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Smart Recloser

Hung Quoc Ngo
Worcester Polytechnic Institute

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SMART RECLOSER

Submitted by:

Hung Ngo

hqngo@wpi.edu

Approved by:

Professor Alexander Emanuel

aemanuel@wpi.edu

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ABSTRACT

The goal of this project is to design, install and test a Smart Recloser system that is able to protect electric power distribution lines from faults. The system was implemented by a microprocessor circuit breaker device that constantly monitors the distribution lines for current increase and disruptions in the power signals. Any notable changes cause the Smart Recloser to open the lines and recloses it only when the fault is cleared. The device was tested through simulations and a small scale implementation.

ACKNOWLEDGEMENTS

I would like to take this opportunity to express our appreciation and gratitude to the Professors and faculty of the WPI ECE department who have all helped supply the necessary knowledge and skillset for this project. Most importantly, I would like to thank my advisor, Professor Alexander Emanuel for motivating and guiding me throughout the course of this project. This MQP would not be possible without their assistance and continual support.

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1.0 INTRODUCTION

Electricity is what connects the world together. It is the source of power that has helped fuel the advances of countless innovators and has pushed our society into the technological era. In today's age, this form of power is as important as ever. It is clear that the preservation and safe distribution of this energy is crucial. Of the countless tools used today, this project will be focusing on the implementation of the Smart Recloser.

The electrical power system involves the distribution of electricity through large conductors spanning across entire countries. Although this power grid has successfully supplied energy to numerous homes, it is also very prone to the dangers of the extreme weather and environment. This can lead to potential lighting strikes, fallen trees, and short circuits of the power lines. These potential factors will cause to irregularities in the distribution system – called faults. These faults may involve high surges of power and current, causing potentially hazardous or fatal conditions for the consumer's end. It is due to this that electrical utility companies implement numerous protection devices.

One important precaution measure used is the autorecloser. It acts as a circuit breaker if any surges of current are detected and opens the power lines. As the name implies, it automatically attempts to close the line numerous times. However, if the faults are persistent and remains, the autorecloser will exceed its set programmed number of tries to close the line, keeping the power lines disconnected. In this case, workers will be necessary to manually reconnect the lines. However, it today's aging distribution system, it is not always easy or safe to detect which lines need maintenance.

Thus, the focus of the project is the design of a Smart Recloser that can detect and monitor faults. If there is a surge of current, the reclose can break the line and reduce any dangerous conditions to the consumer. At the same time, the Smart Recloser will be able to monitor the fault and only reconnect the line when the fault has successfully cleared. Thus, reducing the need for manual labor and providing a smoother distribution of power across the world.

2.0 BACKGROUND

In order understand the scope of the problem and the purpose of this project, it is important to know the general information involving the modern power grid. This section will cover a brief overview of the typical power grid and distributed electricity. This will be followed by various faults and their different effects that may be experienced. Finally, this section will discuss current fault protection systems used.

2.1 ELECTRICAL POWER GRID

The delivery of electric power to the customer has 3 main components: Generation, Transmission, Distribution. A depiction of the power grid can be seen below in figure 2.1.1.

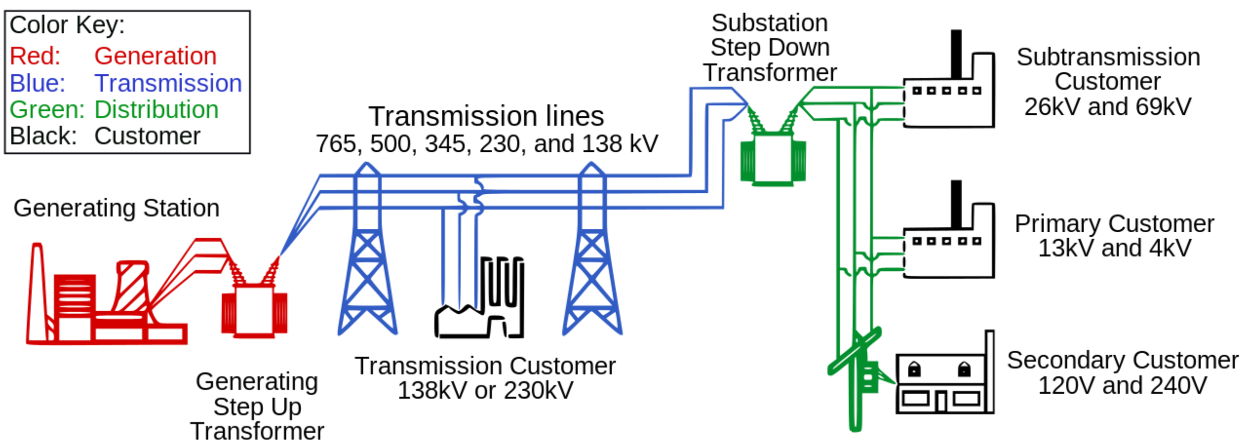


Figure 2.1.1: Electrical Power Grid

At the first stage, generation, electricity is produced at power utility plants. Electricity can be generated through a number of methods involving burning fossils fuels, using nuclear plants, or green technology. The electricity generated at this stage is approximately 13,800volts. The typical characteristics of electricity is 3-phase AC voltage. At the end of generation, the power is stepped up at transformers and prepared for transmission.

At the second stage, transmission, electricity must travel long distances that can span miles. It is important at this stage the the electricity must be stepped up to a high voltage in order to reduced power losses in the line. During transmission, electricity continues to be stepped up and down a number of times.

At the final stage, distribution, electricity is stepped down to appropriate levels according to the customer needs. This electricity is then delivered to the customer for use.

2.2 DISTRIBUTED ELECTRICITY

In a typical power distribution system, electricity will be supplied through a 3-phase AC signal as shown in figure 2.2.1. This is done by supplying electricity through 3 different conductors. Each of these signals has a frequency of 60Hz, but are all 120^{o} out of phase within one another. The advantage of this method is that it provides more power and less conductor material compared to a signal wire used. Thus, it is a more efficient method to supply electricity.

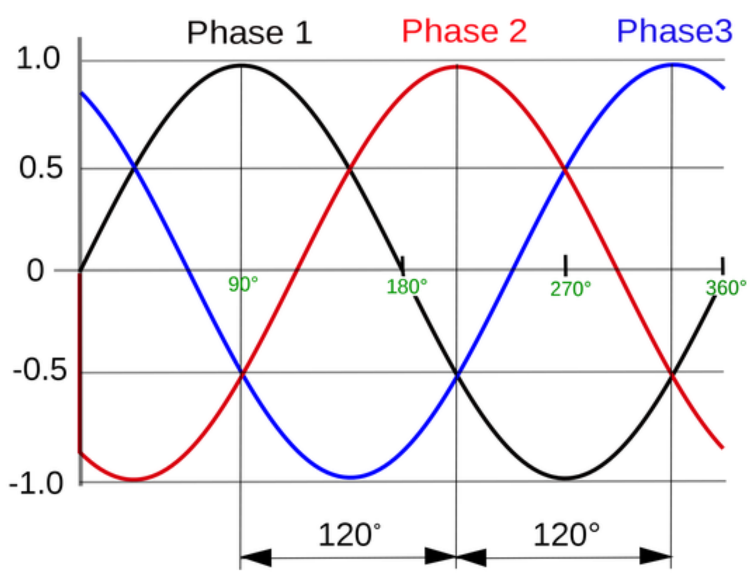


Figure 2.2.1: 3-Phase Electrical Power Signal

In order to fully analyze the effect of faults on distribution lines, it is important to consider how the signal of a 3-phase system may be affected.

2.3 TYPES OF FAULTS

In electrical networks power lines can be subject to a number of probabilities for faults such as lightning, wind, trees falling, or line conductor failure. Once these faults occur, the power system will deviate from its normal voltage and current operating conditions. This is can potentially lead to electrical failures, fires, or even life-threatening situations.

Although there are a number of faults that distribution lines are vulnerable to, this project will analyze two important types of faults: Low Impedance Faults and High Impedance Faults.

2.3.1 LOW IMPEDANCE FAULTS

Low Impedance faults may occur when power lines are short circuited or when there is a lightning strike to power lines. This will cause the current to reach extreme levels. In most cases, this fault may be a quick pulse to the to the distribution system. By analyzing significant rises in current, these type of faults will be easy to detect and resolve. The graph in figure 2.3.1 displays what a Low Impedance fault may look like.

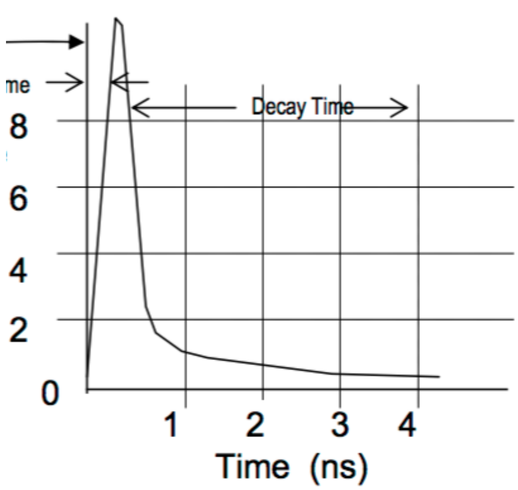


Figure 2.3.1: Low Impedance Faults

2.3.2 HIGH IMPEDANCE FAULTS

High Impedance faults may occur when there is some disruption in the generation or any irregular elements that may affect the power lines. This will cause some harmonics that contribute to the electrical signal to appear deformed and become noisy. Thus, the signal supplied may be disrupted or unbalanced. The figures 2.3.2 display the possible effect on the power line signals.

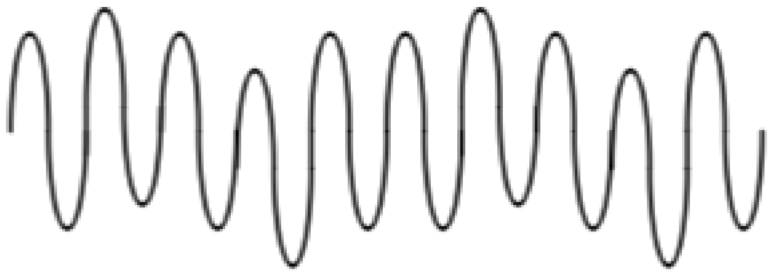


Figure 2.3.2: Low Impedance Faults – Asymmetrical sinusoidal signal

By analyzing both the Low Impedance faults and High Impedance faults, a clear observation between real and assumed faults can be detected. For instance, although the current may peak to high levels, it may not actually be a fault. In some cases, the customer may need to use more current to supply their equipment. Thus, it will appear that a fault has occurred when in fact it has not. The apparent method in differentiating from a real and assumed fault is by detecting any changes in harmonics. Thus, if a true fault occurs, there will be both a change in current levels and harmonics within the signal. By analyzing both scenarios, we will be able to determine which are faults and how to appropriately react. This will be the main basis of this project.

2.4 FAULT PROTECTION

The circuit breaker is a common form of fault protection. These devices are designed as electric switches that protect circuits from overloads. When it detects any faults, their contacts open and disconnect the power lines. An autorecloser is a special type of circuit breaker that automatically reclosed the power lines after a fault occurs. Typically, the recloser will attempt to close the line for a set number of times. However, if the fault is persistent the autorecloser will reach its preprogrammed number and remain open. The aim of this project is to redevelop the recloser and implement an intelligent microprocessor controlled design to the device.

3.0 PROBLEM STATEMENT

The goal of this MQP is to design a Smart Recloser that is able to detect faults and monitor the line to determine when the the fault has cleared, automatically opening and closing the line. This project will focus on a small scale prototype that will be able to serve as a proof of concept. The prototype will be able to analyze single phase distribution lines at lower voltage levels and monitor Low Impedance and High Impedance faults, safely connecting/disconnecting the lines. Thus, successfully protecting the customers' equipment and reducing the need for manual labor.

4.0 SMART RECLOSER - DESIGN APPROACH

The following section provides the initial overview of the Smart Recloser. The block diagram is first introduced to provide a summary of the functional blocks of the system. The behavior of each block is then detailed to describe the purpose of the system.

4.1 BLOCK DIAGRAM OVERVIEW

The Smart Recloser consists of Distribution Line Tester and four major functional blocks: The Current Sensor, Wave Analyzer Circuit, Microcontroller, and the Switching Relay Block. The complete block diagram can be seen in figure 4.1.1.

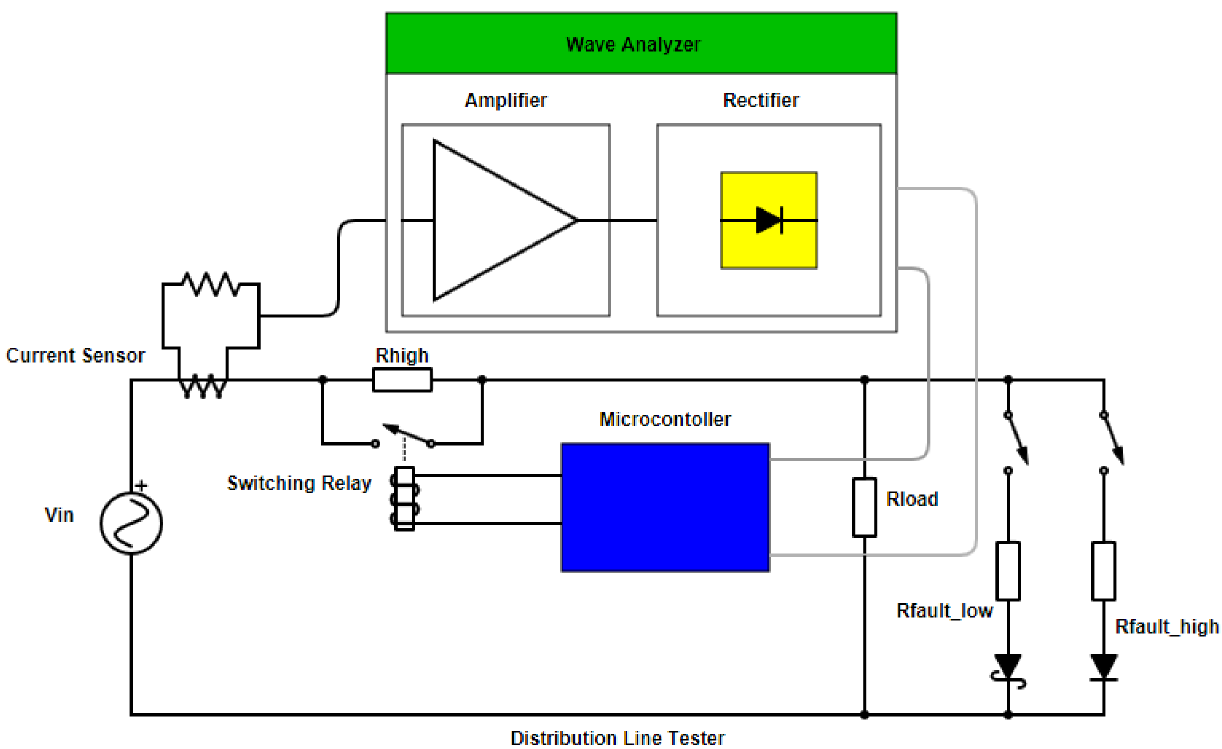


Figure 4.1.1: Block Diagram

In this miniature prototype, the Distribution Line Tester will be able to simulate a power line. Different modes of operation will be studied and will operate during normal conditions and also during faults. By testing this line at different modes of operation, it can show that the Smart Recloser can successfully monitor a power line and react appropriately.

The Current Sensor is a vital part gathering information from power lines. In this application a non-invasive method is chosen to allow the sensor to read the level of current through the Distribution Line. As explained later in this paper, the current sensor will only be able to output a very small level of voltage. This signal will need to be further amplified to successfully read data from the line.

The Fault Sensor circuit will be able to analyze the Distribution Line signal and determine if a fault has occurred. This will be done by observing the harmonics of the signal and comparing differences between the positive and negative halves of the waveform. Any notable changes will output a logic HIGH voltage, otherwise no voltage will be outputted.

The Arduino Uno was selected to control the Smart Recloser. Depending on the data received from the Fault sensor circuit, the microprocessor will be able to connect or disconnect the line automatically.

The Switching Relay Block will be interfaced by the Arduino. The relay will be disconnecting the line if a fault has been detected. If the fault has cleared, the relay will reconnect the line.

These different components of the Smart Recloser was tested using various simulations. The two major functional blocks, the Current Sensor and the Wave Analyzer Circuit was first tested separately. Then the final functional block, the Switching Relay block, was tested to demonstrate closing and open the transmission line.

The circuit schematic used to analyze the Testing Distribution Line is shown in figure 4.1.2.

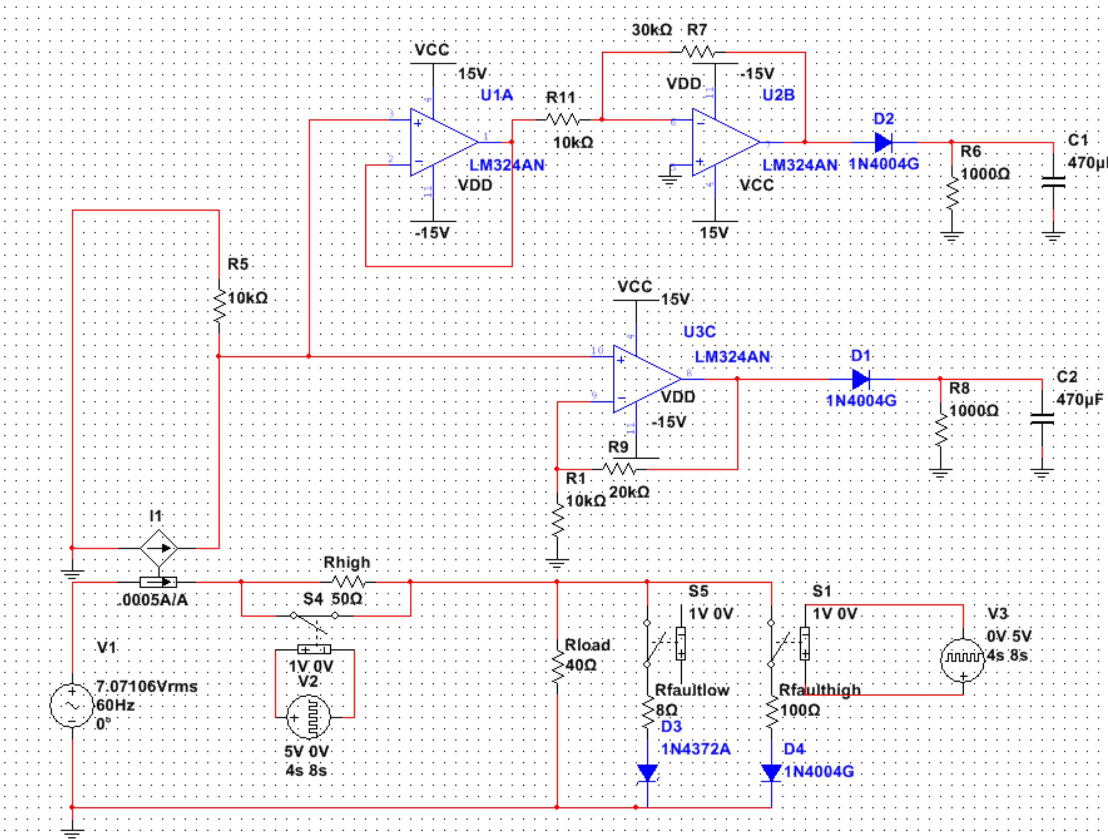


Figure 4.1.2: Wave Analyzer Circuit

4.2 DISTRIBUTION LINE TESTER

The Test Distribution Line will help demonstrate various faults and how the current will affect the load. The transmission line is shown below:

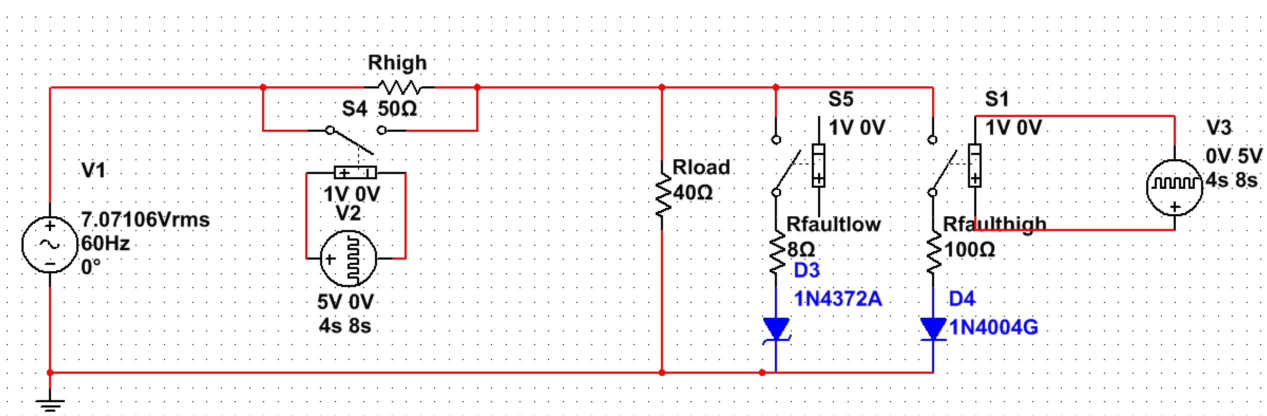


Figure 4.2.1: Testing Distribution Line

Similar to the signals in power lines, the electricity supplied will operate at a frequency of 60Hz. For the purpose of this project, the voltage is downscaled to a safer level of approximately 10Vpk.

There are four main modes of operation to pay attention to: Normal, Low Impedance Fault, High Impedance Fault and High Impedance mode. During the normal operation, we will expect regular current waveforms and safe levels – this is demonstrated through Rload. When the switch S5 connecting Rfaultlow is closed, the low impedance fault operation will be active. During this fault operation, we will notice much higher currents in the waveforms. When the switch S1 connecting Rfaulthigh is closed, the high impedance fault operation will be active. During the fault operation, we will notice slightly higher currents and larger harmonics in the waveforms. Finally, when a fault is detected in either case the circuit will enter High Impedance mode by opening switch S4 – simulating the recloser disconnecting the line. High Impedance mode will help lower the current to safer levels and also allow us to read the change in current flow. This is a vital aspect of the test line, since the line is still connected, it will still be possible to analyze the signal in the distribution line.

