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A Generalized Controller and Protection Scheme for Active Three-phase MOSFET Bridge Rectifier

by

Sabin Tandukar

A thesis

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To the Graduate Faculty:

The members of the committee appointed to examine the thesis of SABIN TANDUKAR find it satisfactory and recommend that it be accepted.

Dr. Steve Chiu, Major Advisor

Dr. Thomas Baldwin, Co-Advisor

Dr. Marco P. Schoen,

Graduate Faculty Representative

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A Generalized Controller and Protection Scheme for Active Three-phase MOSFET Bridge Rectifier

Thesis Abstract--Idaho State University (2019)

The thesis proposes a generalized controller and protection strategy for a three-phase controlled MOSFET bridge rectifier for implementation in Aircraft Electrical System. The MOSFET bridge rectifier topology is highly efficient when compared to diode bridge rectifiers due to its ohmic properties. While the efficiency is lower compared to state of the art topologies like Vienna Rectifier, it produces lower Electro-magnetic Interference (EMI) due to its lower switching frequency. The proposed protection strategy uses sensing resistances to detect overcurrent in the form of differential voltage across the resistor. The protection logic determines the AC supply phase to be isolate while allowing the rectifier to operate with two phases intact. After fault is detected in two phases, all the AC phases are isolated from the rectifier. Various advantages and disadvantages of the controller and protection strategy are discussed. Alternative solutions are also discussed and compared with the proposed design.

Key Words: *power converter, AC-DC converter, three-phase rectifier, power electronics, controls, circuit protection, circuit fault detection*

1. INTRODUCTION

1.1 Aircraft Electrical System

An electrical system is an integral part of most aircraft designs. An aircraft electrical system is a self-contained network of components that generate, transmit, distribute, utilize and store electrical energy, [1]. Electrical energy is used to power subsystems of the aircraft such as the flight control actuation, environmental control system and utility function instead of mechanical, hydraulic and pneumatic energy. Generally, use of electrical power has been continuously increasing in the communication, surveillance and general systems, e.g.: radar, cooling, landing gears and actuator systems, [2].

Aircraft electrical systems generate electricity using generators or alternators. These may be engine driven but may also be powered by Auxiliary Power Unit (APU), hydraulic motor or a RAM Air Turbine (RAT). The generated power may be used without modification or it may be modified through transformers, rectifiers and inverters, [1].

Advanced aircrafts have sophisticated electrical systems that are usually multiple voltage systems using a combination of AC and DC buses to power various aircraft components. The generated power is generally AC with one or more rectifiers units providing conversion to DC voltage to power the DC loads, [1][5].

Essential AC and DC loads are wired to specific buses and designed such that power to these buses are not interrupted under almost all failure conditions. For the situation where all AC power generation is lost, a static inverter is included to power the essential AC bus using the aircraft batteries, [1].

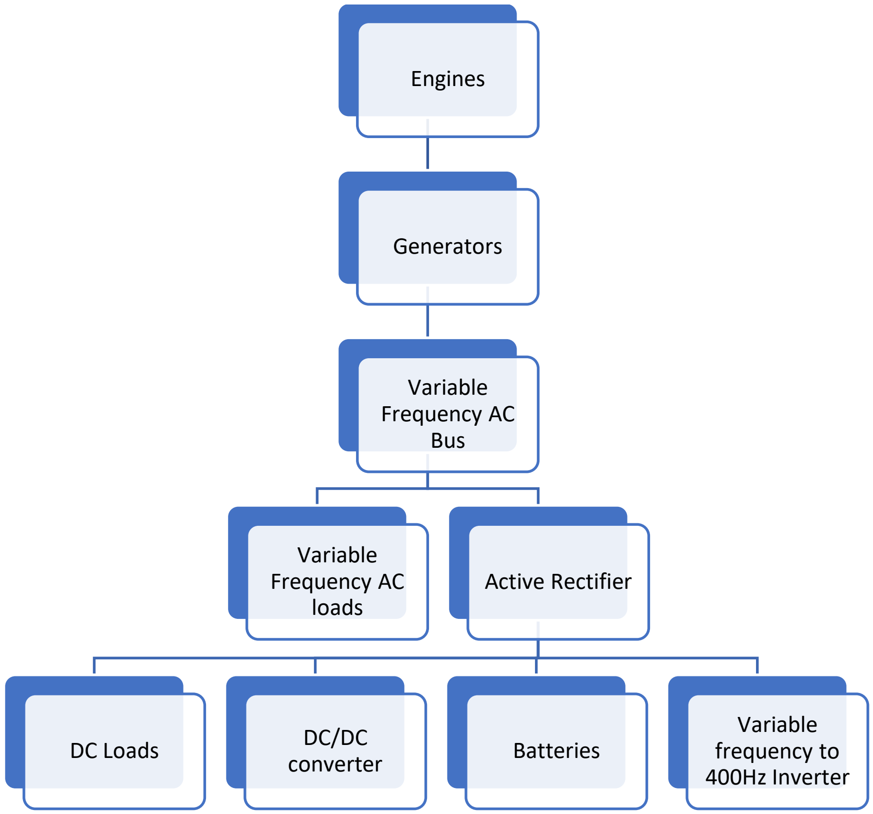


Figure 1.1: General Aircraft Electrical System

Components of the aircraft electrical system have individual protection system so that when one of the components fails, it is isolated from the bus and thus protects the remaining components and the bus from overload. It is essential for the protection system to detect and isolate faults within the faulty areas in the electrical system[1][3].

1.2 Active Rectifier

Since the generated power is generally AC, rectifier are an essential part of the aircraft electrical system to supply power to DC loads through the DC bus. A rectifier can be built using different topologies and semiconductor devices. Rectifiers may also be single-phase or multi-phase, with three-phase being the most common. Most low-power rectification is single-phase with three-phase rectification being used in high power applications like aircraft electrical systems.

Depending on the semiconductor device it uses, the rectification may be passive or active. Passive rectification is done using passive semiconductor device like diodes. Active rectification is a technique for improving the efficiency of rectification by replacing diodes with actively controlled switches such as MOSFETs and BJTs, [5].

Active rectifiers improve efficiency by reducing the voltage drop across the semiconductor switches compared to diodes. While diodes require a 0.3-1V voltage drop to conduct (higher voltage drop for higher currents), active rectifiers acts like resistance when turned on. This means, the voltage drop depends on the current flowing through the switches. For low to medium current loads, the voltage drop is significantly lower than diodes. For higher current loads, multiple transistors can be connected in parallel to decrease the current through each transistor and thereby decreasing the voltage drop, [5][6][7].

Active rectifiers also allows for further improvements to the rectifier design like low harmonic distortion and active power factor correction designs, [5][6].

1.3 Problem Statement

The project was funded by a private company that manufactures aircraft electrical components. The objective of the project is to design a generalized controller and protection strategy for a three-phase active rectifier. Following constraints were applied to the project:

- Fully analog control: Use of programmable components like microcontrollers and FPGAs are prohibited. Since the system will be used in high radiation environment, firmware and software reliability issues may arise due to random flipping of bits in the memory components of microcontrollers and FPGAs. Programmability also brings issues regarding cybersecurity. However, discrete digital components such as logic gates, flipflops, etc. are allowed.

- Low Thermal generation: Since the rectifier circuit will be implemented in extremely high-altitude application, low thermal generation required. At high altitude, due to thin atmosphere, heat cannot be dissipated easily, [7].
- Overcurrent and Short Circuit Protection: The protection strategy should be able to detect and isolate overcurrent and short circuit faults in the rectifier.
- Reliability: The rectifier must be able to operate even when one of the phases is removed/isolated due to any reason. This means, the controller and the protection strategy must allow the rectifier to operate when only one of the phases is faulty.
- Low Electro-Magnetic Interference (EMI) generation: Due to highly sensitive equipment onboard such as radar and communication systems, low to no electro-magnetic interference is desired. The range of high frequency EMIs generated may also propagate through the air and be detectable by outside antennas, [8][9].

1.4 Thesis Outline

The thesis is organized as follows. In Chapter 2, various semiconductor devices used in rectifiers is discussed. Chapter 3 focuses on implementation of single-phase rectifiers with different topologies and Chapter 4 follows up with similar discussion on three-phase rectifiers. In Chapter 5, related rectifier topics like fault detection and isolation, electrical transients and electro-magnetic interference are described. Chapter 6 deals with the simulation and results of the proposed controller and protection strategy for three-phase controlled MOSFET bridge rectifier in LTSpice. The proposed design is compared with existing topologies and techniques in Chapter 7. Chapter 8 discusses the conclusion of the thesis and proposes future work.

2. SEMICONDUCTOR DEVICES

2.1 DIODE

A diode is semiconductor device built using adjacent combination of a p-type and n-type as shown in the following figure.

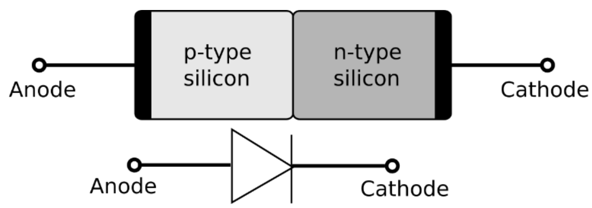
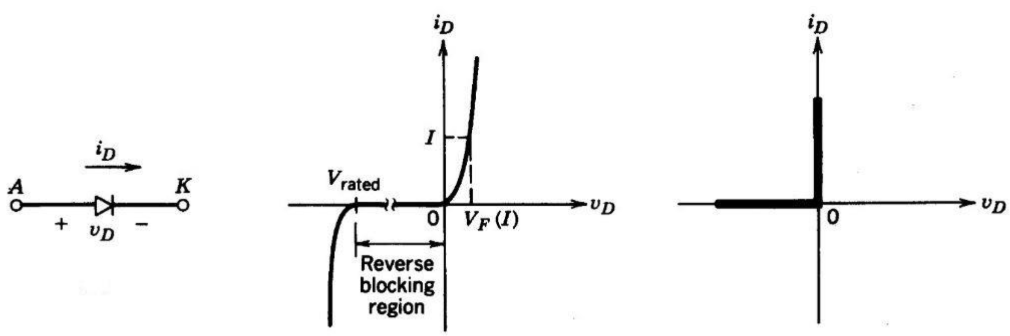


Figure 2.1: Diode p-n junction and symbol [10]

An ideal diode can be considered an ideal switch with zero turn-on resistance that only conducts when the anode voltage with respect to cathode is positive. This is called forward biasing. When the anode voltage with respect to cathode is negative, an ideal diode acts as an open circuit. This is called reverse biasing, [10][11][12].



(a) (b) (c)

Figure 2.2: (a) Diode symbol, (b) Diode I-V characteristics, (c) ideal characteristics [10]

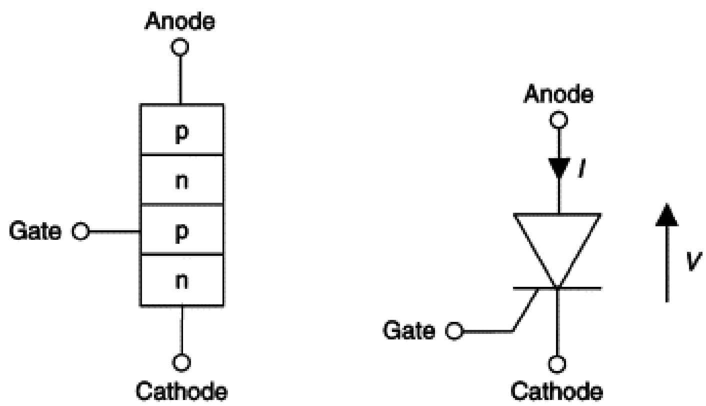
As shown in Figure 2.2(b), when the diode is forward biased, there is a voltage drop across the diode, generally 0.3-0.7V, and the IV characteristic is non-linear. When the diode is reverse biased, a small leakage current flows through diode until the breakdown voltage is reached. After breakdown, a large reverse current flows through the diode. This causes irreversible damage to the diode and in normal operation, the reverse-bias voltage shouldn't exceed the breakdown rating, [10][12].

Depending on the application, different types of diodes are used:

- Schottky diode: It is built using a junction of a semiconductor with a metal. These diodes have low forward voltage drop, generally around 0.3V and so it is used in very low output voltage circuits. These diodes also have limited voltage blocking capabilities (50-100V), [10].
- Fast-recovery diodes: These diodes are used in high-frequency circuits in combination with controllable switches where a small reverse-recovery time is required. Reverse-recovery time is defined as the time period where a small reverse current flows through the diode when it is turned off. Fast-recovery diodes have a reverse recovery time of less than a few microseconds, [10].
- Line-frequency diodes: These diodes are designed for low on-state voltage and as a consequence they have a large reverse-recovery time. However, it is acceptable as they are used in line-frequency applications. These diodes can handle voltages and currents in several kilovolts and kiloamperes. Furthermore, they can be connected in series or parallel to meet voltage and current requirements, [10].

2.2 THYRISTOR

Thyristors, also known as semiconductor-controlled rectifiers (SCR), are one of the oldest types of solid-state power device and they still have the highest power-handling capacity[10]. The vertical cross-section and symbol of the thyristor is shown in Figure 2.3.



(a) (b)

Figure 2.3: (a) Thyristor structure, (b) symbol [10]

As shown in Figure 2.3(a), Thyristors have a unique four-layer construction with alternating layers of p-type and n-type doping. Another unique characteristic of thyristor is its I-V characteristics. When reverse biased, the thyristor acts similar to a reverse-biased diode. A very small leakage current flows through the thyristor until the reverse voltage exceeds the breakdown voltage, [10][11].

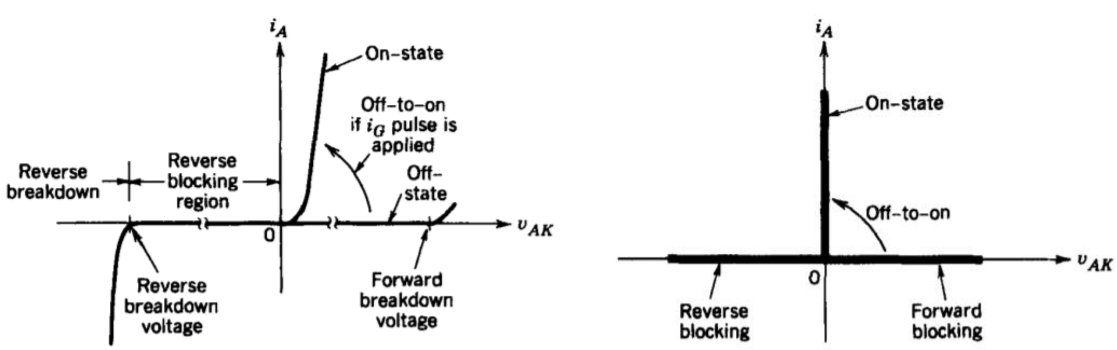


Figure 2.4: (a) I-V characteristics, (b) idealized characteristics [10]

From the I-V characteristics in Figure 2.4(a), it can be seen that the thyristor has two modes of operation when forward-biased. In the forward blocking state, i.e. when a gate voltage has not been applied, a very small leakage current flows through the thyristor until the forward voltage exceeds the forward breakdown voltage. This state is very similar to the reverse bias characteristic of the thyristor or the diode, [10]. Normally, the forward and reverse breakdown voltages are the same, [13].

The device can be turned on by applying a pulse of positive gate current for a short period of time while in forward blocking state. Once the device reaches its on-state, it is latched on and a continuous gate current is not required. However, the thyristor cannot be turned off using the gate signal and the thyristor conducts as a diode. In order for the device to turn off, it needs to be reverse-biased, [10][13].

However, the thyristor current reverses itself before turning zero. The time period in which the reverse current flows through the thyristor is called the reverse-recovery time. The time period from zero crossover of the current to the zero crossover of the voltage is called the circuit-commutated recovery time of the thyristor. If a forward voltage is applied to the thyristor before this interval has passed, the device may accidently turn on which may cause damage to the circuit, [10].

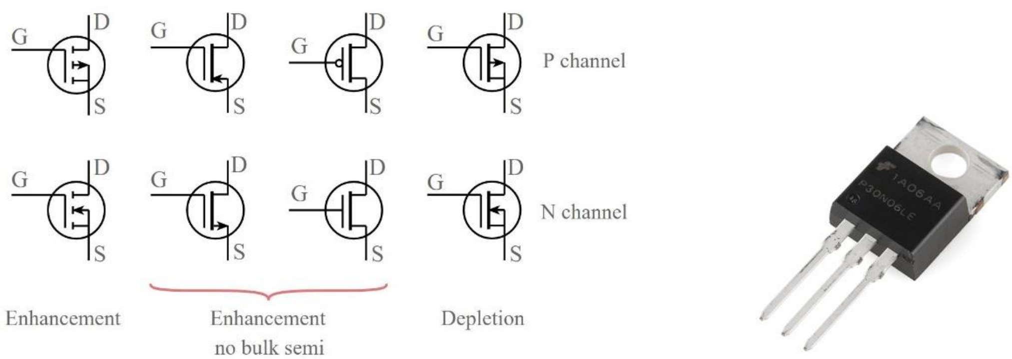
Depending of the requirements of the application, different types of thyristors are used:

- Phase-control thyristor: These are used primarily to rectify line-frequency voltages and currents. The main device characteristics are large voltage and current handling capabilities and a low on-state voltage drop. On-state voltage ranges from 1.5V for 1000V devices to 3.0V for 5-7kV devices, [10][12].
- Inverter-grade thyristors: These are designed to have low circuit commutated recovery time

in addition to low on-state voltage drop. However, lower commutated recovery time generally signifies larger on-state voltage drop, [10][11].

- Light-activated thyristors: These are triggered using a pulse of light guided by optical fibers to a special sensitive region of the thyristor. The primary use of such thyristors are in high voltage applications such as in high voltage dc transmissions where multiple thyristors are connected in series. The differing potentials that each device sees with respect to ground makes it difficult to provide triggering pulses. The ratings range up to 4kV and 3kA with on-stage voltages of about 2V, [10][11].

2.3 MOSFET



(a) (b)

Figure 2.5: (a) MOSFET symbols, (b) a typical MOSFET packaging [14]

A MOSFET (Metal-Oxide Semiconductor Field Effect Transistor) is a type of field-effect transistor which is used for switching and amplifying. It has four terminals: gate, drain, source and bulk. The source and bulk are generally connected so they can be considered a single terminal as shown in Figure 2.5(a). The gate is insulated from the rest of the device. Depending on the voltage applied to gate, the conductivity of the device (between drain and source) can be controlled. This allows the MOSFET to be used as an amplifier or a switching device. The main advantage of MOSFET over bipolar junction transistors is that it requires almost no current to control the load current. However, the gate-to-source voltage (V_{GS}/V_{SG}) must exceed the threshold voltage ($V_{THN,P}$), [10][11][12].

MOSFETs are most commonly used in digital circuits where billions of them may be packed into smartphone or a computer. However, a subset of MOSFET, also called power MOSFET, is used in power supplies, AC-DC converters, DC-DC converters, and motor controllers, although at low voltages (~200V), [12].

2.3.1 Types of MOSFET

a. N-channel MOSFET

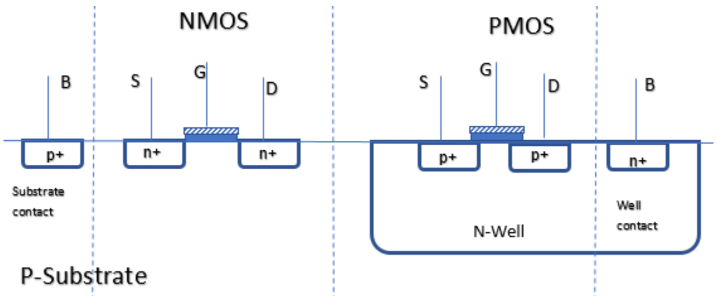


Figure 2.6: Cross-section of a NMOS and PMOS

As shown in Figure 2.6, N-channel MOSFET (NMOS) consist of p-type body and n-type source and drain. NMOS is turned on when $V_{GS} > V_{THN}$. The majority carriers in NMOS is electrons. Electrons are more mobile than holes. Therefore, NMOS can switch about three times faster than PMOS, [1].

b. P-channel MOSFET

As shown in Figure 2.6, P-channel MOSFET (PMOS) consist of n-type body and p-type source and drain. PMOS is turned on when $V_{SG} > V_{THP}$. Thus, PMOS can be considered complementary to NMOS transistors. The complementary nature of PMOS and NMOS is utilized in a class of circuits called Complementary MOS (CMOS). The majority carriers are holes. Therefore, PMOS are about three times slower than NMOS, [15].

