Three-phase Pulse Width Modulated AC/DC Rectifier and DC/AC Inverter

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ECE498: Capstone Design Project

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1 Introduction

The burning of fossil fuels has been an issue for the environment for hundreds of years now. Harmful emissions have continued to pollute the air as a result of using oil, coal, and gas as sources of energy. Electric vehicles, which will also be referred to as electric cars or EVs, have become more popular as people are becoming increasingly aware of the long-term effects of the use of fossil fuels. They are a cheaper alternative to vehicles that run with an Internal Combustion Engine (ICE), which will also be referred to as gasoline cars. There are advantages and disadvantages to both types of vehicles, but the long-term effects of gasoline cars are far worse than those of electric cars. Electric cars can use electricity generated by solar and wind energy, which do not release dangerous emissions into the atmosphere.

Electric cars have batteries that run on direct current (DC) power, while the motors can run on either alternating current (AC) or DC power. DC motors can run directly with the power from the batteries. On the other hand, AC motors need an inverter to convert the DC power to AC. Many internal and external devices such as the radio, windshield wipers, and USB adapters run on DC power, so a rectifier is also needed to convert the AC power back to DC [1].

The goal of this project is to successfully replicate and understand the power flow in an electric vehicle. This final device will mimic driving and regenerative braking in an electric vehicle. In the remainder of this report, the societal and historical context of electric cars will be discussed, multiple types of pulse width modulation (PWM) control techniques will be explored, design requirements, design alternatives, and the design itself will be explained, simulation results will be described, and an implementation schedule is included.

2 Background

Electric cars first appeared in the United States around 1890. At first, they were more attractive in terms of operation and aesthetics compared to the early gasoline cars, which required gear changes and a hand crank to start the engine and were accompanied by vibration, smell, and noise. However, as more oil was discovered and gas became more affordable, gasoline cars could operate for longer distances than electric cars. In addition, a few inventions such as the electric starter and muffler in the early 1900s made gasoline cars even more attractive than electric cars. However, in the mid-1900s, oil prices were high and there were gasoline shortages [2]. According to the United Automobile, Aerospace and Agricultural Implement Workers of America (UAW), "With the invention of lithium-ion batteries in the 1980s, EVs started taking baby steps to compete with ICEs, in terms of price and range. Today, EVs can travel over 300 miles on a charge, and take an 80% charge in a half an hour."

In 1959, Mohamed Atalla and Dawon Kahng invented the metal-oxide-semiconductor field-effect transistor (MOSFET). The MOSFET then led to the power MOSFET and the single-chip microprocessor. The power MOSFET allowed electric vehicles to work at higher switching frequencies and reduced power losses and prices. The single-chip microcontroller allowed command of the drive control and battery [3].

There are two types of electric vehicles, all-electric vehicles (AEVs) and plug-in hybrid electric vehicles (PHEVs). Both types charge from the electrical grid and "in part by regenerative braking, which generates electricity from some of the energy normally lost when braking." AEVs run only on electricity. They can take 30 minutes or a full day to recharge. PHEVs use an

ICE in addition to an electric motor but it can also use hydrogen in a fuel cell, biofuels, or other alternative fuels [4]. As of July 2019, the longest range of a PHEV running only on battery is 126 miles while an AEV can go up to 370 miles [5].

According to David Reichmuth, a senior vehicles engineer, emissions from electric vehicles "will continue to fall, with both coal and natural gas declining while renewable power continues to increase." This information is provided by the US Environmental Protection Agency (EPA) from 2018 and includes the emissions from power plants, the production of coal, natural gas, and other fuels power plants use [6]. Greenhouse gases get trapped in the Earth's atmosphere and humans have been the main cause of the increase of these gases for the past 150 years. In 2017, it was found that transportation contributed 28.9% of these emissions while electricity production contributed 27.5%. Over 90% of the fuel used for transportation is petroleum based and about 62.9% of electricity comes from burning fossil fuels. However, there has been a decrease in carbon dioxide emissions due to the shift from coal to natural gas, the increased use of renewable energy options, and milder temperatures that led to less electricity use [7].

