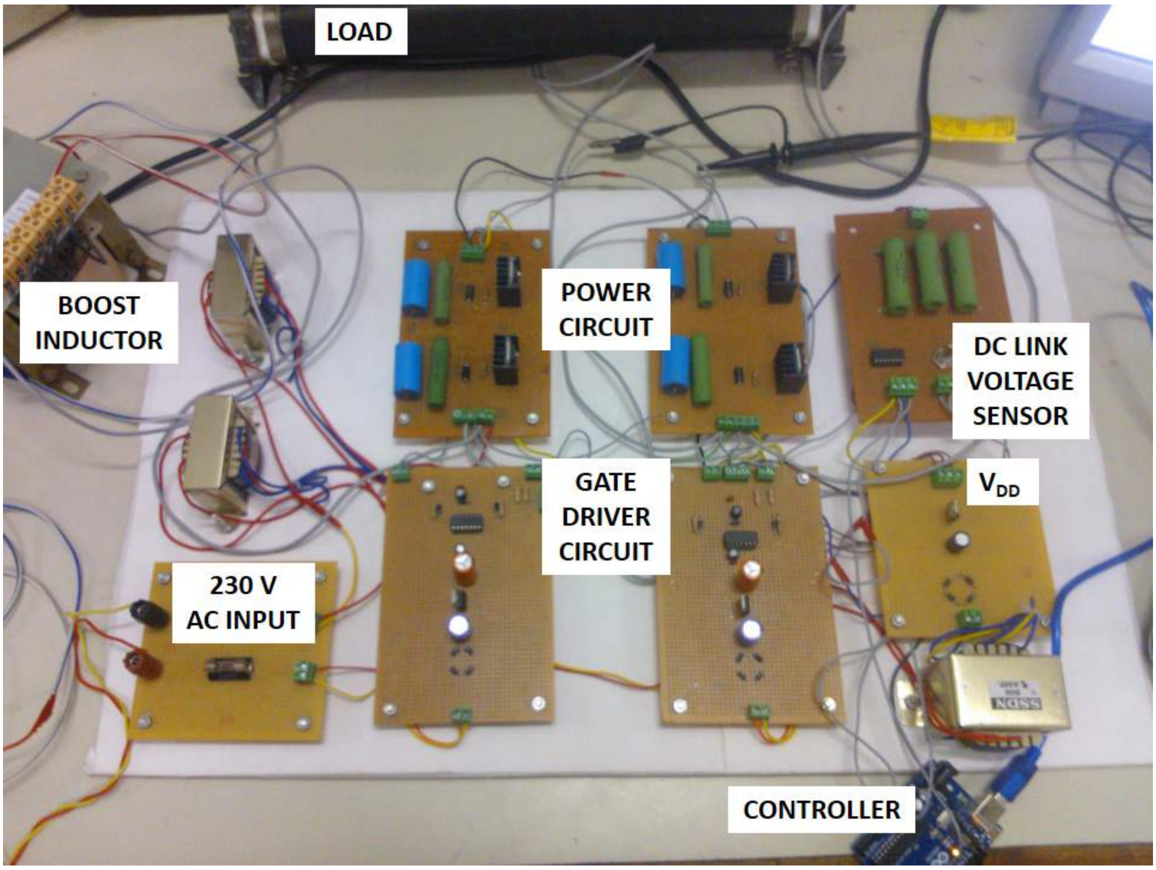


Figure 7.12: Hardware layout

Chapter 8

Controller and Programming

The controller that is used for the closed loop implementation of the system is Arduino Uno. The Arduino Uno is a micro-controller board based on the ATmega328.

The Arduino Uno can be powered via the USB connection or with an external power supply. The power source is selected automatically. The board can operate on an external supply of 6 to 20 V. Each of the 14 digital pins on the Uno can be used as an input or output, using pinMode(), digitalWrite(), and digitalRead() functions. They operate at 5 V. Each pin can provide or receive a maximum of 40 mA and has an internal pull-up resistor (disconnected by default) of 20-50 kΩ.