2.3.2 REGIONS OF OPERATION

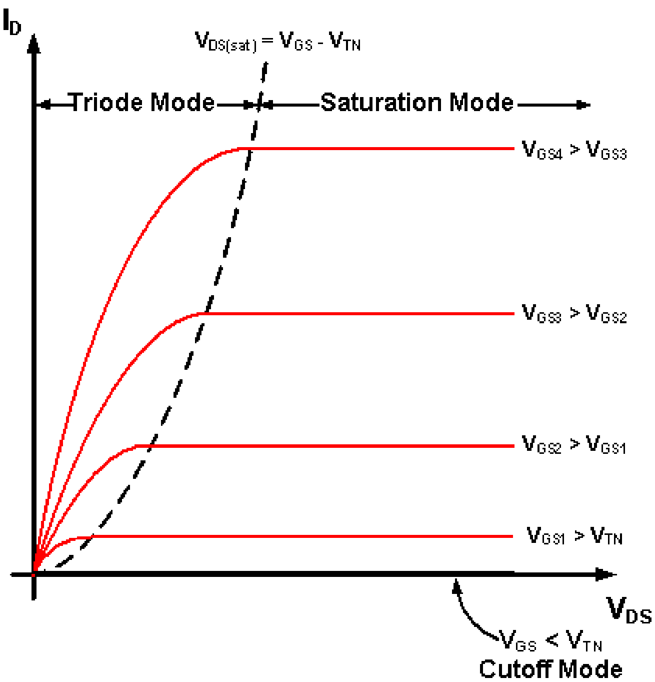


Figure 2.7: NMOS regions of operation [16]

a. Cutoff or Sub-threshold Region

MOSFET operates in the cutoff or sub-threshold region under following condition:

NMOS: $\mathbf{V_{GS} < V_{THN}}$

PMOS: $\mathbf{V_{SG} < V_{THP}}$

In this mode of operation, little to no current flows through the device and it can be considered as an open circuit. While some low power applications work in this region, it is generally not used, [15].

b. Triode or Ohmic Region

MOSFET operates in the triode or ohmic region under following conditions:

NMOS: $\mathbf{V_{GS} > V_{THN}\ ,\ V_{DS} < V_{GS} - V_{THN}}$

PMOS: $\mathbf{V_{SG} > V_{THP}\ ,\ V_{SD} < V_{SG} - V_{THP}}$

In this mode of operation, the current flowing through the MOSFET is given by:

NMOS: $I_D = KP_N \frac{W}{L}((V_{GS} - V_{THN})V_{DS} - \frac{V_{DS}^{\;2}}{2})$

PMOS: $I_D = KP_P \frac{W}{L}((V_{SG} - V_{THP})V_{SD} - \frac{V_{SD}^{\;2}}{2})$

where, $Kp_{n,p}$ is the transconductance parameter and *W* and *L* are the width and length repectively. In this region, the MOSFET acts like a resistor i.e., it scales directly with $V_{DS/SD}$, [15].

c. Saturation Region

MOSFET operates in the saturation region under following conditions:

NMOS: $\mathbf{V_{GS} > V_{THN}}$ **,** $\mathbf{V_{DS} > V_{GS} - V_{THN}}$

PMOS: $\mathbf{V_{SG} > V_{THP}}$ **,** $\mathbf{V_{SD} > V_{SG} - V_{THP}}$

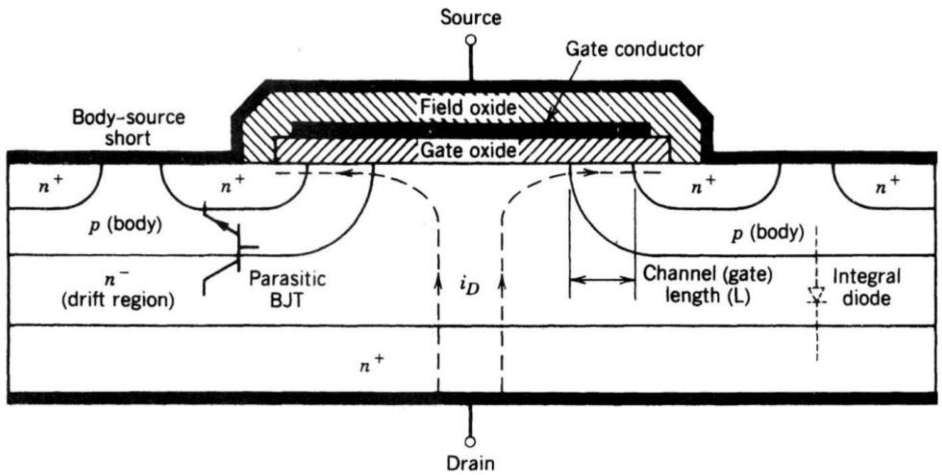
In this mode of operation, the current flowing through the MOSFET is given by:

NMOS: $I_D = \frac{KP_N}{2}\frac{W}{L}(V_{GS} - V_{THN})^2$

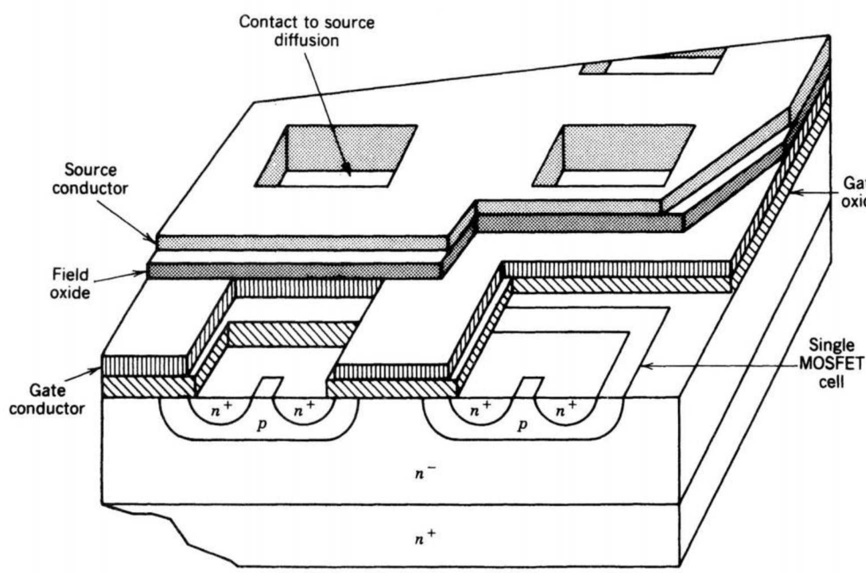
PMOS: $I_D = \frac{KP_P}{2}\frac{W}{L}(V_{SG} - V_{THP})^2$

In this region, the MOSFET can be considered as a constant current source as $V_{DS/SD}$ theoretically has no effect on the current. However, in real devices, current increases with $V_{DS/SD}$ due to channel length modulation. Power MOSFETs generally operate in this region, [15].

2.4 POWER MOSFET



(a)



(b)

Figure 2.8: (a) A single cell of a Power MOSFET, (b) a meshed structure of cells in a Power MOSFET [10]

Generally, Power MOSFETs have different structure than conventional MOSFETs used in digital and low power circuits. As shown in Figure 2.8(a), the structure is vertical instead of planar which allows it to maintain high blocking voltage and high current. The structure shown in the figure is usually termed as VDMOS (Vertical Diffusion MOSFET). The name crudely describes the fabrication sequence of the device, [10][11][12].

As shown in Figure 2.8(b), thousands of cells together form a Power MOSFET. The number of gate/source regions connected electrically in parallel also determines the current carrying capacity of the MOSFET. The source is constructed of thousands of small polygon shaped areas that are connected in parallel and surrounded by the gate region. The geometric shape of the source areas also influences the on-state resistance of the device. These MOSFETs are generally used for switching applications such as rectifiers, DC-DC converters, etc, [10].

There are also Power MOSFETs with lateral structure which are generally used in high-end audio amplifiers. These MOSFETs have a better saturation region performance than vertical MOSFETs.

2.4.1 Body Diode

In Power MOSFETs, the source metallization connects both N+ and P+ implants although only connection to N+ is required. Connecting the N+ and P+ implants prevents the P+ from floating. A floating P+ would entail a parasitic NPN transistor with an unconnected base. Under certain conditions, the parasitic transistor may trigger, making the MOSFET uncontrollable. The connection of P+ to source prevents the NPN transistor from turning on and latching, [10][12].

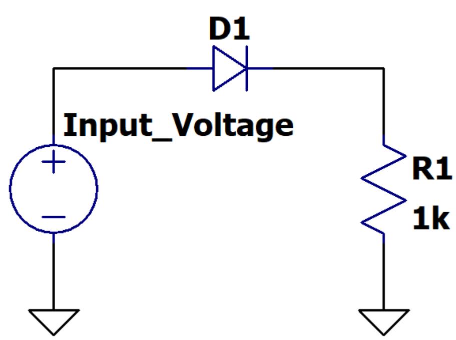
However, this creates a diode between the drain and source of the MOSFET which allows it to block current only in one direction. This diode can be used in various ways for normal operation of MOSFET such as freewheeling diodes for inductive loads in H-bridge, [10][12].

3. SINGLE PHASE RECTIFIERS

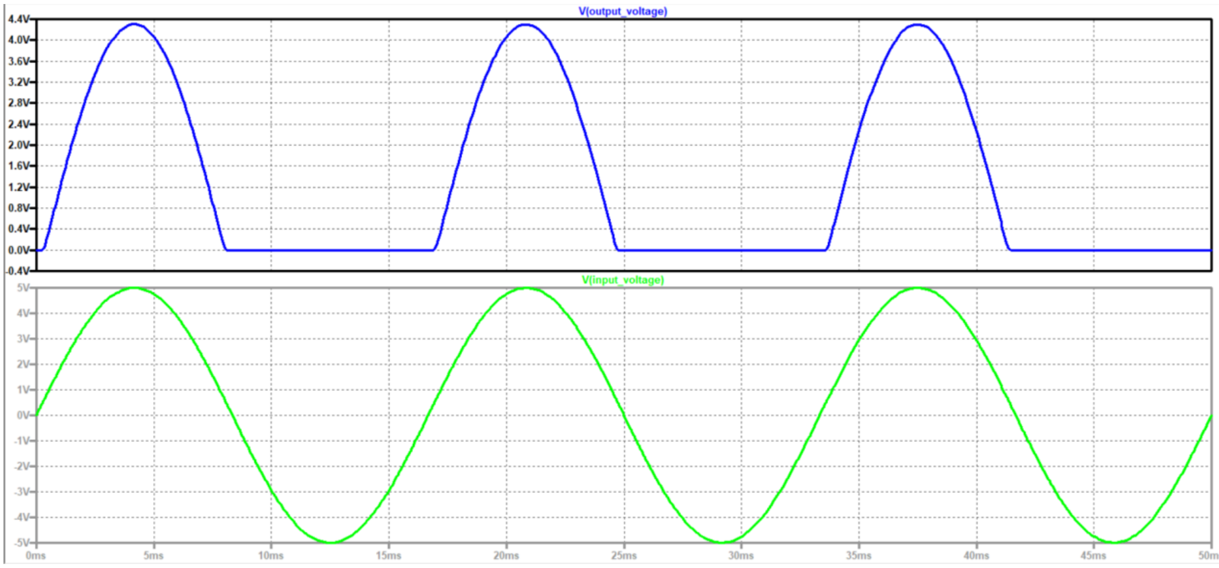
A rectifier is an electrical circuit/device that converts alternating current (AC) into direct current (DC). It does so by ensuring that current flows only in one direction. There are various methods for implementation of rectifiers using diodes, vacuum tubes, MOSFETs, BJTs, thyristors, etc, [10][12].

3.1 Half wave rectifier

In half wave rectifier of a single-phase supply, only one half of the wave (i.e., either positive or negative half of the AC wave) is passed. In mathematical sense, it can be considered as a function that filters values on either positive or negative side and passes values from the other side. Half wave rectifiers can be implemented using a single diode in series with the single-phase supply. It produces a unidirectional and pulsating current and requires additional filters to remove the unwanted harmonics from the output, [10].



(a)



(b)

Figure 3.1: (a) Single phase half-wave rectifier, (b) input (green) and output (blue) of the rectifier

In an ideal half wave rectifier, output voltage of the rectifier is given by:

$$V_{avg/dc} = \frac{Vpeak}{\Pi}$$

$$V_{rms} = \frac{Vpeak}{2}$$

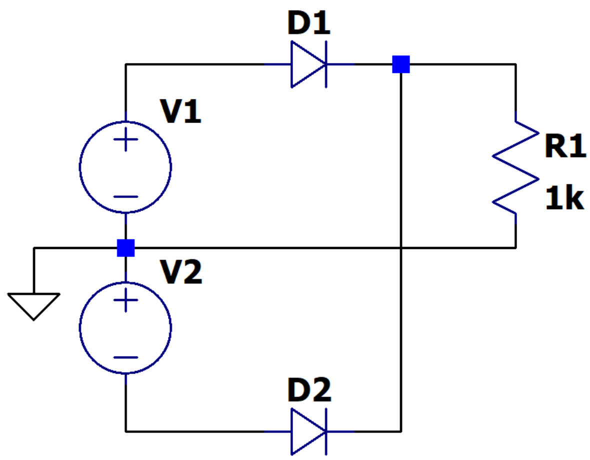
where, $V_{avg/dc}$ is the average or dc value of the output voltage.

V_{rms} is the root mean square value of the output voltage.

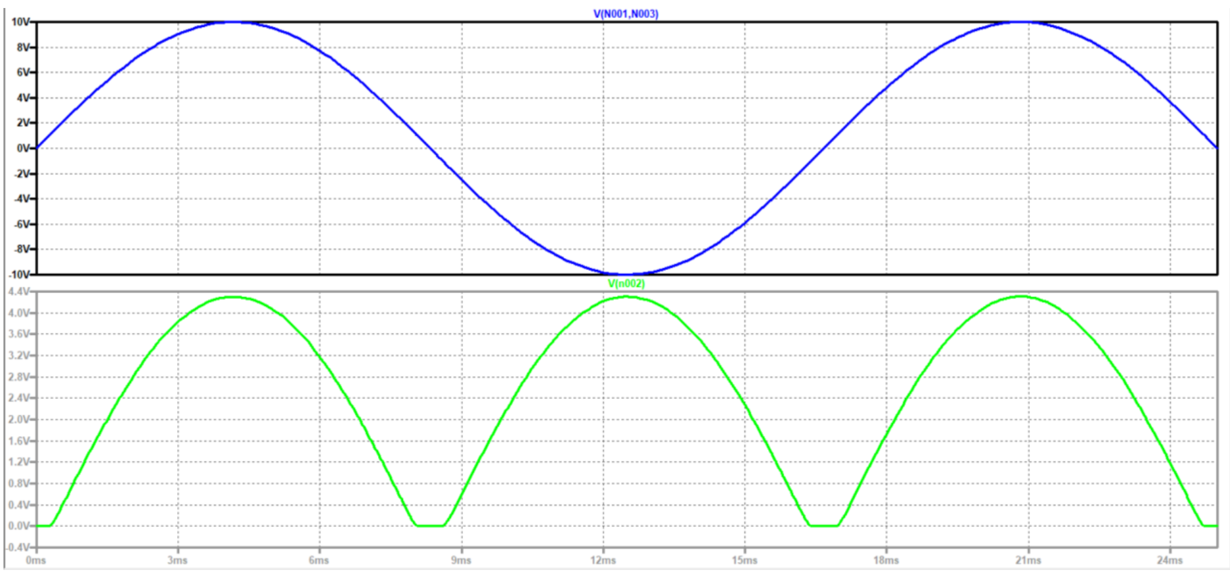
V_{peak} is the peak value of the input voltage.

3.2 Full wave rectifier

In a full wave rectifier of a single phase supply, both positive and negative half of the AC wave is passed to the output. However, the wave is modified such that the current is always flowing in the same direction across the load. It converts the whole input waveform so that a constant polarity is maintained in the output waveform, positive or negative. A full wave rectifier can be built using two diodes and a center tapped transformer or four diodes and any AC source. Since it uses the full wave, it produces less harmonic distortion than the half wave rectifier, [10][12].



(a)

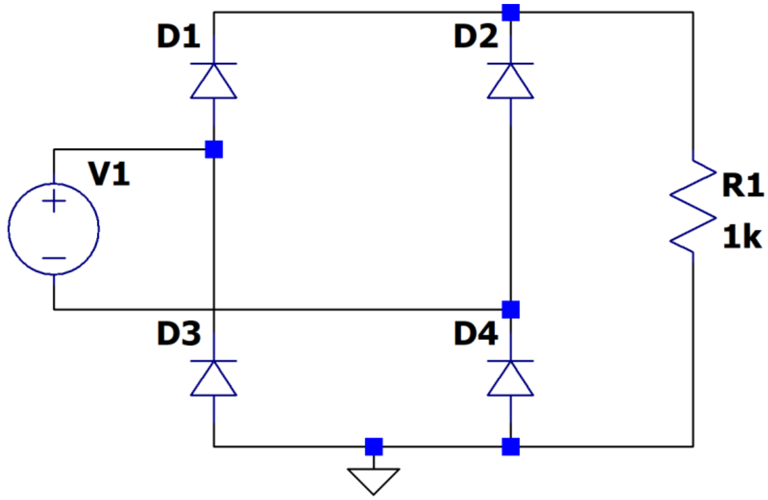


(b)

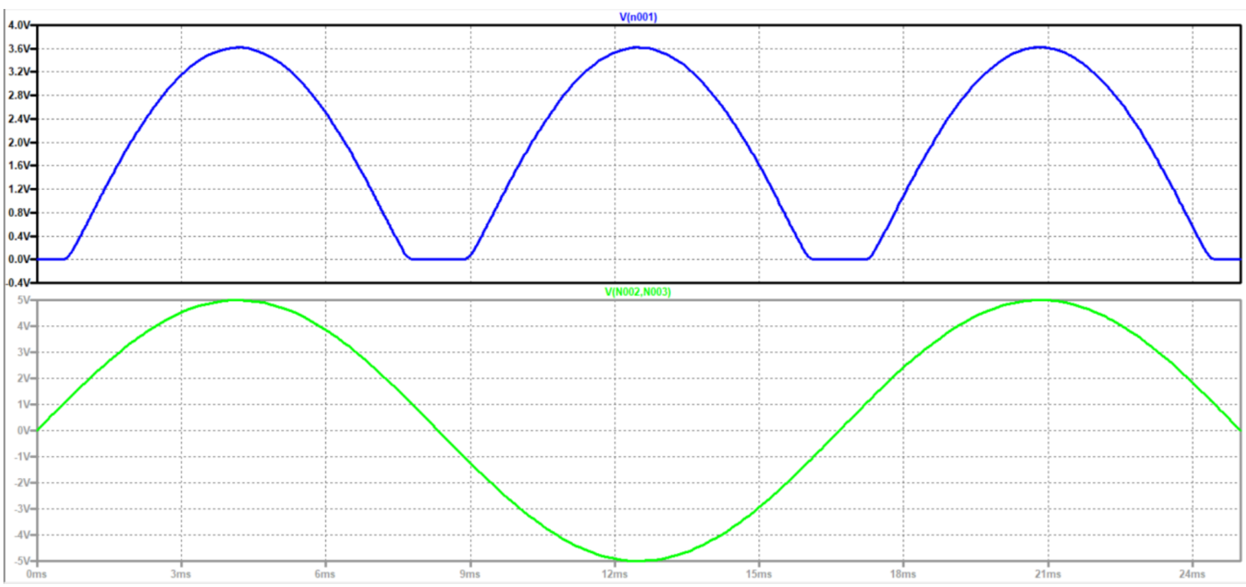
Figure 3.2: (a) Full wave rectifier with two diodes and center-tapped transformer, (b) input (blue) and output (green) of the rectifier

In Figure 3.2(a), voltage sources V1 and V2 represents the secondary side of a center-tapped transformer.

With center-tapped transformer as a source, two diodes connected back-to-back i.e., cathode to cathode or anode to anode depending on the required polarity of the output wave, forms a full wave rectifier, as shown in Figure 3.2(a). This configuration requires twice the secondary winding in the transformer as a bridge rectifier to get the same magnitude of output waveform. Figure 3.2(b) shows the input and output voltage waveform of the rectifier, [10][12].



(a)



(b)

Figure 3.3: (a) Full wave bridge rectifier, (b) input (green) and output (blue) of the rectifier

In Figure 3.3(a), a full wave bridge rectifier using diodes is shown. Figure 3.3(b) shows the input and output voltage waveform of the rectifier.

During the positive cycle of the AC source, diodes D1 and D4 conducts and current flows from the top of the resistor to the bottom. During the negative cycle, diodes D2 and D3 conducts and current flows from the top of the resistor to the bottom again. During both positive and negative cycles of the source, current flowing through the resistor is always in same direction.

In an ideal full wave rectifier, output voltage of the rectifier is given by:

$$V_{avg/dc} = \frac{2*Vpeak}{\Pi}$$

$$V_{rms} = \frac{Vpeak}{\sqrt{2}}$$

where, $V_{avg/dc}$ is the average or dc value of the output voltage.

V_{rms} is the root mean square value of the output voltage.

V_{peak} is the peak value of the input voltage.

3.3 Switch-mode Power Supply

Switch-mode Power Supplies (SMPS) are electrical circuits that use switching elements like transistors and energy storage devices like capacitors and inductors to convert power efficiently. The switching elements are turned on and off at high frequencies and the energy storage devices to conduct power when the switch elements are in non-conducting state. SMPS are highly efficient and are widely used in computers, embedded systems and other sensitive electrical equipment requiring stable and efficient power supply, [17][18].

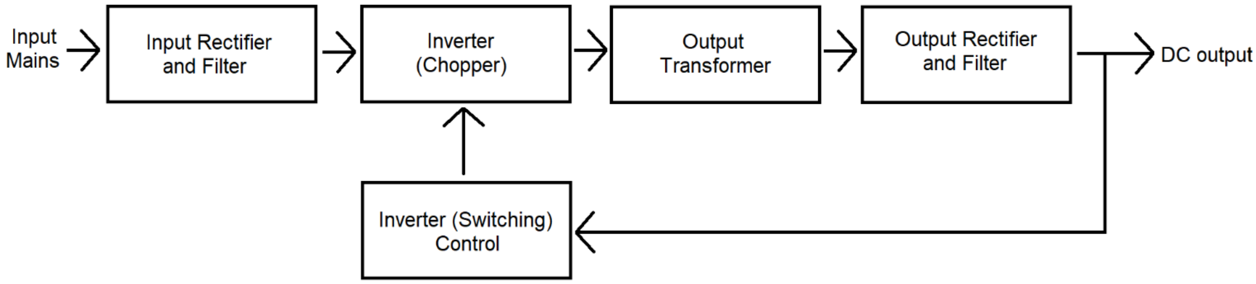


Figure 3.4: Simple SMPS block diagram

A basic AC-DC SMPS normally operates in following steps:

a. Input Rectifier and Filter

The input rectifier takes in the AC and converts to DC. A capacitor is used to filter the ripples in the rectified DC voltage. A SMPS that has been designed to work with AC inputs can also work with DC inputs as the DC signal will just pass through the rectifier.

b. Inverter

The DC signal is then sent through a power oscillator to generate a high frequency AC signal. The frequency of the AC signal is typically kept greater than 20kHz to keep it inaudible to human hearing. The oscillator is normally implemented using MOSFETs which have high efficiency and high current carrying capacity.

c. Transformer

The transformer is used to step-up or step-down the AC voltage as required. It is generally very small with a few windings. These transformers are generally highly efficient. Some non-isolated power supplies may also use an inductor instead of a transformer. These types of switching power supplies include boost, buck and buck-boost converters.

d. Output Rectifier and Filter

The output rectifier converts the output of the transformer to DC. The output is then filtered using filters made of capacitors and inductors. For higher frequencies, smaller capacitors and inductors are needed.

e. Feedback and Control circuit

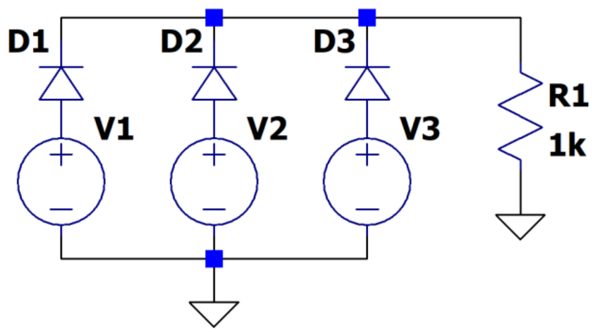
The final output voltage is monitored and compared with a reference voltage. Depending on the difference between output voltage and reference voltage is used to adapt the duty cycle of the power oscillator. Depending on requirements, the control system may not be isolated from the output. The feedback circuits need power to operate so an additional power source may be used.

Some open-loop regulators may also not have a feedback mechanism. They will instead feed constant voltage to the transformer or the inductor assuming that the output will be correct, [17][18].

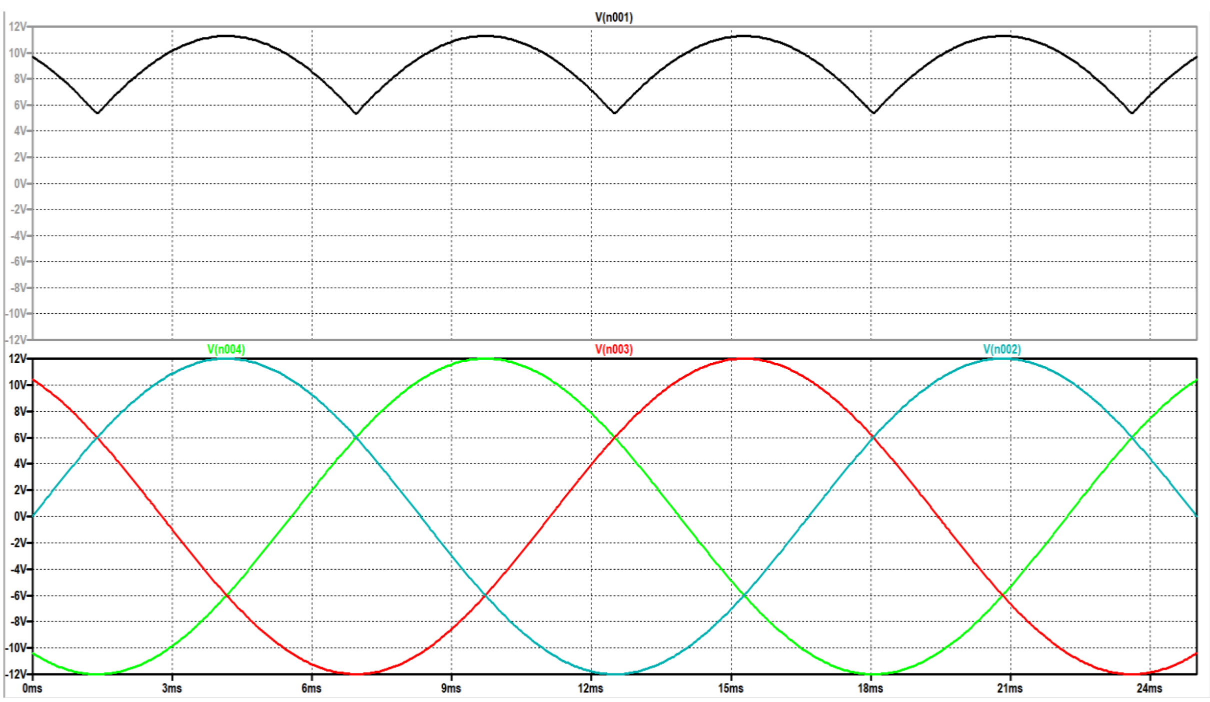
4. THREE PHASE RECTIFIERS

Like single-phase rectifiers, three-phase rectifiers convert three-phase AC signals into DC signal by ensuring current flows in only single direction. Three-phase rectifiers are generally used for industrial and high-power applications. Similar to its single-phase counterpart, it has half-wave, full-wave and full-wave using center tapped transformer variants, [10][12].