In order to understand function of the Smart Recloser, it will be important to understand the modes of operations and the two types of faults that will occur to the Distribution Line Tester.

4.2.1 LOW IMPEDANCE FAULT

The signal response of the Distribution Line Tester during a low impedance fault is shown in figures 4.2.2 and 4.2.3.

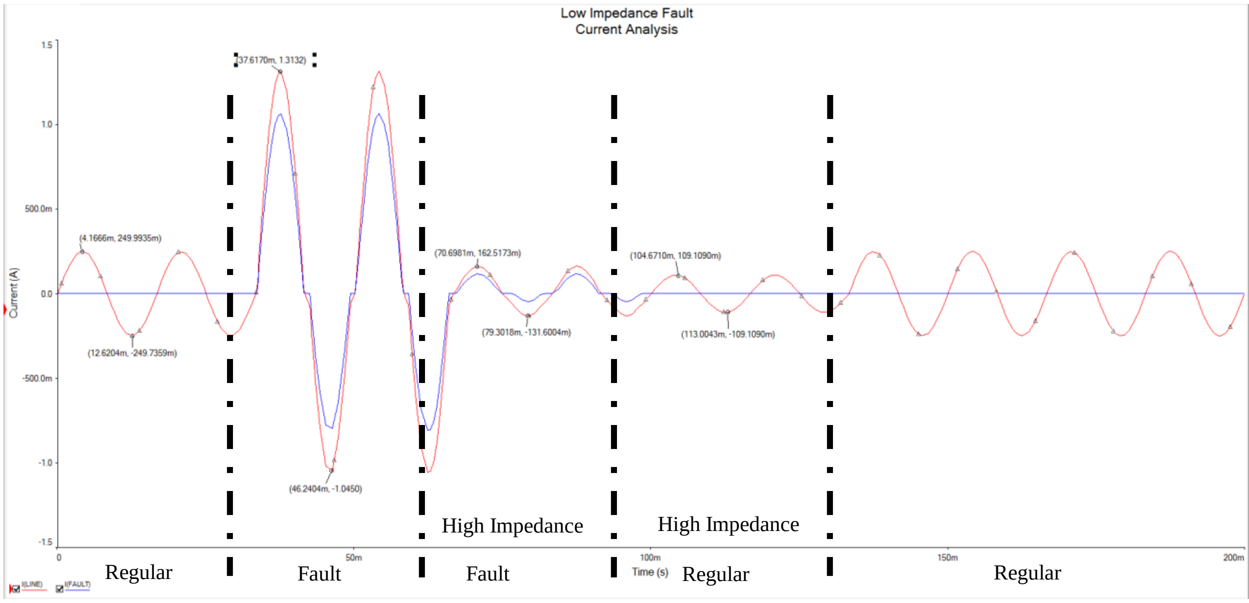


Figure 4.2.2: Low Impedance Fault Current Analysis

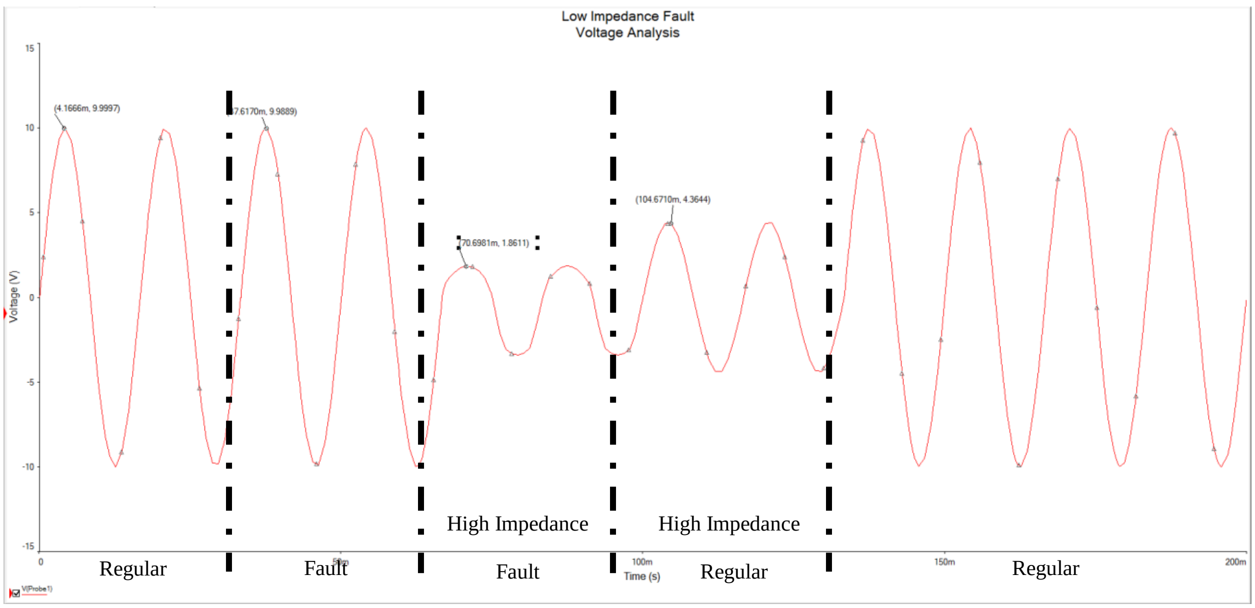


Figure 4.2.3: Low Impedance Fault Voltage Analysis

As shown in the figures above, an important response of the low impedance fault is a significant rise in current. At regular operation, the maximum current is approximately 250mA. However, once a fault occurs, this current peaks to 1.31A. This models an over current fault which can be very dangerous. By analyzing this significant response in current and comparing it to a certain threshold, the recloser will be able to determine if there is a low impedance fault. Once the signal in the test line has returned to normal operation levels, the recloser will be able to know that the fault has cleared.

4.2.2 HIGH IMPEDANCE FAULT

The signal response of the Distribution Line Tester during a high impedance fault is shown in figures 4.2.4 and 4.2.5.

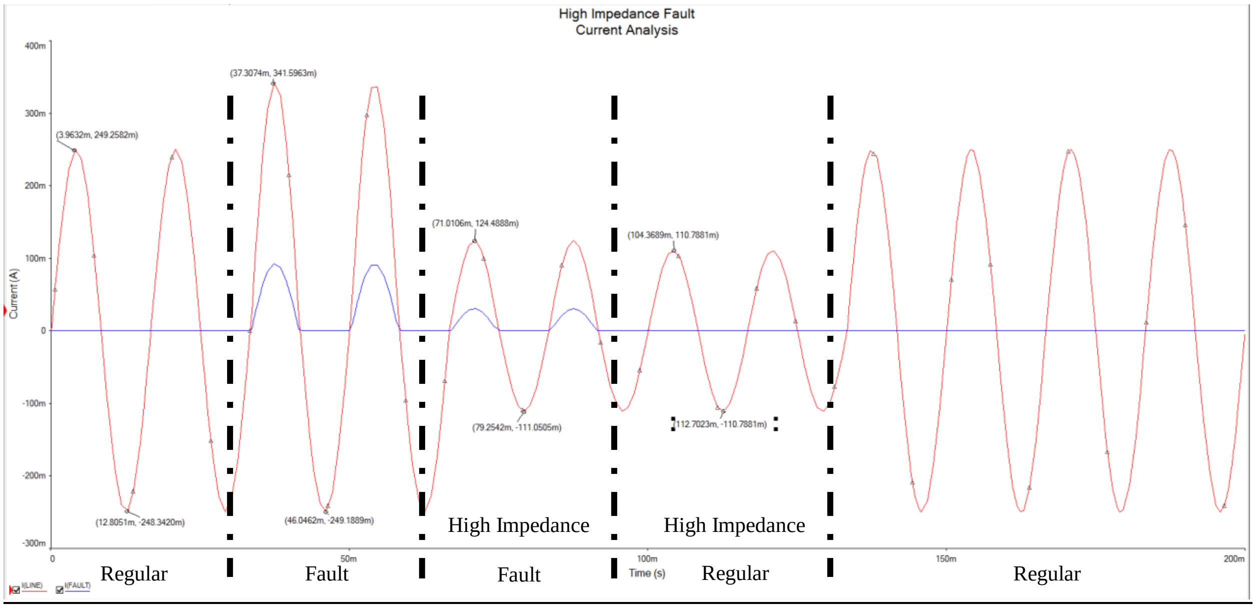


Figure 4.2.4: High Impedance Fault Current Analysis

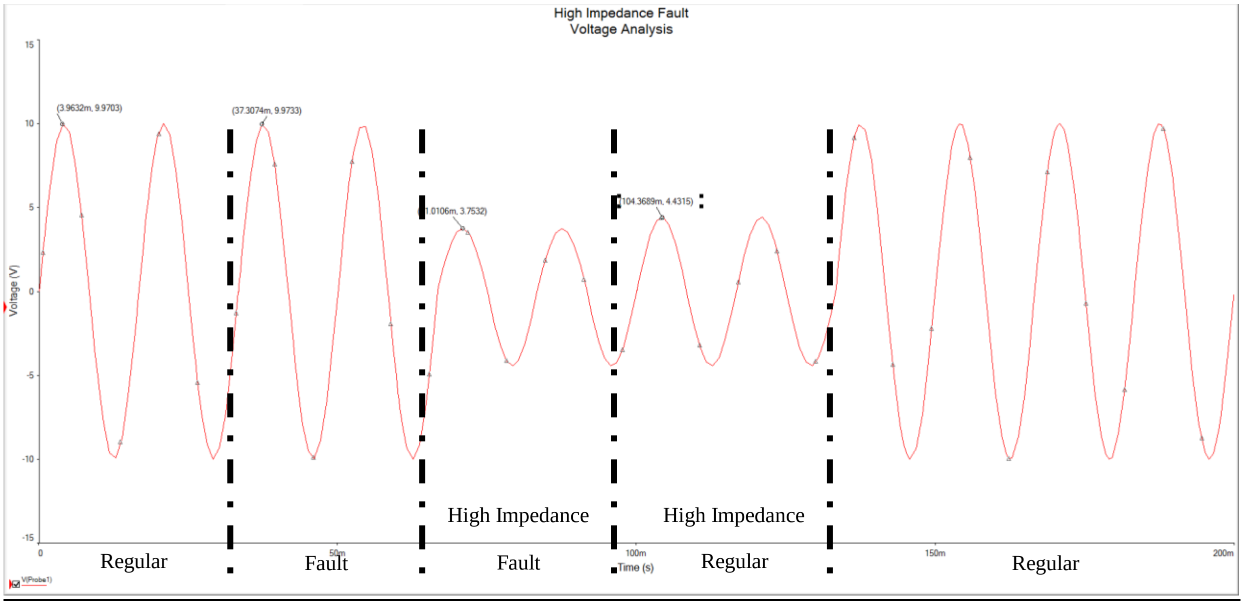


Figure 4.2.5: High Impedance Fault Voltage Analysis

As shown in the figures above, an important response of the high impedance fault is the imbalance of the current waveforms. At regular operations, the upper and lower peaks of the waves are equivalent. However, once a fault appears, the upper wave increases by approximately 90mA. This models a fault in which the current levels are not high, but the waveform symmetry is affected. By analyzing the upper and lower waveforms, the recloser will be able to determine if there is a high impedance fault. If the positive and negatives waves are equivalent, the recloser will know that the fault has cleared.

<u>4.2.3 FOURIER TRANSFORM ANALYSIS</u>

Taking a look into the Fourier Transform of the signal through the Distribution Line Tester at various modes of operation will help us understand the fluctuations in the line. Namely the harmonics that occur during faults. Typically, for a regular signal, the waveform will only have contributions from it first harmonic, at 60Hz. However, when faults occur the Smart Recloser will see the second harmonic affecting the signal as well. This relationship can be observed in figures 4.2.6, 4.2.7, and 4.2.8.

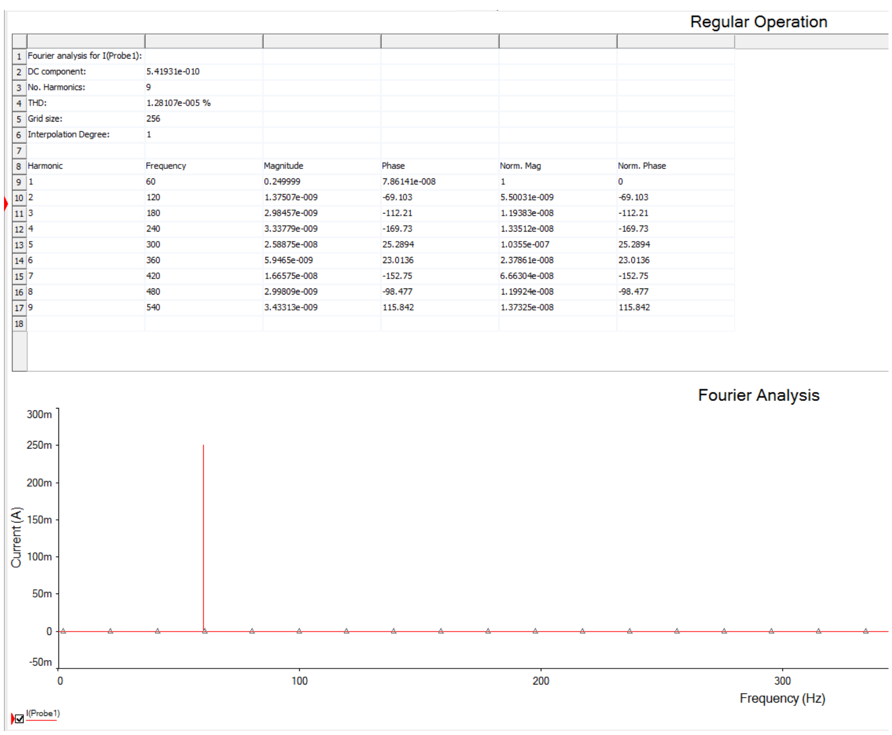


Figure 2.4.6: Fourier Transform – Regular Operation

Low Impedance Fault

1	Fourier analysis for I(Probe1):					
2	DC component:	0.110375				
3	No. Harmonics:	9				
4	THD:	9.7979 %				
5	Grid size:	256				
6	Interpolation Degree:	1				
7						
8	Harmonic	Frequency	Magnitude	Phase	Norm. Mag	Norm. Phase
9	1	60	1.1293	1.52622e-005	1	0
10	2	120	0.0309007	-90	0.0273628	-90
11	3	180	0.0865476	180	0.0766386	180
12	4	240	0.0273568	-90	0.0242247	-90
13	5	300	0.0414565	180	0.0367101	180
14	6	360	0.0225582	-90	0.0199755	-90
15	7	420	0.0208686	179.999	0.0184793	179.999
16	8	480	0.0170957	-89.999	0.0151384	-89.999
17	9	540	0.00968478	179.998	0.00857594	179.998
18						

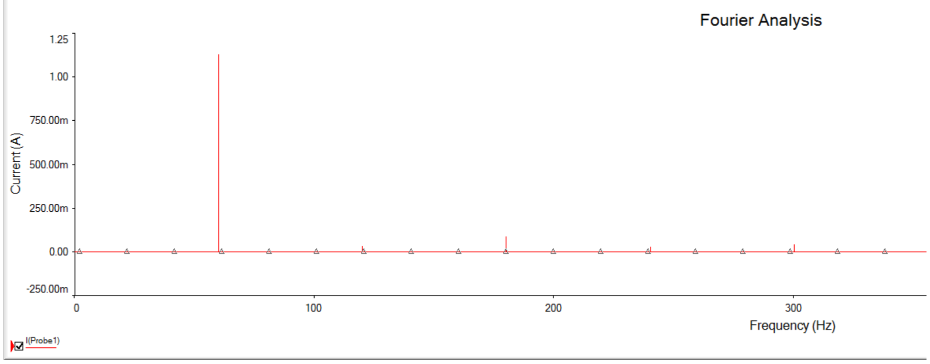


Figure 2.4.7: Fourier Transform – Low Impedance Fault

High Impedance Fault

1	Fourier analysis for I(Probe1):					
2	DC component:	0.0283597				
3	No. Harmonics:	9				
4	THD:	7.22263 %				
5	Grid size:	256				
6	Interpolation Degree:	1				
7						
8	Harmonic	Frequency	Magnitude	Phase	Norm. Mag	Norm. Phase
9	1	60	0.295366	-1.2294e-006	1	0
10	2	120	0.02081	-90	0.0704551	-90
11	3	180	0.00136227	-180	0.00461215	-180
12	4	240	0.00398643	-90	0.0134966	-90
13	5	300	0.000762528	-180	0.00258164	-180
14	6	360	0.00161597	-89.999	0.00547108	-89.999
15	7	420	0.000513153	-180	0.00173735	-180
16	8	480	0.000837653	-90.001	0.00283598	-90.001
17	9	540	0.000377059	-180	0.00127658	-180
18						

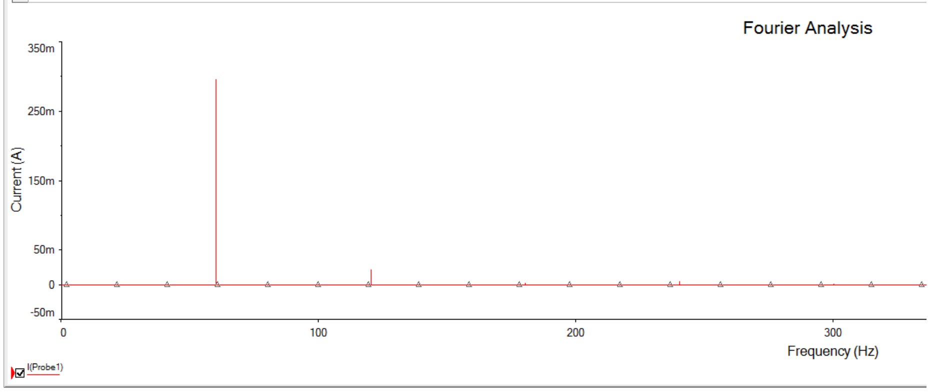


Figure 2.4.8: Fourier Transform – High Impedance Fault

4.3 CURRENT SENSOR

The next phase in the design is to read the current from the power line. This is done using a Current Sensor. The schematic used is shown below in figure 4.3.1.

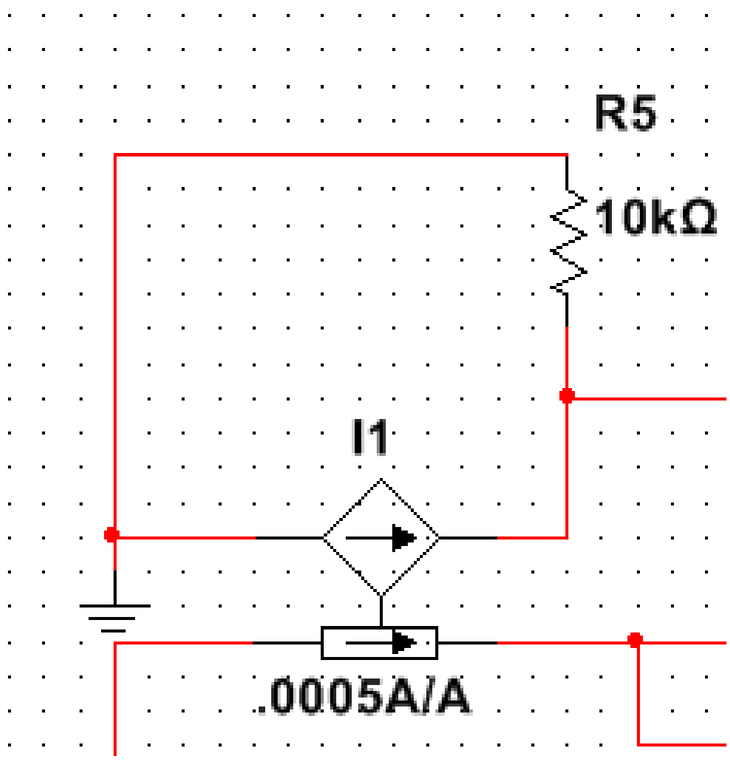


Figure 4.3.1: Current Sensor Circuit

Since it is important not to interfere with the signal through the test distribution line, the current sensor must be able to read the signal without disturbing the current. This can be done by using a non-invasive method in which the sensor can read the magnetic field induced by the current through the conductors. As shown above, the current sensor is effectively a current transformer. Placing a resistor across the sensor, will output a proportional voltage signal.

4.3.1 CURRENT SENSOR OUTPUT

The image in figure 4.3.2 and figure 4.3.3 displays the simulated output of the current sensor for a low impedance fault and high impedance fault.