In the development of electric vehicles, there are labor and ethical issues that arise. In order to make the lithium-ion batteries, cobalt and lithium have to be mined in large quantities. Child labor, injuries, death, lung disease, and contamination of waterways are becoming more prevelant issues as there is an increase demand for resources. The economic state of electric cars will not be beneficial if components have to be imported from other countries into the United States [8]. Replicating the inner workings of an electric vehicle will not involve any of these concerns.

Ben Nelson, an ordinary man from Wisconsin, has an instructable post online with steps to build an electric car. He starts off with a used car and removes anything related to a gasoline car and its ICE. Then, he proceeds to add the necessary parts for an electric car such as motors, batteries, and motor controller. However, he does not ever mention a rectifier or inverter circuit. Ben is successful in getting his new electric car to run and has videos to prove it and to show his process throughout [9].

There are numerous articles regarding how to make AC to DC rectifiers and DC to AC inverters. AC is an electric current that periodically reverses direction. DC only flows in one direction. DC can be converted to AC using an inverter. AC can be converted to DC using a rectifier. In an electric vehicle, there needs to be a controller between the DC battery and the DC or AC motor. Instead of an ICE, electric cars have an electric motor that is powered by a controller, which gets its power from an array of rechargeable batteries [10]. Three-phase power is the most common method to transfer power. In the system, there are three conductors carrying AC of the same frequency and voltage amplitude but with a phase difference of 1/3.

Some examples of PWM techniques for rectifiers are hysteresis-band PWM (HB-PWM), carrier-based sinusoidal PWM (CB-SPWM), and voltage oriented control hysteresis-band PWM (VOC HB-PWM). In V. Vaideeswaran and N. Sankar's paper in the International Journal of Engineering and Advanced Technology (IJEAT), the AC line voltage used was 110V and the reference DC output voltage was 180V. Their conclusion was that the VOC HB-PWM would give the most accurate results, but the CB-SPWM control technique has the smallest total harmonic distortion (THD). These PWM techniques require the use of PI controllers [11].

In Ferdinant Visser's master thesis project for Delft University of Technology, he focuses on research about four PWM techniques - hysteresis modulation, carrier modulation, space vector modulation, and harmonic elimination. Hysteresis modulation is a current control method where the controller generates a sinusoidal reference waveform which is compared to the actual phase current. Carrier based modulation is a voltage control method where a phase-to-phase voltage is generated based on a comparison between a carrier and a reference waveform. Space vector modulation is a voltage control method where three switching state vector over an interval of one switching cycle are averaged. Selective harmonic elimination (SHE) is a PWM method where square wave switching is involved in combination with PWM controlling the fundamental output voltage. Visser also has a section where he explains the difference between a passive vs active AC/DC converter. The active AC/DC converter uses transistors while the passive one uses diodes. In the end, his conclusions are that the hysteresis modulation performs a little better but the robustness of it is worse. A reference signal is already created, so space vector modulation is the overall best PWM method [12].

Malik Zaid, a student at the University of Engineering and Technology in Lahore, wrote a paper about a three-phase inverter where he explains that inverters with PWM helps to reduce the harmonics that may distort the output voltage. He does simulations for 120 and 180 degree conduction showing the phase voltages and differences and link and line voltage. For 120 conduction specifically, only two switches of the six transistors conduct at a time. Waveforms for phase and line to line voltages were shown as well as the hardware. After passing the line voltage phase difference through a filter, the AC sine wave was clearly presented [13]. In an inverter circuit, PWM uses transistors to switch the DC voltage on and off in a defined sequence

to produce the AC output voltage and frequency. Higher switching frequencies lead to cleaner waveforms to the motor due to the increase in pulses over each half wave. The torque and speed of the motor can be controlled using PWM [14].