4.1 Half-wave rectifier



(a)



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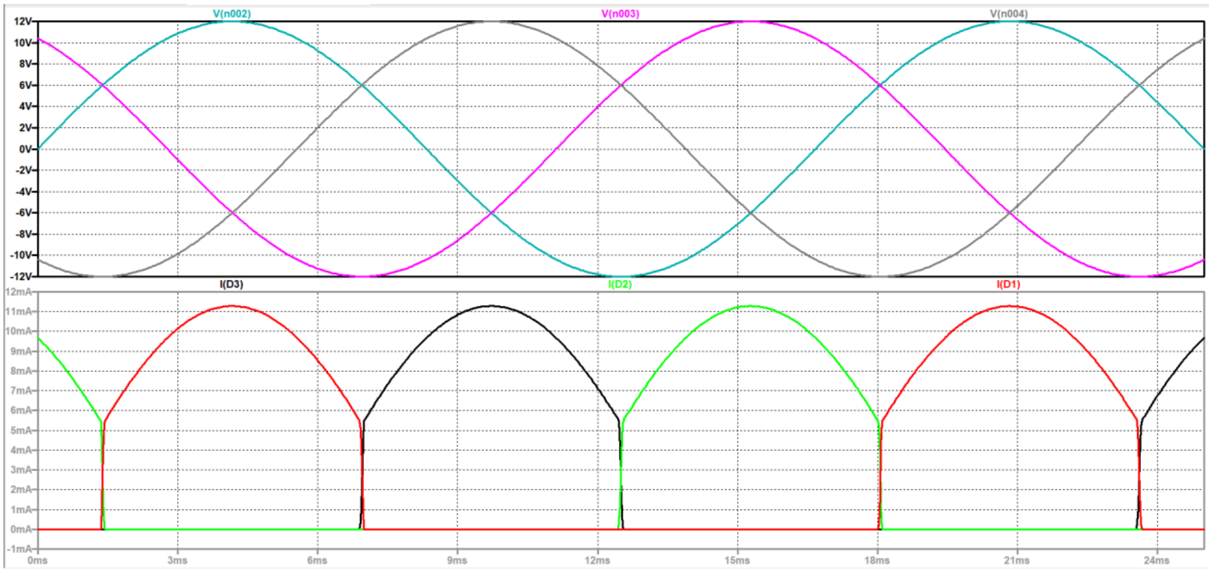


(c)

Figure 4.1: (a) Half-wave three phase rectifier, (b) input (green, red, blue) and output (black) of the rectifier, (c) current through the diodes and input voltages

In Figure 4.1(a), V1, V2 and V3 represents the three-phase voltages of the three-phase AC power supply. Figure 4.1(b) shows the output and input voltages of the rectifier. Figure 4.1(c) shows the input of the rectifier and current through each diode.

In this configuration, each diode conducts when their corresponding voltage sources is the highest in the group: D1 conducts when V1 is highest, D2 when V2 is highest and D3 when V3 is highest. The frequency of output voltage ripple is three times the frequency of input voltage.

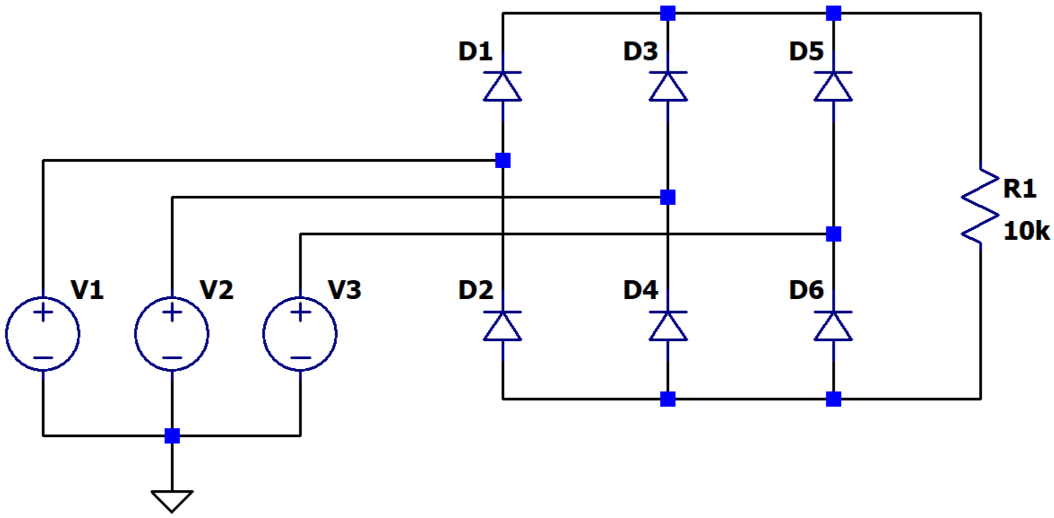
The average output voltage can be given by:

$$V_{avg/dc} = \frac{3\sqrt{3}}{2\pi} V_{peak}$$

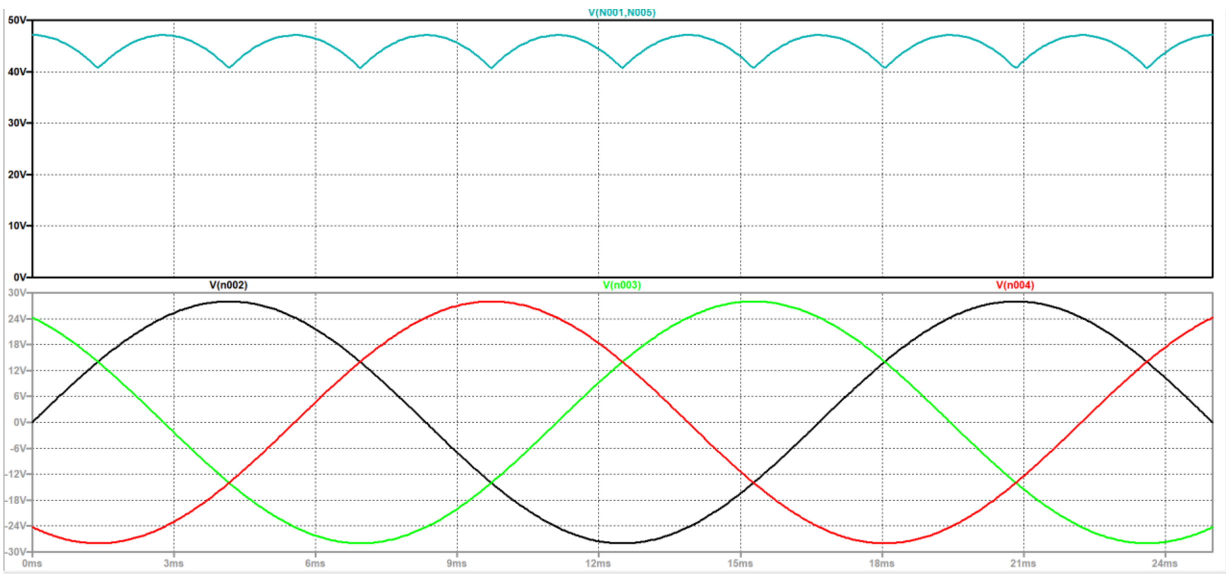
where, $V_{avg/dc}$ is the average or dc value of the output voltage.

V_{peak} is the peak value of the input voltage.

4.2 Full-wave bridge rectifier



(a)



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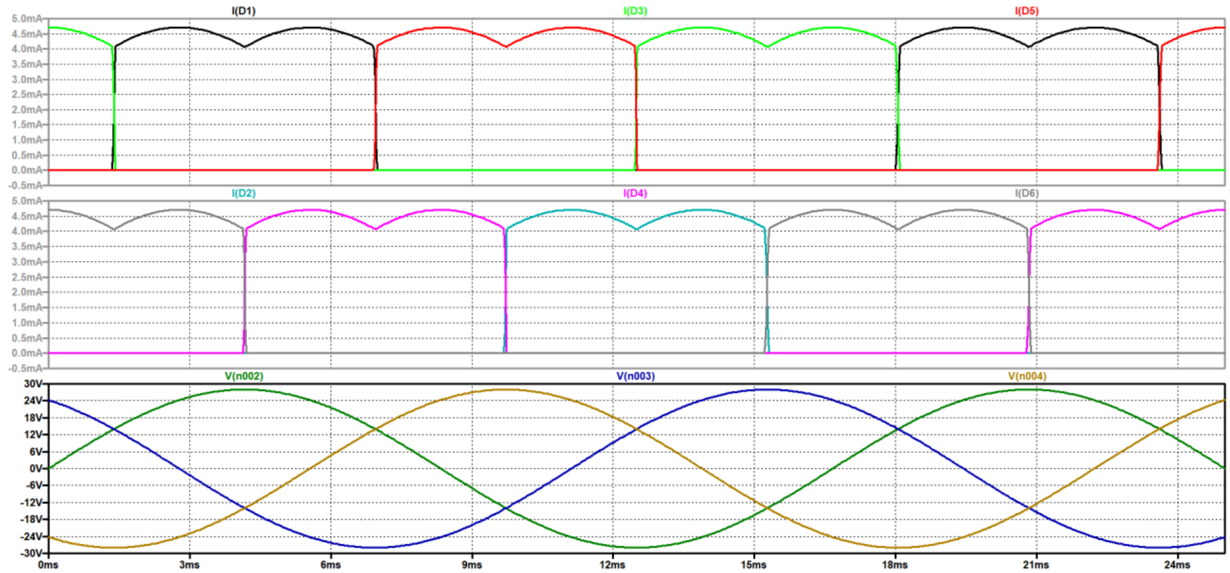


(c)

Figure 4.2: (a) Full-wave three phase bridge rectifier, (b) input (green, red, black) and output across the load resistor (blue) of the rectifier, (c) current through the diodes and input voltages

In Figure 4.2(a), V1, V2 and V3 represents the three phase voltages of the three-phase AC power supply. Figure 4.2(b) shows the output and input voltages of the rectifier. Figure 4.2(c) shows the input of the rectifier and current through each diode.

In this configuration, both the positive half and negative half of the three phases are rectified into a DC signal. D1, D3 and D5 conduct when their respective voltage sources, V1, V2 and V3 are most positive (highest magnitude) and D2, D4 and D6 conduct when their respective voltage sources, V4, V5 and V6 are most negative (highest magnitude). Under normal operation, same branch pairs i.e., D1-D4, D2-D5 and D3-D6 never conduct at the same time. The frequency of output voltage ripple is six times the frequency of input voltage.

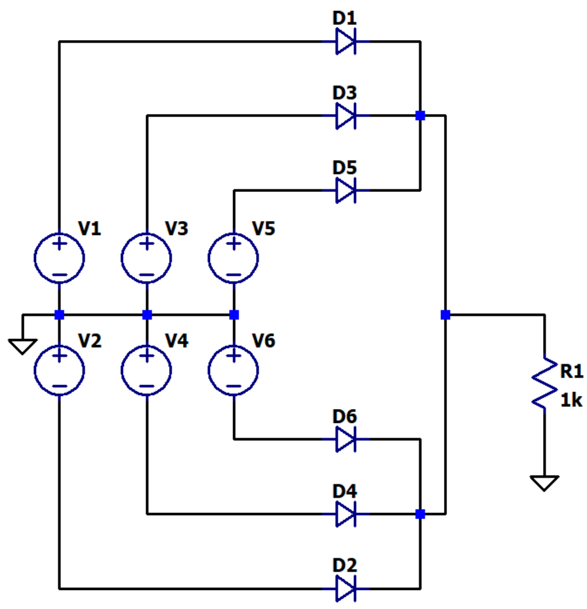
The average output voltage can be given by:

$$V_{avg/dc} = \frac{3\sqrt{3}}{\pi} V_{peak}$$

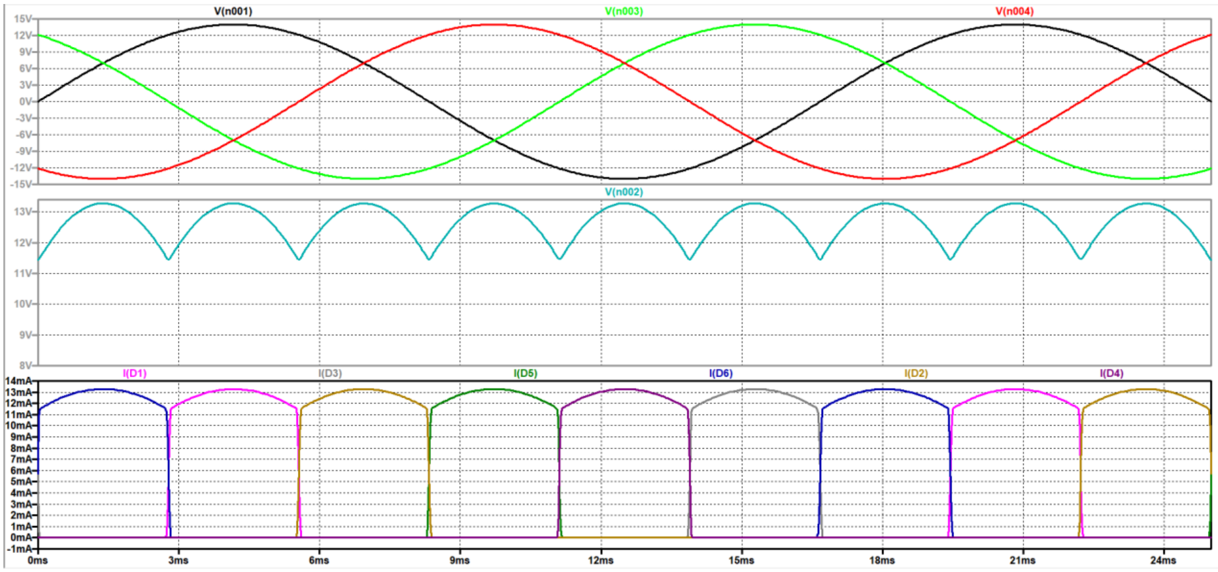
where, $V_{avg/dc}$ is the average or dc value of the output voltage.

V_{peak} is the peak value of the input voltage.

4.3 Three phase full-wave rectifier using center tapped transformer



(a)



(b)

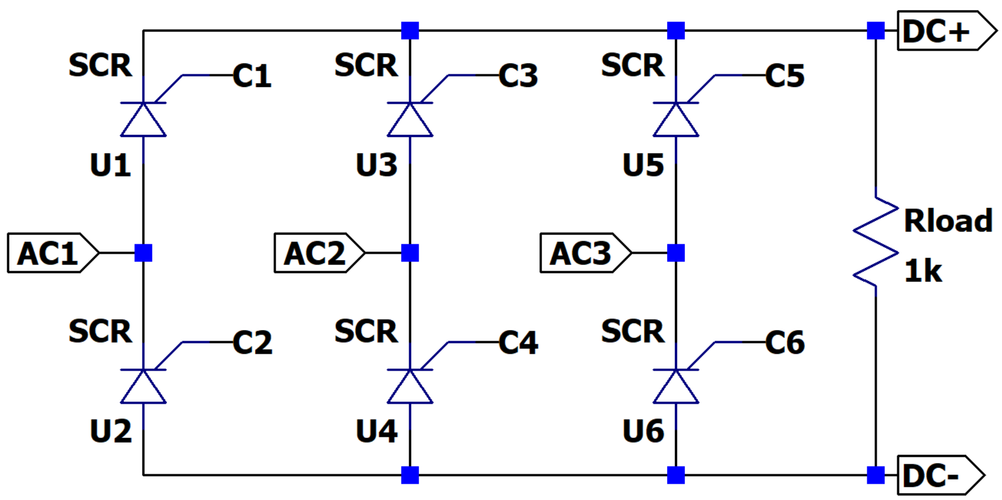
Figure 4.3: (a) Full-wave three phase rectifier using center-tapped transformer, (b) input (green, red, black), output (blue) of the rectifier and current through the diodes

In Figure 4.3(a), V1, V2 and V3 represents the three phase voltages of the three-phase AC power supply. Figure 4.3(b) shows the output, input voltages of the rectifier and current through each diode.

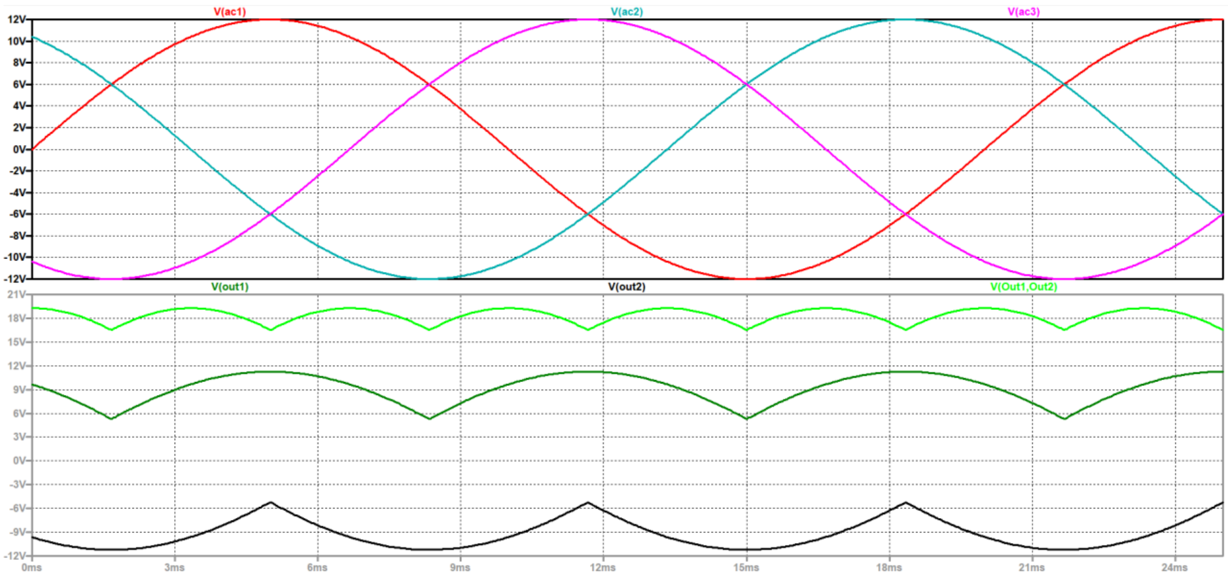
In this configuration, the diode corresponding to the highest voltage conducts and supplies the load. Similar to the bridge rectifier, frequency of ripple is six times the frequency of input voltage.

4.4 Three phase controlled bridge rectifier

All rectifier configurations till now have been built using diodes which cannot be controlled. A controlled three-phase bridge rectifier is built using components like BJTs, IGBTs, thyristors, power MOSFETs, etc. which can be turned on and off using a control signal.



(a)



(b)

(c)

Figure 4.4: (a) Three-phase controlled bridge rectifier, (b) Three-phase AC input (AC1-AC3) and rectified DC outputs (OUT1, OUT2, voltage across load), (c) Three-phase AC input (AC1-AC3) and thyristor control signals (C1-C6)

In Figure 4.4(a), AC1, AC2 and AC3 represents the three phases of the three-phase AC power supply. The controlled bridge rectifier is built similar to the diode bridge rectifier with six thyristors and two thyristors connected to each phase. The control inputs to the thyristors are C1-

C6, controlling the respective thyristors. Figure 4.4(b) shows the input and output voltage waveforms of the rectifier. Figure 4.4(c) shows the input voltage waveform and the control signals.

Similar to diode bridge rectifier, the phase with highest magnitude (both positive and negative) is passes through the thyristor while the lesser phases are blocked. The control/trigger signals are generated at the instance the corresponding phase becomes the highest voltage among the three. For instance, when V(AC1) becomes the highest positive voltage, the control signal C1 goes high which triggers the thyristor U1. Similarly, when V(AC3) becomes the highest negative voltage, C6 goes high which triggers the thyristor U6.

4.5 VIENNA RECTIFIER

Vienna Rectifier is a pulse width modulation rectifier invented by Johann W. Kolar in 1993. It is one of the most prominent three phase rectifier topology for unity power factor operation. Compared to three-phase controlled bridge rectifiers, which are two level rectifiers, it is a three level rectifier. It uses unidirectional switches, which uses multiple diodes surrounding a single switch. It has ohmic operation, i.e. it acts like a resistor for the AC supply. This means that the supply voltages and currents are both sinusoidal in nature, [19][20][21][22].

The advantage of Vienna Rectifier is that it only uses three power switches which makes it cheaper compared to bridge rectifiers with six power switches. The disadvantages of Vienna rectifiers are that they are unidirectional and may require electro-magnetic interference filtering due to high frequency switching of the switch elements, [20][23].

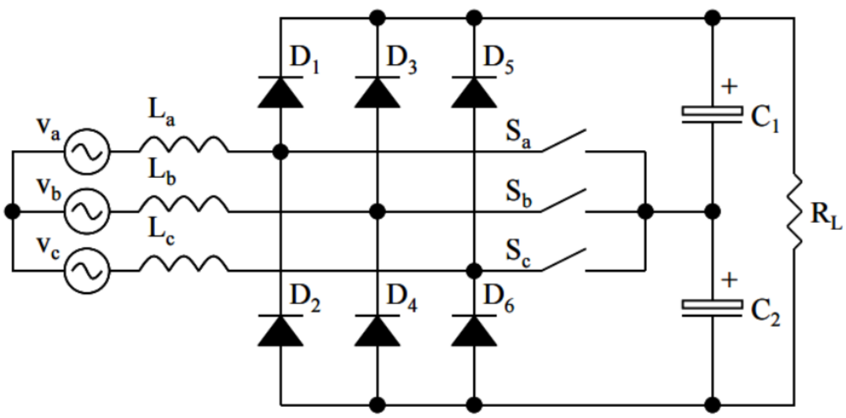


Figure 4.5: Three-phase Three-level Vienna Rectifier [23]

The rectifier essentially functions as a two-switch boost rectifier with one of the switches switched at line frequency and the other two at high frequency. The output of the rectifier is a split DC rail as such the output has three levels and the control is only required for three switches, [19][22][23].