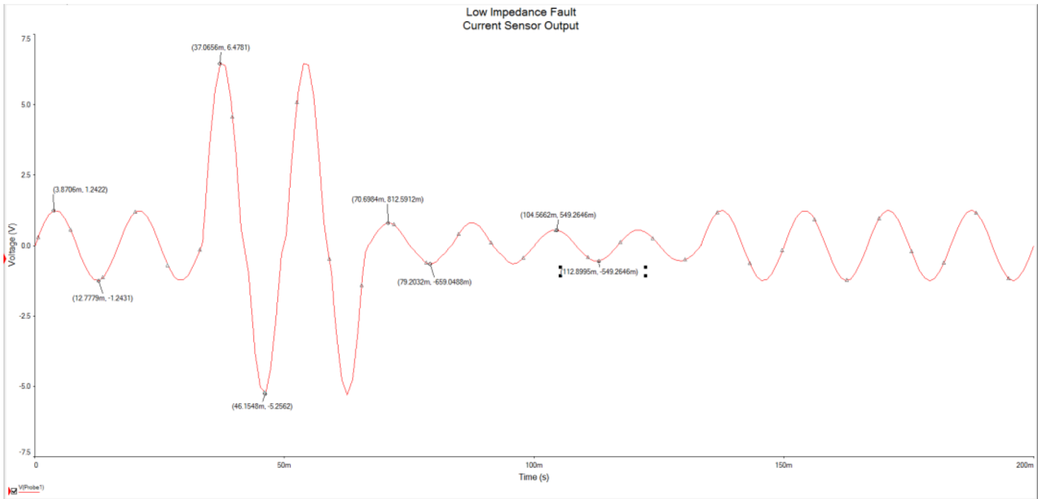


Figure 4.3.2: Low Impedance Fault – Current Sensor Output

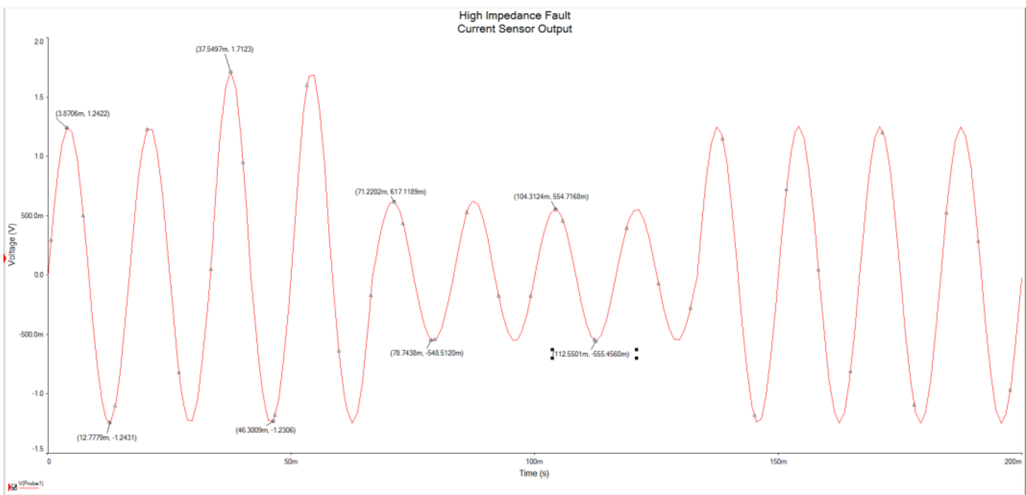


Figure 4.3.3: High Impedance Fault – Current Sensor Output

As shown in the figures above, the output voltage waveforms are directly proportional to the current through the Testing Distribution Line. However, the actual values of the signal will be too small for the Smart Recloser to accurately analyze. Thus, it will be required to amplify the signal further in the following phase.

4.4 WAVE ANALYZER

This section explains the design used for the Wave Analyzer phase of the Smart Recloser. The circuit diagram is shown in figure 4.4.1.

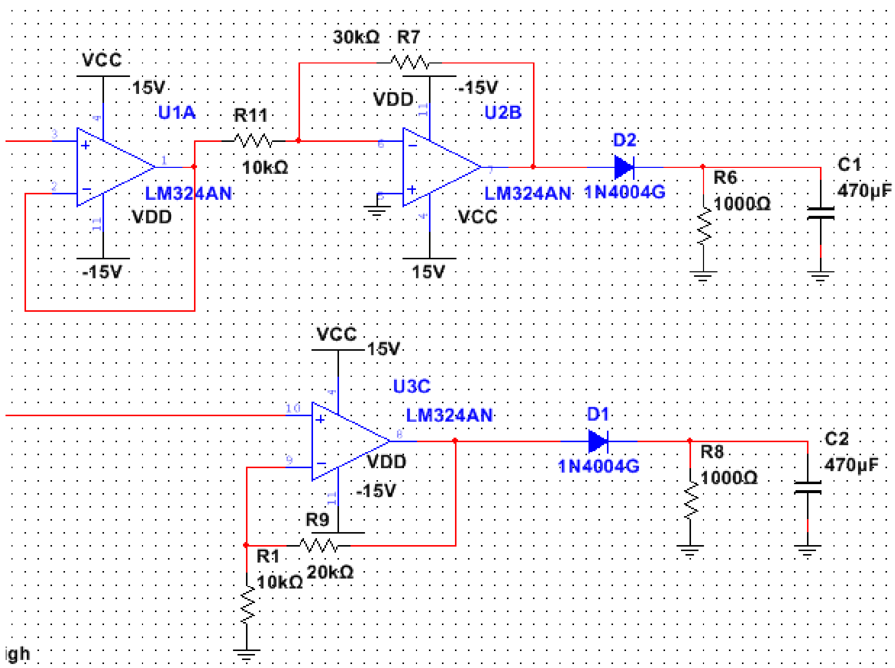


Figure 4.4.1: Wave Analyzer Schematic

The purpose of the Wave Analyzer is to amplify the signal from the Current Sensor and separate the upper and lower waveforms of the the signal. This signal is then rectified to a stable dc voltage and connected in the microcontroller of the following phase. This analyzer is composed of two main components for both the positive and negative halves of the signal, the amplifier and the half-wave rectifier.

4.4.1 AMPLIFIER

The amplifier is used to increase the signal from the current sensor. There are two sets of amplifiers used for the positive and negative waves. The amplifier design is shown in figure 4.4.2 and figure 4.4.3.

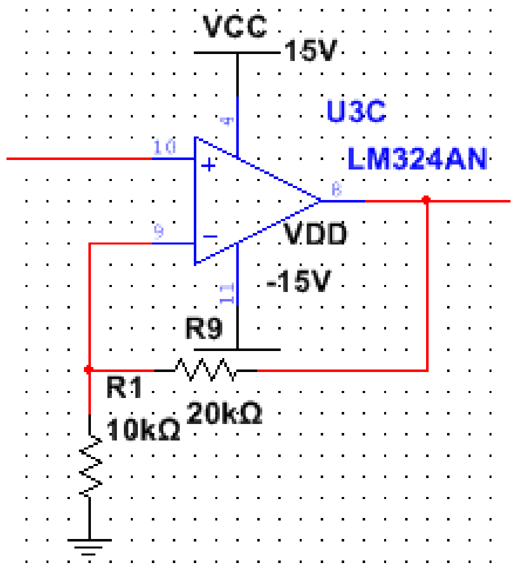


Figure 4.4.2: Upper Half Wave Amplifier Design

The non-inverting amplifier was implemented for the the postive half of the signal. With the above resistor component values, the design will amplify the signal by three times. The amplification is given by the following equation:

A_v = 1 + R9/R1 = 1 + 20kOhm/10kOhm = 3

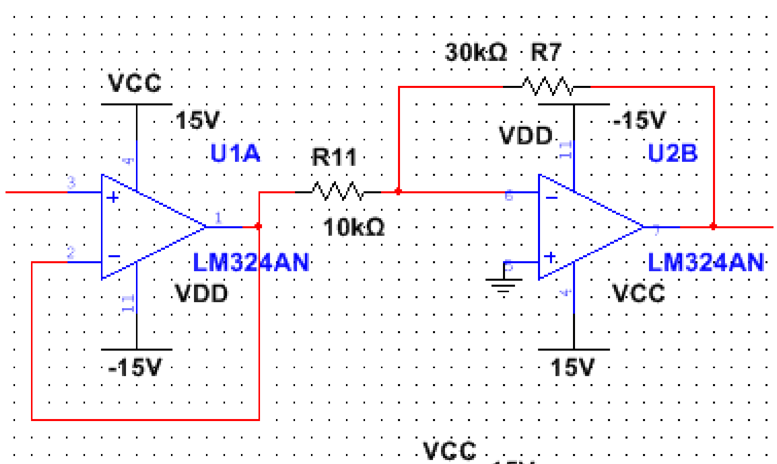


Figure 4.4.3: Lower Half Wave Amplifier Design

Two amplifiers were cascaded to effectively implement the signal. A unity gain amplifier was used in order to ensure that the current output was not affected. An inverting amplifier was then used in order to capture the negative half of the waveform. With the above component values, the design will amplify the signal by three times.

$$\mathbf{A_{v1} * Av_{2} = (1) * (-R7/R11) = -30kOhm/10kOhm = -3}$$

4.4.2 HALF-WAVE RECTIFIER

With the signal amplified to an adequate amount, it is required to rectify the voltage to a constant DC level in order for the microcontroller to analyze the contribution of the upper and lower half waves. The design is shown in figure 4.4.4.

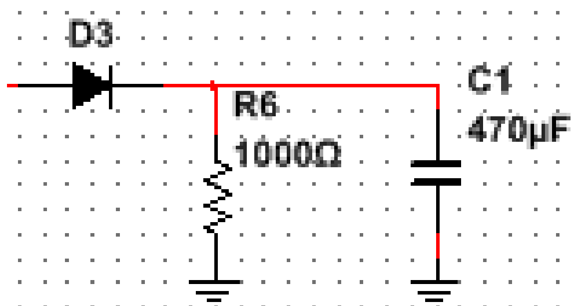


Figure 4.4.4: Half-Wave Rectifier w/ Smoothing Capacitor

The half-wave rectifier and smooth capacitor was used to set the signal to a constant DC voltage level. For the rectifier to work, the components had to be selected in order to ensure that the signal was able to discharge and charge at a desired rate. Furthermore, the smoothing capacitor will also produce a ripple voltage at the output, this ripples is something that needed to be minimized as much as possible. With these two considerations in mind, the design of the rectifier was selected. The values of the components was determined with the following relations.

$$\mathbf{R * C >> 1 / f}$$

$$\mathbf{Vripple = Iload / f C}$$

4.4.3 WAVE ANALYZER OUTPUT

With both components of the Wave Analyzer combined, the output signal should be able to output a close to DC level voltage with varying levels according to the faults seen at the Testing Distribution Line. The outputs for the Wave Analyzer is shown in figure 4.4.5 and figure 4.4.6.

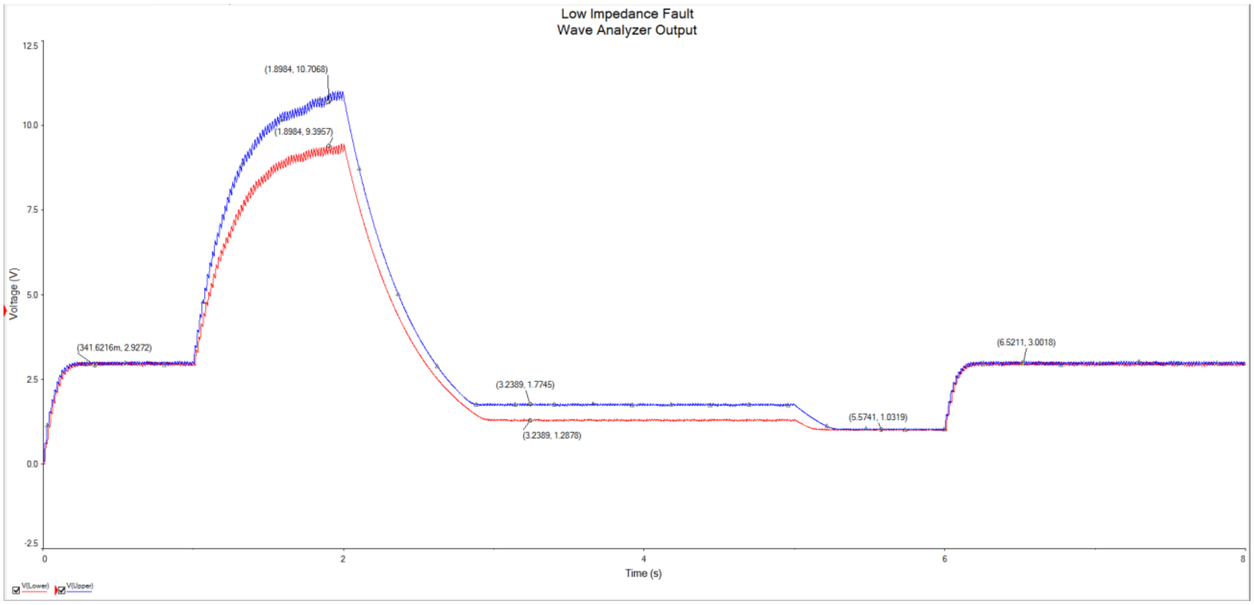


Figure 4.4.5: Low Impedance Fault – Wave Analyzer Output

In the case of a low impedance fault, the voltage increases to a very large amount and there is also some imbalance between upper and lower waveforms. The Smart Recloser will then be able to analyze if the voltage reaches a certain threshold and determine if it is a low impedance fault, this will then trigger the high impedance mode and only clear once the voltage level is under the threshold.

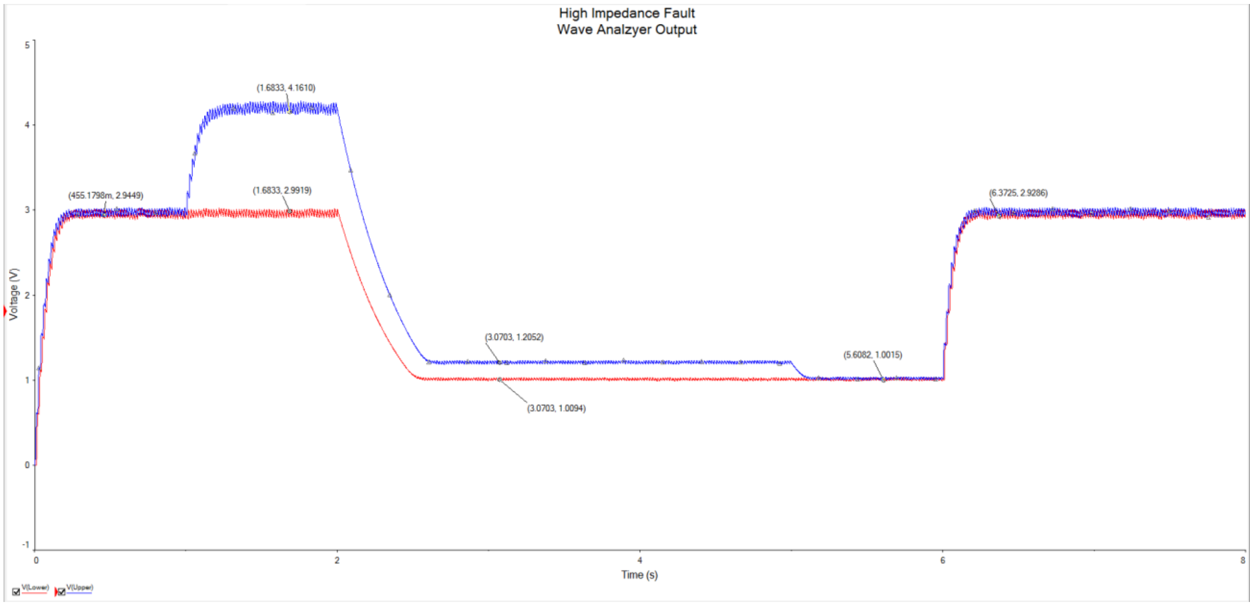


Figure 4.4.6: High Impedance Fault – Wave Analyzer Output

In the case of a high impedance fault, the voltage level does not increase as significantly. However, there is a large difference between upper and lower waveform signals. The Smart Recloser will be able to analyze this difference and determine if it is a high impedance fault, triggering the high impendence mode. The Smart Recloser would only return to normal operation if the upper and lower waveforms were of similar levels.

4.5 MICROCONTROLLER & SWITCHING RELAY

The final blocks of the Smart Recloser comprise of the Microcontroller and the Switching Relay. The Microcontroller will take and analyze the signal from the Wave Analyzer block. According to the measured values of the the signal, the Microcontroller will interface with the Switching Relay in order to set the Testing Distribution Line to regular or high impedance modes. The two blocks are discussed in further detail.

4.5.1 MICROCONTROLLER FLOW CHART

The logic flow chart of the Microcontroller is shown in figure 4.5.1.

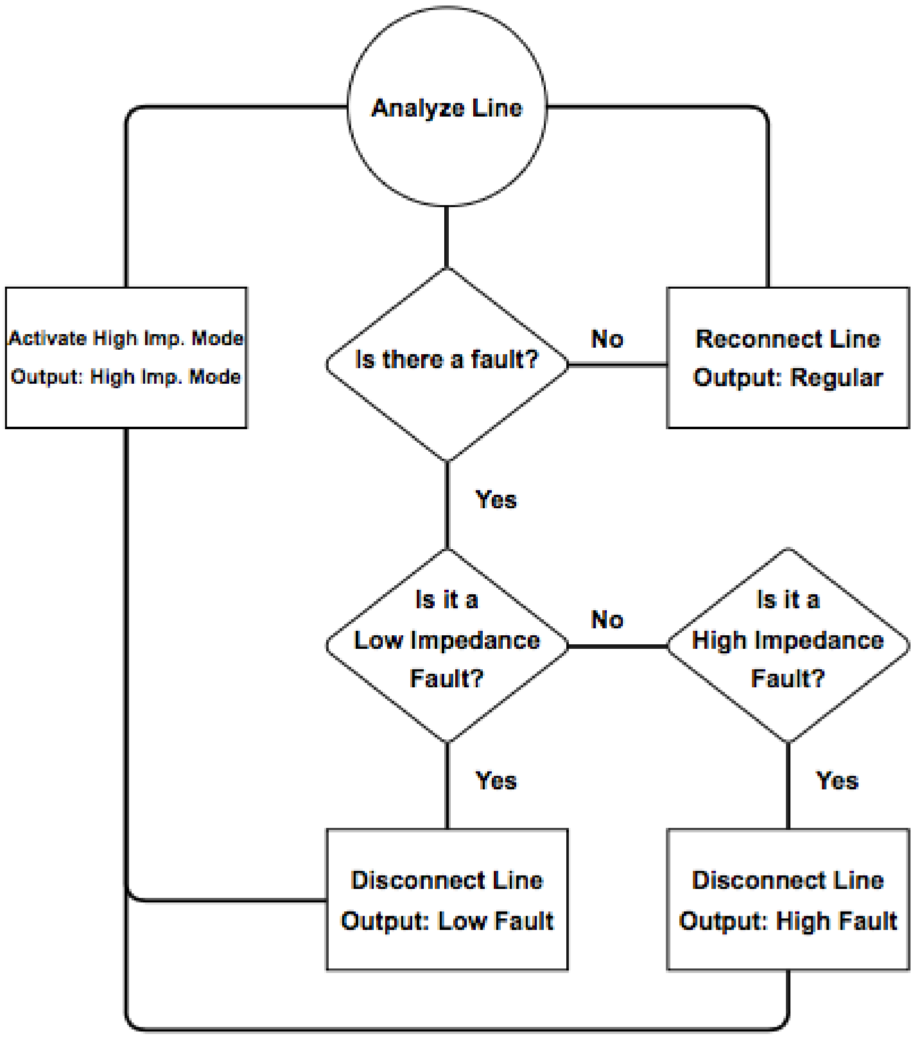


Figure 4.5.1: Microcontroller Flow Chart

The Microcontroller will have multiple functions as it will be analyzing the the signal. The Microcontroller will remain in regular mode until a fault is detected. In this case, the main action of the Microcontroller will be to compare the two input signals and comparing it to certain thresholds.

First, if the sum of the signals passes a certain threshold, then it will determine that there is low impedance fault. This will cause the Microcontroller to signify that it is a low impedance fault and activate the high impedance mode.

Similarly, if the difference of the signals passes a certain threshold, then it will determine that there is a high impedance fault. This will cause the Microcontroller to signify that it is a high impedance fault and activate the high impedance mode.

4.5.2 SWITCHING RELAY BLOCK

The design for the Switching Relay is shown below in figure 4.5.2.

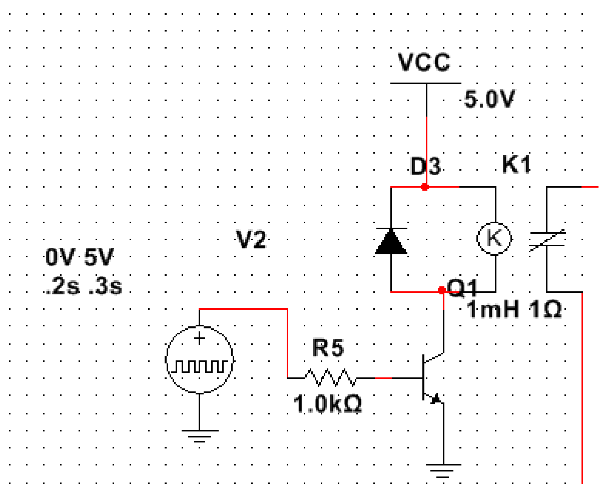


Figure 4.5.2: Switching Relay Schematic

The relay is modeled by an electromagnetic relay, which is activated if a voltage flows through it. This is implemented using a MOSFET to supply the necessary voltage. This relay will only be activated by the Microcontroller during high impedance mode.

5.0 SMART RECLOSER – DESIGN IMPLEMENTATION

This section explores the design implementation of the miniature Smart Recloser Prototype. In order to properly follow the design implementation of the prototype, the basic functionality of the design is introduced. Each major functional block will then be explained and covered. The selected components and parts will be briefly discussed, followed by their measurements and the results of each block.

5.1 DESIGN OVERVIEW

The Smart Recloser is able to successfully detect and react to various faults that occur in the distribution line. By assessing which type of fault is occurring, the distributed signal is affected. This can either cause high levels of current or unbalanced waveforms. This is the principle functionality of the Smart Recloser. By analyzing the positive and negative cycles of the signal, it is possible to compare their values to one another and determine if there is a fault and disconnect the line.

An important concept of the Recloser is that the line does not fully disconnect, rather a high impedance resistor is connected. There are two important reasons for this: 1) the signal in the Distribution Line will be significantly reduced and 2) the Smart Recloser will be able to continue to analyze the line at a much safer level. With this in consideration, the prototype is able to constantly analyze the line and determine when faults occur and when faults are cleared.

Building around this basic functionality, the design of the Smart Recloser could be fully implemented. The full schematic is shown in figure 5.1.1.

