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Circuit Breaker Failure Analysis System

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By

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Abstract

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Electrical malfunctions are one of the leading causes of domestic fires in the United States. Between 2012 and 2016, electrical failures were responsible for 44, 860 residential fires (Richard Campbell, “Home Electrical Fires”). All electrical circuits contain circuit breakers, which are used as safety mechanisms to interrupt current flow when a fault develops. It is not always possible to determine if an electrical fire resulted from a circuit breaker malfunction. Thus, it would be beneficial to have a cost-effective and user-friendly system that allows people to test the circuit breakers in their homes regardless of their technical background. The purpose of this capstone project is to develop a reliable and cost-effective automated system capable of testing multiple residential circuit breakers to determine their trip response in the event of a circuit fault.

The automated system adopts the UL 489 test procedure from the Underwriters Laboratories (UL) to test the circuit breakers. The system contains a computer-controlled power supply that outputs a variable current which generates enough heat to trigger the circuit breaker under test. Moreover, the system uses a solid-state bidirectional current controller known as a TRIAC to regulate the current delivered to the circuit breaker being tested. Overall, the automated system can be used to test new

and currently installed circuit breakers to determine whether they are capable of preventing electrical fires.

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1. Introduction

1.1 Problem Definition

Electricity is a powerful discovery that has many uses in our daily lives. It is used in households to power basic appliances such as air conditioners, stoves, and refrigerators. Electricity is also important in other institutions such as health facilities. For example, modern medicine relies heavily on electronic devices to perform life-saving procedures. Given the many uses of electricity, it is undeniably an essential energy source. However, electricity can become hazardous when high electrical current is being conducted. When too much current flows in an electric circuit, there is potential for fires and equipment failures, which can cause casualties. Therefore, some safety features such as circuit breakers and fuses are installed in electrical systems to counteract the consequences of circuit overloads.

Between 2012 and 2016, fire departments responded to "an estimated average of 44,860 residential fires involving electrical failure malfunction each year" [1]. Home fires caused by electrical malfunctions between 2012 and 2016 accounted for "$1.3 billion in property damage, 440 civilian deaths, and 1250 civilian injuries" [1]. Some leading causes of electrical fires in residential buildings include faulty outlets and appliances, light fixtures with high wattage, and outdated wiring that no longer have the capacity to handle new devices with higher current ratings. To minimize the impacts of electrical damages, circuit breakers are used as safety mechanisms to interrupt current flow until the electrical malfunction is safely addressed. Circuit breakers must be reliable and capable of controlling the electrical power if immediate disconnection is

needed. Thus, the proper maintenance of a circuit breaker is crucial for preventing costly damages to electrical systems [2].

1.2 Project Goal

Fire investigations conducted across the United States do not show the relationship between fire losses and circuit breaker malfunctions. The inability to associate fire losses to circuit breaker failure rates stems from investigating the origins of house fires as opposed to the trip performance of the circuit breakers at the time of the fire. Thus, this capstone project aims to analyze the trip performance of residential circuit breakers through a reliable and cost-effective automated system. The circuit breakers will be tested through computer-controlled power supply modules that are capable of outputting a variable RMS current to the breakers under test. Although multiple circuit breakers can be tested simultaneously using a PC, the breakers require separate power supply modules since they all draw current from the same source. Besides, the components needed to build the automated system are inexpensive as a result of using an AC source. Therefore, multiple power supply modules can be manufactured to test the desired amount of circuit breakers. Overall, the Circuit Breaker Failure Analysis System is a useful tool for learning about circuit breaker testing and the steps for assembling a system through careful selection of parts that satisfy a given set of design requirements.

1.3 Report Overview

The Circuit Breaker Failure Analysis System implements circuit breaker testing through a power supply and a computer-controller. The power supply is broken down into three essential circuits, which are a zero-crossing detector, an isolation circuit, and

a computer-set current controller. These circuits are explained in greater detail in the design section of the report. Before analyzing the internal construction of the power supply and the preliminary testing results, I will discuss the previous research that has been done on the topic and the required test standard set in place by the Underwriters Laboratories for evaluating domestic circuit breakers. The report also includes design limitations such as safety and potential users, but more importantly, an alternative TRIAC circuit is suggested for implementing current control. Lastly, I will discuss the design milestones that were not fully implemented this trimester, and a detailed cost-analysis to emphasize the affordability of the power supply.

2. Background

2.1 Previous Work

Circuit breakers and fuses are installed in electric circuits to minimize the risks of ignition. The purpose of circuit breakers and fuses is to protect electric circuits against overcurrent, short-circuit conditions, and ground faults. Nowadays, electric circuits in homes are protected by circuit breakers instead of fuses because a circuit breaker can interrupt current flow without causing damages to itself, whereas a fuse disintegrates when overheated.