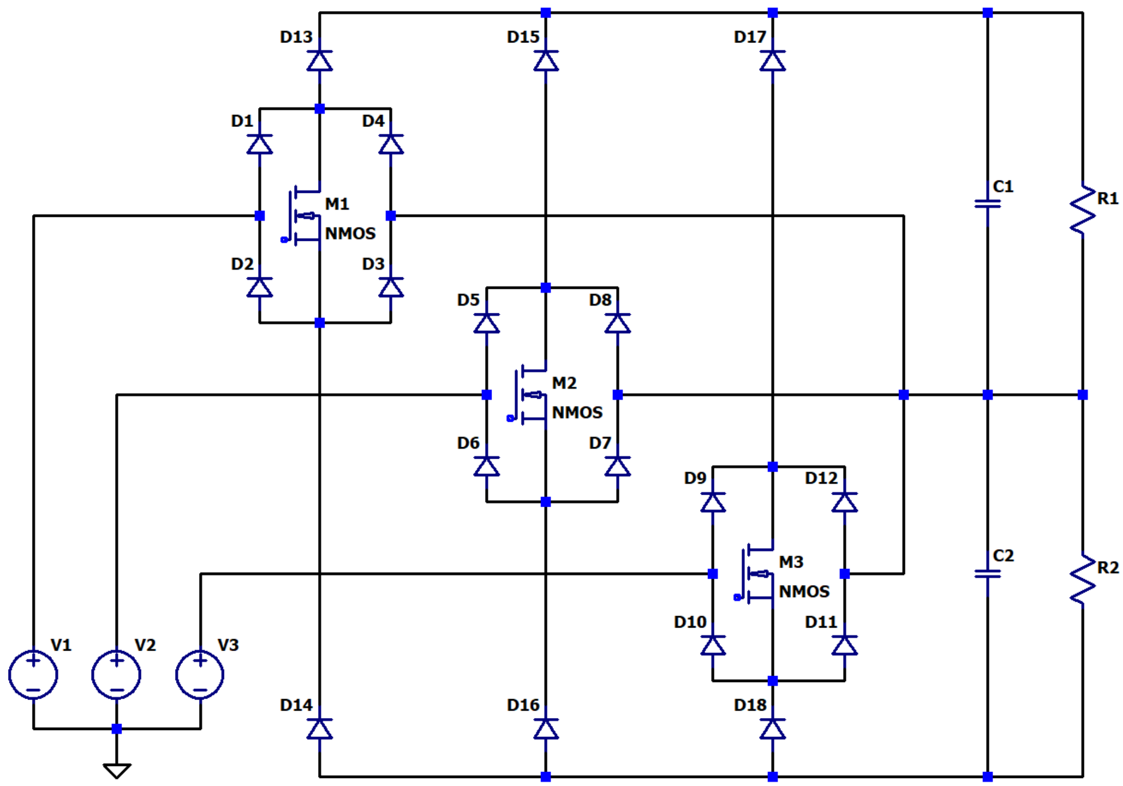


Figure 4.6: Vienna Rectifier PLECS model

As one switch always switches at input frequency, the rectifier can be seen as two different boost rectifiers each boosting the two capacitors separately. The output voltage is always higher than the maximum of the input AC voltage which may not be desirable for all applications, [20][23].

The switches are controlled using the hysteresis control technique. However, the control scheme can be pulse width modulation (PWM) or any other. Figure 4.7 shows the basic concept of the hysteresis control, [23].

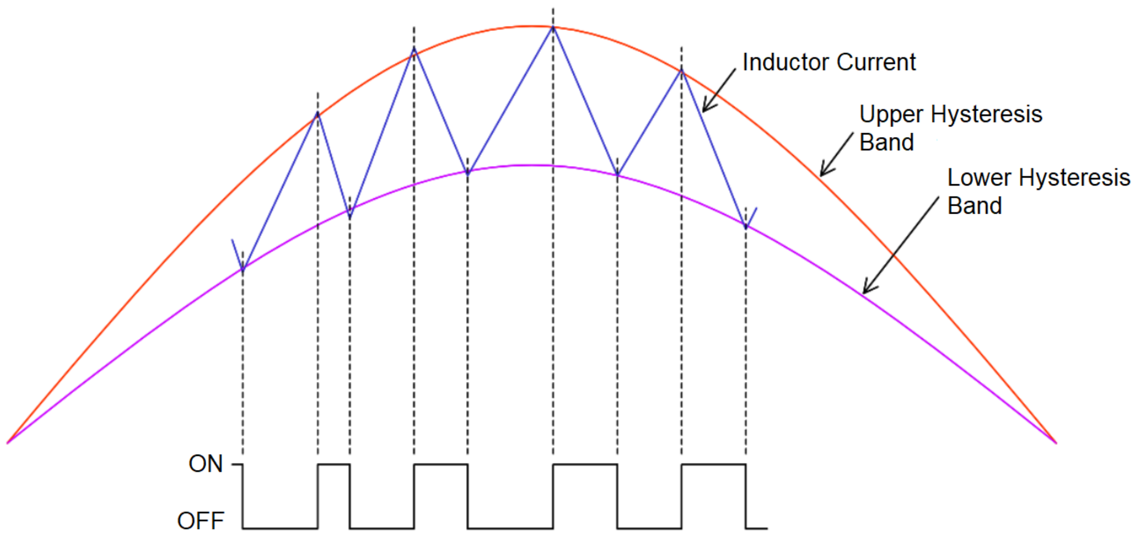


Figure 4.7: Hysteresis control band for the Vienna Rectifier

Two current bands are fixed, and the switches are switched within the boundaries set up by these bands. The frequency of the switching is controlled by these bands. Another type of control is using fixed frequency switching while the pulse width is varied, [23]. Figure 4.8 shows the input AC voltages, AC currents and the output DC voltage of the Vienna Rectifier PLECS model.

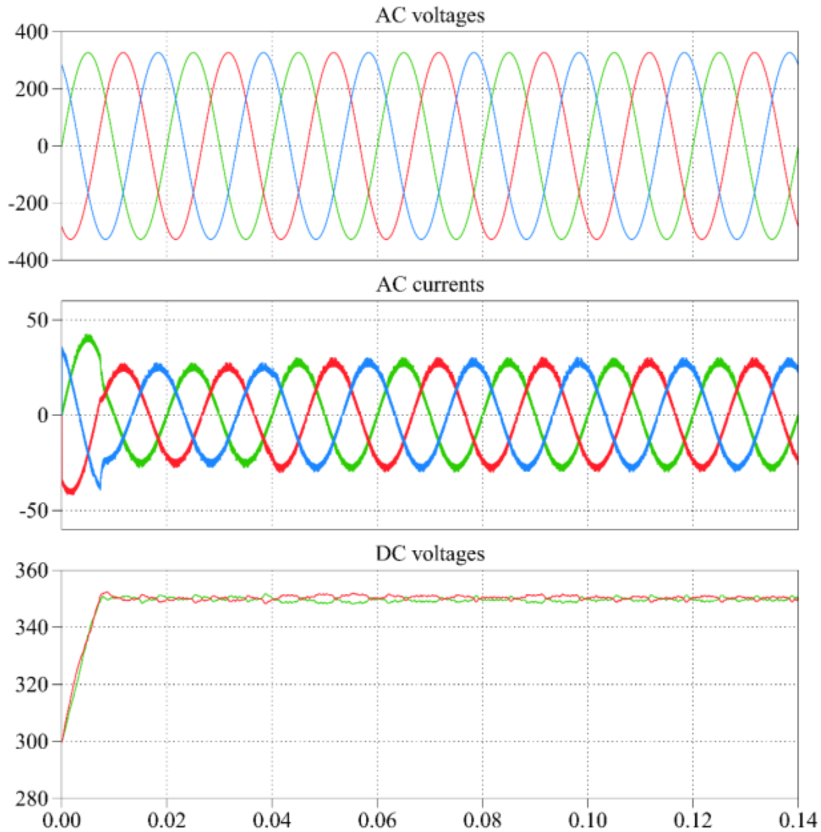


Figure 4.8: Input AC voltages, AC currents and output DC voltage of Vienna Rectifier PLECS Model [23]

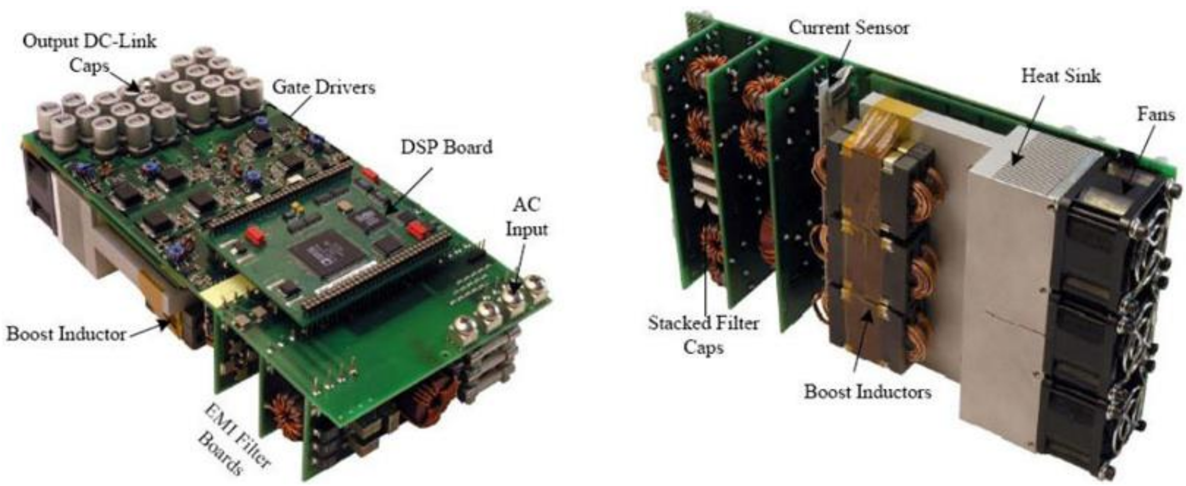


Figure 4.9: Top and Bottom Views of air-cooled 10kW Vienna Rectifier (400kHz PWM) [22]

5. OTHER RECTIFIER TOPICS

5.1 VOLTAGE SMOOTHING IN RECTIFIERS

5.1.1 Ripple Voltage

Ripple voltage is defined as an unwanted ac voltage component within a primarily DC voltage. It is generally seen when the DC voltage is derived from an AC power source using rectification. It may also be due to generation and commutation of DC power.

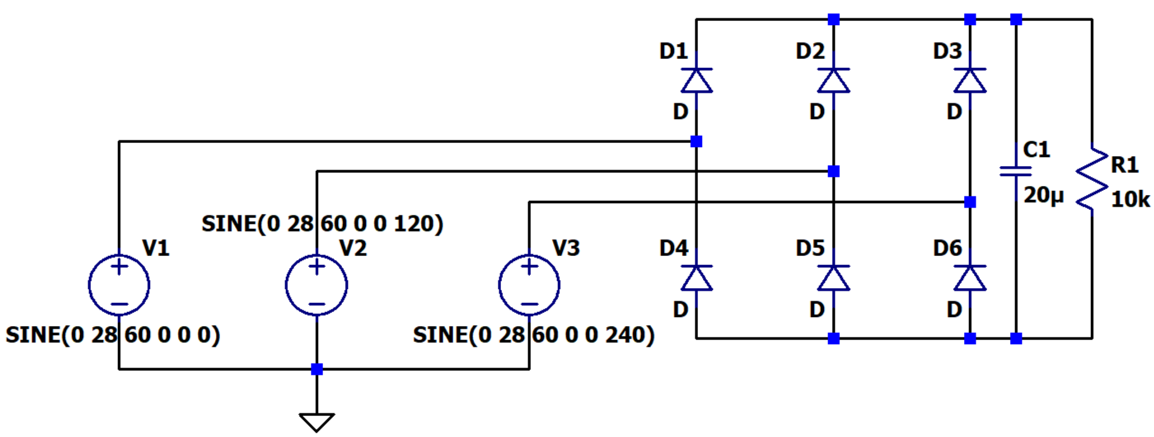
Ripples decrease the efficiency of DC circuits as the AC component is basically wasted power. It also causes unwanted effects like heating, noise, and faulty operation of digital circuits.

5.1.2 Filtering and Voltage Regulation

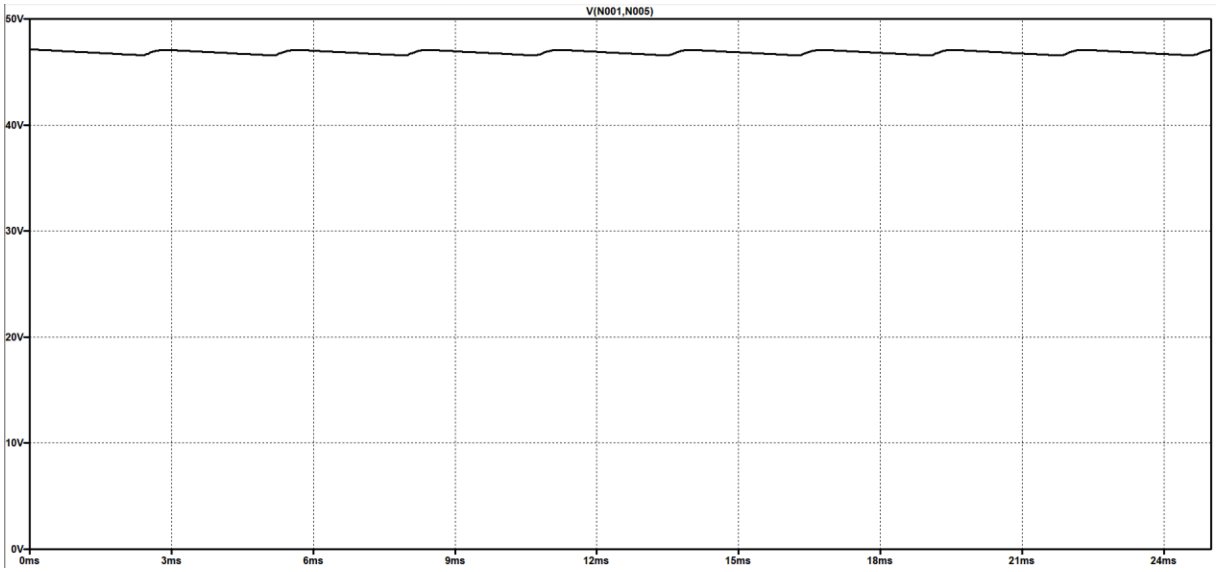
Ripples are generally eliminated in two steps:

a. Filtering

A common method for filtering ripples is for the rectifier to feed into a large smoothing capacitor which can act as charge storage. After the ripple reaches its peak, the capacitor supplies current to the load impedance. It does so till the capacitor voltage falls below the rectifier output voltage. Then, the capacitor starts charging again until peak voltage is reached.



(a)



(b)

Figure 5.1: (a) Three-phase bridge rectifier with smoothing capacitor, (b) Output Voltage

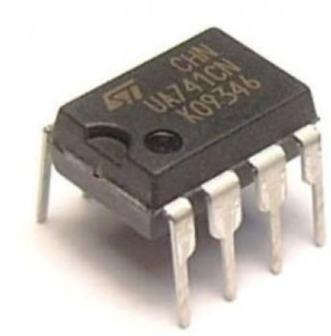
In comparison to the output of three phase bridge rectifier without smoothing capacitance, ripple voltage in the output is greatly reduced.

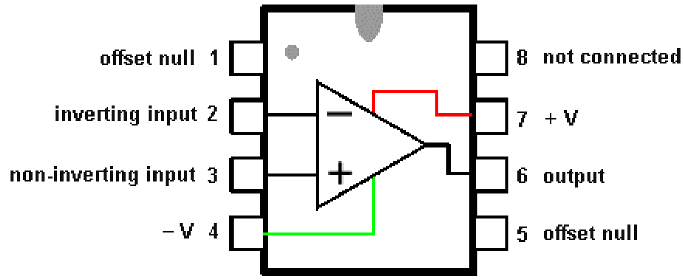
b. Voltage regulation

After the smoothing capacitance has reduced the ripple, a voltage regulator circuit can filter out all of the ripple as long as the minimum ripple voltage is greater than the voltage regulator's output voltage. A simple voltage regulator circuit can be created using a Zener diode.

5.2 OPERATIONAL AMPLIFIER

An ideal operational amplifier, op-amp in short, is an infinite gain differential amplifier with infinite input resistance, zero output resistance and infinite bandwidth. A practical op-amp has large gain (usually hundreds of thousands), high input resistance, low output resistance and finite bandwidth. Op-amps are one of the most widely used electronic devices today. With a few external components, it can perform many functions such as filtering, amplifying and other signal processing tasks, [15].





(a) (b)

Figure 5.2: (a) LM741, an operational amplifier, (b) LM741 pinout

5.2.1 Op-Amp Circuit Configurations:

Some of the op-amp configurations used in controlled rectifiers are discussed below:

a. Differential Amplifier

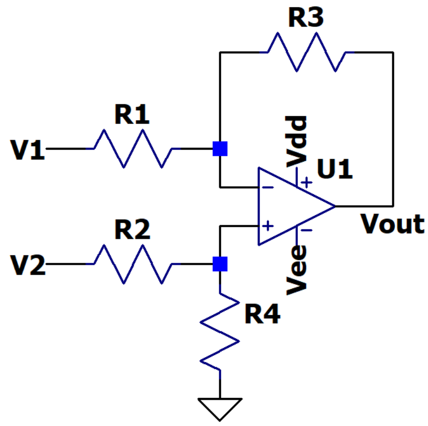
Assuming V_1 and V_2 are two inputs of op-amp, output of the amplifier is given by, [24]:

$$V_{out} = -V_1(\frac{R_3}{R_1}) + V_2(\frac{R_4}{R_2 + R_4})(\frac{R_1 + R_3}{R_1})$$

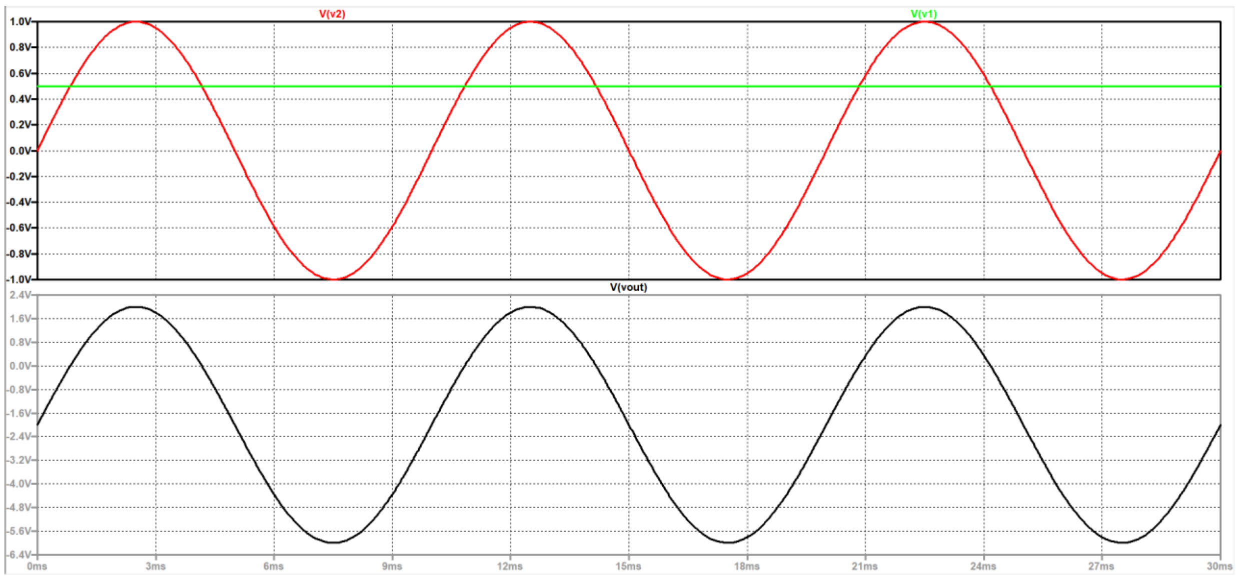
when R_1=R_2 and R_3=R_4,

$$V_{out} = \frac{R_3}{R_1}(V_2 - V_1)$$

When R_1=R_2=R_3=R_4, the amplifier becomes a unity gain differential amplifier, i.e. $V_{out} = V_2 - V_1$



(a)



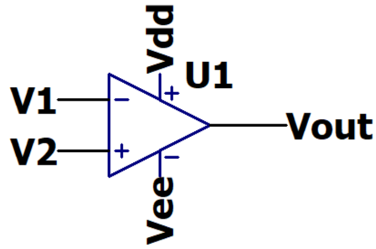
(b)

Figure 5.3: (a) Differential Amplifier, (b) Inputs (green, red) and output (black) of the amplifier

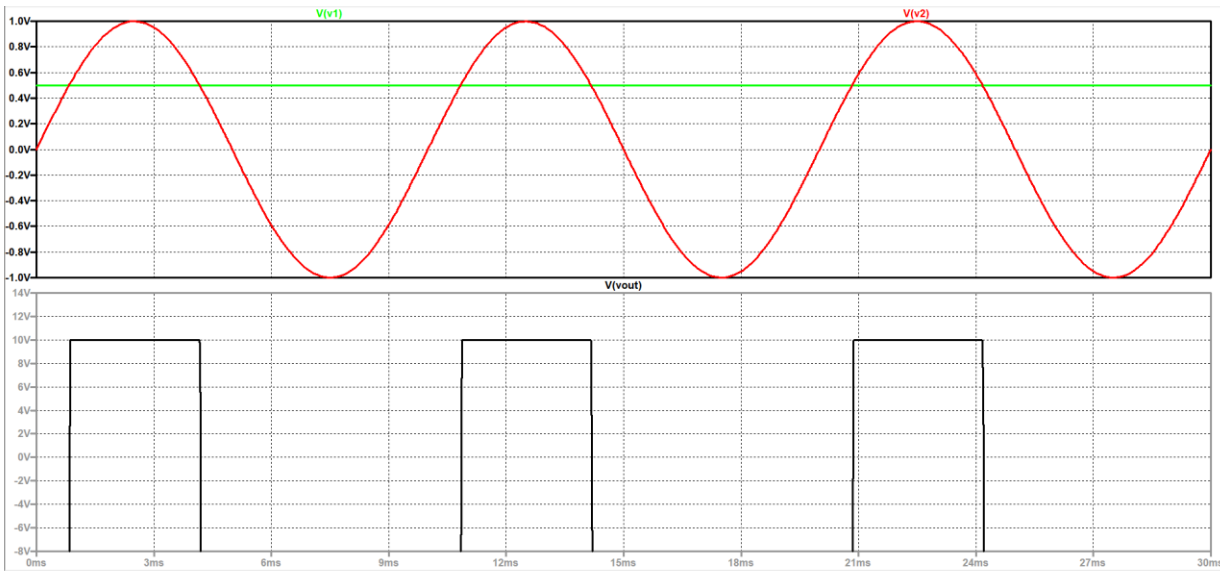
b. Comparator

In the comparator configuration, op-amp compares the voltages at its inverting and non-inverting inputs and outputs the positive rail or negative rail voltage depending on which input is higher. The output of this configuration is given by:

$$\begin{aligned} V_{out} &= V_{DD},\ if\ \ V_{non-inv} > V_{inv} \\ &= V_{EE},\ if\ \ V_{inv} > V_{non-inv} \end{aligned}$$



(a)



(b)

Figure 5.4: (a) Comparator, (b) Inputs (green, red) and output (black) of the comparator

5.3 SHORT CIRCUIT PROTECTION SCHEMES

Short circuit is a condition in electrical circuits that allows current to pass through an unintended path with almost zero electrical impedance. Short circuit faults in a circuit can create an overcurrent condition which can cause catastrophic damage to circuit elements, ranging from overheating to explosion. This will render the circuit unable to perform its function as well as damage the power source and electrical load.

Short circuit protection is implemented in rectifier circuits and MOSFET circuits in different ways. Some of them are detailed in the following sections.

5.3.1 Self-protected power MOSFET

Power MOSFETs like IRSF3011, NCV8411 and ZXMS6004FF are smart power MOSFET with built in short circuit, over-temperature, Electrostatic Discharge (ESD) and over-voltage protection, [25][26][27]. The on-chip circuits turns the MOSFET off when it detects the drain current or the junction temperature exceeding the device specification and keeps it off until the input is turned low. The gate-to-source and gate-to-drain voltages are clamped to reduce the risk of ESD and over-voltages respectively.