8.1 Summary of the Controller Features

- Microcontroller: ATmega328
- Operating voltage: 5 V
- Input voltage (recommended): 7-12 V
- Input voltage (limits): 6-20 V
- Digital I/O pins: 14 (of which 6 provide PWM output)
- Analog input pins: 6

- DC current per I/O pin: 40 mA
- DC current for 3.3 V pin: 50 mA
- Flash memory: 32 kB
- SRAM: 2 kB
- EEPROM: 1 kB
- Clock speed: 16 MHz

8.2 Programming of the Controller

The programming part involves the generation of gating signals to fire the IGBTs such that, a constant DC link voltage is maintained by varying the duty cycle of the pulses accordingly.

In the program, a reference voltage, V_{ref} is fixed and the voltage at the DC link, V_{dc} is sensed through a voltage sensor and its value is given to the controller through the analog pin A0. The controller compares the sensed voltage V_{dc} and the reference voltage V_{ref} and generates an $error = V_{ref} - V_{dc}$.

If $|error| > 0$, the controller checks for the sign of error. If the error is positive, that is, $error > 0$, it implies that $V_{dc} < V_{ref}$ and the controller acts to increase the duty cycle of the firing pulses by 3 % till $|error| = 0$, that is, $V_{dc} = V_{ref}$. Similarly, if the error is negative, that is, $error < 0$, it means that $V_{dc} > V_{ref}$ and the controller acts to decrease the duty cycle by 3 % till $|error| = 0$. The duty cycle is bound by an upper and lower limit to avoid fully ON or fully OFF condition of the switches. Figure 8.1 shows the relevant flowchart of the programming.