According to Anna University in Chennai, India, "The most efficient method of internal control of [voltage source inverters (VSI)] is by a PWM control technique used within the inverter itself." There are two main types of PWM techniques - carrier based and carrier less modulation. Carrier based techniques include sinusoidal PWM, modified PWM, random PWM, third harmonic injection PWM, and space vector modulation. Carrier less techniques include delta modulation, specific harmonic elimination, and wavelet modulation. Sinusoidal PWM (SPWM) compares a three-phase balanced sinusoidal reference voltage signal with a high-frequency common triangular carrier voltage signal. The intersection points of the two signals determines the switching of each MOSFET [15]. Delta modulation involves integrating the output signal, which is compared to a reference signal offset by a constant. The MOSFETs switch states when the integral of the output signal reaches one of the limits of the reference signal [16].

3   Design Requirements

The final design of this project will consist of two separate systems. The two systems

should also be able to run for five minutes without interruption. The first system will replicate

driving an electric vehicle. Below in Figure 1 is a block diagram of the first system, which uses

an inverter circuit.

Figure 1: Block diagram of driving system

A 40VDC power supply will be set to an appropriate level based on component ratings. It will be

the input to the inverter circuit. The inverter circuit will convert the DC voltage to three-phase

AC voltage. It will be built with six of the same type of transistor. The gate voltage going into

each of the MOSFETs should be between 10-15VDC based on their ratings and will be

controlled with an Arduino Mega 2560 Rev3 microcontroller and a gate driver [17]. Two 0.1uF

capacitors will be connected to the gate driver to guarantee low supply impedance [18]. It will

have an external input of 12VDC. A resistor will be connected to the gate of each MOSFET to

limit the current, which should be less than the rated 20-40mA of the Arduino [19]. It will be

4.7kΩ since 12VDC is going into the transistors [20]. The Arduino will be powered by a USB

connection to the computer for testing purposes. Its operating voltage is 5VDC, which the USB

regulates when connected to the computer [19]. A gate driver is needed to increase this voltage

to 12VDC. The MOSFETs control voltage. These transistors will control the output voltage that

will become the input to the AC/induction motor. Voltage, current, and power into the

MOSFETs should not exceed 60V, 70A, and 230W, respectively [17]. SPWM will be used to

control the three-phase AC voltage output through Arduino code [21]. The output of the inverter

circuit will be 15VAC and 2A. The input to the AC/induction motor should not be greater than

15VAC, 2A, and 30W. The current will have to be limited to take this into account. Inductors

and capacitors will be used to create a low pass filter at the output of the inverter circuit to filter

out noise and reduce harmonic components [22]. The output frequency should be around 50Hz,

so the inductor value should be 2mH and the capacitor value should be 5.087mF. These values

can be changed as needed. The desired motor speed will be chosen once the prototype of the

inverter is completed. It should only take two minutes for the AC motor to start spinning. The

DC motor will be controlled by the Sciamble hardware from the University of Minnesota and

computer to simulate the mechanical load in an EV.

The second system will replicate braking in an electric vehicle. Below in Figure 2 is a

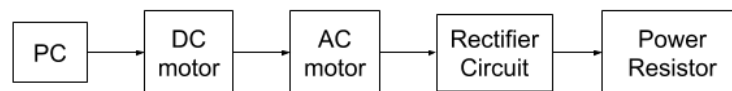block diagram of the second system, which uses a rectifier circuit.

Figure 2: Block diagram of braking system

A computer will control the speed of the DC motor. The DC motor will be coupled to the AC

motor/permanent magnet. The desired motor speed will be chosen once the prototype of the

rectifier is completed. The three-phase AC power will be the input to the rectifier circuit. The

rectifier circuit will convert the three-phase AC voltage to DC voltage. It will again be built with