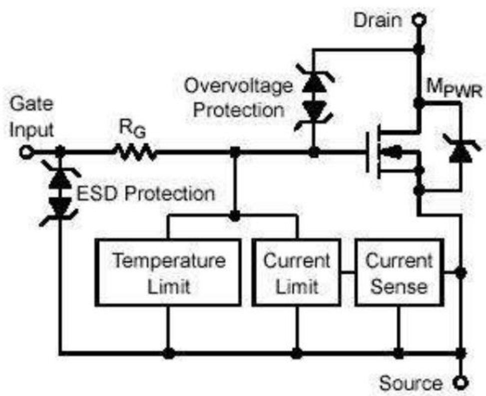


Figure 5.5: Self Protected MOSFET topology [25]

IRSF3011 overcurrent protection:

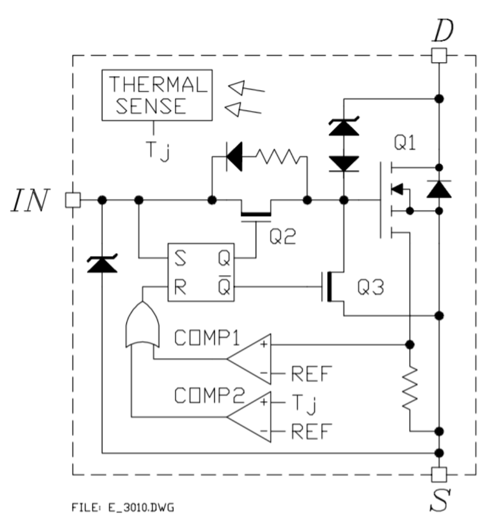


Figure 5.6: IRSF3011 block diagram [25]

A Zener diode is connected between the source and gate to provide ESD protection. The SR flip-flop controls the Q2 and Q3 switches and memorizes the occurrence of overcurrent condition. The flip-flop is cleared by holding the input low for a specified duration, [25].

COMP1 and COMP2 are comparators are used to detect overcurrent and over-temperature conditions. They compare the signals from the MOSFET with a built-in reference and can reset the SR flip-flop and turn Q1 off. During overcurrent or over-temperature condition, Q2 disconnects the gate of Q1 from the input and Q3 shorts the gate and source of the Q1 which results in rapid turn-off of Q1. The Zener diode between drain and gate of Q1 turns Q1 on when the drain to source voltage exceeds 55V, [25].

The following figure shows the overcurrent response of IRSF3011. When the drain current reaches/exceeds the predefined value, the MOSFET is shut down and the drain voltage goes from ~0V to ~10V, [25].

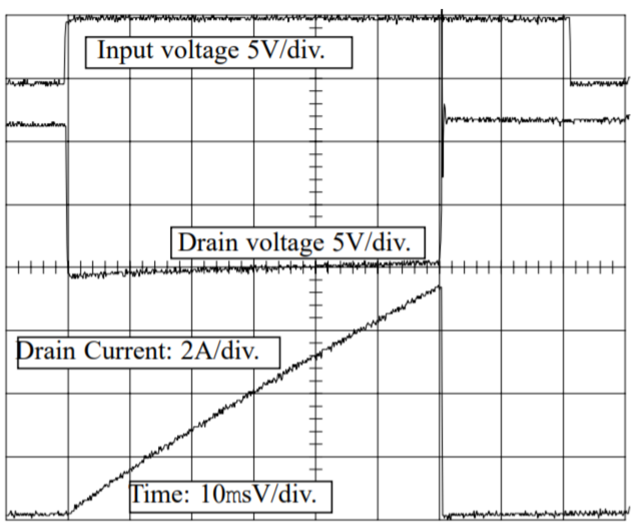


Figure 5.7: Overcurrent response in IRSF3011, [25]

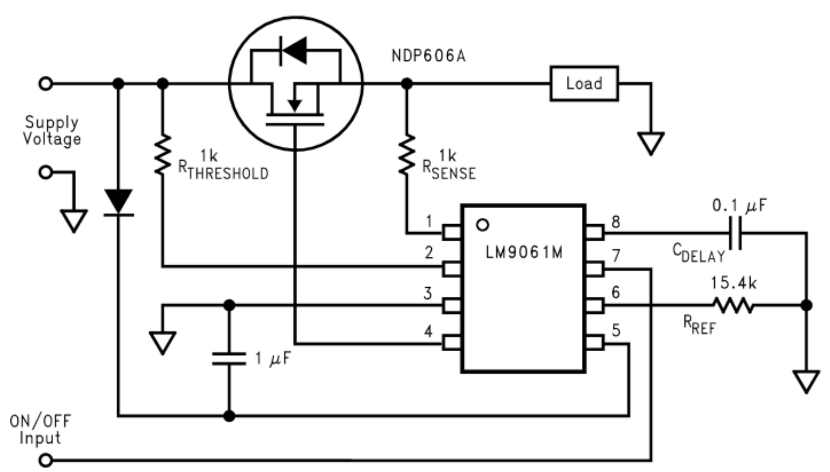
5.3.2 Overcurrent Protection ICs

There are various ICs such as LTC4361-1/2 and LM9061/-Q1 which are used for control as well as protection of Power MOSFETs, [28][29]. These ICs may use sensing resistors or forgo their use entirely.

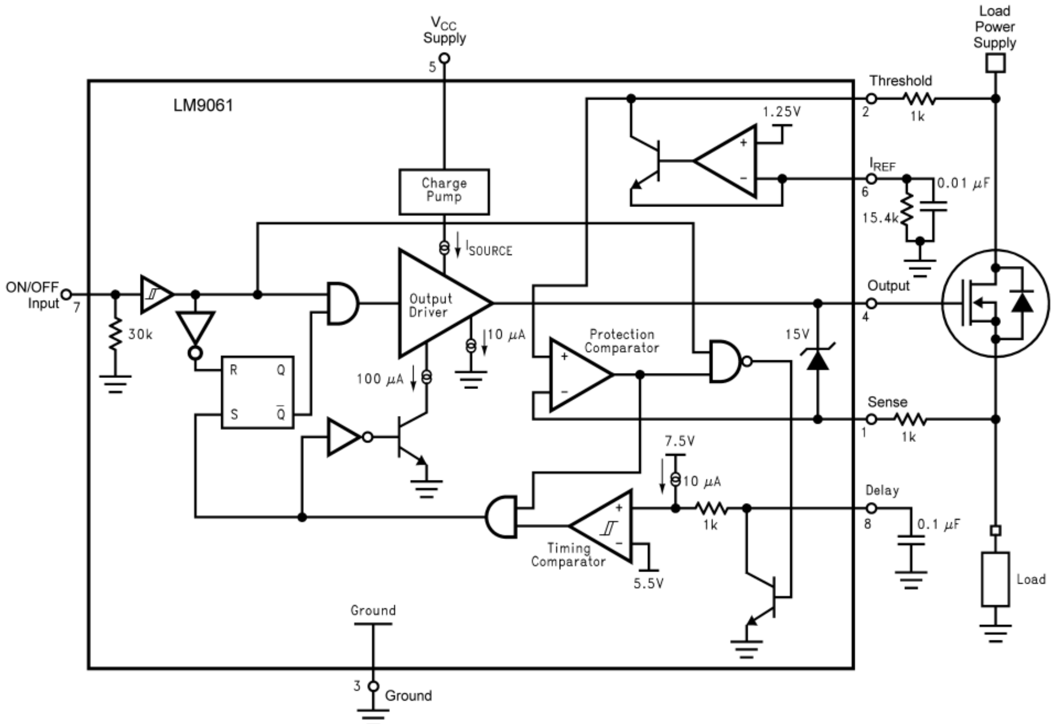
Overcurrent Protection without using sensing resistances is also called lossless overcurrent protection. Lossless overcurrent protection allows all of the energy to be supplied to the load with the only power loss being the that of the MOSFET itself. However, for lossless protection, the characteristics of MOSFET under overcurrent and normal current conditions should be properly characterized. It requires knowledge of key characteristics of the power MOSFET used, [28][29].

Overcurrent Protection ICs detect excessive power dissipation across the sensing resistor or the power MOSFET and latches it off to prevent permanent damage.

LM9061 overcurrent protection:



(a)



(b)

Figure 5.8: (a) LM9061 overcurrent protection circuit, (b) Functional Block Diagram of LM9061 [28]

LM9061 senses the voltage across the power MOSFET through the threshold and sense resistors. The sense input monitors the source voltage while the threshold input monitors the drain and the supply voltage. When the sense voltage drops below the threshold voltage, the protection comparator is turned on which in turn initiates a latch-off to protect the power MOSFET, [28].

5.3.3 Combined DC and Harmonic Overcurrent Protection

In this method, the total harmonic distortion (THD) of the AC supply is analyzed in order to detect fault in the rectifier. For this method, all possible fault conditions are studied thoroughly and the harmonic distortion in the input power supply is studied for each fault. After a fault is detected, the input phase corresponding to the fault is isolated from the rectifier, [30]. The steps to detecting fault conditions in the upper arm are as follows:

a. The algorithm measures the current data of secondary and tertiary (if applicable) sides of the transformer.

b. The DC component and its phase angle is calculated by FFT.

c. The algorithm is always searching for a condition with three DC overcurrent conditions, one with positive phase angle and two with negative phase angles.

d. If the conditions are detected, an informing electrical pulse is generated and sent to a sample and hold unit to measure the period of the condition.

e. If the period is greater than a predefined length, a trip signal is sent to the appropriate breaker.

f. To completely eliminate the DC fault, the trip signal should be sent when the power semiconductor device in the corresponding arm is not conducting. Therefore, the control signal of the devices should be monitored.

g. Finally, the single phase disconnection is carried out while ensuring any arcing phenomenon is certainly cleared. The minimum amount of time for fault elimination can be adjusted if required for this purpose.

For faults happening in the lower arm of the rectifier, only step 3 is changed. In this case, the trip signal is sent when the FFT result for fifth harmonic divided by the fundamental is higher than a predefined value, [30].

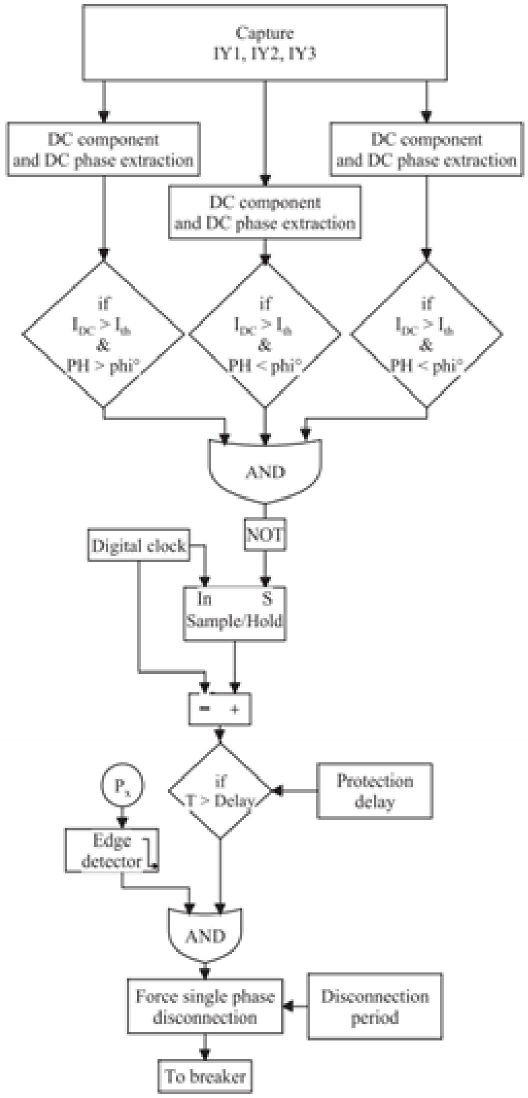
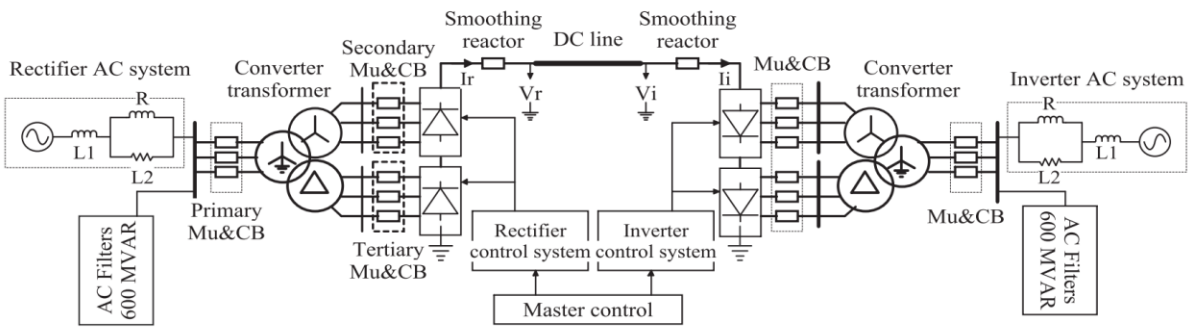
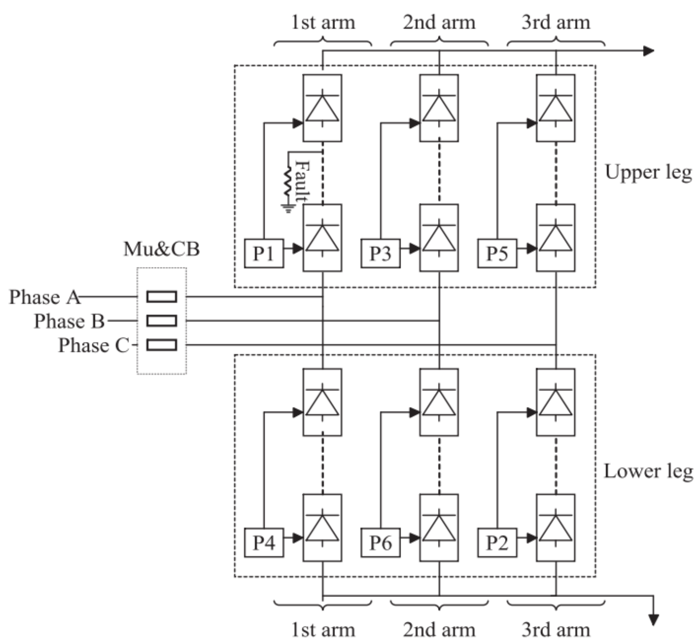


Figure 5.9: Converter Protection Algorithm using Combined DC and Harmonic Overcurrent Protection [30]

Example: The Hydro-Quebec Monopolar HVDC test system



(a)



(b)

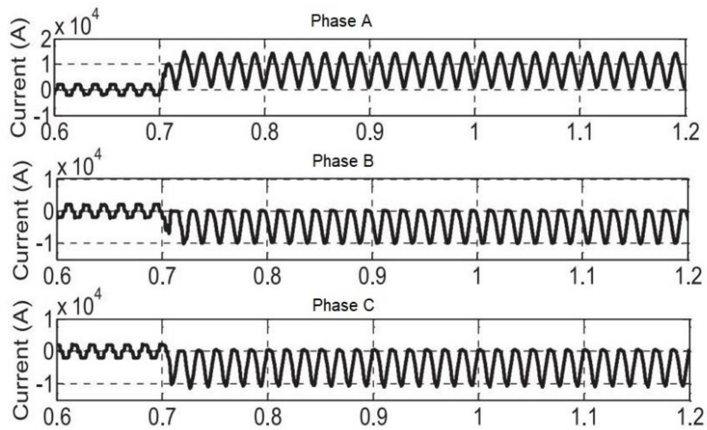
Figure 5.10: (a) Hydro-Quebec Monopolar HVDC system, (b) Internal structure of HVDC rectifier [30]

Following analysis is done for the secondary side of the converter transformer. Two kinds of fault can occur in the rectifier:

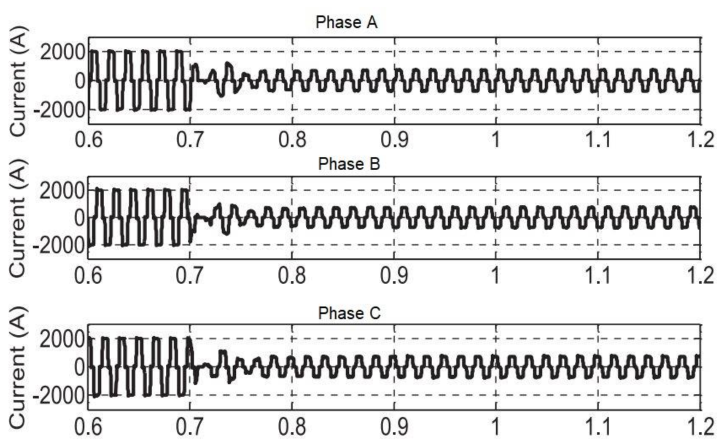
1. Internal faults in the upper leg
2. Internal faults in the lower leg

In case (1), the internal DC fault acts as a permanent AC faults on the phases A, B and C. Detecting one positive and two negative DC components on the secondary side of the transformer would be the criterion for fault detection, [30].

In case (2), 5^{th} and 7^{th} harmonics become available on the primary side of the transformer. Therefore, the division of 5^{th} and 7^{th} harmonic of the primary side to its fundamental can be considered as the fault detection criterion. The fault current in this case is supported by the tertiary rectifier, [30].

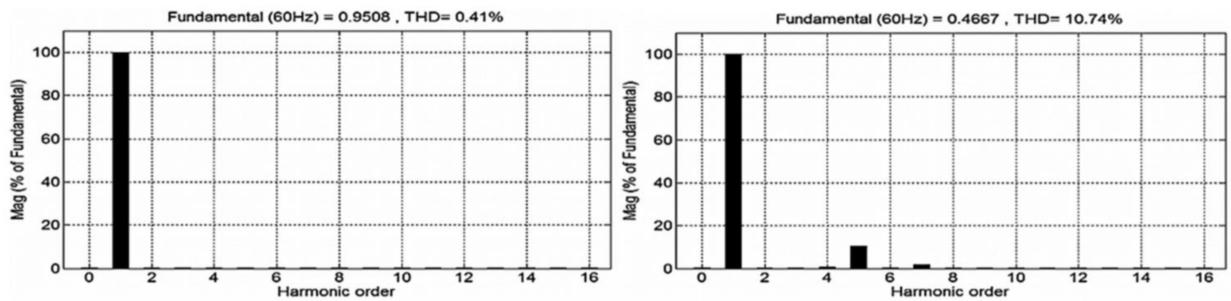


(a)



(b)

Figure 5.11: Current waveform of the three secondary phases for fault in (a) P1 (upper leg), (b) P4 (lower leg) [30]



(a) (b)

Figure 5.12: Harmonic currents of the primary side of the transformer (a) before and, (b) after fault occurrence in P4 (lower leg) [30]

5.4 FAULT ISOLATION

There are multiple ways to isolate AC sources from the rectifier during a fault condition. Some of them are discussed below:

5.4.1 FUSES

Fuses are self-acting electrical safety devices that provide overcurrent protection to an electrical circuit. It is basically a metallic wire or strip that melts down due to high current, thus severing the connection with power supply. It is a one use device and must be replaced or rewired once it has operated. Fuses have specific current and voltage ratings, breaking capacity and response times depending on the type of fuse and application.

5.4.2 RELAYS

Relay is generally defined as an electrical device that creates an electrical connection between two or more points with the application of a control signal. As relays are controlled devices, they can be turned on and off according to need by the overcurrent detection circuit, [31].

a. Electromechanical Relays and Contactors

The most commonly used relay are electromechanical relays (EMR). As the name suggests, they are electro-magnetic devices. A low voltage control signal is used to magnetize an iron core which in turn pulls the metal contacts together to create an electrical connection, [32].

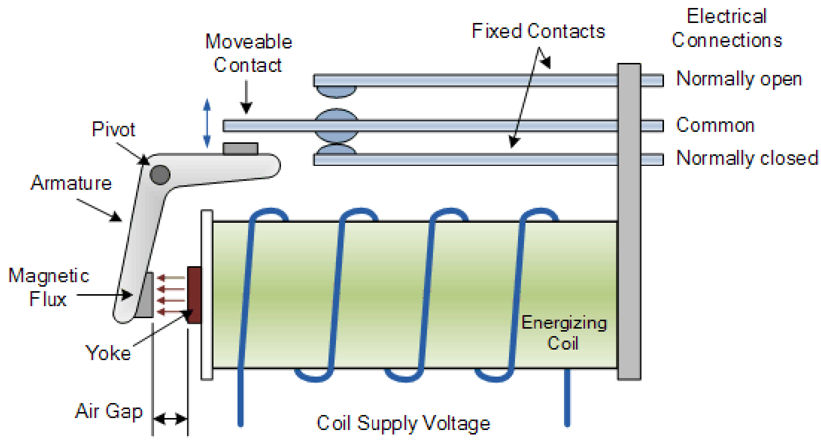


Figure 5.13: Simple Electromechanical Relay construction [31]

An iron core consists of a fixed part called yoke and a movable part called an armature. When a magnetic field is generated, the armature is pulled towards the yoke across the air gap. This will in turn force the moveable contact to move to either of the fixed contacts. The pivot is normally spring-loaded such that the armature will return to its original position when the coil supply voltage is removed. In the simple relay above, the two fixed contacts are labeled “normally closed” and “normally opened”. The labels refer to the state of the relay when the energizing coil voltage is not applied. If a relay is normally closed, the moveable contact is connected to “normally closed” in the absence of control input and vice-versa for “normally opened” relays, [31].

The contacts are electrically conductive pieces of metal which form a circuit for current flow when connected to each other. When the contacts are disconnected, the resistance between them is in hundreds of Mega-ohms. When they are connected together, the theoretical resistance between them should be zero, however, there is always some contact resistance known as on-resistance, similar to MOSFETs. As the relays start to wear down due to usage, the on-resistance will increase further, [31][32].

When the relays are not properly protected from high capacitive and inductive loads, the contacts may suffer from arcing damage as the current will try to flow even when the relay coil is de-energized. Repeated or large arcing damage may cause the contacts to weld together can create a short circuit condition. The arcing may also burn the tips of the contacts which may increase the on-resistance. In extreme cases, the contacts may be burnt to the extent that no or very little current may flow through them. In order to protect from these faults, electrical relay snubber circuits should be used to dampen the arcing current by providing a short circuit for the voltage peak that occurs when the contacts are opened, [31].

When a relay is used to switch a large amount of power through its contacts, it is denoted by a special name: Contactors. These typically have multiple contacts and are usually normally-open. Other than higher power rating, the contactors also have other components not found in lower power relays. These may include arc suppression which allows them to handle large inrush currents from capacitive and inductive loads, [31][32].

A contactor is controlled through its coil input which may be driven by either an AC or DC supply depending on the design of the contactor. The coil may require the same voltage as the load the contactor is controlling or it may be controlled using lower voltage such that it may be controlled using lower voltage components such as microcontrollers and Programmable Logic Controllers (PLC), [32][33].

When the coil is energized, the electromagnet produces a magnetic field which attracts the moving contacts of the contactor. The magnetic force generated by the electromagnet holds the moving and fixed contacts together. When the electromagnet is deenergized, gravity of spring returns the moving contacts back to its original position. Figure 5.14 shows a simple contactor schematic for three-phase motor control, [33].

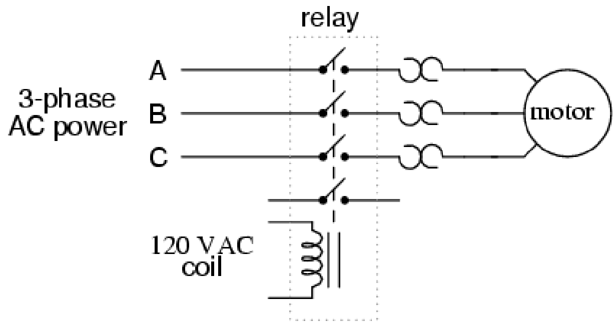


Figure 5.14: Simple Contactor Schematic for three-phase motor control [32]

b. Solid State Relays

Solid state relays (SSR) are purely electrical, contactless relays, i.e. there are no mechanical moving parts within the relay. Similar to EMR, these are also controlled using a control signal. The SSR is built using three parts: a sensor, a coupler and a power semiconductor device such as thyristor or MOSFET. Solid State Relays have no moving contacts and are therefore less noisy and faster than electro-mechanical relays. They also do not wear out as the physical contacts of EMR. However, SSRs also have lower ability to withstand momentary overloads compared to their mechanical counterparts. Also, SSRs provide limited switching arrangements in comparison to EMRs, [31].