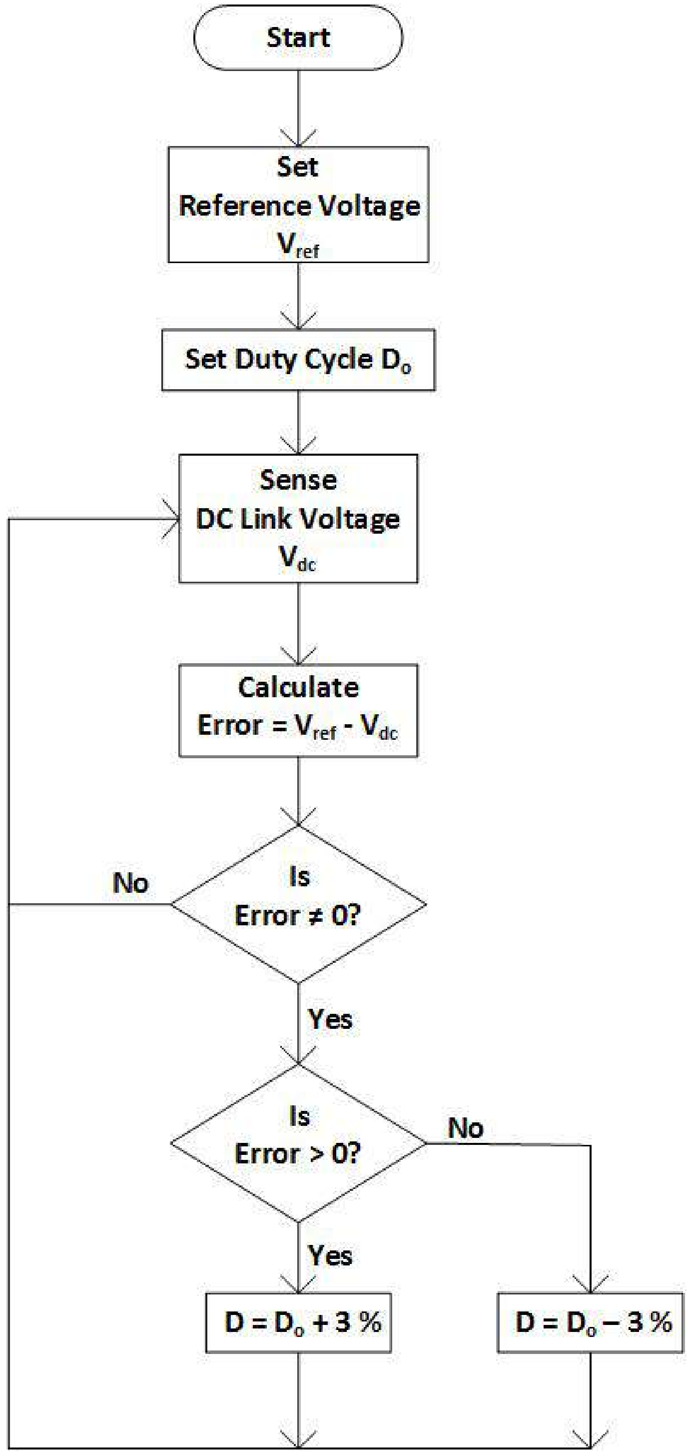


Figure 8.1: Flowchart of programming

Chapter 9

Conclusion and Future Work

9.1 Conclusion

Three-phase PWM reversible rectifier is used, which draws near sinusoidal current from the AC grid and maintains unity power factor at the supply side. With this converter, the power can also flow in either direction. The PWM rectifier is simulated and gives appropriate results under steady state as well as dynamic conditions with R load and RL load. A single phase prototype which is to be implemented in the hardware is also simulated and the above stated operations have also been tested in hardware in both open loop and closed loop operation and the results are found to be satisfactory.

9.2 Future Work

The system hardware needs to be tested with transient conditions of loading. Also, harmonic analysis can be done on the project and % THD can be reduced by appropriate measures. The reversal of power flow condition can also be implemented by connection with a grid. This would validate the application of this system.

References

[1] B. R. Andersen. VSC Transmission Tutorial. *CIGRE B4 Meeting, Bangalore, India*, 2005.

[2] B. R. Andersen, L. Xu, P. J. Horton, and P. Cartwright. Topologies for VSC Transmission. *Power Engineering Journal*, 16(3), June 2002.

[3] Georgios D. Demetriades, Nikolas Flourentzou, and Vassilios G. Agelidis. VSC-Based HVDC Power Transmission Systems: An Overview. *IEEE Transactions on Power Electronics*, March 2009.

[4] D. V. Garasiya, Santosh C. Vora, and P. N. Kapil. Simulation, Design and Practical Realization of Single Phase PWM Boost Rectifier. *Nirma University International Conference on Engineering (NUiCONE)*, 2012.

[5] Erik Koldby and Mats Hyttinen. Challenges on the Road to an Offshore HVDC Grid. *Nordic Wind Conference*, September 2009.

[6] D. Madhan Mohan, Bhim Singh, and B. K. Panigrahi. A Two-Level 24-Pulse Voltage Source Converter Based HVDC System for Active and Reactive Power Control. *International Conference on Power, Control and Embedded Systems*, 2010.

[7] K. R. Padiyar. *HVDC Power Transmission Systems*. New Age International Publishers, second edition, 2012.

[8] Muhammad H. Rashid. *Power Electronics: Circuits, Devices and Applications*. Prentice Hall of India Private Limited, third edition, August 2004.

[9] International Rectifier. IR2110 - High and Low Side Driver.

[10] Jose R. Rodrguez, Juan W. Dixon, Jose R. Espinoza, Jorge Pontt, and Pablo Lezana. PWM Regenerative Rectifiers: State of the Art. *IEEE Transactions on Industrial Electronics*, 52(1), February 2005.

[11] Vijay K. Sood. *HVDC and FACTS Controllers: Applications of Static Converters in Power Systems*. Kluwer Academic Publishers, 2004.