In the U.S, fire investigators have been unable to identify circuit breaker malfunctions as a contributing factor to home electrical fires, and thus electrical faults are usually listed as the cause of ignition. To estimate the contribution of defective circuit breakers to annual fire losses, Dr. Jesse Aronstein, a consulting engineer who focuses on electrical failure analysis, collaborated with professor Richard Lowry of Vassar College to analyze the failure rates of a particular circuit breaker known as the

FPE-Stab-Lok. Dr. Aronstein and Professor Lowry published a paper in IEEE titled "Estimating Fire Losses Associated with FPE Stab-Lok Circuit Breaker Malfunction" in which they claimed that the failure rate of those circuit breakers "varies from brand to brand, and is essentially zero for some brands and significant for others as demonstrated by the Underwriters Laboratories" [3]. Dr. Aronstein and professor Lowry tested single-pole and double-pole FPE Stab-Lok circuit breakers rated at 15 amps, 20 amps, and 40 amps, and these breakers are installed in large numbers in residential buildings [3]. Two populations of FPE Stab-Lok circuit breakers were tested and the results listed in table 1 and table 2 show that the majority of FPE Stab-Lok circuit breakers are unreliable. Dr. Aronstein tested 830 FPE Stab-Lok circuit breakers in apartment buildings and compared the results to that of another 830 circuit breakers tested in 35 homes across the United States. Both test results are shown in table 1 and table 2:

Type of FPE Stab-Lok® Circuit Breakers Tested	No. Tested	No Trip Failures @135% of Rated Current*	Critical Safety Failures**
Single-Pole 15A	241	47 (20%)	0
Single-Pole 20A	211	17 (8%)	0
Double-Pole 20A	194	67 (35%)	10 (5%)
Double Pole 30A	77	32 (42%)	6 (8%)
Double Pole 40 Amp & higher	107	75 (70%)	8 (7%)

Table 1: Summary of Dr. Aronstein's test results for "830 circuit breakers tested from a 63-unit apartment building to demonstrate failure rate of FPE Stab-Lok circuit breakers" [3]

Type of FPE Stab-Lok® Circuit Breakers Tested	No. Tested	No Trip Failures @135% of Rated Current*	Critical Safety Failures**
Single-Pole	425	71 (17%)	4 (1%)
Single Pole GFI/Breaker	5	3 (60%)	4 (80%)***
Double Pole	134	46 (34%)	14 (10%)

Table 2: Summary of Dr. Aronstein's test results for "830 FPE Stab-Lok circuit breakers from 35 homes across the United States" [3]

The FPE Stab-Lok circuit breakers were tested based on the UL 489 test criterion set by the Underwriters Laboratories. The UL 489 test standard is a mandated procedure for testing domestic circuit breakers to evaluate their trip performances. Moreover, the UL 489 test standard states that domestic breakers must trip within an hour of a test cycle at 135% of the breakers' current rating. If a circuit breaker does not meet the 135% current threshold, it is classified as defective. Also, the test results listed in table 1 and table 2 show that the majority of the circuit breakers tested by Dr. Jesse Aronstein, whether double-pole or single-pole, failed to trip accordingly, thus not meeting the required test standard. This is a major setback in fire safety prevention since the tested circuit breakers are currently installed in residential buildings.

The Circuit Breaker Failure Analysis System excludes industrial circuit breakers and can only be used to test domestic breakers. This is because industrial circuit breakers are held to a different test standard that is more rigorous than the UL 489 test guideline provided for residential circuit breakers.

2.2 Circuit Breaker Testing Procedure

The Circuit Breaker Failure Analysis System will follow the mandated UL 489 test procedure to determine the reliability of the circuit breakers within a three-hour test period. Suppose a thermal circuit breaker rated at 20 amps is being tested. Initially, a user initiates a test cycle by applying 100% of the breaker's current rating, and the applied current steadily increases until the circuit breaker is triggered, as indicated in figure 1. If the breaker fails to trip within the first hour of the test cycle, the applied current is linearly increased to 135% of the current rating and is held constant for an additional hour. If the trip mechanism of the circuit breaker is not released within the second-hour mark, the applied current is linearly increased to 150% of the current rating and the circuit breaker may or may not trip within the third-hour mark [3]. As shown in figure 1, the circuit breaker has successfully tripped and the test current drops to zero within the first hour. In figure 2, the circuit breaker is said to be in marginal operation because the trip mechanism is released within two hours at 135% of the rated current. Figures 3 and 4 depict two types of failure behaviors. In figure 3, the circuit breaker trips at a current value that is above the 135% threshold. In Figure 4, the circuit breaker is said to be jammed, meaning that the breaker can sustain 150% of the current rating and does not trip at any applied current [3].