six of the same type of transistor. The gate voltage going into each of the MOSFETs will again be 12VDC and controlled with an Arduino Mega 2560 Rev3 microcontroller and a gate driver with two 0.1uF capacitors connected. A 4.7kΩ resistor will be connected to the gate of each MOSFET to limit the current. The Arduino will be powered by a USB connection to the computer, which allows it to output 5VDC and the gate driver will increase this voltage to 12VDC. These transistors will control the output voltage that will become the input to the power resistor. Again, voltage, current, and power into the MOSFETs should not exceed 60V, 70A, and 230W, respectively. MATLAB calculations will determine the PWM to control the DC voltage output through Arduino code. The output of the rectifier circuit should be 28VDC and 7A. The input to the DC motor should not be greater than 28VDC AC, 7A, and 196W. The current will have to be set to 7A to take this into account. A 1000uF capacitor will be used to filter the output of the rectifier circuit due to the larger output voltage [23]. This value can be changed as needed. The DC voltage should be able to be measured within two minutes of starting the computer program to start the DC motor.

4   Design Alternatives

The first major design alternative that was considered was the type of source. The source

for the inverter system could have been from the computer instead of the DC power supply. The

source for the rectifier system could have been the three-phase AC input from the wall outlet

instead of the computer. In the first scenario, the source would have been the computer

connected to the DC motor. The motor would have then been connected to a DC generator where

DC voltage would be the output. This output would then become the input into the inverter

circuit and converted to three-phase AC voltage to power a resistor load or AC motor. In the

second scenario, the source would have been the three-phase AC input connected to the rectifier

circuit. The rectifier circuit would convert AC voltage to DC voltage to power a DC motor. The

motor would have then been connected to a DC generator that would be controlled by the

computer to replicate a mechanical load.

Using the computer instead of a three-phase AC source and using a DC supply instead of

the computer allows the braking and driving processes in an electric vehicle to be more

accurately represented.

There were also some alternatives considered for three-phase PWM control which

included delta modulation and space vector modulation (SVM). Delta modulation uses a sine

voltage as a reference signal and a delta-shaped signal as a carrier signal, which is generated by

integrating the output pulse. An error signal is passed into a hysteresis comparator and quantized

into an upper or lower limit to determine the point for the switching pulses. This is a technique

that is easy to implement, has a continuous inverter voltage control and direct control of the line

harmonics. However, the inverter output waveform is not synchronized with the control signal. SVM is specifically used for three-phase induction motor drives. It reduces the lower output AC voltage that happens with SPWM and generates an output voltage and current with less harmonic distortion. However, it is a more complicated control technique [15]. In a paper written by Renu Sharma (a post graduate power systems student at the Institute of Engineering and Technology), Deepak Kumar Goyal (an assistant professor at Government Engineering College) and Harpreet Singh (an assistant professor at the Institute of Engineering and Technology), they conclude that SVPWM has become the most popular and important technique for three-phase voltage source inverters for the control of AC induction motors. It generates less THD than the SPWM control technique [24].

In the final design, SPWM was chosen for the inverter circuit. The switching frequency is high to make the output better, so there is an increase in switching losses and stress on the transistors. However, it is easy to implement and control and is compatible with most modern digital systems [15]. The rectifier circuit will use MATLAB to calculate the duty cycles to switch on and off the MOSFETs. The comparisons necessary in SPWM for the inverter circuit will be calculated in MATLAB as well.

5   Design

The three-phase pulse width modulated AC/DC rectifier and DC/AC inverter can be split

up into two separate systems of five different blocks each. Below in Figure 3 is a top level block

diagram of the driving system.

Figure 3: Top level block diagram of driving system

These five blocks consist of the source, inverter circuit, AC/induction motor, DC motor, and

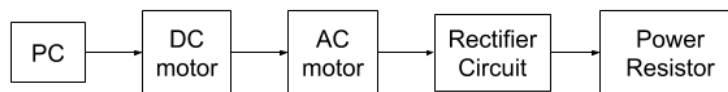computer. Below in Figure 4 is a top level block diagram of the braking system.

Figure 4: Top level block diagram of braking system

These five blocks consist of the computer, DC motor, AC motor/permanent magnet, rectifier

circuit, and load.