Appendix

International
IOR Rectifier

Data Sheet No. PD-6.011E

IR2110

HIGH AND LOW SIDE DRIVER

Features

- Floating channel designed for bootstrap operation
  Fully operational to +500V
  Tolerant to negative transient voltage
  dV/dt immune
- Gate drive supply range from 10 to 20V
- Undervoltage lockout for both channels
- Separate logic supply range from 5 to 20V
  Logic and power ground ±5V offset
- CMOS Schmitt-triggered inputs with pull-down
- Cycle by cycle edge-triggered shutdown logic
- Matched propagation delay for both channels
- Outputs in phase with inputs

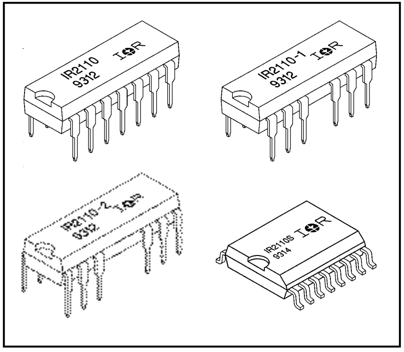
Description

The IR2110 is a high voltage, high speed power MOSFET and IGBT driver with independent high and low side referenced output channels. Proprietary HVIC and latch immune CMOS technologies enable ruggedized monolithic construction. Logic inputs are compatible with standard CMOS or LSTTL outputs. The output drivers feature a high pulse current buffer stage designed for minimum driver cross-conduction. Propagation delays are matched to simplify use in high frequency applications. The floating channel can be used to drive an N-channel power MOSFET or IGBT in the high side configuration which operates up to 500 volts.

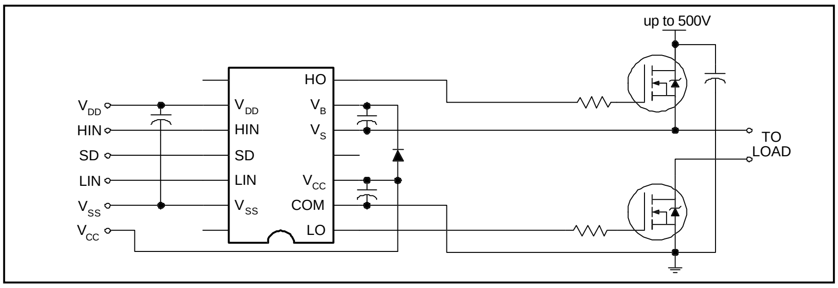
Product Summary

V_{OFFSET}	**500V max.**
I_O+/-	**2A / 2A**
V_{OUT}	**10 - 20V**
$t_{on/off}$ (typ.)	**120 & 94 ns**
Delay Matching	**10 ns**

Packages



Typical Connection



IR2110

International IOR Rectifier

Absolute Maximum Ratings

Absolute Maximum Ratings indicate sustained limits beyond which damage to the device may occur. All voltage parameters are absolute voltages referenced to COM. The Thermal Resistance and Power Dissipation ratings are measured under board mounted and still air conditions. Additional information is shown in Figures 28 through 35.

Parameter		Value		
Symbol	Definition	Min.	Max.	Units
V_B	High Side Floating Supply Voltage	-0.3	525	V
V_S	High Side Floating Supply Offset Voltage	V_B - 25	V_B + 0.3	
V_{HO}	High Side Floating Output Voltage	V_S - 0.3	V_B + 0.3	
V_{CC}	Low Side Fixed Supply Voltage	-0.3	25	
V_{LO}	Low Side Output Voltage	-0.3	V_{CC} + 0.3	
V_{DD}	Logic Supply Voltage	-0.3	V_{SS} + 25	
V_{SS}	Logic Supply Offset Voltage	V_{CC} - 25	V_{CC} + 0.3	
V_{IN}	Logic Input Voltage (HIN, LIN & SD)	V_{SS} - 0.3	V_{DD} + 0.3	
dV_S/dt	Allowable Offset Supply Voltage Transient (Figure 2)	—	50	V/ns
P_D	Package Power Dissipation @ $T_A \le$ +25°C (14 Lead DIP)	—	1.6	W
	(14 Lead DIP w/o Lead 4)	—	1.5	
	(16 Lead DIP w/o Leads 5 & 6)	—	1.6	
	(16 Lead SOIC)	—	1.25	
$R_{\theta JA}$	Thermal Resistance, Junction to Ambient (14 Lead DIP)	—	75	°C/W
	(14 Lead DIP w/o Lead 4)	—	85	
	(16 Lead DIP w/o Leads 5 & 6)	—	75	
	(16 Lead SOIC)	—	100	
T_J	Junction Temperature	—	150	°C
T_S	Storage Temperature	-55	150	
T_L	Lead Temperature (Soldering, 10 seconds)	—	300	