Couplers are used to provide electrical isolation between the control signal and the load. For many SSRs, the coupling is optical. The controls voltage turns on the internal LED of the SSR which illuminates and switches on the photo-sensitive diode. The diode current in turn switches the power semiconductor component, [31].

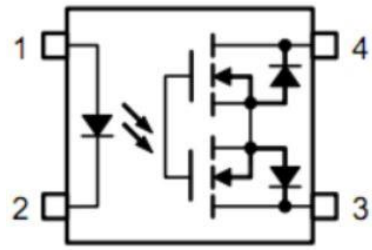


Figure 5.15: Simple schematic for SSR using bi-directional MOSFET switch [31]

While single MOSFETs or multiple power MOSFETs in parallel configuration work well for DC loads, they cannot be used for AC loads as the internal body diodes allows the MOSFETs to block current only in one direction. For AC operation, two MOSFETs connected back to back with their sources tied to each other can be used to form a bidirectional MOSFET switch as shown in above figure. Access to the common source is also provided so the MOSFETs can be connected in parallel for DC load operation, [31].

Advantages of Solid State Relays over Electro-magnetic Relays:

- Since there are no moving parts, SSRs have higher switching speed compared to EMRs
- The on-resistance of SSRs do not change with usage while the metal contacts of the EMR may wear and tear
- SSRs have noiseless and bounceless operation
- SSRs are smaller in size than EMRs of similar capacity
- SSRs are easier to store and handle due to less sensitivity to mechanical shock, humidity and temperature
- SSRs do not spark during turn-on and turn-off, so it can be used in hazardous environments where sparking can create dangerous conditions

Disadvantages of Solid State Relays over Electro-magnetic Relays:

- SSRs have higher on-resistance and lower off-resistance compared to EMRs

- SSRs have non-linear Voltage/Current characteristics. Since it is made with semiconductor components, it displays semiconductor electrical properties
- SSRs may be sensitive to polarity of the output voltage, for example: power MOSFETs can block currents only in one direction. EMRs aren't affected by the output voltage polarity
- SSRs may switch unwantedly due to voltage transients
- SSRs mostly short circuit due to failures while EMRs tends to open-circuit

5.4.3 CROWBAR ISOLATOR

A Crowbar circuit is built using both fuse and semiconductor devices. A crowbar circuit protects a circuit against overvoltage during power supply malfunction or power surge. It works by sensing an overvoltage and shorting out the power supply. This cause the voltage to drop in rest of the circuit and the current surge through the power supply trips a circuit breaker or blow a fuse. Without a circuit breaker or fuse, the power supply and the crowbar circuit will be damaged, [34].

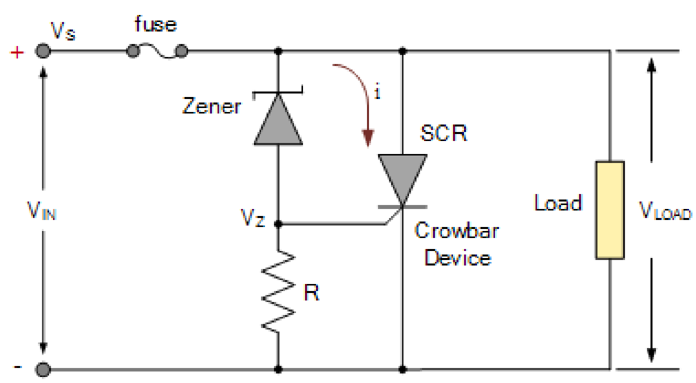


Figure 5.16: A simple crowbar circuit [35]

Figure 5.16 shows a simple crowbar circuit built using a fuse, Zener diode, resistor and a thyristor. The threshold voltage is defined by the Zener diode. When the threshold voltage of the Zener diode is surpassed by the power supply, it starts conducting which triggers the thyristor. The thyristor shorts the power supply and the high current blows the fuse, thus protecting the load from the overvoltage, [34][35][36].

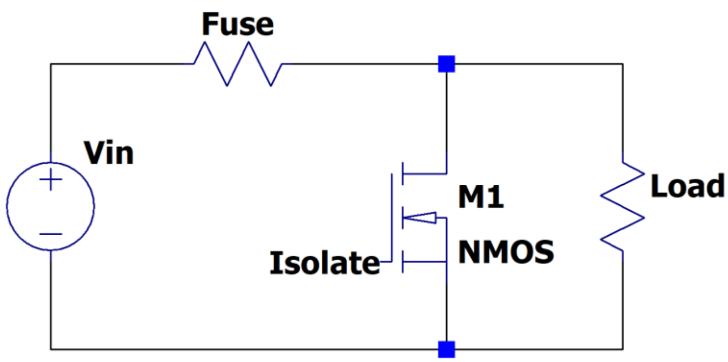


Figure 5.17: Controlled Crowbar Circuit

Figure 5.17 shows a simple controlled crowbar circuit. It used the same concepts as the original crowbar circuit however the semiconductor device is controlled using a control signal instead of automatically triggered through a Zener diode or a voltage divider. However, the end result is the same. The power supply is shorted, and the high current blows the fuse which isolates the power supply from the load.

5.5 ELECTRICAL TRANSIENTS

An electrical transient is the result of a sudden change in circuits such as when a switch opens or closes or when a fault occurs somewhere in a circuit. While a transient period is very small, the transient can subject circuit components to excessive stress and in extreme cases, may damage the circuit, [9].

When a sudden change in the circuit occurs, the energy in various energy storing elements in the circuit, i.e. inductors and capacitors, are redistributed to meet the new requirements. However, this redistribution of energy cannot take place instantaneously due to two reasons, [9]:

- The change is current through an inductor is opposed by an emf: $L\frac{dI}{dt}$. An instantaneous change is current would require an infinite voltage. Since this is not practically possible, the currents do not change instantaneously but do create a voltage spike in the system to change the current as rapidly as possible.

- The current flowing through a capacitor is given by the rate of change of voltage across it: $C\frac{dV}{dt}$. An instantaneous change is voltage would require an infinite current. This is also not practically possible for practical power supplies. The system will however draw a large amount of current from the supply to change the voltage across the capacitor as fast as possible. This can be observed specially when a rectifier with capacitive load is turned on.

5.5.1 Electrical Transients in Rectifiers

Electrical transients occurs in rectifiers due to presence of various capacitances and inductances. The capacitances and inductances may be intentional or parasitic. Capacitances can occur in the form of ripple filter, diode depletion layer capacitance, MOSFET body capacitances, etc. Inductances can occur in the form of load inductance, the output inductance of the input transformer, line inductances and ripple filter, [9].

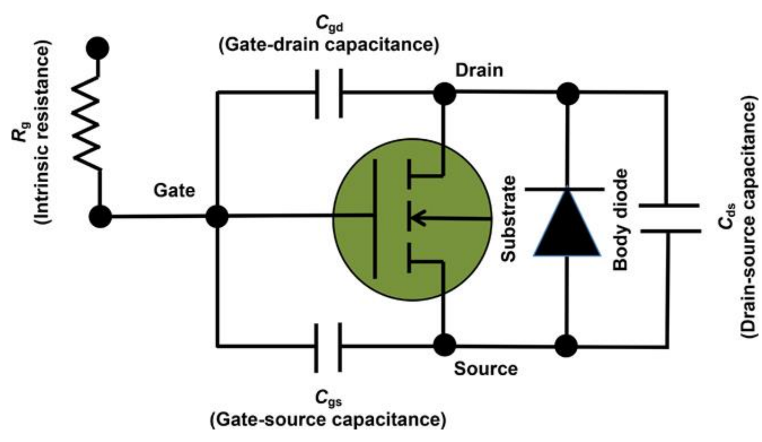


Figure 5.18: MOSFET with its intrinsic parasitic resistance and capacitance [37]

Considering the diode rectifier in Figure 5.19.

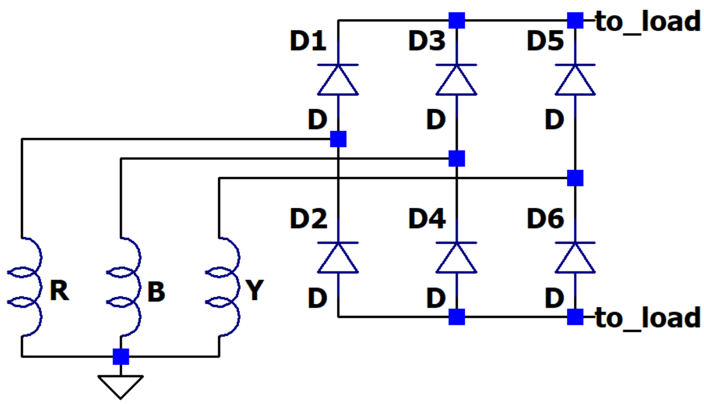


Figure 5.19: Simple three-phase diode bridge rectifier

When Red is most positive, the current is fed to the load by D1 and returned by D4 as Blue is the most negative. As Blue becomes the most positive and Yellow the most negative, the current is fed by D3 and returned through D6. The upper and lower envelope of the three phases forms the voltage across the load.

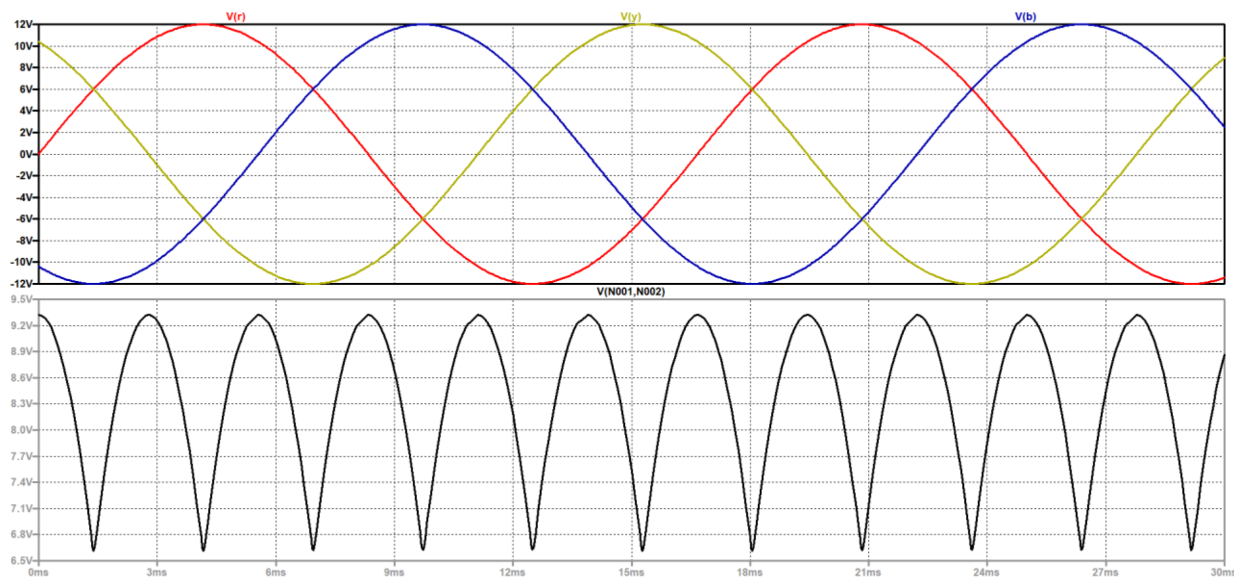


Figure 5.20: Three phase input AC voltage

However, the current cannot transfer instantaneously from one path to another if there is any inductance present in the system. So, at the point where the current is supposed to switch from D1 to D4, the two phases are short circuited by the rectifier. As the voltage difference between the two phases increase, current reduces in D1 and increases in D4 until all the current is flowing through D4. During this period of time, the output voltage is somewhere between the phase voltages. The length of time period is dependent on the inductance of the power supply as the rate of current change is given by the voltage difference divided by the inductance of the two phases, [9].

Considering a controlled bridge rectifier as shown in the following figure, capacitances have been added. These capacitances represent the natural capacitance between the windings and the ground and any ripple filter capacitance that may have been added. The diodes are replaced with controllable switches which represent semiconductor devices like thyristors and MOSFETs, [9].

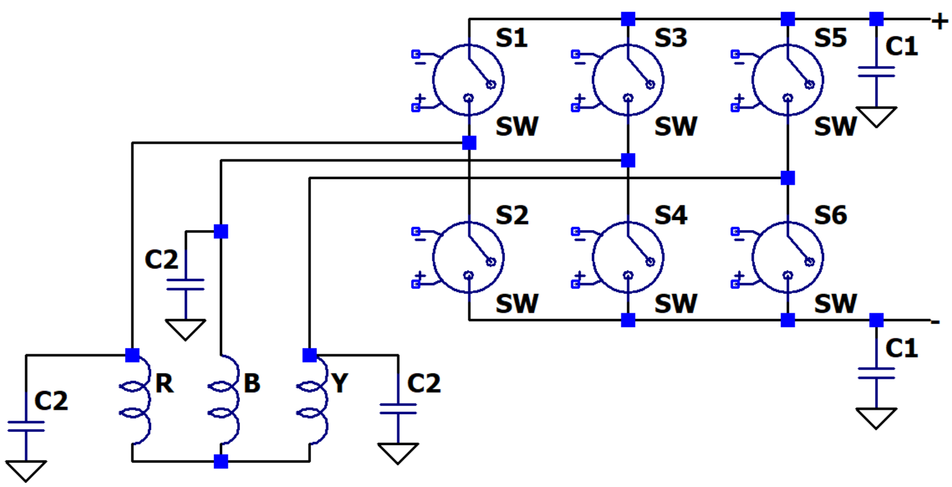


Figure 5.21: Simple three-phase controlled bridge rectifier

Initially S1 and S4 are conducting. Following the previous sequence, S3 conducts next. This connects C2 of that phase to C1 on the positive bus. Since the two capacitors are at different voltages, an equalizing transient current flows through them. The transient circuit consists of the two capacitances, the inductance between them and any resistance that may exist between the paths. Ignoring the resistance, the transient current is given by, [9]:

$$I_{transient} = (V_B - V_R)\left(\frac{C}{L}\right)^{1/2} \sin w_o t$$

where, $C = \frac{C1.C2}{C1 + C2}$, $w_o = \sqrt{\frac{1}{LC}}$ and $V_B - V_R$ is the difference in voltage between blue and red phases. The transient can be much higher than load current when $V_B - V_R$ is very high or even when the surge impedance $\left(\frac{L}{C}\right)^{1/2}$ is very low. Also, the current is oscillatory ($\sin w_o t$) and may attempt to reverse. This can damage the semiconductor switches like thyristors and MOSFETs which have limited current carrying capacity, [9].

5.6 ELECTRO-MAGNETIC INTERFERENCE IN RECTIFIERS

Electro-magnetic Interference (EMI) is defined as a disturbance generated by an external source that affects and electrical circuit by mutual induction, capacitive coupling or conduction, [38]. The disturbance can the affect the operation of the circuit adversely and in some cases completely stop it from functioning, [39][40]. For example, in communication systems, it may add noise to data being transmitted which increase the error rate or even complete loss of the original data. EMI can also be used for radio jamming, as in electronic warfare, [41].

The increase in switching frequency in power electronics greatly improves the performance and efficiency of power converters like Vienna rectifier and Switch-Mode Power Supplies (SMPS). Higher frequency also ensures that MOSFET switches used in SMPS operated in saturation region as long as possible and minimize the duration the switch operates in the ohmic region. High frequency operation also reduces the sizes of passive components used in the converters, [8][39][40].

However, this also brings about the increase in electro-magnetic interference (EMI) levels. With the increase in switching frequency, parasitic effects also become more prevalent in the converters. Significant magnetic and electrostatic coupling effects are created by high $\frac{dV}{dt}$ and high $\frac{dI}{dt}$ leading to radiated fields and circulating currents. Electro-magnetic interference noise can interfere with the electronic system in critical control and communication functions, which has an impact on system reliability. In some applications with a high reliability requirement EMI is especially important as much less interference can be tolerated, [8][9][39][40].

If a node of the converter is connected to another circuit through a parasitic capacitance, a current will be injected into the circuit which will be proportional to $\frac{dV}{dt}$. This will simply be due to the current through the capacitor being equal to $C\frac{dV}{dt}$. The current flowing through the parasitic capacitance will be directly proportional to the frequency of switching transients as the impedance of the capacitance is low for higher frequencies. The voltage developed at the victim circuit will be proportional to its input impedance and current flowing through the parasitic capacitance. This can result in a false relay operation, perhaps tripping some switches unnecessarily. Problems arising from this phenomena can be especially problematic for industrial and aerospace applications where large power supplies are controlled using circuits of much lower power. The power required turn on and off these devices is almost infinitesimal compared to power being transferred from the converter to the load. Accidently tripping thyristors or MOSFETs can create short circuit condition across the AC power supply, [8][9].

Similar to being connected through capacitance, the converter may also be coupled with another circuit through a mutual inductance. When current changes rapidly in a circuit, the flux linkage with the circuit changes as well as the flux linkage with nearby circuits, [9]. By Faraday's law, the emf generated in these circuits can be derived as:

$$self\ induced\ emf = -L\frac{dI}{dt}$$

$$mutually\,induced\,emf = -M\frac{dI}{dt}$$

where, L is the inductance of the first circuit, M is the mutual inductance between the circuit and neighboring circuit, [9].

Therefore, voltages are coupled from one circuit to another especially under transient conditions. Currents induced in control circuits due to mutual induction may result in unwanted switching or relaying which may cause short-circuit faults, [9].

In aircraft electrical systems, some of the nearby circuits may consist of antennas which may be better at transmitting noise at certain frequencies. High $\frac{dV}{dt}$ or $\frac{dI}{dt}$ would create many high frequency harmonics which will have higher likelihood of resonating with some part of the electrical system and may turn that random part of the circuit into a tuned antenna, [9].

6. SIMULATION AND OUTPUT

6.1 Three-Phase Controlled Bridge Rectifier

The aim of the design is to emulate a three-phase diode bridge rectifier using MOSFET power switches. To this effect, the topology of the rectifier is same as the diode bridge rectifier with the diodes swapped out for MOSFETs. The positive and negative outputs and the three-phase input of the rectifier is fed back into the controller block through a voltage divider circuit such that the voltage and current fed into the controller is minimized while the shape and relation between the voltages (magnitude-wise) are maintained.

The controller block is built using comparators. The comparators may be comparator ICs or op-amps configured as comparators. The comparators determine the highest positive or negative phase voltage and turns on the MOSFET connected to the respective phase. Depending on whether the voltage is highest positive-wise or negative-wise, the upper or lower leg MOSFET is turned on. This controller configuration allows the rectifier to even work with one of the phases knocked off or disconnected which boosts the reliability of the design.

6.1.1 Bridge Rectifier Schematic

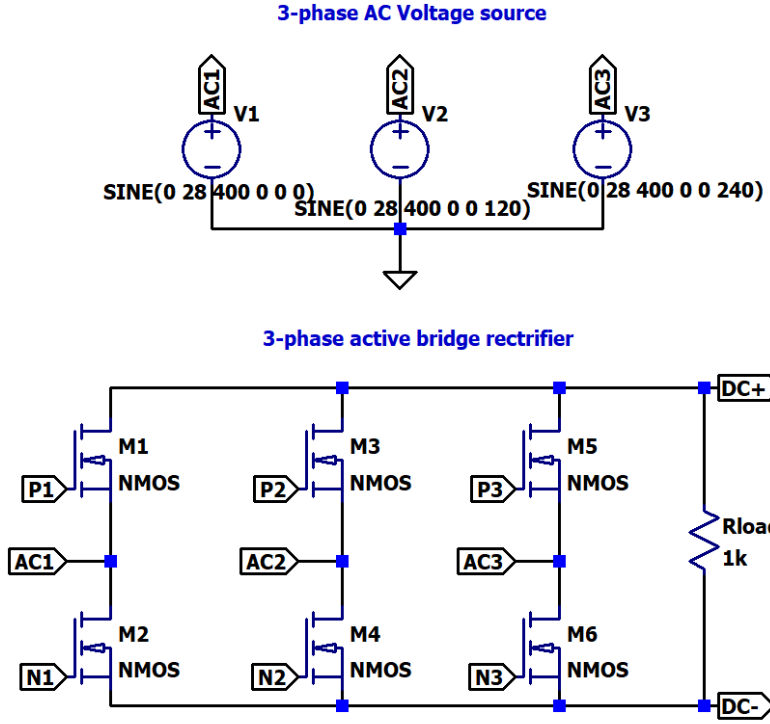
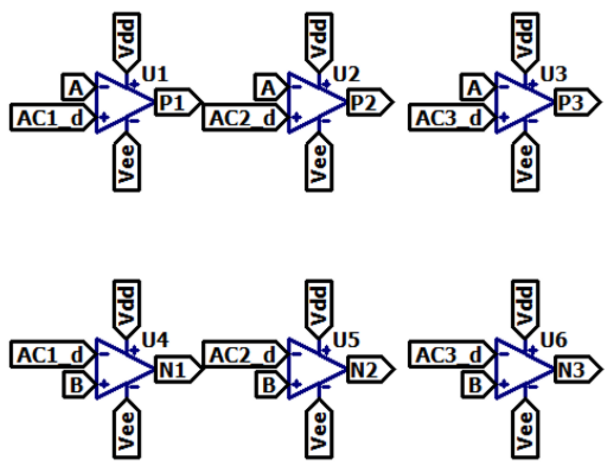
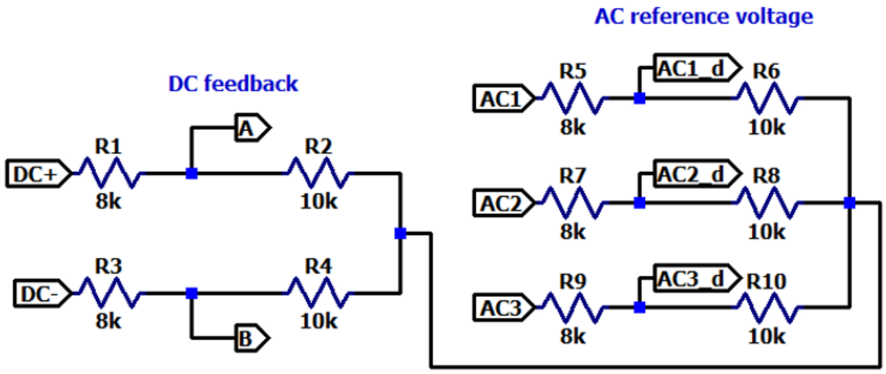


Figure 6.1: Three-phase controlled bridge rectifier and three phase power supply

6.1.2 Feedback Controller



(a)



(b)

Figure 6.2: (a) Controller and (b) Feedback for three phase bridge rectifier

6.1.3 Circuit Description

As shown in Figure 6.1, the bridge rectifier is built with six MOSFET (M1-M6). The three phases of the power supply are named AC1, AC2 and AC3. The output of rectifier is DC+ and DC- which is connected across the load resistance.

The gates of the MOSFETs are connected to the output of the six op-amps in comparator configuration (U1-U6) as shown in Figure 6.2(a). The outputs of comparators are P1-P3 for the upper arm MOSFETs and N1-N3 for the lower arm.

The outputs (DC+ and DC-) and inputs (AC1, AC2 and AC3) are fed back into the comparators through a voltage divider for controls implementation as shown in Figure 6.2(b).