For both systems, the circuits will be built on breadboards. Six IRFP054 power

MOSFETs will be used in each circuit in combination with three gate drivers. These will be the

MIC4422 MOSFET drivers, which have been used in previous projects and can be used with the

Arduino's 5VDC output and increase it to 12VDC for the gate of the transistors [25] [26]. Below

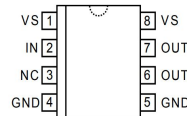in Figure 5 is a pin diagram of the MOSFET driver.

Figure 5: Pin diagram of MOSFET driver

Pin 2 (IN) will be connected to the Arduino's 5VDC output, pins 4 and 5 (GND) will be connected to ground, pins 1 and 8 (Vs) will be connected to an external 12VDC input with 0.1uF capacitors connecting those pins to 4 and 5 (GND), respectively, to ensure low supply impedance, and pins 6 and 7 (OUT) will be connected to the gates of two MOSFETs [18]. The outputs of the driver will be 12VDC and 9A. The MOSFETs are N-Channel MOSFETs, because P-Channel MOSFETs are more difficult to control. This specific IRFP054 MOSFET was also chosen based on its voltage, current, and power ratings. The maximum voltage, current, and power it can handle is 60V, 70A, and 230W, respectively. They will use the PWM digital output pins from the Arduino, which only go up to 5VDC. The transistors need 10-15VDC at its gate to switch on, which is why a gate driver is necessary. A 4.7kΩ resistor will also be connected to the gate to limit current. The source of the MOSFETs will be connected to ground and the drain will be the output [27]. The motors will come from the Sciamble brand from the University of Minnesota but only the DC motor will be controlled by the computer. The DC supply and computer will be provided by Professor Luke Dosiek. The Arduino will eventually be powered by an external battery pack with the Arduino code loaded. Each system should only need a maximum of two minutes to convert the voltage from DC to AC and AC to DC. The two systems should also be able to run for five minutes without interruption.

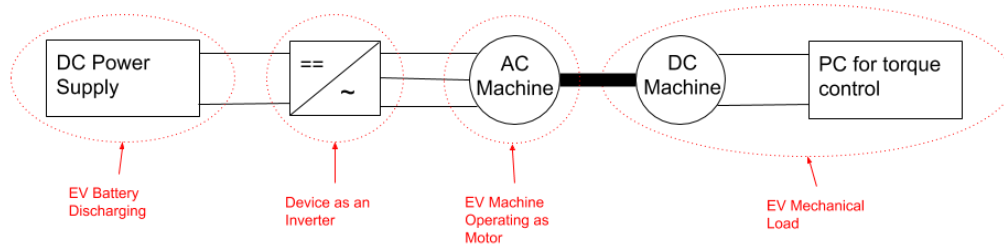Below in Figure 6 is a detailed block diagram of the driving system.

Figure 6: Detailed block diagram of driving system

For driving, the 40VDC supply will be used as the battery of an EV. The inverter will convert the

DC voltage to AC voltage to power the AC/induction motor, which represents the main traction

motor in an EV. The input to the AC motor should not be greater than 15VAC, 2A, and 30W.

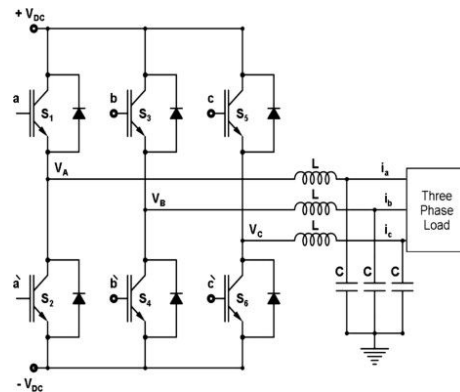Below in Figure 7 is a circuit diagram of the inverter circuit.