Recommended Operating Conditions

The Input/Output logic timing diagram is shown in Figure 1. For proper operation the device should be used within the recommended conditions. The V_S and V_{SS} offset ratings are tested with all supplies biased at 15V differential. Typical ratings at other bias conditions are shown in Figures 36 and 37.

Parameter		Value		
Symbol	Definition	Min.	Max.	Units
V_B	High Side Floating Supply Absolute Voltage	V_S + 10	V_S + 20	V
V_S	High Side Floating Supply Offset Voltage	Note 1	500	
V_{HO}	High Side Floating Output Voltage	V_S	V_B	
V_{CC}	Low Side Fixed Supply Voltage	10	20	
V_{LO}	Low Side Output Voltage	0	V_{CC}	
V_{DD}	Logic Supply Voltage	V_{SS} + 5	V_{SS} + 20	
V_{SS}	Logic Supply Offset Voltage	-5	5	
V_{IN}	Logic Input Voltage (HIN, LIN & SD)	V_{SS}	V_{DD}	
T_A	Ambient Temperature	-40	125	°C

Note 1: Logic operational for V_S of -4 to +500V. Logic state held for V_S of -4V to $-V_{BS}$.

Dynamic Electrical Characteristics

V_{BIAS} (V_{CC}, V_{BS}, V_{DD}) = 15V, C_L = 1000 pF, T_A = 25°C and V_{SS} = COM unless otherwise specified. The dynamic electrical characteristics are measured using the test circuit shown in Figure 3.

Symbol	Parameter Definition	Figure	Value Min.	Value Typ.	Value Max.	Units	Test Conditions
t_{on}	Turn-On Propagation Delay	7	—	120	150	ns	V_S = 0V
t_{off}	Turn-Off Propagation Delay	8	—	94	125		V_S = 500V
t_{sd}	Shutdown Propagation Delay	9	—	110	140		V_S = 500V
t_r	Turn-On Rise Time	10	—	25	35		
t_f	Turn-Off Fall Time	11	—	17	25		
MT	Delay Matching, HS & LS Turn-On/Off	—	—	—	10		Figure 5

Static Electrical Characteristics

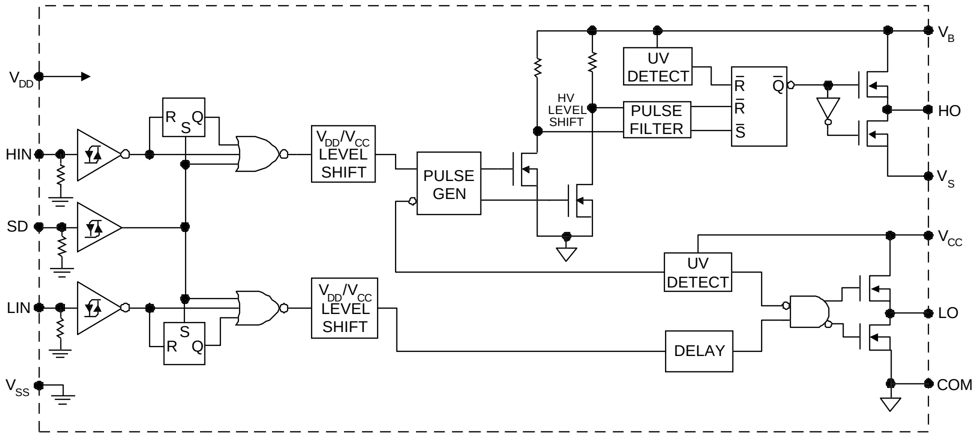
V_{BIAS} (V_{CC}, V_{BS}, V_{DD}) = 15V, T_A = 25°C and V_{SS} = COM unless otherwise specified. The V_{IN}, V_{TH} and I_{IN} parameters are referenced to V_{SS} and are applicable to all three logic input leads: HIN, LIN and SD. The V_O and I_O parameters are referenced to COM and are applicable to the respective output leads: HO or LO.