6.1.4 Circuit Operation

The output DC voltages (DC+ and DC-) are compared with the three phase voltages. When any of three phases is more positive (larger in magnitude and numerically), the corresponding upper arm MOSFET in the bridge rectifier is turned on by the corresponding op-amp. For example, analyzing the highlighted portion of the three phase waveform in Figure 6.3:

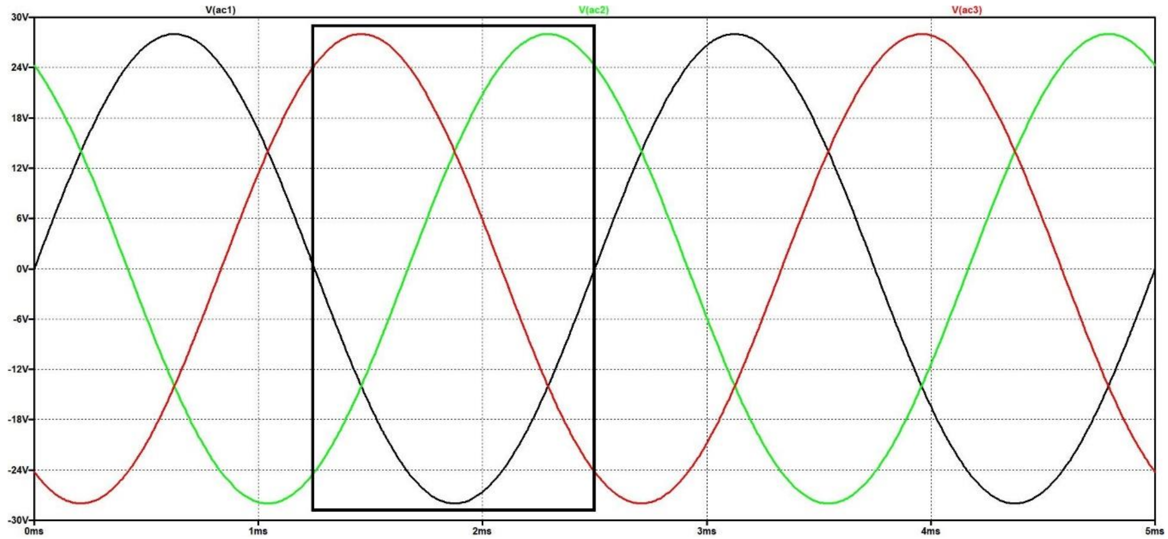


Figure 6.3: Three phase supply voltages and control signals for the bridge rectifier MOSFETs

Let the time at the intersection between V(AC3) (red) and V(AC2) (green) be t=0.

At t=0-, V(AC3) is the highest voltage. So, at this moment of rectifier operation, the output of comparator U3 is high and it is keeping MOSFET M5 on. Thus, the output V(DC+) is equal to V(AC3).

At t=0+, V(AC2) is the highest voltage. So, at that moment, the output of comparator U2 is high and MOSFET M3 turns on. Thus, the output V(DC+) becomes V(AC2).

Similar analysis can be done for the negative cycle and voltage output DC-. Keeping within the highlighted timeframe above, assume the time at the intersection between V(AC3) and V(AC1) (black) be t=0.

At t=0-, V(AC1) is the most negative (largest in magnitude, lowest numerically). So, at that moment, the output of comparator U4 is high and MOSFET M2 is turned on. So, the output V(DC-) is equal to V(AC1).

At t=0+, V(AC3) is the most negative. So, at that moment, the output of comparator U6 is high and MOSFET M6 is turned. So, the output V(DC-) is equal to V(AC3).

6.1.5 Output

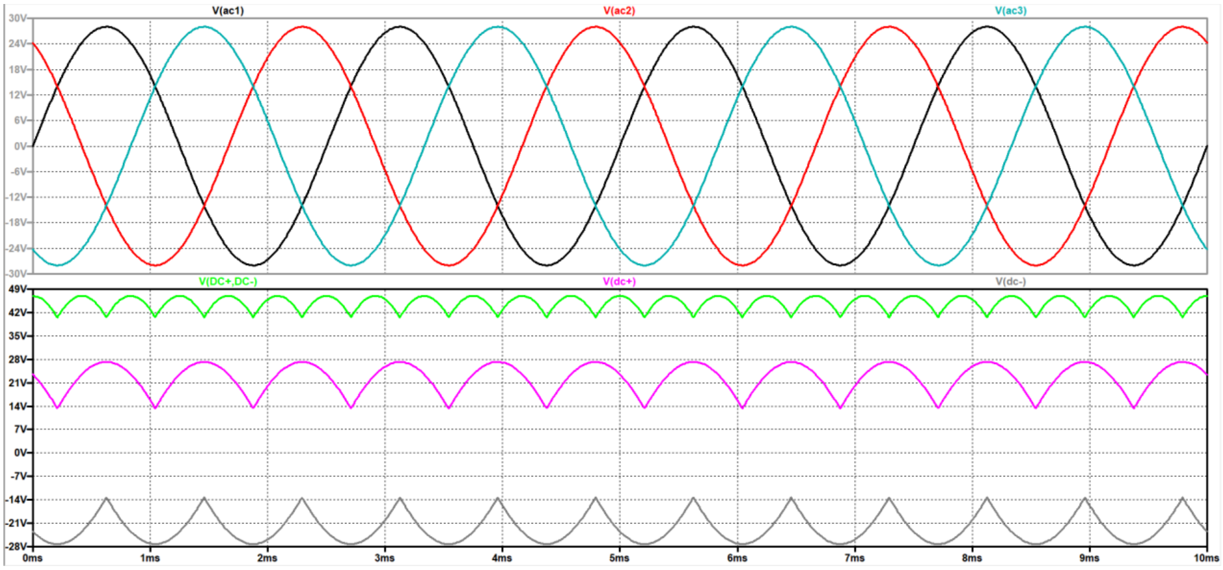


Figure 6.4: Three-phase voltage input (black, red and blue), DC voltage output (DC+(purple), DC-(grey) and voltage across load resistor (green))

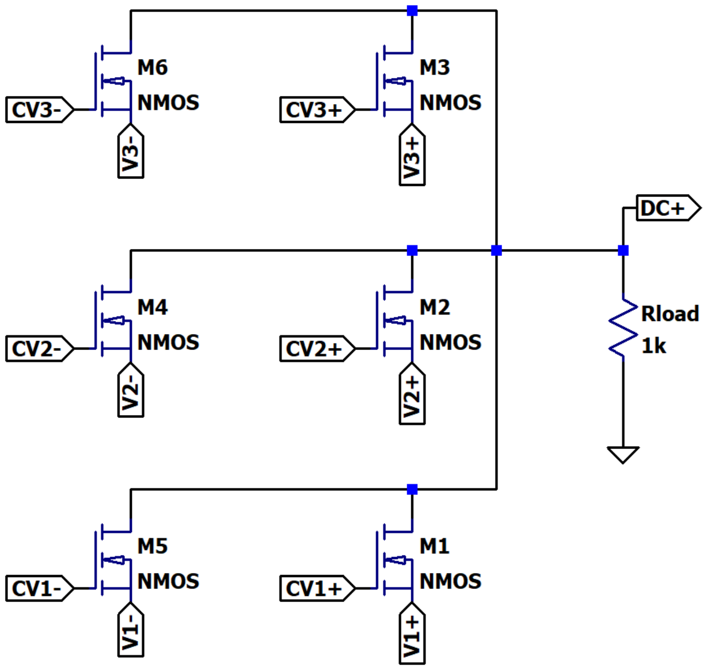
From Figure 6.4, it can be seen that V(DC+) is always follows the highest magnitude positive voltage and V(DC-) is always follows the highest magnitude negative voltage.

6.2 Three phase full-wave controlled rectifier using center tapped transformer

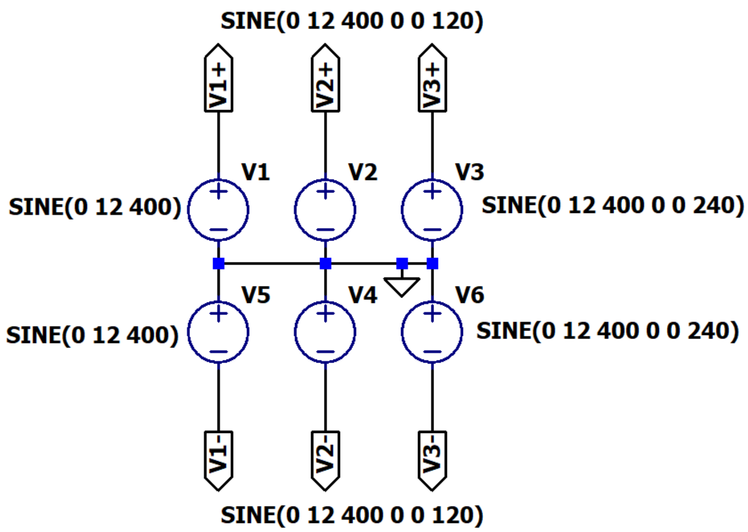
Similar to three-phase bridge rectifier, the aim of the design is to emulate three-phase full wave diode rectifier using center-tapped transformer using power MOSFETs. Similarly, the topology of the rectifier is same as the diode rectifier with the diodes swapped out for MOSFETs. The output and input three-phase voltage of the rectifier is fed back into the controller block through a voltage divider circuit such that the voltage and current fed into the controller is minimized while the shape and relation between the voltages (magnitude-wise) are maintained.

The controller block is once again, built using comparators. The comparators compare the input three-phase voltages (both sides) with the output voltage. The ICs turn on the MOSFET corresponding to the highest magnitude phase.

6.2.1 Rectifier Schematic



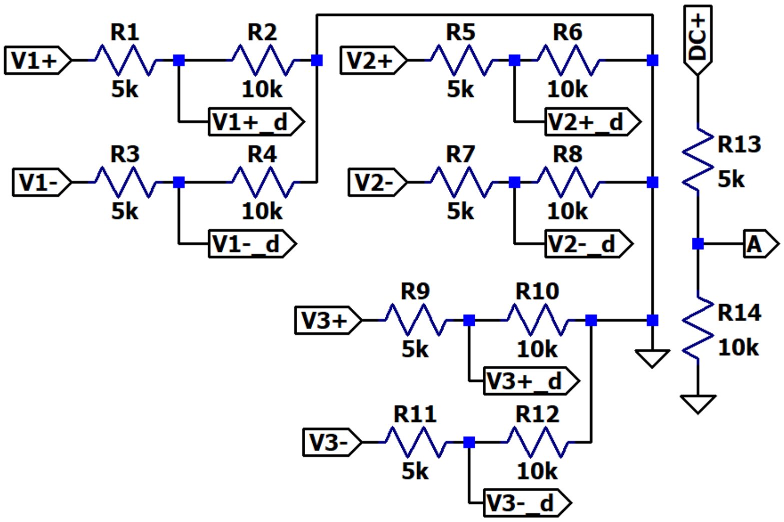
(a)



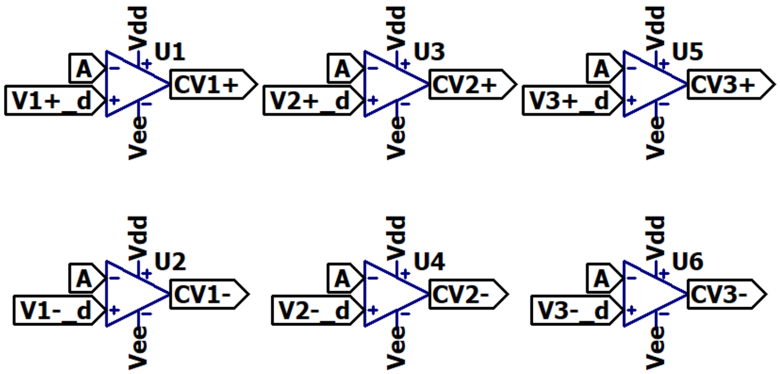
(b)

Figure 6.5: (a) Three phase full-wave controlled rectifier using center-tapped transformer, (b) SPICE model for center tapped transformer

6.2.2 Feedback Controller



(a)



(b)

Figure 6.6: (a) Voltage Feedback, (b) Controller

6.2.3 Circuit Description

As shown in Figure 6.5(a), the center-tapped rectifier is built using six MOSFETs (M1-M6). Figure 6.5(b) shows the secondary side of a center-tapped transformer. The voltage source pairs: V1-V5, V2-V4 and V3-V6, form the three phases of the AC supply. The three phases of the power supply are divided into two parts: (V1+, V2+, V3+) and (V1-, V2-, V3-) which are fed into the rectifier.

The gates of the MOSFETs are connected to the output of the six op-amps in comparator configuration (U1-U6). As shown in Figure 6.6(b), the outputs of comparators are CV1+, CV1-, CV2+, CV2-, CV3+ and CV3-. These signals control on-off cycle of the MOSFETs. The output of rectifier is DC+ which is connected to the load resistance.

The output (DC+) and inputs (V1+, …. , V3-) are fed back into the comparators through a voltage divider for controls implementation as shown in Figure 6.6(a).

6.2.4 Circuit Operation

The output voltage DC+ is compared with the input voltages. Whenever the output voltage drops below one of the input voltages, the corresponding MOSFET is turned on and the output voltage is always equal to the highest input voltage. For example, when the output DC+ drops below V3-, CV3- goes high and turns on M6 while turning off whichever MOSFET was turned on before.

6.2.5 Output

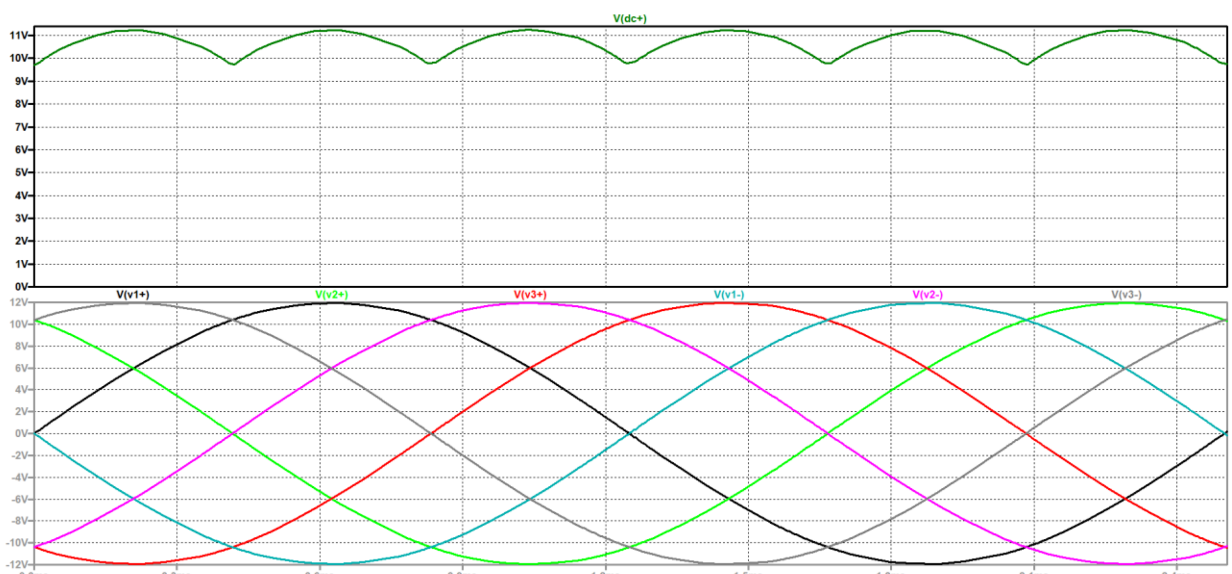


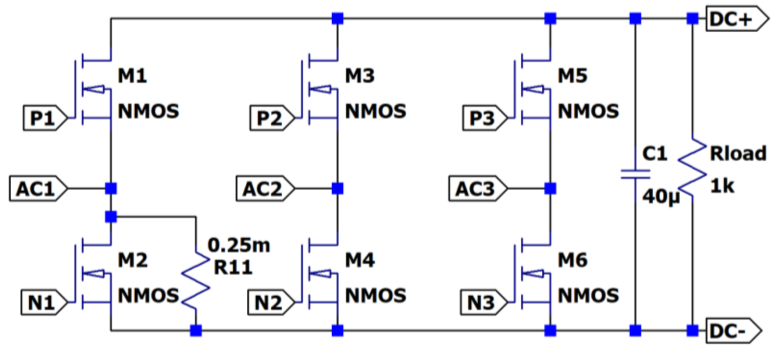
Figure 6.7: Output (green) and input voltages

From Figure 6.7, it can be seen that V(DC+) is always following the highest input voltage.

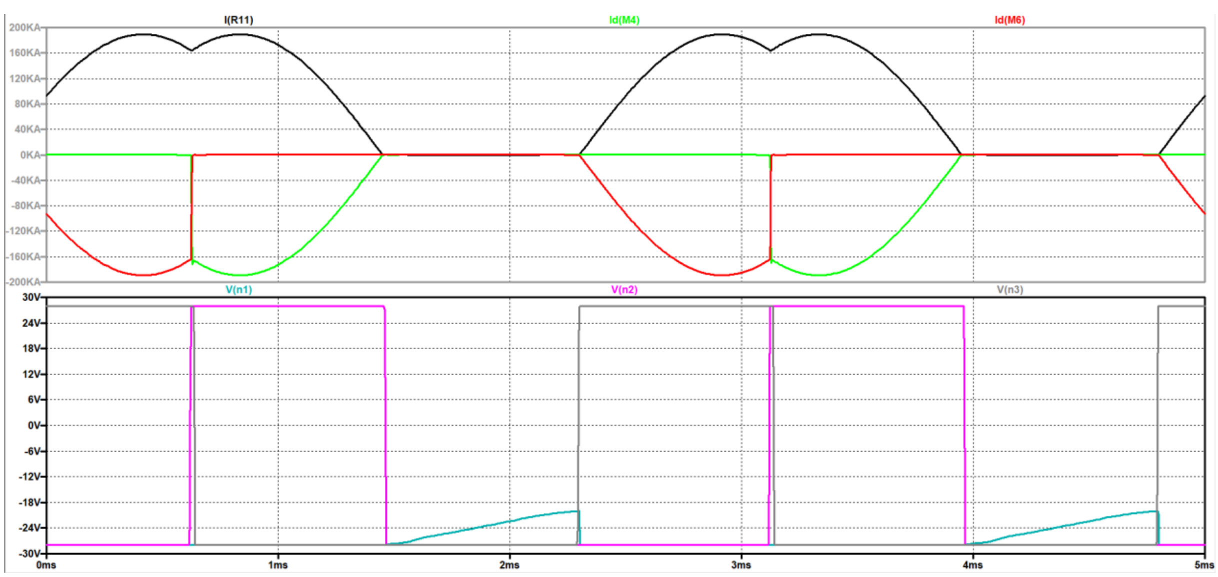
6.3 Short Circuit Detection and Protection

6.3.1 Overcurrent in bridge rectifiers during short circuit

In bridge rectifiers, short circuit faults may arise due to shorting of source and drain of power MOSFETs. This creates a low impedance which is equivalent to the MOSFET being turned on for all time period. This creates an overcurrent condition in the circuit by shorting two phases together.



(a)



(b)

Figure 6.8: (a) Bridge rectifier with short circuit across MOSFET M2, (b) Current through short circuit (black), M4 (green) and M6 (red) and control signals for M2 (blue), M4 (purple) and M6 (grey)

Figure 6.8(a) shows a bridge rectifier with a short circuit condition. The 0.25mΩ resistance across M2 can be considered a short circuit due to shorting of drain and source of M2. Figure 6.8(b) shows the current flowing through M2, M4 and M6 during the short circuit. It can be seen that the two of the phases are always shorted and high current flows between them.

Most of the current passes through the MOSFETs during "on" cycle with the load resistor and capacitance only taking in the current required to maintain the output voltage. Practically, the short circuit current is limited by the power supply rating and doesn't reach kiloamperes. However, the surge in current will damage the power supply and power MOSFETs by overheating and may also cause fire and explosions in some cases.

6.3.2 Short Circuit Detection

Short circuit in the rectifier is detected using the differential voltage across the sensing resistances inserted in the rectifier in series with the MOSFETs. The sensing resistance are placed as shown in Figure 6.9.

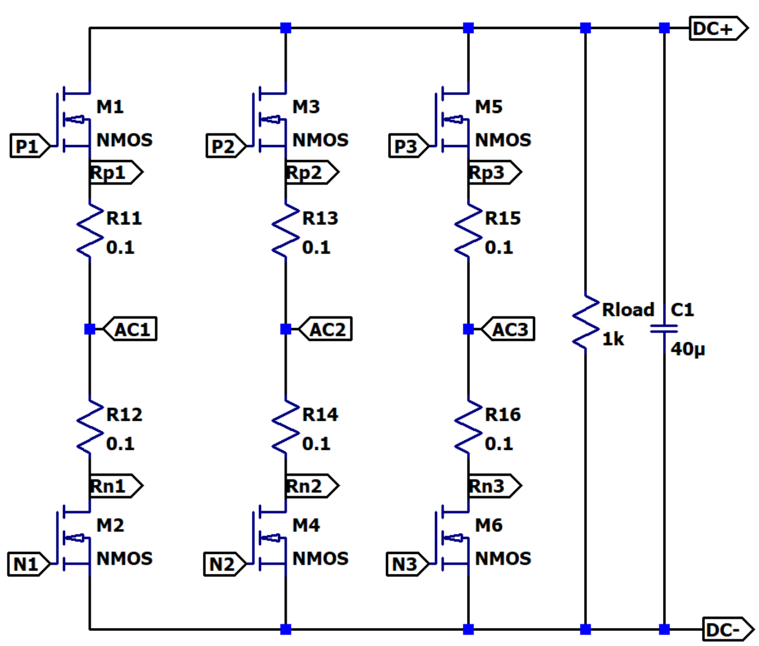


Figure 6.9: Three phase bridge rectifier with sensor resistances

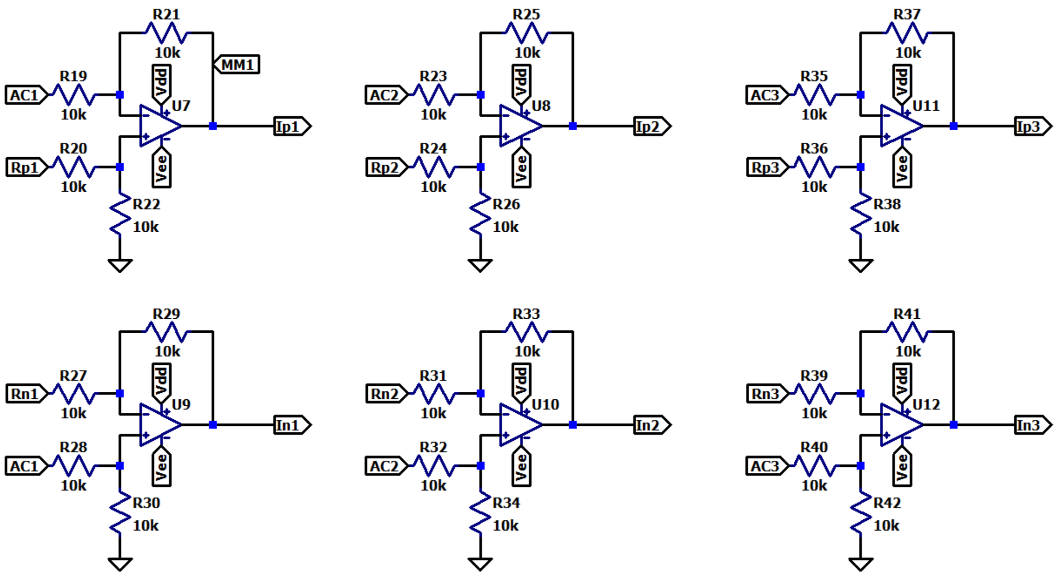


Figure 6.10: Differential Amplifier setup for voltage measurement across sensor resistors

As shown in Figure 6.10, the measured voltage is compared with a reference voltage in order to detect overcurrent. When the measured voltage goes above the reference voltage, it can be considered that an overcurrent condition has occurred. For example, if 5A is considered an overcurrent, a reference voltage of 0.5V (5A x 0.1Ω) is used.