Figure 7: Circuit diagram of inverter circuit

A 17VDC signal will be connected to the drain of each transistor. SPWM will be used to control

the motor speed through the Arduino code. The comparison of a triangle wave to a sine wave

with a slightly smaller amplitude will be done in MATLAB to find the duty cycles to determine

which each of the six MOSFETs are on or off [28]. These will then be implemented into the

Arduino code to turn on or off each switch. The three outputs will then be connected to the

three-phase AC/induction motor. The output frequency should be around 50Hz, so, the inductor

value should be 2mH and the capacitor value should be 5.087mF. These values can be changed

as needed. The AC motor is then mechanically coupled to the DC motor, which is

torque-controlled by the lab computer to simulate the mechanical load of an EV such as friction,

drag, and acceleration/inertia. Below in Figure 8 is a detailed block diagram of the braking
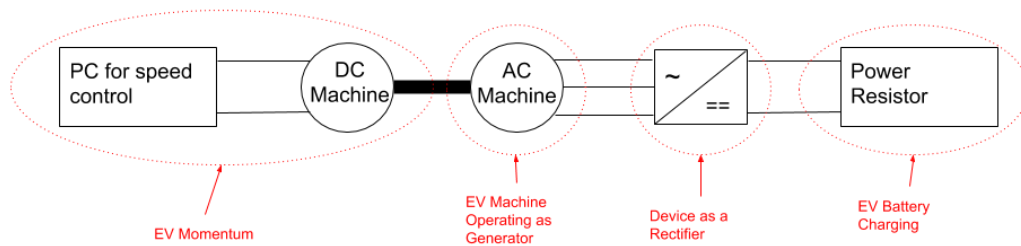
system.

Figure 8: Detailed block diagram of braking system

The braking system will use the same DC motor as in the driving system. The computer will

control the speed of the DC motor, which represents an EV putting its momentum back into the

system. The desired speed will be determined once the rectifier circuit is built. It is mechanically

coupled to the AC machine, which is now spinning as a generator. The input to the AC motor

should not be greater than 28VAC, 7A, and 196W. The AC machine still represents the traction

motor in an EV. Below in Figure 9 is a circuit diagram of the rectifier circuit.
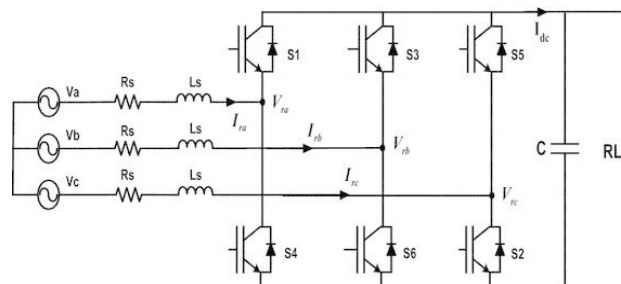

Figure 9: Circuit diagram of rectifier circuit

The comparison of AC voltages from each of the three phases will be compared in MATLAB to determine which MOSFETs are switched on or off [29]. The duty cycles will be calculated in MATLAB as well, so they can be implemented into the Arduino code to control the MOSFETs. Then, the outputs of the AC machine get converted by the rectifier circuit, which sends the DC voltage into a resistor representing the EV battery getting recharged. A 1000uF capacitor will be used to filter the output due to the larger output power. This value can be changed as needed.

The goal is to replicate what happens in an electric vehicle using two different types of AC motors and a DC motor. The motors should not take more than two minutes to start moving and should continue this movement for at least five minutes. If there is time, bidirectional power flow can be implemented in both the inverter and rectifier circuits in which the systems can switch between driving and braking in real time.

6 Preliminary Testing Results

In Figures 10 and 11 below, the Simulink model and its voltage output of a three-phase

inverter is provided by Rashmil Dahanayake from the University of New South Wales [30].
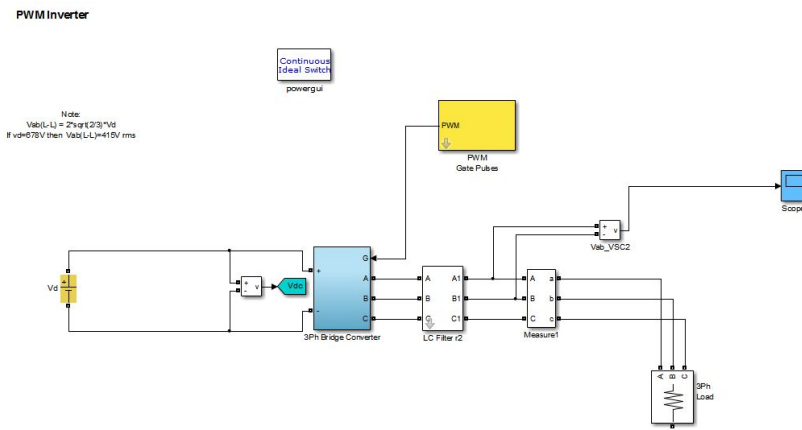