Symbol	Parameter Definition	Figure	Value Min.	Value Typ.	Value Max.	Units	Test Conditions
V_{IH}	Logic "1" Input Voltage	12	9.5	—	—	V	
V_{IL}	Logic "0" Input Voltage	13	—	—	6.0		
V_{OH}	High Level Output Voltage, V_{BIAS} - V_O	14	—	—	1.2		I_O = 0A
V_{OL}	Low Level Output Voltage, V_O	15	—	—	0.1		I_O = 0A
I_{LK}	Offset Supply Leakage Current	16	—	—	50	µA	V_B = V_S = 500V
I_{QBS}	Quiescent V_{BS} Supply Current	17	—	125	230		V_{IN} = 0V or V_{DD}
I_{QCC}	Quiescent V_{CC} Supply Current	18	—	180	340		V_{IN} = 0V or V_{DD}
I_{QDD}	Quiescent V_{DD} Supply Current	19	—	15	30		V_{IN} = 0V or V_{DD}
I_{IN+}	Logic "1" Input Bias Current	20	—	20	40		V_{IN} = V_{DD}
I_{IN-}	Logic "0" Input Bias Current	21	—	—	1.0		V_{IN} = 0V
V_{BSUV+}	V_{BS} Supply Undervoltage Positive Going Threshold	22	7.5	8.6	9.7	V	
V_{BSUV-}	V_{BS} Supply Undervoltage Negative Going Threshold	23	7.0	8.2	9.4		
V_{CCUV+}	V_{CC} Supply Undervoltage Positive Going Threshold	24	7.4	8.5	9.6		
V_{CCUV-}	V_{CC} Supply Undervoltage Negative Going Threshold	25	7.0	8.2	9.4		
I_{O+}	Output High Short Circuit Pulsed Current	26	2.0	2.5	—	A	V_O = 0V, V_{IN} = V_{DD} PW ≤ 10 µs
I_{O-}	Output Low Short Circuit Pulsed Current	27	2.0	2.5	—		V_O = 15V, V_{IN} = 0V PW ≤ 10 µs

IR2110

International
IOR Rectifier

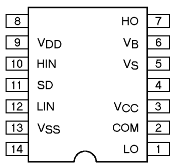
Functional Block Diagram

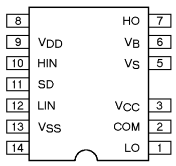


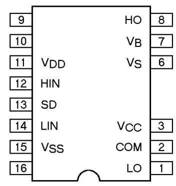
Lead Definitions

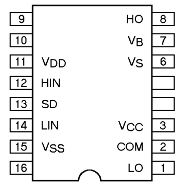
Lead Symbol	Description
V_{DD}	Logic supply
HIN	Logic input for high side gate driver output (HO), in phase
SD	Logic input for shutdown
LIN	Logic input for low side gate driver output (LO), in phase
V_{SS}	Logic ground
V_B	High side floating supply
HO	High side gate drive output
V_S	High side floating supply return
V_{CC}	Low side supply
LO	Low side gate drive output
COM	Low side return

Lead Assignments









14 Lead DIP	14 Lead DIP w/o Lead 4	16 Lead DIP w/o Leads 4 & 5	16 Lead SOIC (Wide Body)
IR2110	**IR2110-1**	**IR2110-2**	**IR2110S**
Part Number			