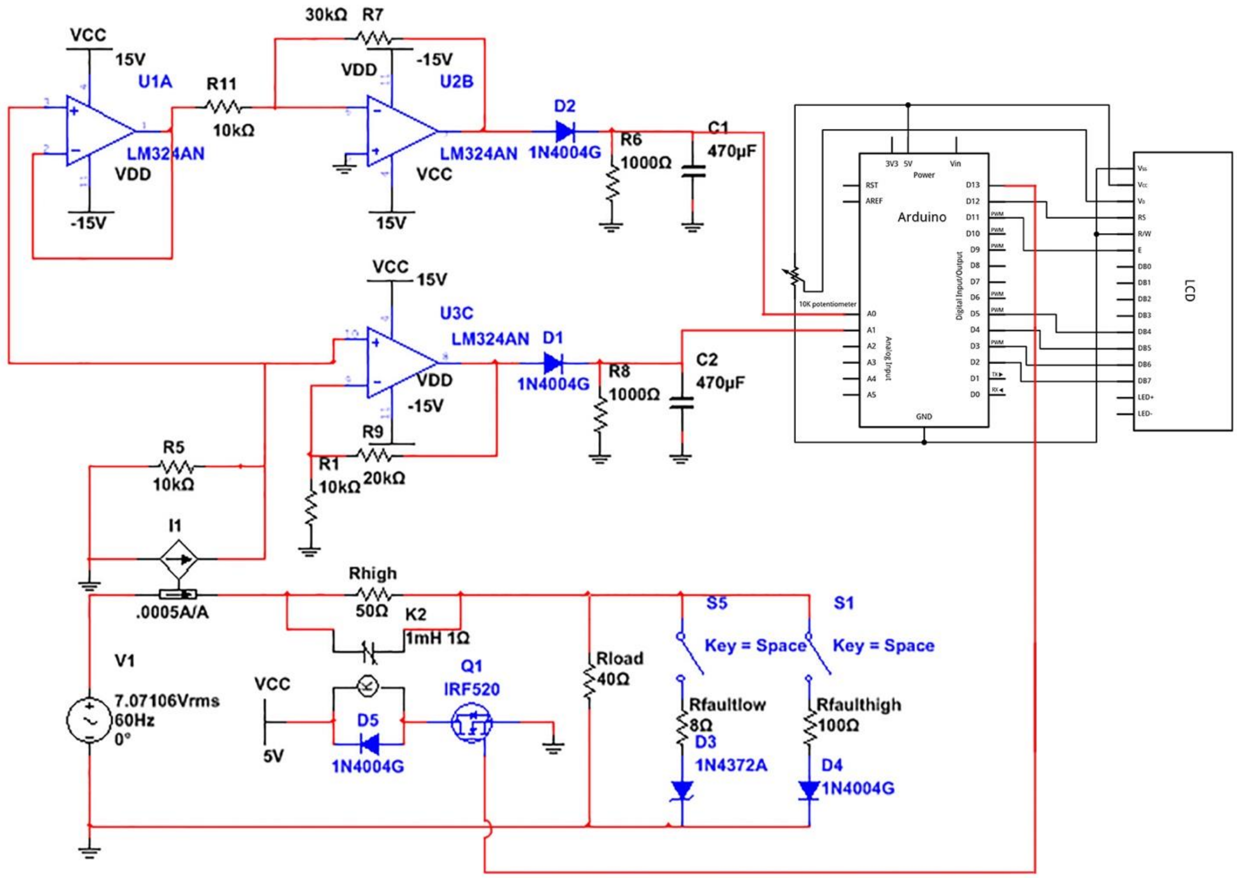


Figure 5.1.1: Full Schematic

5.2 DISTRIBUTION LINE TESTER & CURRENT SENSOR

This section analyzes the signal through the Distribution Line at various faults and the response from the current sensor. This will help show how the waveforms are affected and how the Smart Recloser could ultimately observe the line.

5.2.1 TESTING DISTRIBUTION LINE IMPLEMENATION

The parts used for the Testing Distribution Line are shown below.

The adjustable power resistor from Vishay in figure 5.2.1 was used to implement the load resistor, high impedance resistor, and the low impedance fault resistor. It is important to note that there is ± 5% accuracy to the resistance value. More details of the selected power resistor can be seen in Appendix A.

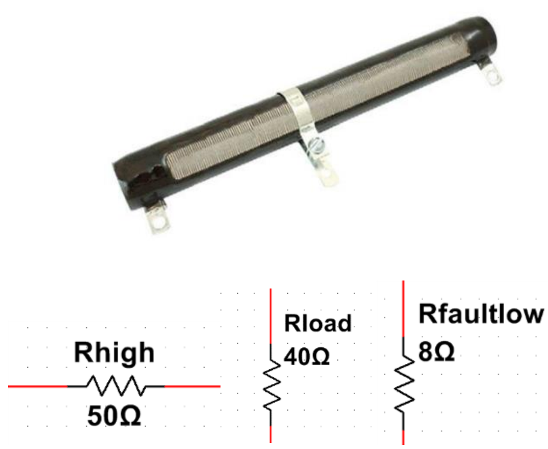


Figure 5.2.1: Vishay Power Wire Wound Resistor Model

A potentiometer and the 1N4004 diode were used to implement the high impedance fault resistor. This design was chosen in order to allow the Smart Recloser to analyze different fault intensities. The concept will remain the same. The figure 5.2.2 shows the parts used.

Figure 5.2.2: High Impedance Fault Model

5.2.2 CURRENT SENSOR IMPLEMENTATION

The parts used for the Current Sensor are shown below.

A split Core Current Transformer from EChun was used to implement the Current Sensor. This part was used due to its not invasive property to the signal. Using the sensor will not affect the current flow through the Distribution Line, however it will still allow the Smart Recloser to constantly read the signal. This component has a 2000/1 primary to secondary winding ratio. Further details of the Current Transformer can be found in Appendix C. The part used is shown in figure 5.2.3.

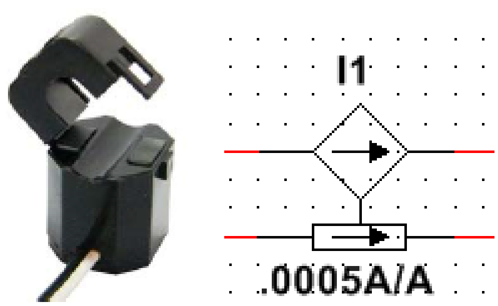


Figure 5.2.3: Current Sensor Model

5.2.3 REGULAR & HIGH IMPEDANCE MODE ANALYSIS

The oscilloscope graphs during regular operation and high impedance mode are shown in figure 5.2.4 and figure 5.2.5.

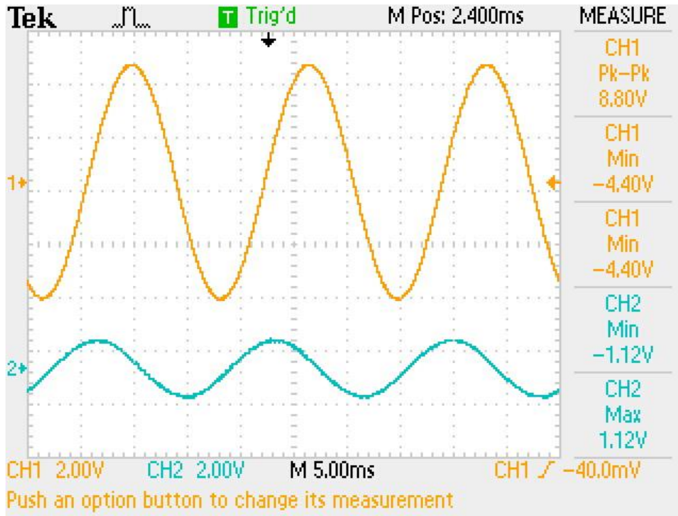


Figure 5.2.4: Regular Operation – Distribution Line & Current Sensor

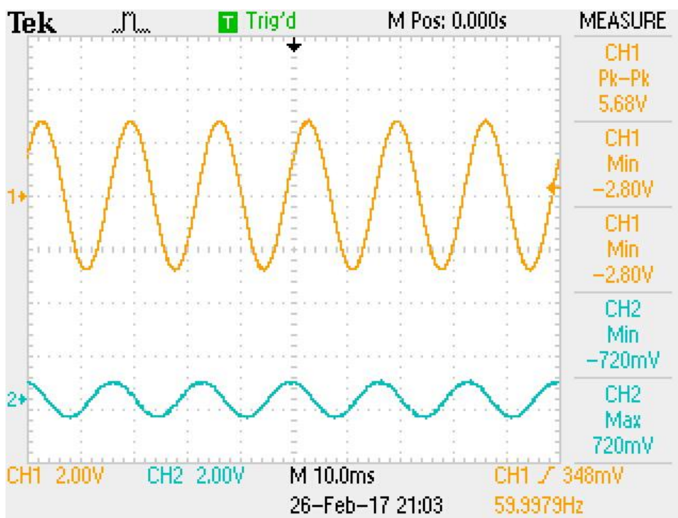


Figure 5.2.5: High Impedance Mode – Distribution Line & Current Sensor

The waveform in channel 1 displays the voltage across the load resistor in the Distribution Line Tester. The wave form in channel 2 displays the voltage at the output of the Current Sensor. At regular operation, signal will flow as a perfect symmetrical sinusoidal signal. At high impedance mode, the high resistance will decrease the voltage. It is interesting to note that amplitudes are not as expected with a 10Vpk 60Hz power source. The variance may be due to some internal resistance. More importantly, in both cases, the positive and negative cycles of the waveform are equivalent to one another. This will be affected by the various faults.

5.2.4 LOW IMPEDANCE FAULT ANALYSIS

The oscilloscope graphs during a low impedance fault are shown in figure 5.2.6 and figure 5.2.7.

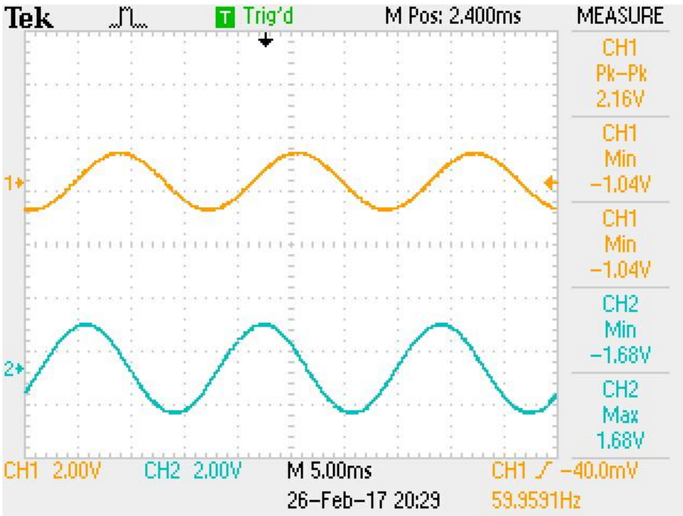


Figure 5.2.6: Low Impedance Fault – Distribution Line & Current Sensor

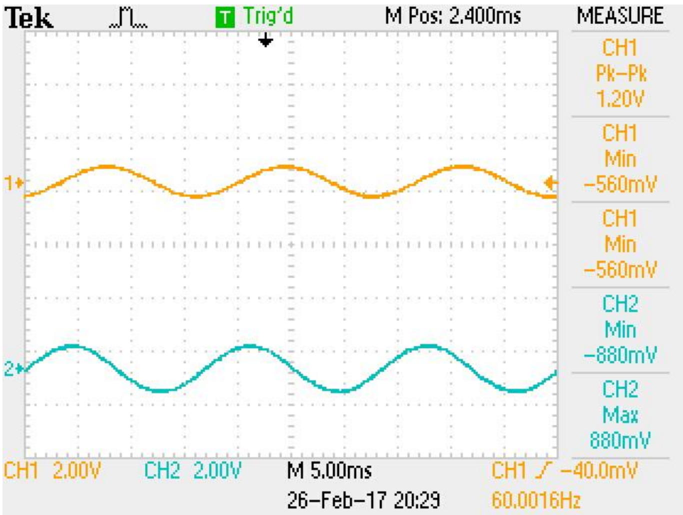


Figure 5.2.7: Low Impedance Fault w/ High Impedance Mode – Distribution Line & Current Sensor

During the low impedance fault, it is clear that the voltage induced at the current sensor increases significantly. This increase in voltage will allow the Smart Recloser compare the normal conditions to these fault values. Surpassing a certain threshold will allow the Recloser to determine when to open/close the line.

5.2.5 HIGH IMPEDANCE FAULT ANALYSIS

The oscilloscope graphs during an intense high impedance fault are shown in figure 5.2.8 and figure 5.2.9.

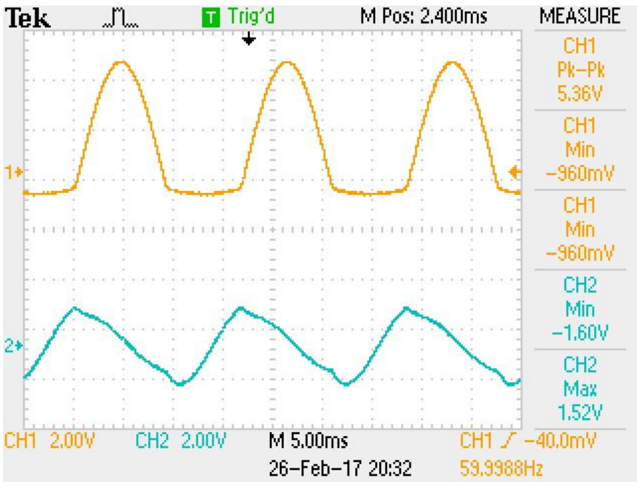


Figure 5.2.8: High Impedance Fault I – Distribution Line & Current Sensor

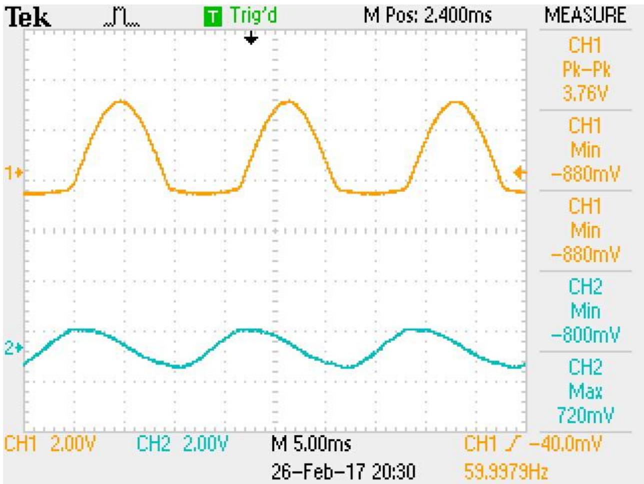


Figure 5.2.9: High Impedance Fault w/ High Impedance Mode I – Distribution Line & Current Sensor

During a high impedance fault, it is clear that the signal is distorted and loses its symmetry. At both the fault occurrences, the positive and negative cycles of the waveforms are not equal. This will allow the Smart Recloser to compare the upper and lower values of the signal and determine if they are equal. By analyzing these values, a high impedance fault can be detected.

It will be interesting to analyze different intensities of a high impedance fault. At a lower intensity, some distortion can be seen. However, it will be clear that a fault with the High Impedance Mode activated will make it difficult for the Smart Recloser to detect. Thus, the Smart Recloser may need to analyze both a threshold for the total voltage and the difference in the upper and lower halves of the waveforms. The oscilloscope graphs during a slight high impedance fault are shown in figure 5.2.10 and figure 5.2.11.

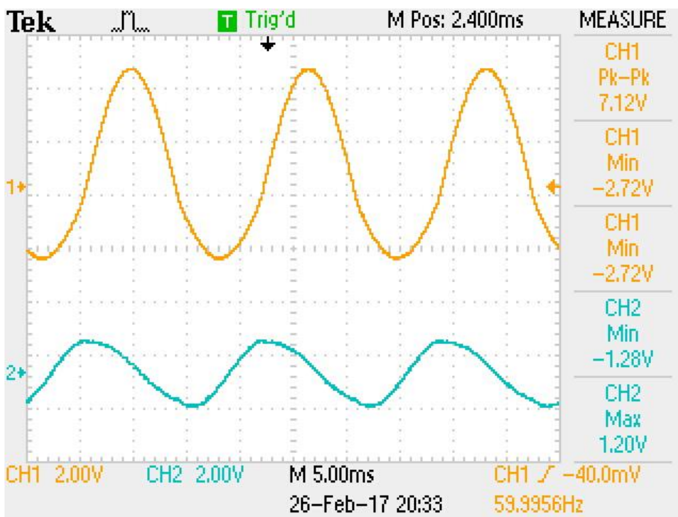


Figure 5.2.10: High Impedance Fault II – Distribution Line & Current Sensor

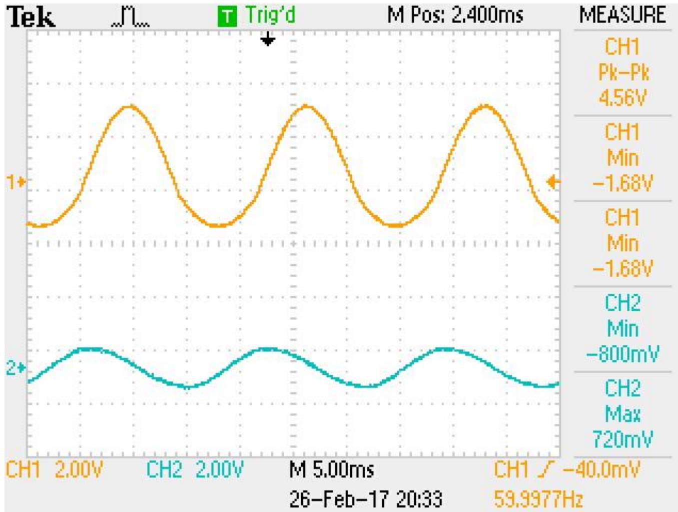


Figure 5.2.11: High Impedance Fault w/ High Impedance Mode II – Distribution Line & Current Sensor

5.3 WAVE ANALYZER

This section explains the two major parts of the Wave Analyzer block, the amplifier and the half-wave rectifier. The Wave Analyzer helps interface the signal from the Current Sensor to the Microcontroller. Ultimately, the Wave Analyzer will output an amplified, DC signal to the following stage. Thus, the signal will vary according to the various modes of operation and faults.

5.3.1 AMPLIFIER IMPLEMENTATION

There are two separate sets of amplifier designs used. In both implementations, the LM324 Op Amp was used. This op amp was supplied with +15V, -15V at its power rails. The specification of this Op Amp can be seen in Appendix D.

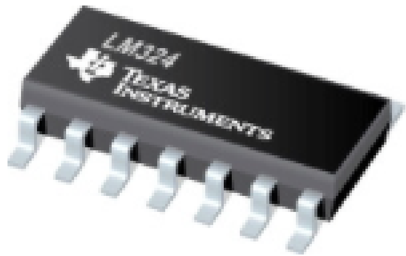


Figure 5.3.1: LM324 Op Amp

Two amplifier designs were used in order to amplify both the positive and negative cycles of the waveform. The amplifier design for the positive half cycle is shown in figure 5.3.2.

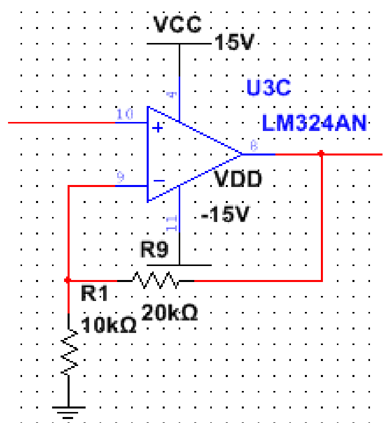


Figure 5.3.2: Amplifier for Positive Cycle Waveform

The non-inverting amplifier was used to help increase the voltage response from the Current Sensor. Using this implementation, the signal should follow this response:

$$\text{Vout} = \text{Vin}\ (1+\frac{R1}{R2}) = \text{Vin} * 3$$

The amplifier design for the positive half cycle is shown in figure 5.3.3.

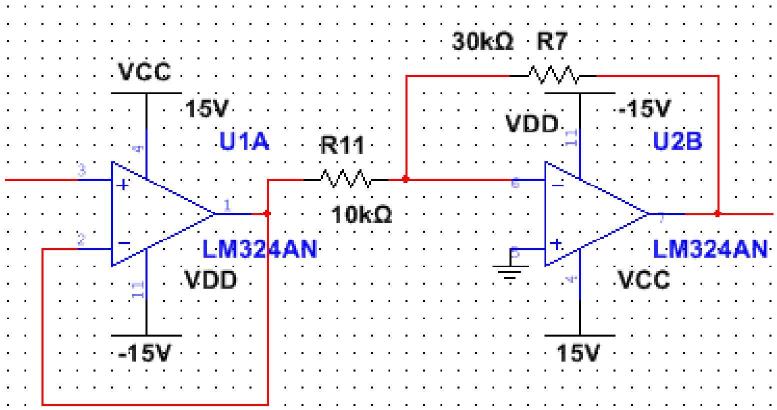


Figure 5.3.3: Amplifier for Negative Cycle Waveform

A unity gain amplifier cascaded with an inverting amplifier was used to capture the negative part of the wave. Since it was required to attain the negative part of the signal from the Current Sensor, an inverting amplifier was necessary. To properly implement the amplifier without altering the signal from the Current Sensor the unity gain amplifier was used. With this implementation, the signal should follow this response:

$$Vout = Vin\ (1 * (-R2/R1)) = -Vin * 3$$

Thus, with the appropriate resistors selected, both amplifier designs for the positive and negative cycles will amplify the signal equally.

5.3.2 HALF-WAVE RECTIFIER IMPLEMATATION

Using the amplified signal, it was necessary to rectify the wave form to a steady DC level to interface the following functional block, the Microcontroller. The design schematic and components are shown in figure 5.3.4.

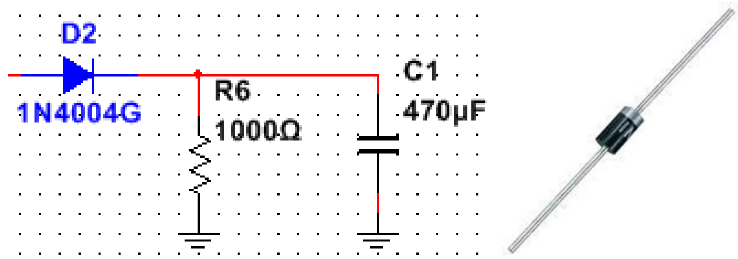


Figure 5.3.4: Half-Wave Rectifier

In order to retain only the positive part of the signal, the half-wave rectifier with a smoothing cap was used. This will eliminate the the negative cycles and allow the capacitor to charge to a nearly constant DC level. In order to allow the capacitor to charge long enough, the time constant had to follow this relationship:

$$R * C >> 1/f$$

Estimating the component values within the above range, the rectifier could work properly.