Figure 10: Three phase inverter circuit

A DC source is inputted to an inverter circuit. The inverter circuit then converts DC voltage to

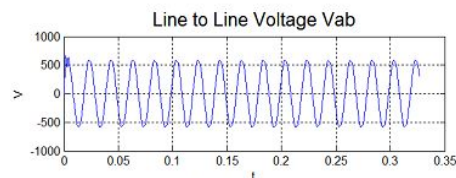three-phase AC, and the output is filtered with an inductor and capacitor.

Figure 11: Three phase inverter voltage output

The result is a clean AC output voltage.

In Figures 12 and 13 below, the Simulink model and its voltage and current output of a

SVPWM three-phase rectifier is provided by Syed Abdul Rahman Kashif from the UET Lahore
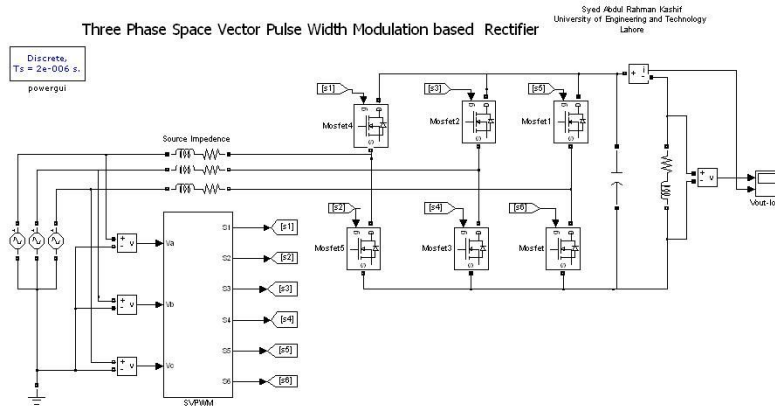
[31].

Figure 12: Three phase rectifier circuit

A three-phase AC source is inputted to a rectifier circuit. The rectifier circuit then converts the

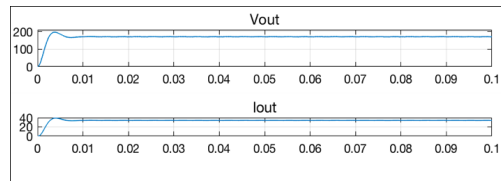AC voltage to DC, and the output is filtered with a capacitor.

Figure 13: Three phase rectifier voltage and current output

The result is a steady DC output voltage and current.

7   Implementation Schedule

<u>Winter Break</u>

- Create Simulink Models from scratch of the rectifier and inverter circuits

- Work on MATLAB PWM duty cycle calculations

<u>Winter Term</u>

Week 1

- Create Multisim circuits

- Build inverter circuit on breadboard

- Order any other necessary parts - gate drivers, batteries

Week 2

- Continue working on inverter circuit

- Build rectifier circuit on breadboard

- Begin code for PWM control with Arduino

Week 3

- Test inverter circuit

- Continue working on both circuits and Arduino code

Week 4

- Continue working on both circuits and Arduino code

- Reapply for SRG if needed

Week 5

- Test rectifier circuit

- Continue working on both circuits and Arduino code

- Have PWM integrated with both circuits

Week 6

- Start to integrate the output of the inverter to the AC motor

- Start to integrate the output of the rectifier to the power resistor

Week 7

- Continue working on integration

- Finalize both circuits

Week 8

- Finalize integration

Week 9

- Work on poster/paper

Week 10

- Finalize poster/paper

References

[1] Jason Torchinsky, "This Is Why Cars Use AC-Producing Alternators When They Run On DC Power," G/O Media Inc., 19 June 2018.