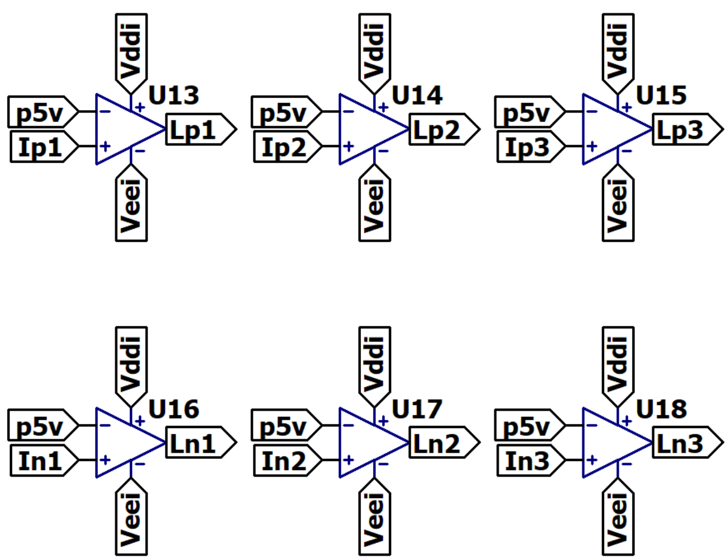


Figure 6.11: Overcurrent Detection circuit (p5v = 0.5V)

In the circuit shown in Figure 6.11, voltage across the sensor resistor is compared with 0.5V. When one of the voltages goes above the reference voltage, the corresponding comparator signals the protection logic for further action. With this configuration, the detection circuit can pinpoint the location of the transistor which has shorted out.

6.3.3 Protection Logic

After an overcurrent condition is detected, signal is sent to a combinational logic circuit for protection implementation. The purpose of the logic circuit is to determine which AC phase to cut off from the circuit and whether to isolate all of the three phases. It also latches when the detection signal is received as the comparator output voltage goes to zero after the corresponding phase voltage is isolated from the circuit.

The logic for phase isolation is given by:

$$P1\_isolate = Lp1 + Ln1$$
$$P2\_isolate = Lp2 + Ln2$$
$$P3\_isolate = Lp3 + Ln3$$

Logically, it means that whenever overcurrent/short circuit is detected for one of the MOSFETs, its corresponding phase voltage is disconnected from the circuit.

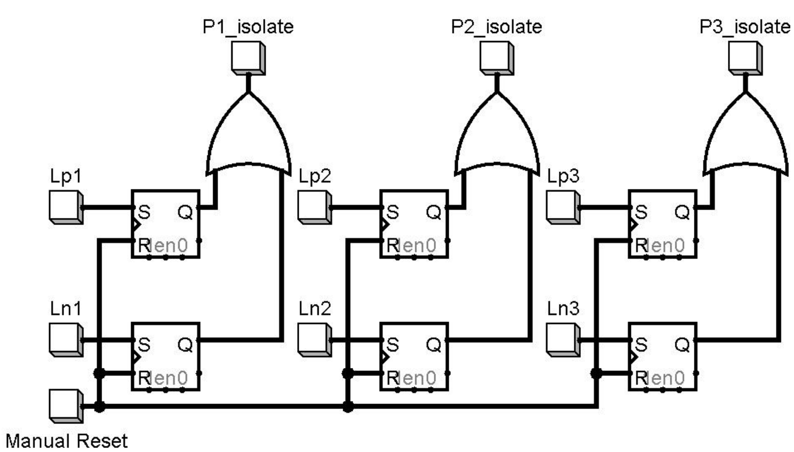


Figure 6.12: Logic Circuit for Phase voltage isolation

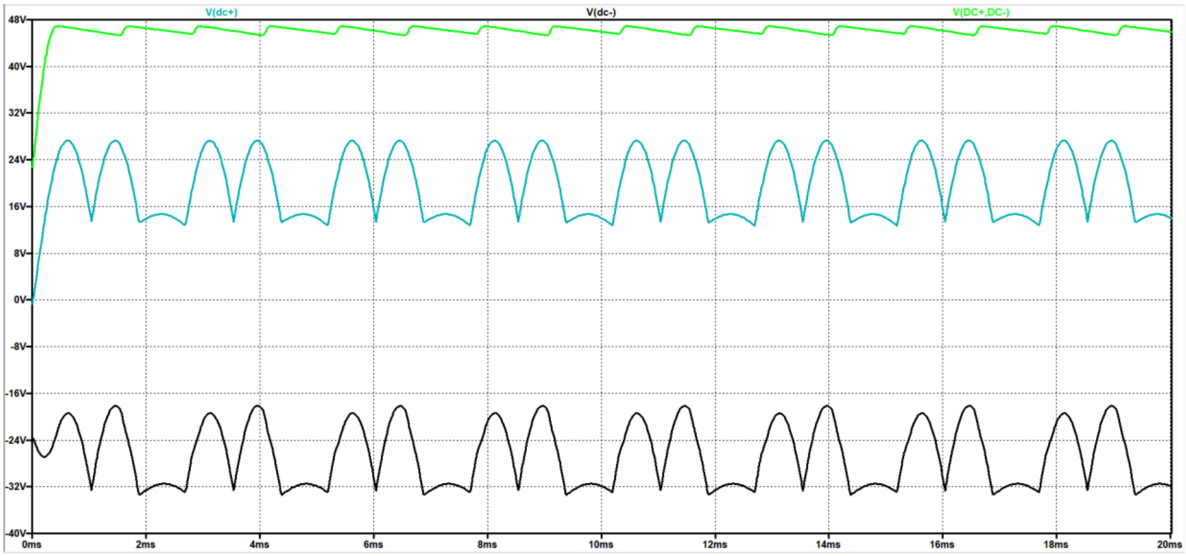


Figure 6.13: Output voltage with one phase disconnected, DC+ (blue), DC- (black) and voltage across load resistor (green)

Figure 6.13 shows that the output of the rectifier is still usable after one of the phases is disconnected. Therefore, when fault is detected on the arm connected to one of the phases, the corresponding phase is disconnected but the other phases are kept connected and the rectifier operates as normal.

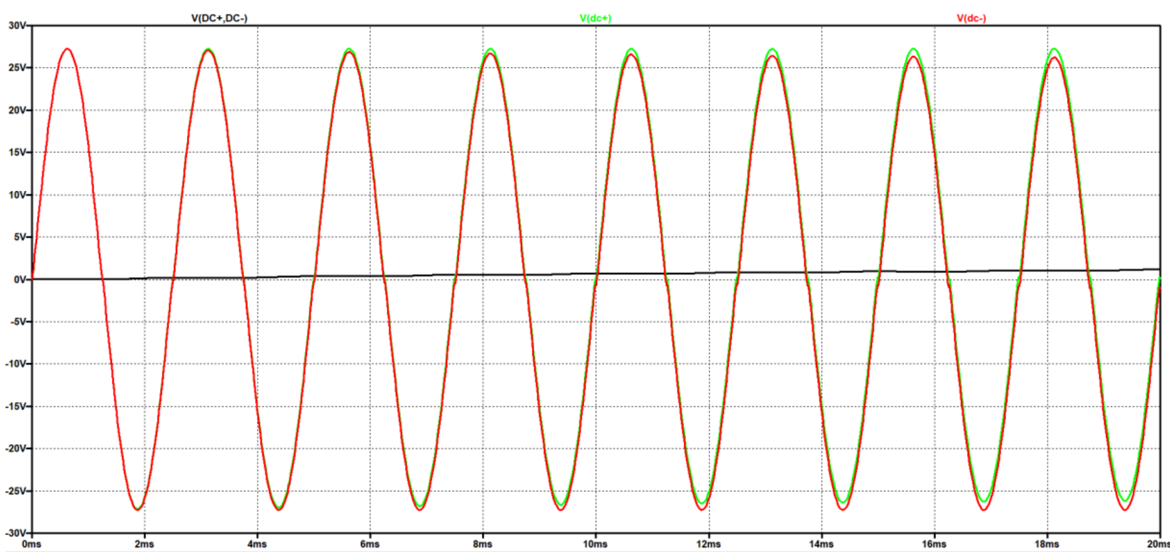


Figure 6.14: Output voltage with two phases disconnected, DC+ (green), DC- (red) and voltage across load resistor (black)

When overcurrent is detected for more than two phases, the second phase is also disconnected from the rectifier. In this situation, the third and final phase is also disconnected as the output is unusable after two of the phases have been disconnected as shown in Figure 6.14.

The logic for disconnection of all phases is given by:

$$full\_disconnect = (P1\_isolate.P2\_isolate) + P3\_isolate(P1\_isolate \oplus P2\_isolate)$$

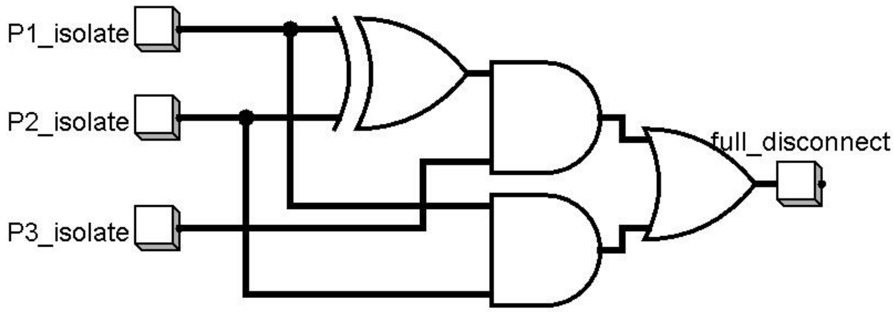


Figure 6.15: Full disconnect logic implementation

Table 6.1: Truth table for full disconnection logic

P1_isolate	P2_isolate	P3_isolate	Full-disconnect
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	1
1	1	1	1

7. DISCUSSION

7.1 Overcurrent Detection and Protection Circuit

The main advantages of the designed overcurrent detection circuit are:

a. Adaptability to device specifications and power requirement

b. Ability to pinpoint the location of short circuit

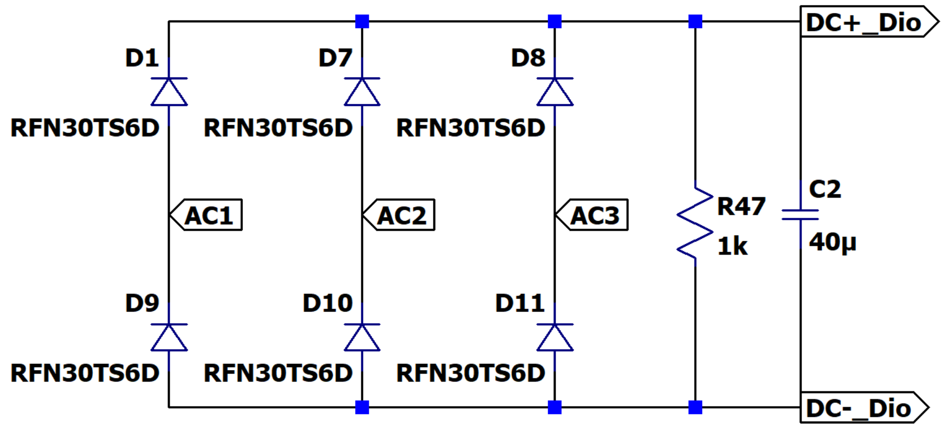
Since the detection circuit can pinpoint the fault location, in case of a phase fault, the corresponding phase can be isolated, and the rectifier operated with two phases. This may be more acceptable than completely turning off the rectifier for critical loads.

Self-protected Power MOSFETs are limited by the capacity they are manufactured with. As they automatically latch during the overcurrent condition, the user may have little to no control over the latching action. So, during an overcurrent condition the rectifier may completely turn off which may not be a suitable response for rectifiers supplying critical loads. These MOSFETs also do not have the ability to locate the position of the fault.

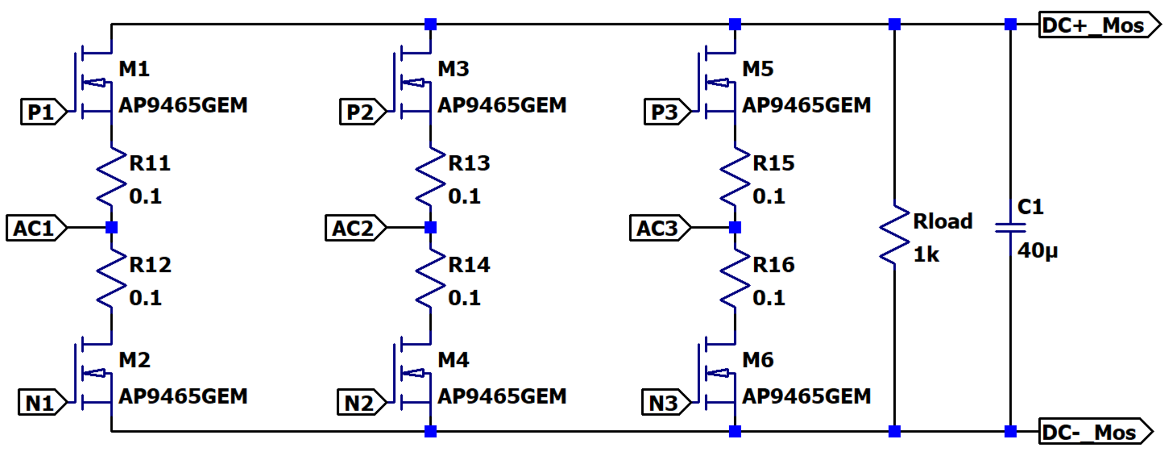
Similar to self-protecting MOSFETs, overcurrent protection ICs aren’t able to pinpoint the fault location, only the presence of a fault. Integrated Circuits like LM9061 also require complete characterization of the Power MOSFET to detect overcurrent conditions. For this application, that would not be possible as it is not known which MOSFET is going to be used. LM9061 also triggers the overcurrent condition response when the source voltage drops below the drain voltage during MOSFET turn-on. However, during the rectifier operation, the source voltage drops below and rises above the drain voltage during the turn-on period. This occurs due to the transients caused by the MOSFET capacitances. It also completely turns off all the MOSFETs during the overcurrent condition similar to the self-protected power MOSFETs.

Combined DC and Harmonic Overcurrent Protection, in contrast to the aforementioned two methods, is device independent and can pinpoint the location of the fault. However, it uses FFT of the transformer secondary and primary currents to detect and locate the faults, [30]. This requires significant computational power as the calculations need to be accurate as well as fast for real-time detection of faults. For this given application, it cannot be used since one of the constraints imposed is that programmable elements such as microcontrollers and CPUs aren't allowed due to reliability concerns.

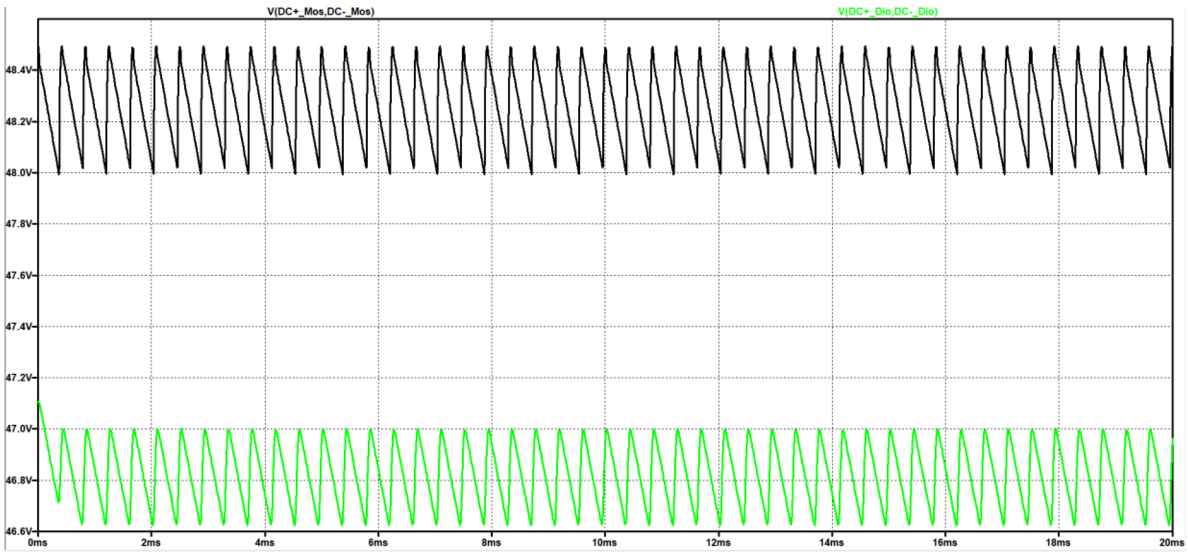
7.2 Power Efficiency



(a)



(b)



(c)

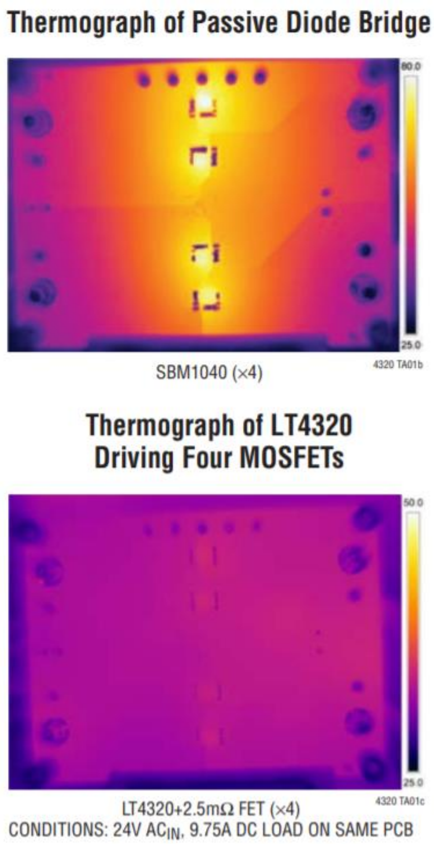
Figure 7.1: (a) Three phase bridge rectifier using diode (RFN30TS6D), (b) Three phase bridge rectifier using MOSFET (AP9465GEM), (c) Output of the diode rectifier (green) and MOSFET rectifier (black)

The output voltage of rectifiers using a diode, RFN30TS6D and a power MOSFET, AP9465GEM are compared in the above figure. It can be seen that there is more voltage drop across the circuit elements in the diode rectifier when compared to power MOSFET rectifier. This directly correlates to less energy loss in power MOSFET rectifiers.

Assuming a load current of 20A (within the current rating of both RFN30TS6D and AP9465GEM), the power loss difference in the two rectifiers can be calculated as:

$$\begin{aligned} power\_loss\_diff &= (Voltage\_MOSrectifier - Voltage\_Diorectifier) \times Load\_current \\ &= (48.5 - 47) \times 20A \\ &= 30W \end{aligned}$$

In high power configurations with low voltage, high current, the difference in power loss is even greater. This difference is power dissipation gives the power MOSFET rectifiers advantages over diode rectifiers such as higher efficiency and lower cooling requirements.



Temperature Rise

CURRENT	MOSFET 2.5mΩ	DIODE SBM 1040
2A	0.6°C	15°C
4A	3.5°C	32°C
6A	6.7°C	49°C
8A	11°C	66°C
10A	16°C	84°C

DC Input, On Same PCB

Figure 7.2: Thermograph for passive diode (SBM1040) bridge rectifier and MOSFET (2.5mΩ FET) rectifier [42]

The figure clearly shows the heat dissipation difference between diode and MOSFET rectifiers. For an input of 24VAC, temperature rise of the diode rectifier much higher (84^0C) than the MOSFET rectifier (16^0C) at 10A, [42]. For low voltage, high current systems the temperature rise would be even higher for diode rectifiers and therefore requires bigger cooling elements like heat sinks and cooling fans which will consume more energy by itself, reducing the overall efficiency of the rectifiers.

7.3 Electro-magnetic Interference

While the three-phase controlled bridge has higher efficiency than the diode bridge rectifier, it still falls short to Vienna Rectifier. Vienna Rectifier and its derivatives have efficiencies of up to 99% while the efficiency of a MOSFET bridge rectifier is largely dependent on the semiconductor switch's on-resistance and the load current, [22].

However, Vienna Rectifiers require high frequency switching (up to 1MHz) to ensure unity power factor operation and boost function. This creates a wide range of high frequency harmonics which can induce currents and voltages in the control and communication circuit onboard the aircraft. The high frequency harmonics may also be transmitted by the antennas onboard and disrupt wireless communication. Owing to the large electromagnetic interference produced, up to 2/3rd of the Vienna Rectifier may be EMI filters to comply with industry standards, [22].

In comparison, linear rectifiers like the MOSFET bridge rectifiers produce little to no high frequency electromagnetic interference. Unlike Vienna Rectifiers, the proposed design switches the MOSFETs at the same frequency as the input AC mains. While this creates harmonic distortion in the AC mains, there is little to no high frequency noise.

7.4 Sensing Resistance

The Sensing Resistance is the core of the protection strategy as the overcurrent is sensed as differential voltage across the resistance. While it allows for highly generalized protection strategy, it also comes with a big disadvantage. As a resistor, it dissipates power proportional to the current passing through it (also known as ohmic loss). Therefore, the resistor should be chosen with the current drawn by the load in mind. The resistor shouldn’t be too large as a significant voltage may drop across it which removes the advantage of MOSFET bridge rectifier over diode bridge rectifiers. For this reason, it may advisable to use the wires connecting the MOSFETs and the AC supply as the sensing resistance. This would remove the need for extra components as well as not affect the overall efficiency of the rectifier.

8. CONCLUSION AND FUTURE WORK

8.1 Conclusion

The thesis research proposes a generalized controller and protection strategy for three-phase MOSFET bridge rectifiers used in aircraft electrical systems. Like any engineering design, the proposed system has trade-offs when compared to other three-phase rectifier topologies. For example, the bridge rectifier operates as a linear rectifier and therefore has lower efficiency compared to topologies like the Vienna Rectifier (and its derivatives). However, due to high frequency switching used in Vienna Rectifiers, it produces a wide range of high frequency EMI which can disrupt the communication and radar systems onboard the aircraft. EMIs can be even more problematic for military aircraft as the high frequency noise may be radiated by onboard antennas making the aircraft detectable.

The main advantage of the protection strategy proposed in the thesis is its ability to pinpoint the location MOSFET that has shorted out. The design is also independent of the type of semiconductor device used as the overcurrent is detected through the differential voltage across the sensing resistance instead of across the MOSFET. So, the detection is dependent on actual current instead of the semiconductor device used. The threshold for overcurrent can also be adjusted by changing the magnitude of the compared voltage in the protection logic circuit. The trade-off for this flexibility is the power dissipated by the sensing resistance when the current passes through it.

The protection logic and the controller also allows the rectifier to work with one of the phases disconnected. This means that even in the case of fault in one of the arms of the rectifier, it can still operate to provide a usable DC power supply.

8.2 Future Work

In future iterations of the design, the transient suppression circuits such as snubber circuits can be added to the bridge rectifier to deal with transient voltages and currents. These transients appear in the circuit during startup (inrush current) as well as during switching of the MOSFETs due to the inductances present in the circuit. Other options for inrush current suppression would be slow start circuits, current limiters and a series impedance with the input power supply.

While the efficiency of the MOSFET bridge rectifier is higher than the diode bridge rectifier, the rectifier should be tested with practical electrical loads to study the working behavior and actual efficiency of the bridge rectifier. Although high frequency EMI is almost not present due to the low frequency switching of the semiconductor devices, there is harmonic distortions in the AC power supply. The effects of these harmonic distortions on the overall efficiency must be studied.

While op-amps in comparator configuration were used to generate control signals in the simulation, dedicated comparator devices can be used in their place. Comparators provide better saturation operation than op-amps. In comparators, the output circuit is designed to switch between upper and lower output voltages rapidly in response to changes in its input voltages with short propagation delays and output rise and fall times specified by the manufacturer. On the other hand, the output stages of op-amps are designed for linear operation with the aim of amplifying the input differential voltage with minimal distortion. Due to these differences, comparators are generally faster and more efficient than op-amps while working in the saturation region, [43]. Comparator ICs like TLV1805 also provide shutdown pin which can be used to turn off specific MOSFETs using the protection logic, [44].

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