5.3.3 REGULAR AND HIGH IMPEDANCE MODE ANALYSIS

The oscilloscope graphs during regular operation and high impedance mode are shown in figure 5.3.5 and figure 5.3.6.

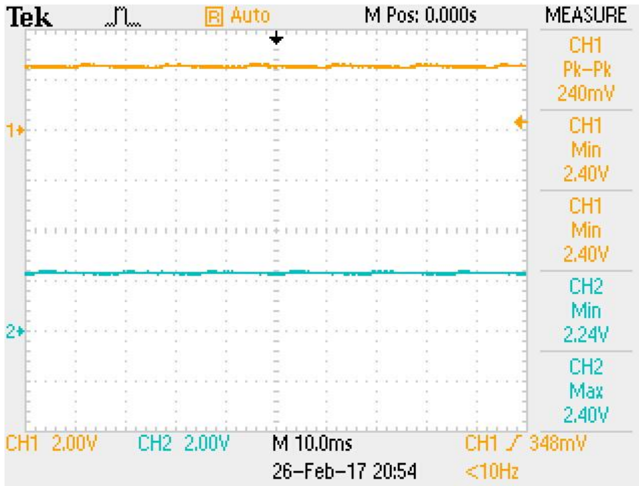


Figure 5.3.5: Regular Operation –Wave Analyzer Output

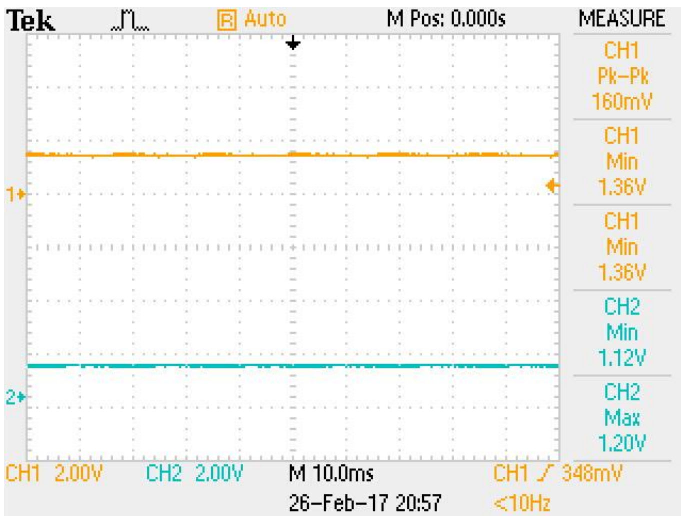


Figure 5.3.6: High Impedance Mode –Wave Analyzer Output

The waveform in channel 1 displays the rectified voltage for the positive cycle. The waveform in channel 2 displays the rectified voltage for the negative cycle.

At Regular Operation, the wave analyzer outputs approximately 2.40V and 2.24V for the positive and negative cycles of the signal. It would be expected that these two value to be equal, but this may be due to the accuracy of the amplifier components.

At High Impedance Mode, the wave analyzer outputs approximately 1.36V and 1.12V. As expected, the voltage levels reduce to a lower level due to the high impedance connected in the Distribution Line. Again, without any faults, it is expected that a symmetrical signal should result in equal voltage levels at the output.

These inequalities will be considered and the offset will be applied to the Microcontroller code.

5.3.4 LOW IMPEDANCE FAULT

The oscilloscope graphs during a low impedance fault are shown in figure 5.3.7 and figure 5.3.8.

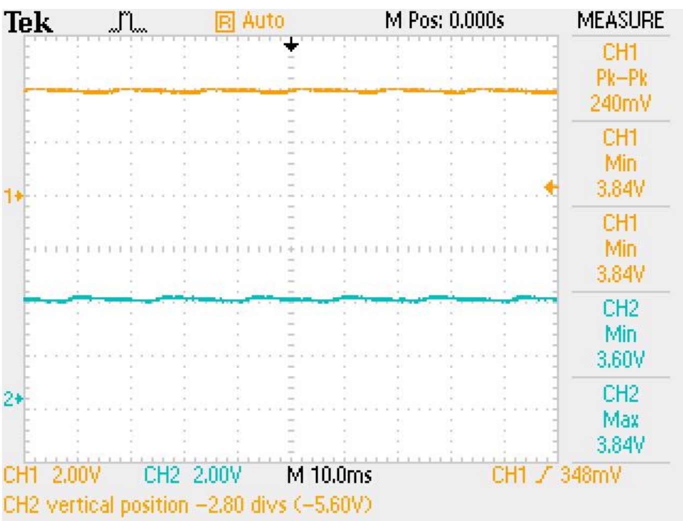


Figure 5.3.7: Low Impedance Fault –Wave Analyzer Output

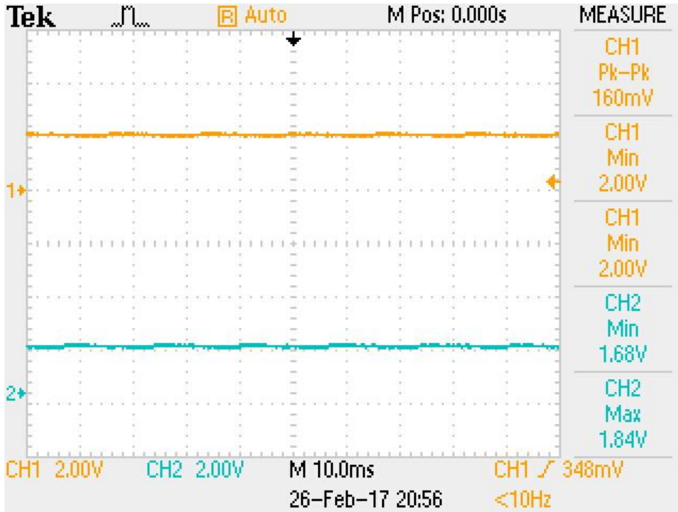


Figure 5.3.8: Low Impedance Fault w/ High Impedance Mode –Wave Analyzer Output

When a Low Impedance Fault occurs the voltage levels at the output increases to 3.84V and 3.60V. This significant increase in voltage will allow the Smart Recloser to detect that a Low Impedance Fault has occurred. Activating the High Impedance Mode, these voltage levels will reduce to a safer level. However, these voltage level will still be higher than during the High Impedance Mode. If the levels have decreased further, then the Smart Recloser can detect that the fault has cleared.

5.3.5 HIGH IMPEDANCE FAULT

The oscilloscope graphs during an intense high impedance fault are shown in figure 5.3.9 and figure 5.3.10.

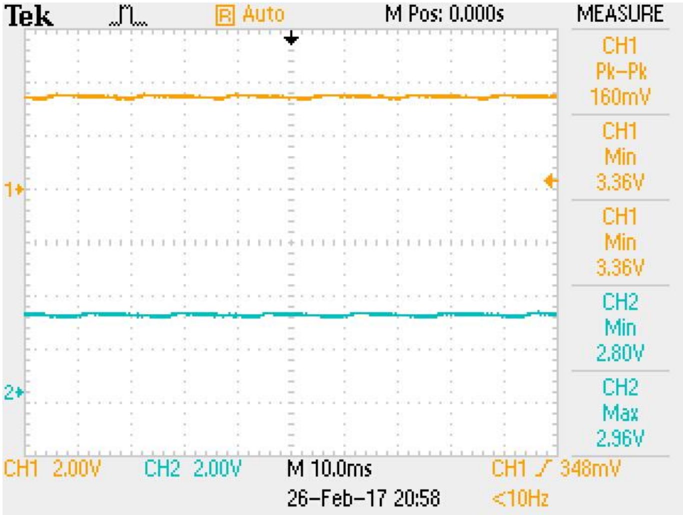


Figure 5.3.9: High Impedance Fault I –Wave Analyzer Output

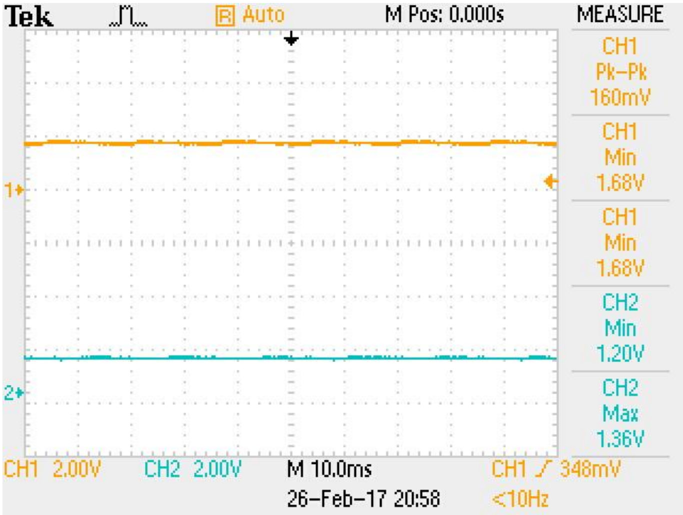


Figure 5.3.10: High Impedance Fault w/ High Impedance Mode I –Wave Analyzer Output

A significant property of High Impedance Faults is that although the current may not increase significantly, the positive and negative cycles of the signal will not be symmetric anymore. Observing the oscilloscopes during a High Impedance Fault, it is clear that there is a significant difference between the positive (3.36V) and negative (2.80V) cycles. This difference will allow the Smart Recloser to differentiate this type of fault as a High Impedance Fault. With the fault is persistent and the High Impedance mode activated, the difference of 1.68V to 1.20V is still significant. Once the fault has lowered, the Smart Recloser will analyze the fault as cleared.

It is important to also observe how the Smart Recloser can handle High Impedance Faults at different intensities. The oscilloscope graphs during a slight high impedance fault are shown in figure 5.3.11 and figure 5.3.12.

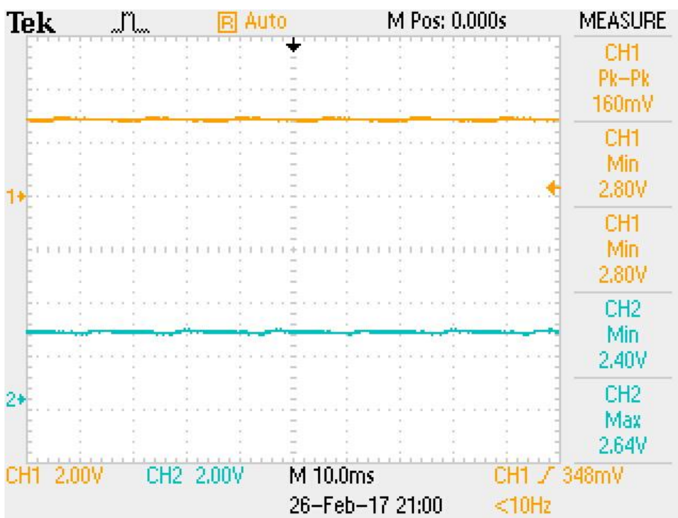


Figure 5.3.11: High Impedance Fault II –Wave Analyzer Output

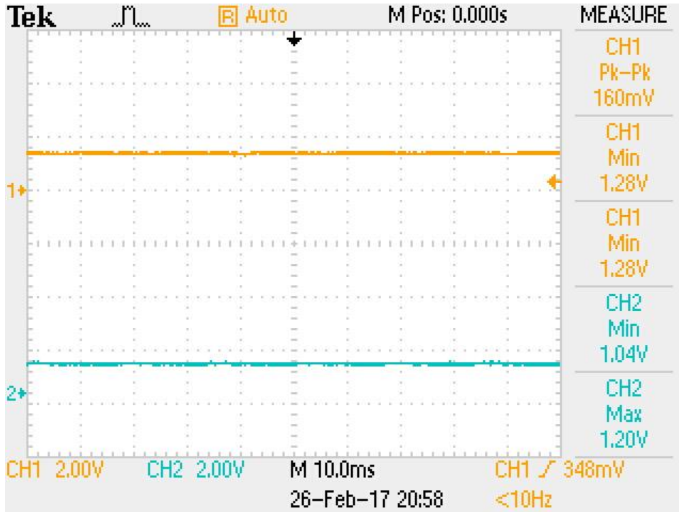


Figure 5.3.12: High Impedance Fault w/ High Impedance Mode II –Wave Analyzer Output

At lower intensities, measuring the symmetry between the positive and negative cycles of the signal may become more difficult. As shown above, the voltage levels do not increase significantly, however there is a slight difference between the upper and lower halves of the waves (2.80V and 2.40V). This small difference will still allow the Smart Recloser to detect that fault. Similarly, when the High Impedance mode is activated, at a voltage level of 1.28V and 1.04V, the signal does behave normally and the Smart Recloser will keep the line open.

As the intensities of the High Impedance Faults become less severe, the accuracy of the Smart Recloser will become crucial. Since the difference between the positive and negative cycles may be minor, the Recloser will need to intelligently determine is there is truly a fault or not.

5.4 MICROCONTROLLER & SWITCHING RELAY BLOCK

This section discusses the Microcontroller and Switching Relay design. The Microcontroller section will first go into the hardware and wiring scheme, then the software and coding decisions will be explained. Finally, the Switching Relay will conclude how the Smart Recloser interacts with the line depending on the faults that occur.

5.4.1 MICROCONTROLLER HARDWARE IMPLEMENTATION

The Microcontroller selected was the Arduino Uno. An important feature of this Microcontroller is to intelligently analyze the Distribution Line and properly react. In order to allow the user to physically observe the state of the Smart Recloser, a LCD screen was utilized. The Arduino Uno will be able to respond to the LCD and let the observer see what is happening. These components can be further investigated in Appendix E and Appendix F.

Figure 5.4.1: Arduino Uno

Figure 5.4.2: LCD 2 x 16

The Microcontroller will need to interface multiple signals and modules. It will receive two signals from the Wave Analyzer, the positive and negative cycles. After some analysis, it must output a response to the Relay Switching Block and the LCD screen. The wiring schematic of the Microcontroller is shown in figure 5.4.3.

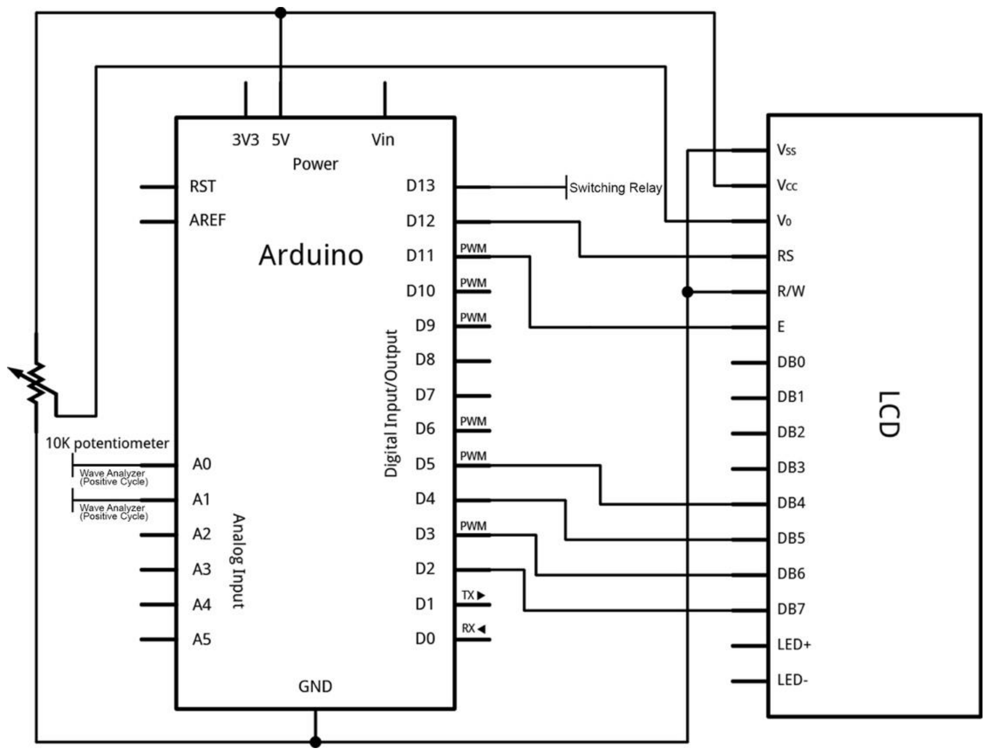


Figure 5.4.3: Arduino Uno Schematic

5.4.2 MICROCONTROLLER SOFTWARE IMPLEMENTATION

The logic for the Microcontroller has to implement various functionalities. This includes correctly detecting when a fault has occurred, differentiating between a low and high impedance fault, and also determining when a fault has cleared. At the same time, the Microcontroller will need to send signals to the Switching Relay to activate the High Impedance mode and send signals to the LCD screen to show the current state of the Smart Recloser.

These different functionalities are summarized in the flow chart of figure 5.4.4. Furthermore, it will be useful to give a brief overview of sections of the implemented code. The full code can be found in Appendix G.

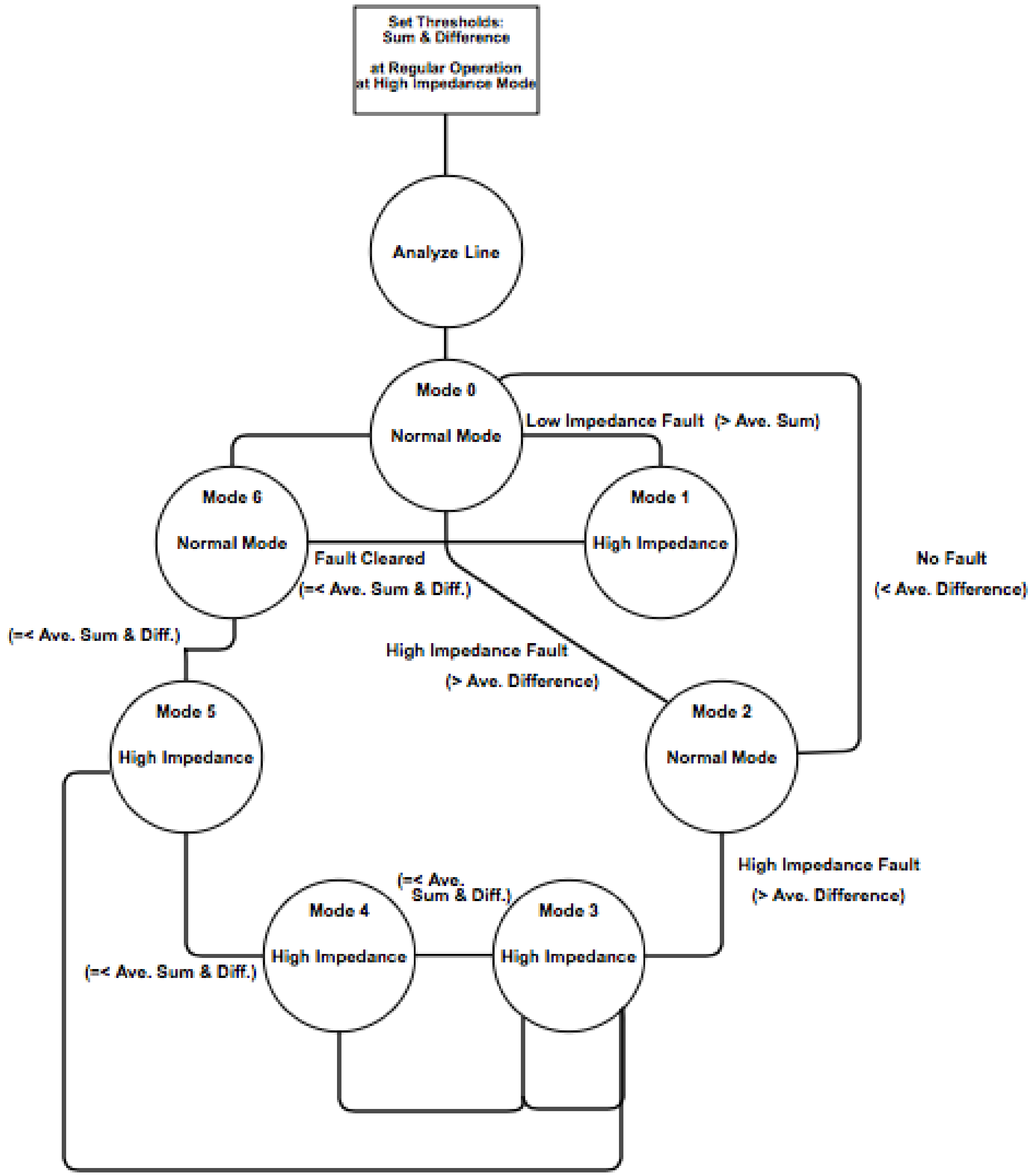


Figure 5.4.4: Microcontroller Flow Chart

The Microcontroller begins with analyzing the Distribution Line during regular operation and high impedance mode. By setting the average values, a threshold could be set to detect when a fault occurs and has cleared. The Microcontroller will compare the positive and negative cycles of the input signal. By analyzing the sum of the two values, it will be able to detect any overcurrent. Likewise, observing the differences will let the Microcontroller detect distortions in the Distribution Line. Furthermore, the LCD screen will continuously update itself according to its current state. The code for initializing these values are shown below:

```
/////////Gather data for Regular Operation////////
digitalWrite(RelayPin, HIGH);
delay(5000);

Serial.println ("\t Regular Operation Analyzation");

for (int i=0; i<5; i++){
  //Read Data from pins
  UpperValue = analogRead(UpperWave); // Read input from upper waveform
  LowerValue = analogRead(LowerWave); // Read input from lower waveform
  sum = UpperValue + LowerValue; // Get the sum of the Upper and Lower Waveforms
  difference = LowerValue - UpperValue; // Get the difference between the Upper and Lower Waveforms

  //Print the values of the Upper and Lower Wave forms onto the Serial Monitor
  Serial.print ("\t Sum = ");
  Serial.print(sum);
  Serial.print ("\t Difference = ");
  Serial.println(difference);

  //Add to Total Sum, Total Difference
  tot_sum_reg += sum;
  tot_diff_reg += difference;
  delay (1000);
}

//Calculate Sums & Differences
ave_sum_reg = ceil(tot_sum_reg/5);
ave_diff_reg = tot_diff_reg/5;

Serial.print ("\t Total Sum = ");
Serial.print(tot_sum_reg);
Serial.print ("\t Total Difference = ");
Serial.println(tot_diff_reg);
Serial.print ("\t Average Sum = ");
Serial.print(ave_sum_reg);
Serial.print ("\t Average Difference = ");
Serial.println(ave_diff_reg);
```