[2] Department of Energy, "The History of the Electric Car," U.S. Department of Energy, 15 September 2014.

[3] Wikipedia, "History of the electric vehicle," Wikipedia, 10 November 2019.

[4] Office of Energy Efficiency and Renewable Energy, "Electric Vehicle Basics," U.S. Department of Energy, 2019.

[5] Mark Kane, "Compare EVs: Guide To Range, Specs, Pricing & More," Eric Loveday, 22 July 2019.

[6] David Reichmuth, "New Data Show Electric Vehicles Continue to Get Cleaner," Union of Concerned Scientists, 8 March 2018.

[7] Environmental Protection Agency, "Sources of Greenhouse Gas Emissions," United States Environmental Protection Agency, 13 September 2019.

[8] UAW Research, "Taking the high road: Strategies For a Fair EV Future," UAW International, 2019.

[9] bennelson, "Build Your Own Electric Car!," Autodesk, Inc., 9 July 2017.

[10] Marshall Brain, "How Electric Cars Work," http://howstuffworks.com/, 27 March 2002.

[11] V. Vaideeswaran and N. Sankar, "Control Techniques of Three Phase PWM Rectifier," *International Journal of Engineering and Advanced Technology (IJEAT)*, Volume-8, Issue-2S, December 2018.

[12] Ferdinant Visser, "Design and implementation of a bi-directional 3 phase converter for a 30kW range extender application," Delft University of Technology, 12 September 2011.

[13] Malik Zaid, "Three Phase Inverter," LinkedIn Corporation, 31 December 2016.

[14] Mike Glampe, "How Pulse Width Modulation in a VFD works," KEB America Inc., 2019.

[15] Anna University, Chennai, "11_chapter 3," Anna University, Chennai, pp. 33-55.

[16] Wikipedia, "Pulse-width modulation," Wikipedia, 11 November 2019.

[17] *Power MOSFET*, IRFP054, Vishay Siliconix, 14 March 2011, pp. 1-2.

[18] *9A-Peak Low-Side MOSFET Driver*, MIC4422, Micrel, August 2005, pp. 1-12.

[19] Arduino Mega 2560, Arduino, 2019.

[20] Mark Osborne, "Arduino PWM MOSFET Gate Resistor," WordPress, 24 October 2015.

[21] Engineering Funda, "PWM Inverter (Working, Principle, 3-phase Inverter, Waveform, Sine PWM inverter) Engineering Funda," YouTube, 27 April 2017.

[22] D Mohankumar, "PWM Inverter," AspenCore, Inc., 7 July 2010.

[23] LearningaboutElectronics, "What is a Smoothing Capacitor?," LearningaboutElectronics, 2018.

[24] Renu Sharma, Deepak Kumar Goyal, and Harpreet Singh, "Analysis of Space Vector PWM for Three Phase Inverter and Comparison with SPWM," *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*, Vol. 5, Issue 1, January 2016.

[25] Beurnii, "How to chose a mosfet driver," Arduino Forum, 16 July 2015.

[26] g4ce, "Guidance for MOSFET circuit to increase PWM voltage level," Arduino Forum, 21 July 2017.

[27] Oscar Liang, "HOW TO USE MOSFET – BEGINNER'S TUTORIAL," OscarLiang.com, 7 October 2013.

[28] katkimshow, "Fundamentals of Power Electronics: Three-Phase Diode Rectifier Basics," YouTube, 18 March 2018.

[29] katkimshow, "Three-Phase Full-Wave Rectifier Average Output Voltage," YouTube, 20 March 2019.

[30] Rashmil Dahanayake, "3 Phase Inverter," The MathWorks, Inc., 17 December 2013.

[31] Syed Abdul Rahman Kashif, "Space Vector Pulse Width Modulation Based Three Phase Rectifier," The MathWorks, Inc., 23 September 2011.

Appendices

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