Figure 5.4.5: Code – Regular Operation Initialization

```
///////Gather data for High Impedance Operation///////
digitalWrite(RelayPin, LOW);
delay(4000);

Serial.println ("\t High Impedance Analyzation");

for (int i=0; i<5; i++){
  //Read Data from pins
  UpperValue = analogRead(UpperWave); // Read input from upper waveform
  LowerValue = analogRead(LowerWave); // Read input from lower waveform
  sum = UpperValue + LowerValue; // Get the sum of the Upper and Lower Waveforms
  difference = LowerValue - UpperValue; // Get the difference between the Upper and Lower Waveforms

  //Print the values of the Upper and Lower Wave forms onto the Serial Monitor
  Serial.print ("\t Sum = ");
  Serial.print(sum);
  Serial.print ("\t Difference = ");
  Serial.println(difference);

  //Add to Total Sum, Total Difference
  tot_sum_high += sum;
  tot_diff_high += difference;
  delay (1000);
}

//Calculate Sums & Differences
ave_sum_high = ceil(tot_sum_high/5);
ave_diff_high = tot_diff_high/5;

Serial.print ("\t Total Sum = ");
Serial.print(tot_sum_high);
Serial.print ("\t Total Difference = ");
Serial.println(tot_diff_high);
Serial.print ("\t Average Sum = ");
Serial.print(ave_sum_high);
Serial.print ("\t Average Difference = ");
Serial.println(ave_diff_high);
```

Figure 5.4.6: Code – High Impedance Mode Initialization

```
Fault_Sum = ave_sum_reg + 300; //Threshold when Low Impedance Occurs
Fault_Diff = ave_diff_reg + 2; //Threshold when High Impedance Occurs
Reg_Sum = ave_sum_high; //Threshold when fault is cleared
Reg_Diff = ave_diff_high; //Threshold when fault is cleared
```

Figure 5.4.7: Code – Threshold Values

After the initialization of the Smart Recloser, the Microcontroller will enter into a constant loop to analyze the Distribution Line. During Mode 0, the Smart Recloser will operate at normal mode, in which no fault is occurring. It is during this phase that the Recloser will be observing for faults in the line. The code is shown below.

```
switch(mode){
  case 0: // check if there is a Fault
  {
    if (sum >= Fault_Sum) // Check for Low Impedance Fault
    {
      Serial.println("\t There is a Low Impedance Fault!");
      Serial.println("\t Disconnecting Line...");

      lcd.clear();
      lcd.setCursor(0,0);
      lcd.print("Fault Detected!");
      lcd.setCursor(0,1);
      lcd.print("Low Impedance");
        delay(3000);
      lcd.clear();
      lcd.setCursor(0,0);
      lcd.print("Disconnecting");
      lcd.setCursor(0,1);
      lcd.print("Line............");

      mode = 1;
      digitalWrite(RelayPin, LOW);
    }
    else if (difference >= Fault_Diff) // Check for High Impedance Fault
    {
      Serial.println("\t Checking for Fault!");
      mode = 2;
    }
    else // Remain in Regular Operation Mode
    {
      Serial.println("\t Regular Operation...");

      lcd.clear();
      lcd.setCursor(0,0);
      lcd.print("Normal Operation");

      digitalWrite(RelayPin, HIGH);
    }
    break;
  }
```

Figure 5.4.8: Code – Mode 0

In mode 1, a Low Impedance Fault has occurred. This happens due to the large amount of current through the Distribution Line. At this stage, the High Impedance Mode is activated and the Smart Recloser will be detecting when the signal levels have returned to normal. If the line is operating at normal levels, then the Smart Recloser will start to transition back into mode 0.

```
case 1: //High Impedance Mode w/ Low Impedance Fault
{
  if ((sum <= Reg_Sum + 5) & (difference <= Reg_Diff)) // Check if Fault has cleared
  {
    Serial.println("\t Fault has cleared");
    Serial.println("\t Reconnecting Line...");

    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print("Disconnected");
    lcd.setCursor(0,1);
    lcd.print("Fault Cleared");

    mode = 6;
  }
  else // Remain in High Impedance Mode until Low Impedance Fault has cleared
  {
    Serial.println("\t High Impedance Mode - Low Impedance Fault");

  lcd.clear();
  lcd.setCursor(0,0);
  lcd.print("Disconnected");
  lcd.setCursor(0,1);
  lcd.print("Fault Detected");

    digitalWrite(RelayPin, LOW);
  }
  break;
}
```

Figure 5.4.9: Code – Mode 1

In mode 2, a High Impedance Fault has been detected. This happens when the signal through the line is not symmetric. This is determined by comparing the difference between the positive and negative cycles of the signal. However, due to the accuracy of the design, the Microcontroller will need to check one more time. If there is a constant fault, then the High Impedance mode is activated.

```
case 2: //Check if there is a High Impedance Fault
{
  if (difference >= Fault_Diff) // Check if there is a consistent High Impedance Fault
  {
    Serial.println("\t There is a High Impedance Fault!");
    Serial.println("\t Disconnecting Line...");

    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print("Fault Detected!");
    lcd.setCursor(0,1);
    lcd.print("High Impedance");
      delay(3000);
    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print("Disconnecting");
    lcd.setCursor(0,1);
    lcd.print("Line............");

    mode = 3;

    digitalWrite(RelayPin, LOW);
  }
  else
  {
    mode = 0;
    Serial.println("\t Regular Operation...");
    digitalWrite(RelayPin, HIGH);
  }
  break;
}
```

Figure 5.4.10: Code – Mode 2

In the following three modes, mode 3-5, the Microcontroller is detecting if the signal has returned to normal levels for three cycles. If this requirement is met, then the fault has cleared.

```
case 3: //High Impedance Mode w/ High Impedance Fault
{
  if ((sum <= Reg_Sum) & (difference <= Reg_Diff)) // Check if Fault has cleared
  {
    Serial.println("\t Checking if fault has cleared...");

    mode = 4;
  }
  else // Remain in High Impedance Mode until High Impedance Fault has cleared
  {
    Serial.println("\t High Impedance Mode - High Impedance Fault");

    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print("Disconnected");
    lcd.setCursor(0,1);
    lcd.print("Fault Detected");

    mode = 3;
    digitalWrite(RelayPin, LOW);
  }
  break;
}

case 4: //High Impedance Mode w/ High Impedance Fault
{
  if ((sum <= Reg_Sum) & (difference <= Reg_Diff)) // Check if Fault has cleared
  {
    Serial.println("\t Checking if fault has cleared...");

    mode = 5;
  }
  else // Remain in High Impedance Mode until High Impedance Fault has cleared
  {
    Serial.println("\t High Impedance Mode - High Impedance Fault");

    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print("Disconnected");
    lcd.setCursor(0,1);
    lcd.print("Fault Detected");

    mode = 3;
    digitalWrite(RelayPin, LOW);
  }
  break;
}

case 5: //High Impedance Mode w/ High Impedance Fault
{
  if ((sum <= Reg_Sum) & (difference <= Reg_Diff)) // Check if Fault has cleared
  {
    Serial.println("\t Fault has cleared");
    Serial.println("\t Reconnecting Line...");

    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print("Disconnected");
    lcd.setCursor(0,1);
    lcd.print("Fault Cleared");

    mode = 6;
  }
  else // Remain in High Impedance Mode until High Impedance Fault has cleared
  {
    Serial.println("\t High Impedance Mode - High Impedance Fault");

    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print("Disconnected");
    lcd.setCursor(0,1);
    lcd.print("Fault Detected");

    mode = 3;
    digitalWrite(RelayPin, LOW);
  }
  break;
}
```

Figure 5.4.11: Code – Mode 3, 4, 5

In mode 6, the fault has been cleared and the High Impedance resistor has been disconnected from the line. There will be a delay period before the Microcontroller loop is returned back to normal operation at mode 0.

```
case 6: //Wait Period
{
    Serial.println("\t Fault has cleared - Preparing Line");

      delay(3000);
    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print("Preparing Line");
    lcd.setCursor(0,1);
    lcd.print("................");
    digitalWrite(RelayPin, HIGH);
     delay(10000);
    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print("Line Connected");

    mode = 0;
  }
  break;
}
```

Figure 5.4.12: Code – Mode 6

5.4.3 RELAY IMPLEMENATATION

The Switching Relay will utilize a MOSFET in order to drive the relay. By receiving a signal from the Microcontroller, the relay will connect or disconnect the High Impedance resistor. The schematic for the Switching Relay is shown in figure 5.4.13. Further specifications for the relay is shown in Appendix H.

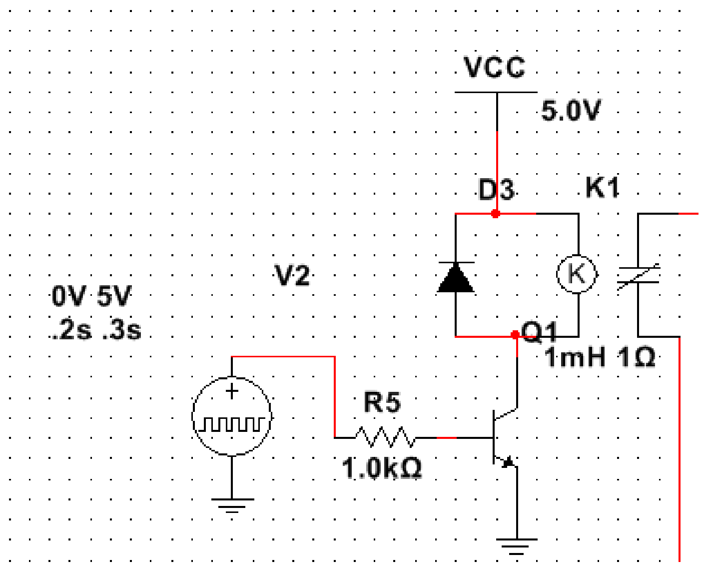


Figure 5.4.13: Relay Schematic

6.0 CONLCUSION

This MQP design successfully built and tested a functional Smart Recloser miniature prototype. The prototype combines the features of the traditional Circuit Breaker and Auto Recloser with the intelligent design of a Microcontroller. These features allow the device to operate with power distribution lines. This project helps prove the plausible implementation of a Smart device to the electrical power system.

The Smart Recloser can be improved by exploring the accuracy of the design. Currently, the Recloser can accurately detect Low Impedance faults and intense High Impedance Faults. It will be better to investigate how the Smart Recloser will be able to analyze High Impedance faults at different intensities. This design will allow the Smart Recloser to simulate different types of faults and assess how the device will respond.

An important consideration to keep in mind is the actual real-world implementation. In general, the Smart Recloser will need to be scaled to handle much higher levels of current and voltages as in a Distribution Line. Furthermore, it will be important to factor in the time response of the device. In case of faults it may be important that have a quick response in connecting or disconnecting the line. However, another factor is reconnecting the line safely. The Smart Recloser needs to have a safety measure in case there are line works operating at the line to clear any sources of faults. Another standpoint is the High Impedance mode design. Conceptually, the Smart Recloser will connect a very high impedance to lower the Distribution Line voltage and current. Actually implementing this concept to real power systems may not be practical or safe. In essence, the fault will still be affecting the load and the power source. Due to this there will be some potential danger to this design.

APPENDIX A: Power Resistor

VISHAY® www.vishay.com

AVT

Vishay Huntington

Wirewound Resistors, Industrial Power, Vitreous Coated, Adjustable Tubular

FEATURES

- High temperature vitreous coating
- Complete welded construction
- Tight tolerance of 5 % for values above 1 Ω
- Excellent stability in operation (< 3 % change in resistance)
- Material categorization: for definitions of compliance please see www.vishay.com/doc?99912

Pb-free RoHS COMPLIANT HALOGEN FREE GREEN (5-2008)

STANDARD ELECTRICAL SPECIFICATIONS					
GLOBAL MODEL	HISTORICAL MODEL	POWER RATING $P_{25\,°C}$ W	RESISTANCE RANGE Ω ± 5 %	RESISTANCE RANGE Ω ± 10 %	WEIGHT (typical) g
AVT010	AVT-10	12	0.1 to 10.2K	0.1 to 10.2K	6.69
AVT020	AVT-20	20	1.0 to 18K	1.0 to 18K	12.57
AVT20A	-	15	1.0 to 60K	0.10 to 60K	8.64
AVT025	AVT-25	25	0.1 to 23K	0.1 to 23K	20.72
AVT25A	AVT-25A	30	0.1 to 30K	0.1 to 30K	20.72
AVT25B	AVT-25B	30	0.1 to 24K	0.1 to 24K	14.25
AVT050	AVT-50	50	0.1 to 57K	0.1 to 57K	42.08
AVT50A	AVT-50A	60	0.1 to 75K	0.1 to 75K	65.64
AVT50B	AVT-50B	70	0.1 to 84.3K	0.1 to 84.3K	64.82
AVT075	AVT-75	75	0.1 to 85.5K	0.1 to 85.5K	106.37
AVT75A	AVT-75A	90	0.1 to 114K	0.1 to 114K	183.82
AVT080	-	90	1.0 to 190K	0.10 to 190K	121.58
AVT100	AVT-100	100	0.1 to 132K	0.1 to 132K	91.37
AVT130	AVT-130	130	0.1 to 192K	0.1 to 192K	192.36
AVT160	AVT-160	175	0.1 to 398K	0.1 to 398K	250.8
AVT175	-	175	1.0 to 500K	0.10 to 500K	250.8
AVT200	AVT-200	225	0.1 to 337K	0.1 to 337K	309.97
AVT225	AVT-225	225	0.1 to 337K	0.1 to 337K	309.97

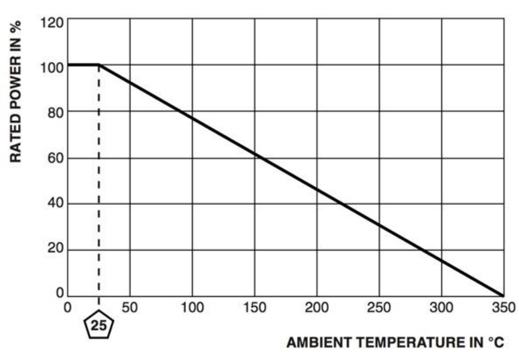
Revision: 03-Jun-16 1 Document Number: 31841

For technical questions, contact: ww2dresistors@vishay.com

TECHNICAL SPECIFICATIONS		
PARAMETER	**UNIT**	**RESISTOR CHARACTERISTICS**
Power Rating	W	12 to 225
Resistance Range	Ω	1 to 398K
Resistance Tolerance	%	5, 10
Temperature Coefficient	ppm/°C	± 260 for 20 Ω and above, ± 400 for 1 Ω to 19.99 Ω
Operating Temperature	°C	-55 °C to 350 °C
Temperature Rise	°C	325 °C above an ambient of 25 °C
Maximum Altitude	f.a.s.l.	10 000
Short-Term Overload	-	10x rated power for 5 s
Surge Windings		Available
Maximum Working Voltage	-	$(P \times R)^{0.5}$
Insultation Resistance	Ω	1M
Dielectric Voltage	V_{RMS}	1000 V_{AC}
Creepage		Varies by wattage, see "Terminal Setback" in Dimensions table
Terminal Sleeves		n/a
Inductance	µH	Varies by wattage and resistance
Non-Inductive Winding		Available
Terminal Strength	lb	10 lbs
Electrical or Mechanical Customization		Contact factory: ww2dresistors@vishay.com

MATERIAL SPECIFICATIONS	
Element	Copper-nickel alloy or nickel-chrome alloy, depending on resistance value
Core	Cordierite, steatite
Coating	Special high temperature vitreous enamel
Standard Terminals	Tinned alloy 42
Optional Terminals	Alloy 42
Terminal Bands	Alloy 42
Part Marking	HEI, model, wattage, value, tolerance, date code

DERATING



APPENDIX B: 1N4004 Diode

VISHAY.

1N4001 thru 1N4007

Vishay General Semiconductor

General Purpose Plastic Rectifier

DO-204AL (DO-41)

FEATURES

- Low forward voltage drop
- Low leakage current
- High forward surge capability
- Solder dip 275 °C max. 10 s, per JESD 22-B106
- Compliant to RoHS Directive 2002/95/EC and in accordance to WEEE 2002/96/EC

Pb e3 RoHS COMPLIANT

TYPICAL APPLICATIONS

For use in general purpose rectification of power supplies, inverters, converters and freewheeling diodes application.

Note

- These devices are not AEC-Q101 qualified.

MECHANICAL DATA

Case: DO-204AL, molded epoxy body
Molding compound meets UL 94 V-0 flammability rating
Base P/N-E3 - RoHS compliant, commercial grade

Terminals: Matte tin plated leads, solderable per J-STD-002 and JESD 22-B102
E3 suffix meets JESD 201 class 1A whisker test

Polarity: Color band denotes cathode end

PRIMARY CHARACTERISTICS	
$I_{F(AV)}$	1.0 A
V_{RRM}	50 V to 1000 V
I_{FSM} (8.3 ms sine-wave)	30 A
I_{FSM} (square wave t_p = 1 ms)	45 A
V_F	1.1 V
I_R	5.0 μA
T_J max.	150 °C

MAXIMUM RATINGS (T_A = 25 °C unless otherwise noted)

PARAMETER		SYMBOL	1N4001	1N4002	1N4003	1N4004	1N4005	1N4006	1N4007	UNIT
Maximum repetitive peak reverse voltage		V_{RRM}	50	100	200	400	600	800	1000	V
Maximum RMS voltage		V_{RMS}	35	70	140	280	420	560	700	V
Maximum DC blocking voltage		V_{DC}	50	100	200	400	600	800	1000	V
Maximum average forward rectified current 0.375" (9.5 mm) lead length at T_A = 75 °C		$I_{F(AV)}$	1.0							A
Peak forward surge current 8.3 ms single half sine-wave superimposed on rated load		I_{FSM}	30							A
Non-repetitive peak forward surge current square waveform T_A = 25 °C (fig. 3)	t_p = 1 ms	I_{FSM}	45							A
	t_p = 2 ms		35							
	t_p = 5 ms		30							
Maximum full load reverse current, full cycle average 0.375" (9.5 mm) lead length T_L = 75 °C		$I_{R(AV)}$	30							μA
Rating for fusing (t < 8.3 ms)		I^2t (1)	3.7							A^2s
Operating junction and storage temperature range		T_J, T_{STG}	- 50 to + 150							°C

Note

(1) For device using on bridge rectifier appliaction

ELECTRICAL CHARACTERISTICS (T_A = 25 °C unless otherwise noted)										
PARAMETER	**TEST CONDITIONS**	**SYMBOL**	**1N4001**	**1N4002**	**1N4003**	**1N4004**	**1N4005**	**1N4006**	**1N4007**	**UNIT**
Maximum instantaneous forward voltage	1.0 A	V_F	1.1							V
Maximum DC reverse current at rated DC blocking voltage	T_A = 25 °C	I_R	5.0							μA
	T_A = 125 °C		50							
Typical junction capacitance	4.0 V, 1 MHz	C_J	15							pF

THERMAL CHARACTERISTICS (T_A = 25 °C unless otherwise noted)									
PARAMETER	**SYMBOL**	**1N4001**	**1N4002**	**1N4003**	**1N4004**	**1N4005**	**1N4006**	**1N4007**	**UNIT**
Typical thermal resistance	$R_{\theta JA}$ (1)	50							°C/W
	$R_{\theta JL}$ (1)	25							

Note
(1) Thermal resistance from junction to ambient at 0.375" (9.5 mm) lead length, PCB mounted

ORDERING INFORMATION (Example)				
PREFERRED P/N	**UNIT WEIGHT (g)**	**PREFERRED PACKAGE CODE**	**BASE QUANTITY**	**DELIVERY MODE**
1N4004-E3/54	0.33	54	5500	13" diameter paper tape and reel
1N4004-E3/73	0.33	73	3000	Ammo pack packaging

RATINGS AND CHARACTERISTICS CURVES

(T_A = 25 °C unless otherwise noted)

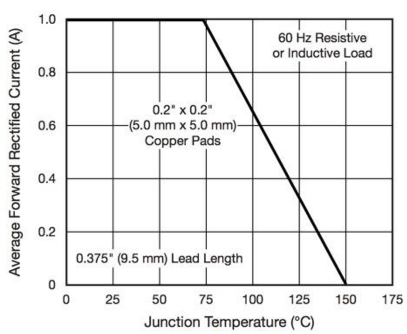


Fig. 1 - Forward Current Derating Curve

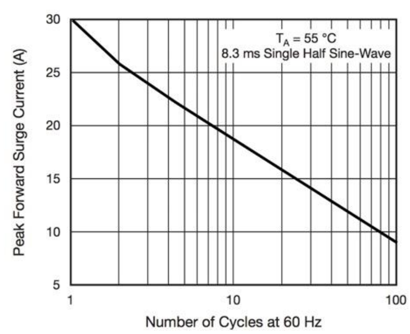


Fig. 2 - Maximum Non-repetitive Peak Forward Surge Current

APPENDIX C: Current Sensor

ECHUN Electronic Co., Ltd

Split Core Current Transformer ECS1030-L72

The ECS10 Series are split-core current transformers. The CT can be mounted to existing panels, such as control centers or load centers, to measure or monitor wattage. These CTs can be mounted without removing existing cables for easier installation

RoHS

Electrical Specifications

Rated Primary Current(Amp.) 50/60Hz	30nom(1~60A max)
Turnn ratio	Np:Ns=1:2000
Current Ratio	30A/15mA
D.C.Resistance at 20 ℃	250 Ω
Accuracy @RL≦10Ω	2%
Linearity @R_L≦10Ω	0.5%
Phase error at rated current range	≦4°
Operating Temperature Range	-40~65℃
Storage Temperature Range	-45~85℃
Dielectric Withstanding Voltage(Hi-pot)	2.5KV/1mA/1min
Insulation Resistance	DC500V/100MΩ min

Mechanical Specifications

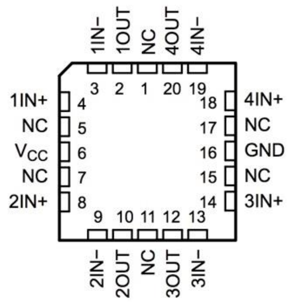
CUP	PBT
Opening Dimensions	>10mm
Output type	UL1015 22AWG PVC WIRE(doubling wire)
Approx.Weight	60g

Changping Town. Dongguan City. Guang Dong. China.
Tel : +86-13428448868 E-mail:echun.sales@gmail.com www.echun-elc.com

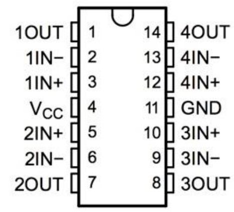
APPENDIX D: Op Amp 324a

5 Pin Configuration and Functions

FK Package
20-Pin LCCC
(Top View)



D, DB, J, N, NS, PW, W
14-Pin SOIC, SSOP, CDIP, PDIP, SO, TSSOP, CFP
(Top View)



Pin Functions

PIN			I/O	DESCRIPTION
NAME	LCCC NO.	SOIC, SSOP, CDIP, PDIP, SO, TSSOP, CFP NO.		
1IN–	3	2	I	Negative input
1IN+	4	3	I	Positive input
1OUT	2	1	O	Output
2IN–	9	6	I	Negative input
2IN+	8	5	I	Positive input
2OUT	10	7	O	Output
3IN–	13	9	I	Negative input
3IN+	14	10	I	Positive input
3OUT	12	8	O	Output
4IN–	19	13	I	Negative input
4IN+	18	12	I	Positive input
4OUT	20	14	O	Output
GND	16	11	—	Ground
NC	1	—	—	Do not connect
	5			
	7			
	11			
	15			
	17			
V_{CC}	6	4	—	Power supply

6 Specifications

6.1 Absolute Maximum Ratings

over operating free-air temperature range (unless otherwise noted)(1)

		LM2902		LMx24, LMx24x, LMx24xx, LM2902x, LM2902xx, LM2902xxx		UNIT
		MIN	MAX	MIN	MAX	
Supply voltage, V_{CC} (2)		±13	26	±16	32	V
Differential input voltage, V_{ID} (3)			±26		±32	V
Input voltage, V_I (either input)		–0.3	26	–0.3	to 32	V
Duration of output short circuit (one amplifier) to ground at (or below) T_A = 25°C, V_{CC} ≤ 15 V (4)		Unlimited		Unlimited		
Operating virtual junction temperature, T_J			150		150	°C
Case temperature for 60 seconds	FK package				260	°C
Lead temperature 1.6 mm (1/16 inch) from case for 60 seconds	J or W package		300		300	°C
Storage temperature, T_{stg}		–65	150	–65	150	°C

(1) Stresses beyond those listed under *Absolute Maximum Ratings* may cause permanent damage to the device. These are stress ratings only, and functional operation of the device at these or any other conditions beyond those indicated under *Recommended Operating Conditions* is not implied. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability.
(2) All voltage values (except differential voltages and V_{CC} specified for the measurement of I_{OS}) are with respect to the network GND.
(3) Differential voltages are at IN+, with respect to IN−.
(4) Short circuits from outputs to VCC can cause excessive heating and eventual destruction.

6.2 ESD Ratings

			VALUE	UNIT
LM224K, LM224KA, LM324K, LM324KA, LM2902K, LM2902KV, LM2902KAV				
$V_{(ESD)}$	Electrostatic discharge	Human-body model (HBM), per ANSI/ESDA/JEDEC JS-001 (1)	±2000	V
		Charged-device model (CDM), per JEDEC specification JESD22-C101	±1000	
LM124, LM124A, LM224, LM224A, LM324, LM324A, LM2902, LM2902V				
$V_{(ESD)}$	Electrostatic discharge	Human-body model (HBM), per ANSI/ESDA/JEDEC JS-001 (1)	±500	V
		Charged-device model (CDM), per JEDEC specification JESD22-C101	±1000	

(1) JEDEC document JEP155 states that 500-V HBM allows safe manufacturing with a standard ESD control process.

6.3 Recommended Operating Conditions

over operating free-air temperature range (unless otherwise noted)

		LM2902		LMx24, LMx24x, LMx24xx, LM2902x, LM2902xx, LM2902xxx		UNIT
		MIN	MAX	MIN	MAX	
V_{CC} Supply voltage		3	26	3	30	V
V_{CM} Common-mode voltage		0	V_{CC} – 2	0	V_{CC} – 2	V
T_A Operating free air temperature	LM124			–55	125	°C
	LM2904	–40	125			
	LM324			0	70	
	LM224			–25	85	

6.4 Thermal Information

THERMAL METRIC(1)		LMx24, LM2902					LMx24			UNIT
		D (SOIC)	DB (SSOP)	N (PDIP)	NS (SO)	PW (TSSOP)	FK (LCCC)	J (CDIP)	W (CFP)	
		14 PINS	14 PINS	14 PINS	14 PINS	14 PINS	20 PINS	14 PINS	14 PINS	
$R_{\theta JA}$ (2)(3)	Junction-to-ambient thermal resistance	86	86	80	76	113	—	—	—	°C/W
$R_{\theta JC}$ (4)	Junction-to-case (top) thermal resistance	—	—	—	—	—	5.61	15.05	14.65	°C/W

(1) For more information about traditional and new thermal metrics, see the *IC Package Thermal Metrics* application report, SPRA953.
(2) Short circuits from outputs to VCC can cause excessive heating and eventual destruction.
(3) Maximum power dissipation is a function of $T_{J(max)}$, $R_{\theta JA}$, and T_A. The maximum allowable power dissipation at any allowable ambient temperature is $P_D = (T_{J(max)} - T_A)/R_{\theta JA}$. Operating at the absolute maximum T_J of 150°C can affect reliability.
(4) Maximum power dissipation is a function of $T_{J(max)}$, $R_{\theta JA}$, and T_C. The maximum allowable power dissipation at any allowable case temperature is $P_D = (T_{J(max)} - T_C)/R_{\theta JC}$. Operating at the absolute maximum T_J of 150°C can affect reliability.

6.5 Electrical Characteristics for LMx24 and LM324K

at specified free-air temperature, V_{CC} = 5 V (unless otherwise noted)

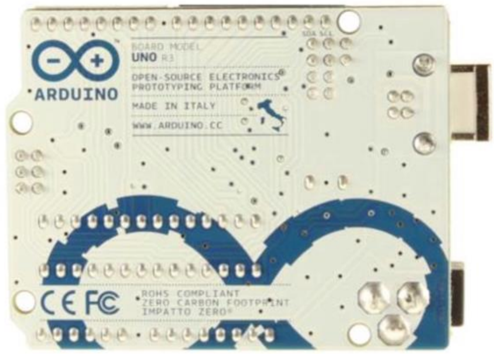
PARAMETER		TEST CONDITIONS(1)		T_A (2)	LM124, LM224			LM324, LM324K			UNIT
					MIN	TYP(3)	MAX	MIN	TYP(3)	MAX	
V_{IO}	Input offset voltage	V_{CC} = 5 V to MAX, $V_{IC} = V_{ICR}$min, V_O = 1.4 V		25°C		3	5		3	7	mV
				Full range			7			9	
I_{IO}	Input offset current	V_O = 1.4 V		25°C		2	30		2	50	nA
				Full range			100			150	
I_{IB}	Input bias current	V_O = 1.4 V		25°C		–20	–150		–20	–250	nA
				Full range			–300			–500	
V_{ICR}	Common-mode input voltage range	V_{CC} = 5 V to MAX		25°C	0 to V_{CC} – 1.5			0 to V_{CC} – 1.5			V
				Full range	0 to V_{CC} – 2			0 to V_{CC} – 2			
V_{OH}	High-level output voltage	R_L = 2 kΩ		25°C	V_{CC} – 1.5			V_{CC} – 1.5			V
		R_L = 10 kΩ		25°C							
		V_{CC} = MAX	R_L = 2 kΩ	Full range	26			26			
			R_L ≥ 10 kΩ	Full range	27	28		27	28		
V_{OL}	Low-level output voltage	R_L ≤ 10 kΩ		Full range		5	20		5	20	mV
A_{VD}	Large-signal differential voltage amplification	V_{CC} = 15 V, V_O = 1 V to 11 V, R_L ≥ 2 kΩ		25°C	50	100		25	100		V/mV
				Full range	25			15			
CMRR	Common-mode rejection ratio	$V_{IC} = V_{ICR}$min		25°C	70	80		65	80		dB
k_{SVR}	Supply-voltage rejection ratio (ΔV_{CC} /ΔVIO)			25°C	65	100		65	100		dB
V_{O1}/ V_{O2}	Crosstalk attenuation	f = 1 kHz to 20 kHz		25°C		120			120		dB
I_O	Output current	V_{CC} = 15 V, V_{ID} = 1 V, V_O = 0	Source	25°C	–20	–30	–60	–20	–30	–60	mA
				Full range	–10			–10			
		V_{CC} = 15 V, V_{ID} = –1 V, V_O = 15 V	Sink	25°C	10	20		10	20		
				Full range	5			5			
		V_{ID} = –1 V, V_O = 200 mV		25°C	12	30		12	30		μA
I_{OS}	Short-circuit output current	V_{CC} at 5 V, V_O = 0, GND at –5 V		25°C		±40	±60		±40	±60	mA
I_{CC}	Supply current (four amplifiers)	V_O = 2.5 V, no load		Full range		0.7	1.2		0.7	1.2	mA
		V_{CC} = MAX, V_O = 0.5 V_{CC}, no load		Full range		1.4	3		1.4	3	

(1) All characteristics are measured under open-loop conditions, with zero common-mode input voltage, unless otherwise specified. MAX V_{CC} for testing purposes is 26 V for LM2902 and 30 V for the others.
(2) Full range is –55°C to 125°C for LM124, –25°C to 85°C for LM224, and 0°C to 70°C for LM324.
(3) All typical values are at T_A = 25°C

APPENDIX E: Arduino Uno

Arduino Uno

Arduino Uno R3 Front



Arduino Uno R3 Back

Arduino Uno R2 Front

Arduino Uno SMD

Arduino Uno Front

Arduino Uno Back

Overview

The Arduino Uno is a microcontroller board based on the ATmega328 (datasheet). It has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs, a 16 MHz ceramic resonator, a USB connection, a power jack, an ICSP header, and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with a AC-to-DC adapter or battery to get started.
The Uno differs from all preceding boards in that it does not use the FTDI USB-to-serial driver chip. Instead, it features the Atmega16U2 (Atmega8U2 up to version R2) programmed as a USB-to-serial converter.
Revision 2 of the Uno board has a resistor pulling the 8U2 HWB line to ground, making it easier to put into DFU mode.
Revision 3 of the board has the following new features:

- 1.0 pinout: added SDA and SCL pins that are near to the AREF pin and two other new pins placed near to the RESET pin, the IOREF that allow the shields to adapt to the voltage provided from the board. In future, shields will be compatible both with the board that use the AVR, which operate with 5V and with the Arduino Due that operate with 3.3V. The second one is a not connected pin, that is reserved for future purposes.
- Stronger RESET circuit.
- Atmega 16U2 replace the 8U2.

"Uno" means one in Italian and is named to mark the upcoming release of Arduino 1.0. The Uno and version 1.0 will be the reference versions of Arduino, moving forward. The Uno is the latest in a series of USB Arduino boards, and the reference model for the Arduino platform; for a comparison with previous versions, see the index of Arduino boards.

Summary

Microcontroller	ATmega328
Operating Voltage	5V
Input Voltage (recommended)	7-12V

Input Voltage (limits)	6-20V
Digital I/O Pins	14 (of which 6 provide PWM output)
Analog Input Pins	6
DC Current per I/O Pin	40 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	32 KB (ATmega328) of which 0.5 KB used by bootloader
SRAM	2 KB (ATmega328)
EEPROM	1 KB (ATmega328)
Clock Speed	16 MHz

Schematic & Reference Design

EAGLE files: arduino-uno-Rev3-reference-design.zip (NOTE: works with Eagle 6.0 and newer)
Schematic: arduino-uno-Rev3-schematic.pdf
Note: The Arduino reference design can use an Atmega8, 168, or 328, Current models use an ATmega328, but an Atmega8 is shown in the schematic for reference. The pin configuration is identical on all three processors.

Power

The Arduino Uno can be powered via the USB connection or with an external power supply. The power source is selected automatically.
External (non-USB) power can come either from an AC-to-DC adapter (wall-wart) or battery. The adapter can be connected by plugging a 2.1mm center-positive plug into the board's power jack. Leads from a battery can be inserted in the Gnd and Vin pin headers of the POWER connector.
The board can operate on an external supply of 6 to 20 volts. If supplied with less than 7V, however, the 5V pin may supply less than five volts and the board may be unstable. If using more than 12V, the voltage regulator may overheat and damage the board. The recommended range is 7 to 12 volts.
The power pins are as follows:

- **VIN.** The input voltage to the Arduino board when it's using an external power source (as opposed to 5 volts from the USB connection or other regulated power source). You can supply voltage through this pin, or, if supplying voltage via the power jack, access it through this pin.
- **5V.**This pin outputs a regulated 5V from the regulator on the board. The board can be supplied with power either from the DC power jack (7 - 12V), the USB connector (5V), or the VIN pin of the board (7-12V). Supplying voltage via the 5V or 3.3V pins bypasses the regulator, and can damage your board. We don't advise it.
- **3V3.** A 3.3 volt supply generated by the on-board regulator. Maximum current draw is 50 mA.
- **GND.** Ground pins.

Memory

The ATmega328 has 32 KB (with 0.5 KB used for the bootloader). It also has 2 KB of SRAM and 1 KB of EEPROM (which can be read and written with the EEPROM library).

Input and Output

Each of the 14 digital pins on the Uno can be used as an input or output, using pinMode(), digitalWrite(), and digitalRead() functions. They operate at 5 volts. Each pin can provide or receive a maximum of 40 mA and has an internal pull-up resistor (disconnected by default) of 20-50 kOhms. In addition, some pins have specialized functions:

- **Serial: 0 (RX) and 1 (TX).** Used to receive (RX) and transmit (TX) TTL serial data. These pins are connected to the corresponding pins of the ATmega8U2 USB-to-TTL Serial chip.
- **External Interrupts: 2 and 3.** These pins can be configured to trigger an interrupt on a low value, a rising or falling edge, or a change in value. See the attachInterrupt() function for details.
- **PWM: 3, 5, 6, 9, 10, and 11.** Provide 8-bit PWM output with the analogWrite() function.

- **SPI: 10 (SS), 11 (MOSI), 12 (MISO), 13 (SCK).** These pins support SPI communication using the SPI library.
- **LED: 13.** There is a built-in LED connected to digital pin 13. When the pin is HIGH value, the LED is on, when the pin is LOW, it's off.

The Uno has 6 analog inputs, labeled A0 through A5, each of which provide 10 bits of resolution (i.e. 1024 different values). By default they measure from ground to 5 volts, though is it possible to change the upper end of their range using the AREF pin and the analogReference() function. Additionally, some pins have specialized functionality:

- **TWI: A4 or SDA pin and A5 or SCL pin.** Support TWI communication using the Wire library.

There are a couple of other pins on the board:

- **AREF.** Reference voltage for the analog inputs. Used with analogReference().
- **Reset.** Bring this line LOW to reset the microcontroller. Typically used to add a reset button to shields which block the one on the board.

See also the mapping between Arduino pins and ATmega328 ports. The mapping for the Atmega8, 168, and 328 is identical.

Communication

The Arduino Uno has a number of facilities for communicating with a computer, another Arduino, or other microcontrollers. The ATmega328 provides UART TTL (5V) serial communication, which is available on digital pins 0 (RX) and 1 (TX). An ATmega16U2 on the board channels this serial communication over USB and appears as a virtual com port to software on the computer. The '16U2 firmware uses the standard USB COM drivers, and no external driver is needed. However, on Windows, a .inf file is required. The Arduino software includes a serial monitor which allows simple textual data to be sent to and from the Arduino board. The RX and TX LEDs on the board will flash when data is being transmitted via the USB-to-serial chip and USB connection to the computer (but not for serial communication on pins 0 and 1).
A SoftwareSerial library allows for serial communication on any of the Uno's digital pins.
The ATmega328 also supports I2C (TWI) and SPI communication. The Arduino software includes a Wire library to simplify use of the I2C bus; see the documentation for details. For SPI communication, use the SPI library.

Programming

The Arduino Uno can be programmed with the Arduino software (download). Select "Arduino Uno from the **Tools > Board** menu (according to the microcontroller on your board). For details, see the reference and tutorials.
The ATmega328 on the Arduino Uno comes preburned with a bootloader that allows you to upload new code to it without the use of an external hardware programmer. It communicates using the original STK500 protocol (reference, C header files).
You can also bypass the bootloader and program the microcontroller through the ICSP (In-Circuit Serial Programming) header; see these instructions for details.
The ATmega16U2 (or 8U2 in the rev1 and rev2 boards) firmware source code is available . The ATmega16U2/8U2 is loaded with a DFU bootloader, which can be activated by:

- On Rev1 boards: connecting the solder jumper on the back of the board (near the map of Italy) and then resetting the 8U2.
- On Rev2 or later boards: there is a resistor that pulling the 8U2/16U2 HWB line to ground, making it easier to put into DFU mode.

You can then use Atmel's FLIP software (Windows) or the DFU programmer (Mac OS X and Linux) to load a new firmware. Or you can use the ISP header with an external programmer (overwriting the DFU bootloader). See this user-contributed tutorial for more information.

Automatic (Software) Reset

Rather than requiring a physical press of the reset button before an upload, the Arduino Uno is designed in a way that allows it to be reset by software running on a connected computer. One of the hardware flow control lines (DTR) of the ATmega8U2/16U2 is connected to the reset line of the ATmega328 via a 100 nanofarad capacitor. When this line is asserted (taken low), the reset line drops long enough to reset the chip. The Arduino software uses this capability to allow you to upload code by simply pressing the upload button in the Arduino environment. This means that the bootloader can have a shorter timeout, as the lowering of DTR can be well-coordinated with the start of the upload.
This setup has other implications. When the Uno is connected to either a computer running Mac OS X or Linux, it resets each time a connection is made to it from software (via USB). For the following half-second or so, the bootloader is running on the Uno. While it is programmed to ignore malformed data (i.e. anything besides an upload of new code), it will intercept the first few bytes of data sent to the board after a connection is opened. If a sketch running on the board receives one-time configuration or other data when it first starts, make sure that the software with which it communicates waits a second after opening the connection and before sending this data.
The Uno contains a trace that can be cut to disable the auto-reset. The pads on either side of the trace can be soldered together to re-enable it. It's labeled "RESET-EN". You may also be able to disable the auto-reset by connecting a 110 ohm resistor from 5V to the reset line; see this forum thread for details.

USB Overcurrent Protection

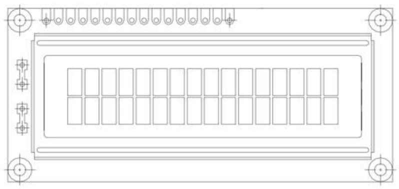
The Arduino Uno has a resettable polyfuse that protects your computer's USB ports from shorts and overcurrent. Although most computers provide their own internal protection, the fuse provides an extra layer of protection. If more than 500 mA is applied to the USB port, the fuse will automatically break the connection until the short or overload is removed.

Physical Characteristics

The maximum length and width of the Uno PCB are 2.7 and 2.1 inches respectively, with the USB connector and power jack extending beyond the former dimension. Four screw holes allow the board to be attached to a surface or case. Note that the distance between digital pins 7 and 8 is 160 mil (0.16"), not an even multiple of the 100 mil spacing of the other pins.

APPENDIX F: LCD 2x16

16 x 2 Character LCD



FEATURES

- 5 x 8 dots with cursor
- Built-in controller (KS 0066 or Equivalent)
- + 5V power supply (Also available for + 3V)
- 1/16 duty cycle
- B/L to be driven by pin 1, pin 2 or pin 15, pin 16 or A.K (LED)
- N.V. optional for + 3V power supply

MECHANICAL DATA

ITEM	STANDARD VALUE	UNIT
Module Dimension	80.0 x 36.0	mm
Viewing Area	66.0 x 16.0	mm
Dot Size	0.56 x 0.66	mm
Character Size	2.96 x 5.56	mm

ABSOLUTE MAXIMUM RATING

ITEM	SYMBOL	STANDARD VALUE			UNIT
		MIN.	TYP.	MAX.	
Power Supply	VDD-VSS	- 0.3	–	7.0	V
Input Voltage	VI	- 0.3	–	VDD	V

NOTE: VSS = 0 Volt, VDD = 5.0 Volt

ELECTRICAL SPECIFICATIONS

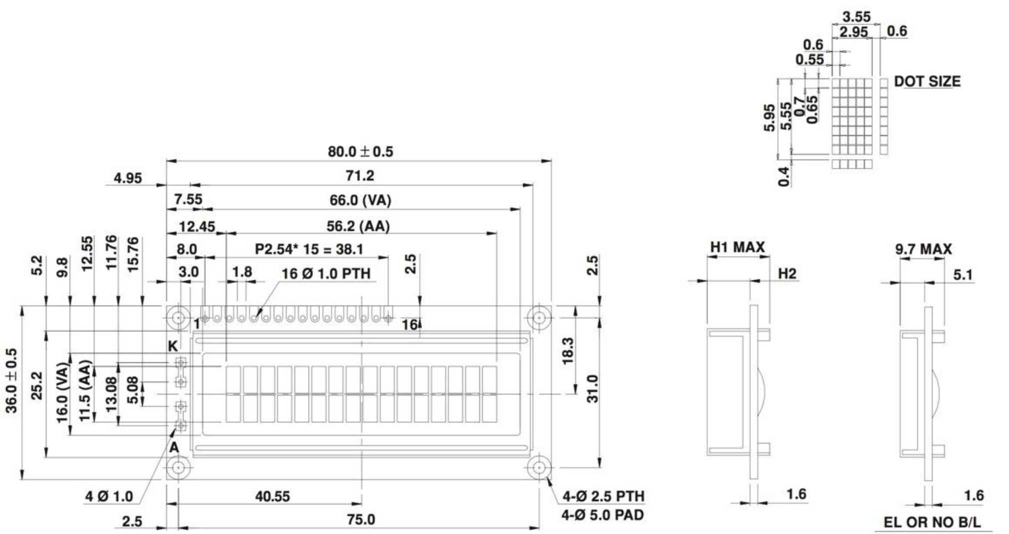
ITEM	SYMBOL	CONDITION		STANDARD VALUE			UNIT
				MIN.	TYP.	MAX.	
Input Voltage	VDD	VDD = + 5V		4.7	5.0	5.3	V
		VDD = + 3V		2.7	3.0	5.3	V
Supply Current	IDD	VDD = 5V		–	1.2	3.0	mA
Recommended LC Driving Voltage for Normal Temp. Version Module	VDD - V0	- 20 °C		–	–	–	V
		0°C		4.2	4.8	5.1	
		25°C		3.8	4.2	4.6	
		50°C		3.6	4.0	4.4	
		70°C		–	–	–	
LED Forward Voltage	VF	25°C		–	4.2	4.6	V
LED Forward Current	IF	25°C	Array	–	130	260	mA
			Edge	–	20	40	
EL Power Supply Current	IEL	Vel = 110VAC:400Hz		–	–	5.0	mA

DISPLAY CHARACTER ADDRESS CODE:

Display Position	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
DD RAM Address	00	01														0F
DD RAM Address	40	41														4F

PIN NUMBER	SYMBOL	FUNCTION
1	Vss	GND
2	Vdd	+ 3V or + 5V
3	Vo	Contrast Adjustment
4	RS	H/L Register Select Signal
5	R/$\overline{W}$	H/L Read/Write Signal
6	E	H →L Enable Signal
7	DB0	H/L Data Bus Line
8	DB1	H/L Data Bus Line
9	DB2	H/L Data Bus Line
10	DB3	H/L Data Bus Line
11	DB4	H/L Data Bus Line
12	DB5	H/L Data Bus Line
13	DB6	H/L Data Bus Line
14	DB7	H/L Data Bus Line
15	A/Vee	+ 4.2V for LED/Negative Voltage Output
16	K	Power Supply for B/L (OV)

DIMENSIONS in millimeters



LED - H/L B/L

	HIGH	LOW
H1	13.2	12.1
H2	8.6	7.5

APPENDIX G: Code

```
[code]
/*
  SMART RECLOSER CODE
  By: Hung Ngo
  Department: Electrical and Computer Engineering, WPI
  Date: February 23, 2017
  Summary: This code implements a Smart Recloser that is capable of detecting
Low Impedance and High Impedance faults.

*/

// include the library code:
#include <LiquidCrystal.h>

// initialize the library with the numbers of the interface pins
LiquidCrystal lcd(12, 11, 5, 4, 3, 2);

// Set up values
const int UpperWave = A0;    // select the input pin for upper wave
const int LowerWave = A1;    // select the input pin for lower wave
int RelayPin = 13;
int mode = 0; // mode of operation, 0 = Regular Operation, 1 = High Impedance,
int ave_sum_reg, ave_sum_high, tot_sum_reg, tot_sum_high = 0;
int ave_diff_reg, ave_diff_high, tot_diff_reg, tot_diff_high = 0;
int UpperValue;  // variable to store the value coming from A0
int LowerValue;  // variable to store the value coming from A1
int sum, difference = 0; // variable to compare upper and lower waveforms
int Fault_Sum, Fault_Diff, Reg_Sum, Reg_Diff = 0;

void setup() {
  // initialize serial communications at 9600 bps:
  Serial.begin(9600);
  // set up the number of columns and rows on the LCD
  lcd.begin(16, 2);
  // set Relay Pin as output
  pinMode(RelayPin, OUTPUT);
  lcd.print("SMART RECLOSER");
  lcd.setCursor(0,1);
  lcd.print("Analzying Line");

  ////////CODE FOR AVERAGE VALUES///////

  // Clear Extra Data from Digital Reads
  UpperValue = analogRead(UpperWave); // Read input from upper waveform
  LowerValue = analogRead(LowerWave); // Read input from lower waveform
  delay(1000);

  /////////Gather data for Regular Operation///////
  digitalWrite(RelayPin, HIGH);
  delay(5000);

  Serial.println ("\t Regular Operation Analyzation");

  for (int i=0; i<5; i++){
    //Read Data from pins
    UpperValue = analogRead(UpperWave); // Read input from upper waveform
    LowerValue = analogRead(LowerWave); // Read input from lower waveform
    sum = UpperValue + LowerValue; // Get the sum of the Upper and Lower
Waveforms
    difference = LowerValue - UpperValue; // Get the difference between the
Upper and Lower Waveforms
```

```
    //Print the values of the Upper and Lower Wave forms onto the Serial Monitor
    Serial.print ("\t Sum = ");
    Serial.print(sum);
    Serial.print ("\t Difference = ");
    Serial.println(difference);

    //Add to Total Sum, Total Difference
    tot_sum_reg += sum;
    tot_diff_reg += difference;
    delay (1000);
  }

  //Calculate Sums & Differences
  ave_sum_reg = ceil(tot_sum_reg/5);
  ave_diff_reg = tot_diff_reg/5;

  Serial.print ("\t Total Sum = ");
  Serial.print(tot_sum_reg);
  Serial.print ("\t Total Difference = ");
  Serial.println(tot_diff_reg);
  Serial.print ("\t Average Sum = ");
  Serial.print(ave_sum_reg);
  Serial.print ("\t Average Difference = ");
  Serial.println(ave_diff_reg);

  ///////Gather data for High Impedance Operation///////
  digitalWrite(RelayPin, LOW);
  delay(4000);

  Serial.println ("\t High Impedance Analyzation");

  for (int i=0; i<5; i++){
    //Read Data from pins
    UpperValue = analogRead(UpperWave); // Read input from upper waveform
    LowerValue = analogRead(LowerWave); // Read input from lower waveform
    sum = UpperValue + LowerValue; // Get the sum of the Upper and Lower
Waveforms
    difference = LowerValue - UpperValue; // Get the difference between the
Upper and Lower Waveforms

    //Print the values of the Upper and Lower Wave forms onto the Serial Monitor
    Serial.print ("\t Sum = ");
    Serial.print(sum);
    Serial.print ("\t Difference = ");
    Serial.println(difference);

    //Add to Total Sum, Total Difference
    tot_sum_high += sum;
    tot_diff_high += difference;
    delay (1000);
  }

  //Calculate Sums & Differences
  ave_sum_high = ceil(tot_sum_high/5);
  ave_diff_high = tot_diff_high/5;

  Serial.print ("\t Total Sum = ");
  Serial.print(tot_sum_high);
  Serial.print ("\t Total Difference = ");
  Serial.println(tot_diff_high);
  Serial.print ("\t Average Sum = ");
  Serial.print(ave_sum_high);
  Serial.print ("\t Average Difference = ");
```

```
  Serial.println(ave_diff_high);


  //////Set Thresholds/////
  Fault_Sum = ave_sum_reg + 300; //Threshold when Low Impedance Occurs
  Fault_Diff = ave_diff_reg + 2; //Threshold when High Impedance Occurs
  Reg_Sum = ave_sum_high; //Threshold when fault is cleared
  Reg_Diff = ave_diff_high; //Threshold when fault is cleared

  Serial.println("\t ");
  Serial.print ("\t Threshold Fault Sum = ");
  Serial.print(Fault_Sum);
  Serial.print ("\t Threshold Fault Difference = ");
  Serial.println(Fault_Diff);
  Serial.print ("\t Threshold Regular Sum = ");
  Serial.print(Reg_Sum);
  Serial.print ("\t Threshold Regular Difference = ");
  Serial.println(Reg_Diff);
  ///////////////////////

  digitalWrite(RelayPin, HIGH);
  Serial.println("\t Starting Smart Recloser");
  Serial.println("\t ");
  delay(3000);
}

void loop() {

  // Set up intial values for Positive and Negative Half Cycles Waves
  UpperValue = analogRead(UpperWave); // Read input from upper waveform
  LowerValue = analogRead(LowerWave); // Read input from lower waveform
  sum = UpperValue + LowerValue; // Get the sum of the Upper and Lower Waveforms
  difference = LowerValue - UpperValue; // Get the difference between the Upper
and Lower Waveforms

  //Print the values of the Upper and Lower Wave forms onto the Serial Monitor
  Serial.print("UpperValue = ");
  Serial.print(UpperValue);
  Serial.print("\t LowerValue = ");
  Serial.print(LowerValue);
  Serial.print ("\t Sum = ");
  Serial.print(sum);
  Serial.print ("\t Difference = ");
  Serial.println(difference);

  switch(mode){
    case 0: // Normal operation, recloser constantly checks if there is a Fault
    {
      if (sum >= Fault_Sum) // Check for Low Impedance Fault
      {
        Serial.println("\t There is a Low Impedance Fault!");
        Serial.println("\t Disconnecting Line...");

        lcd.clear();
        lcd.setCursor(0,0);
        lcd.print("Fault Detected!");
        lcd.setCursor(0,1);
        lcd.print("Low Impedance");
          delay(3000);
        lcd.clear();
        lcd.setCursor(0,0);
        lcd.print("Disconnecting");
        lcd.setCursor(0,1);
        lcd.print("Line...........");
```

```
        mode = 1;
        digitalWrite(RelayPin, LOW);
      }
      else if (difference >= Fault_Diff) // Check for High Impedance Fault
      {
        Serial.println("\t Checking for Fault!");
        mode = 2;
      }
      else // Remain in Regular Operation Mode
      {
        Serial.println("\t Regular Operation...");

        lcd.clear();
        lcd.setCursor(0,0);
        lcd.print("Normal Operation");

        digitalWrite(RelayPin, HIGH);
      }
      break;
    }

    case 1: //There is a Low Impedance Fault, activate High Impedance Mode and
wait for fault to clear
    {
      if ((sum <= Reg_Sum + 5) & (difference <= Reg_Diff)) // Check if Fault
has cleared
      {
        Serial.println("\t Fault has cleared");
        Serial.println("\t Reconnecting Line...");

        lcd.clear();
        lcd.setCursor(0,0);
        lcd.print("Disconnected");
        lcd.setCursor(0,1);
        lcd.print("Fault Cleared");

        mode = 6;
      }
      else // Remain in High Impedance Mode until Low Impedance Fault has
cleared
      {
        Serial.println("\t High Impedance Mode - Low Impedance Fault");

      lcd.clear();
      lcd.setCursor(0,0);
      lcd.print("Disconnected");
      lcd.setCursor(0,1);
      lcd.print("Fault Detected");

        digitalWrite(RelayPin, LOW);
      }
      break;
    }

    case 2: //High Impedance Fault has been detected, check again if there is
truely a fault
    {
      if (difference >= Fault_Diff) // Check if there is a consistent High
Impedance Fault
      {
        Serial.println("\t There is a High Impedance Fault!");
        Serial.println("\t Disconnecting Line...");
```

```
        lcd.clear();
        lcd.setCursor(0,0);
        lcd.print("Fault Detected!");
        lcd.setCursor(0,1);
        lcd.print("High Impedance");
          delay(3000);
        lcd.clear();
        lcd.setCursor(0,0);
        lcd.print("Disconnecting");
        lcd.setCursor(0,1);
        lcd.print("Line............");

        mode = 3;

        digitalWrite(RelayPin, LOW);
      }
      else
      {
        mode = 0;
        Serial.println("\t Regular Operation...");
        digitalWrite(RelayPin, HIGH);
      }
      break;
    }

    case 3: //There is a High Impedance Fault, activate High Impedance Mode and
wait for fault to clear for 3 cycles. (This will be the first cycle)
    {
      if ((sum <= Reg_Sum) & (difference <= Reg_Diff)) // Check if Fault has
cleared
      {
        Serial.println("\t Checking if fault has cleared...");

        mode = 4;
      }
      else // Remain in High Impedance Mode until High Impedance Fault has
cleared
      {
        Serial.println("\t High Impedance Mode - High Impedance Fault");

        lcd.clear();
        lcd.setCursor(0,0);
        lcd.print("Disconnected");
        lcd.setCursor(0,1);
        lcd.print("Fault Detected");

        mode = 3;
        digitalWrite(RelayPin, LOW);
      }
      break;
    }

    case 4: //There is a High Impedance Fault, activate High Impedance Mode and
wait for fault to clear for 3 cycles. (This will be the second cycle)
    {
      if ((sum <= Reg_Sum) & (difference <= Reg_Diff)) // Check if Fault has
cleared
      {
        Serial.println("\t Checking if fault has cleared...");

        mode = 5;
      }
      else // Remain in High Impedance Mode until High Impedance Fault has
cleared
```

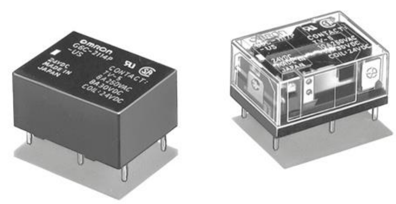
```
      {
        Serial.println("\t High Impedance Mode - High Impedance Fault");

        lcd.clear();
        lcd.setCursor(0,0);
        lcd.print("Disconnected");
        lcd.setCursor(0,1);
        lcd.print("Fault Detected");

        mode = 3;
        digitalWrite(RelayPin, LOW);
      }
      break;
    }

    case 5: //There is a High Impedance Fault, activate High Impedance Mode and
wait for fault to clear for 3 cycles. (This will be the third cycle)
    {
      if ((sum <= Reg_Sum) & (difference <= Reg_Diff)) // Check if Fault has
cleared
      {
        Serial.println("\t Fault has cleared");
        Serial.println("\t Reconnecting Line...");

        lcd.clear();
        lcd.setCursor(0,0);
        lcd.print("Disconnected");
        lcd.setCursor(0,1);
        lcd.print("Fault Cleared");

        mode = 6;
      }
      else // Remain in High Impedance Mode until High Impedance Fault has
cleared
      {
        Serial.println("\t High Impedance Mode - High Impedance Fault");

        lcd.clear();
        lcd.setCursor(0,0);
        lcd.print("Disconnected");
        lcd.setCursor(0,1);
        lcd.print("Fault Detected");

        mode = 3;
        digitalWrite(RelayPin, LOW);
      }
      break;
    }

    case 6: //If fault has cleared, reconnect line and enter wait period
    {
        Serial.println("\t Fault has cleared - Preparing Line");

          delay(3000);
        lcd.clear();
        lcd.setCursor(0,0);
        lcd.print("Preparing Line");
        lcd.setCursor(0,1);
        lcd.print("................");
        digitalWrite(RelayPin, HIGH);
         delay(10000);
        lcd.clear();
        lcd.setCursor(0,0);
        lcd.print("Line Connected");
```

```
        mode = 0;
      }
      break;
 }


  delay(1000);
}

[/code]
```

APPENDIX H: Relay

G6C
PCB Power Relay

Miniature High Capacity Relays with SPST-NO 10A and SPST-NO + SPST-NC 8A



- SPST-NO 10A and SPST-NO + SPST-NC 8A for power switching and output that satisfy the needs for space-saving.
- Small High-capacity Relays Compact: 20 × 15 × 10 mm (L × W × H).
- Low power consumption: 200 mW.
- Ultrasonically cleanable models is available.
- Exclusive P6C model for sockets is now available.

RoHS Compliant

■Model Number Legend

G6C-□-□□□□□-□-□-□-□
1 2 3 4 5 6 7 8 9

1. Relay Function
None: Single-side stable
U : Single-winding latching
K : Double-winding latching

2. Contact Form
11: SPST-NO (1a)
21: SPST-NO (1a) + SPST-NC (1b)

3. Contact Type
1: Single

4. Enclosure rating
4: Fully sealed
7: Flux protection

5. Terminal Shape
P: PCB terminals
Socket mounting Terminals

6. Contact Material
None: Standard (Ag-alloy (Cd free))
FD : AgSnIn Contacts (Suitable for DC inductive load with high inrush current)

7. Approved Standards
US: UL/CSA

8. Washability
None: Standard model (not compatible with ultrasonically cleanable models)
U : For ultrasonically cleanable

9. Mounting
None: Mounted directly to PCB
P6C : Mounted to Socket

■Application Examples

Ideal for output applications of control equipments

G6C

■Ratings

Coil: 1-Pole, Single-side Stable Type (Including models for ultrasonically cleanable)

Item / Rated voltage	Rated current (mA)	Coil resistance (Ω)	Must operate voltage (V)	Must release voltage (V)	Max. voltage (V)	Power consumption (mW)
			% of rated voltage			
3 VDC	67	45	70% max.	10% min.	160% (at 23°C)	Approx. 200
5 VDC	40	125				
6 VDC	33.3	180				
12 VDC	16.7	720				
24 VDC	8.3	2,880				

Coil: Single-winding Latching Type (Including models for ultrasonically cleanable)

Item / Rated voltage	Rated current (mA)	Coil resistance (Ω)	Must set voltage (V)	Must reset voltage (V)	Max. voltage (V)	Power consumption	
			% of rated voltage			Set coil (mW)	Reset coil (mW)
3 VDC	67	45	70% max.	70% max.	160% (at 23°C)	200	200
5 VDC	40	125					
6 VDC	33.3	180					
12 VDC	16.7	720					
24 VDC	8.3	2,880					

Coil: Double-winding Latching Type (Including models for ultrasonically cleanable)

Item / Rated voltage	Rated current (mA)		Coil resistance (Ω)		Must set voltage (V)	Must reset voltage (V)	Max. voltage (V)	Power consumption	
	Set coil	Reset coil	Set coil	Reset coil	% of rated voltage			Set coil (mW)	Reset coil (mW)
3 VDC	93.5	93.5	32.1	32.1	70% max.	70% max.	130% (at 23°C)	280	280
5 VDC	56.0	56.0	89.3	89.3					
6 VDC	46.7	46.7	129	129					
12 VDC	23.3	23.3	514	514					
24 VDC	11.7	11.7	2,056	2,056					

Note 1. The rated current and coil resistance are measured at a coil temperature of 23°C with a tolerance of ±10%.
2. The operating characteristics are measured at a coil temperature of 23°C.
3. The "Max. voltage" is the maximum voltage that can be applied to the relay coil.

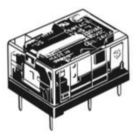
Contact

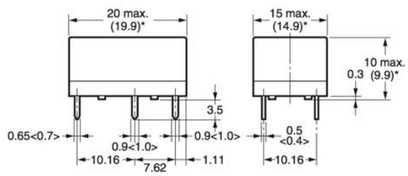
Item / Contact Form / Rated load	SPST-NO (1a)		SPST-NO (1a) + SPST-NC (1b)	
	Resistive load	Inductive load (cosϕ = 0.4; L/R = 7 ms)	Resistive load	Inductive load (cosϕ = 0.4; L/R = 7 ms)
Rated load	10 A (8 A) at 250 VAC 10 A (10 A) at 30 VDC	5 A (5 A) at 250 VAC 5 A (5 A) at 30 VDC	8 A (8 A) at 250 VAC 8 A (8 A) at 30 VDC	3.5 A (3.5 A) at 250 VAC 3.5 A (3.5 A) at 30 VDC
Contact type	Single			
Contact material	Ag-Alloy (Cd free)			
Rated carry current	10 A (10 A)		8 A (8 A)	
Max. switching voltage	380 VAC, 125 VDC			
Max. switching current	10 A (10 A)		8 A (8 A)	

Note. The values shown in parentheses ( ) are for -FD models only.

■Dimensions

Flux Protection Model
G6C-□117P-US



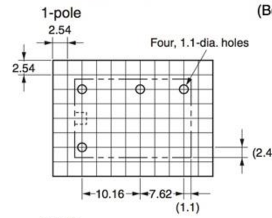


* Average value

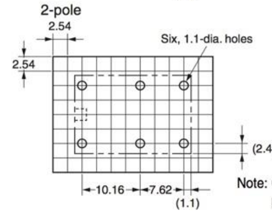
Dimensions in pointed brackets < > are for the Relay mounted to Socket(-P6C).

PCB Mounting Holes
(Bottom View)
Tolerance: ±0.1

1-pole

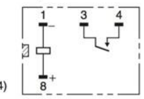


2-pole

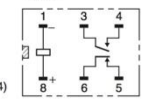


Terminal Arrangement/ Internal Connections
(Bottom View)

1-pole



2-pole

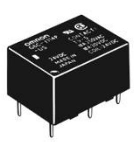


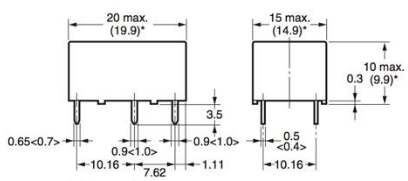
Note: Check carefully the coil polarity of the Relay.

Note: Orientation mark is indicated as follows:

G
6
C

Fully Sealed Model
G6C-□114P-US



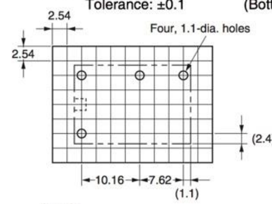


* Average value

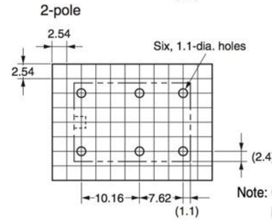
Dimensions in pointed brackets < > are for the Relay mounted to Socket(-P6C).

PCB Mounting Holes
(Bottom View)
Tolerance: ±0.1

1-pole

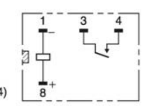


2-pole

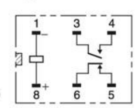


Terminal Arrangement/ Internal Connections
(Bottom View)

1-pole



2-pole



Note: Check carefully the coil polarity of the Relay.

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