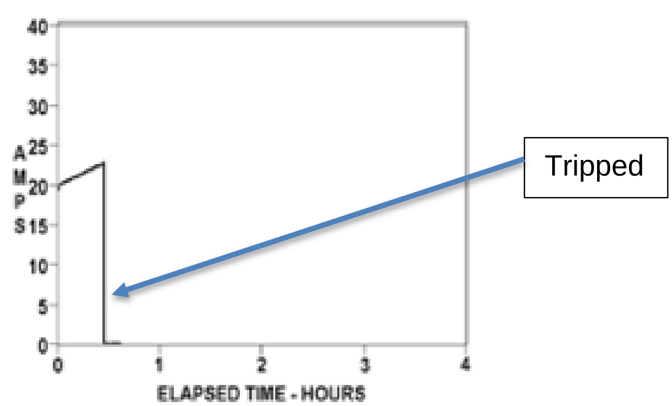

Figure 1: Correct operation of 20A FPE Stab-Lok breaker [3]

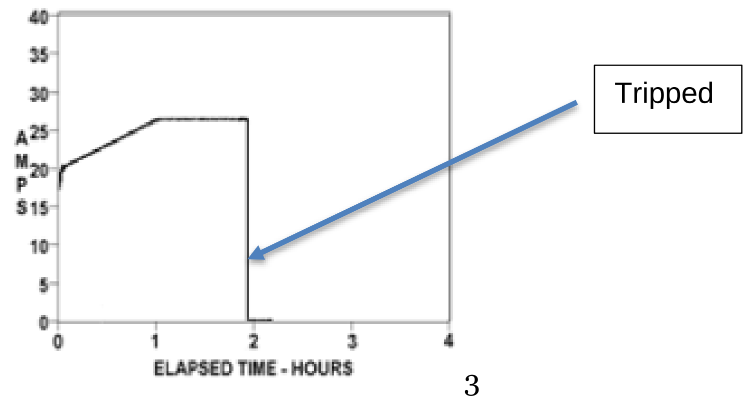

Figure 2: Marginal Operation of 20A FPE Stab-Lok breaker [3]

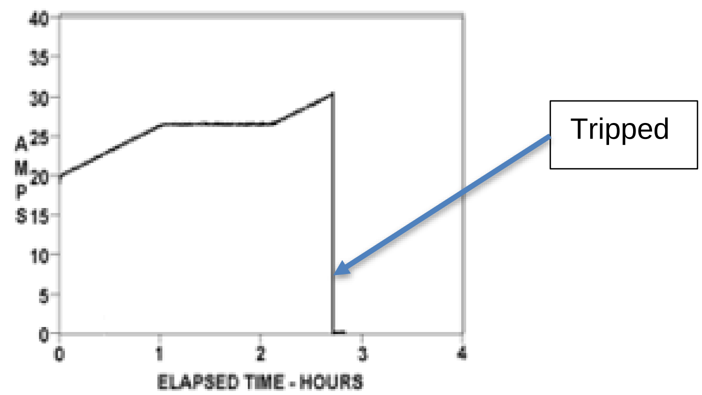

Figure 3: Calibration failure of 20A FPE Stab-Lok breaker [3]

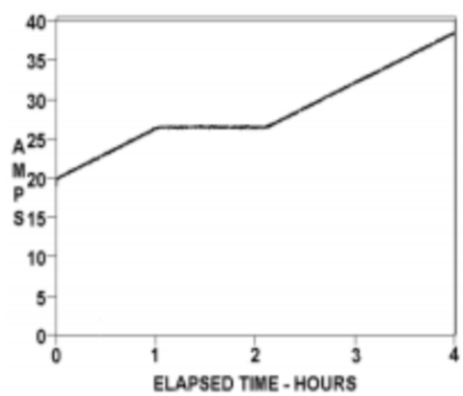

Figure 4: Jammed 20A FPE Stab-Lok breaker [3]

Although a jammed circuit breaker fails to trigger at any applied current, its latching mechanism is usually released but fails to open the point of contact that breaks open the circuit to alter the flow of current. In figure 5, a double-pole thermal circuit

breaker has successfully tripped. Point A is disengaged from the bimetallic strip at point B, which opens both sets of contact at point C. In figure 6, point A and point B are disconnected, but both sets of contact at point C remain closed [3]. Therefore, the circuit breaker is said to be jammed and will sustain any applied current. This phenomenon presents a major concern in fire safety since a jammed circuit breaker cannot interrupt current flow in an electric circuit.

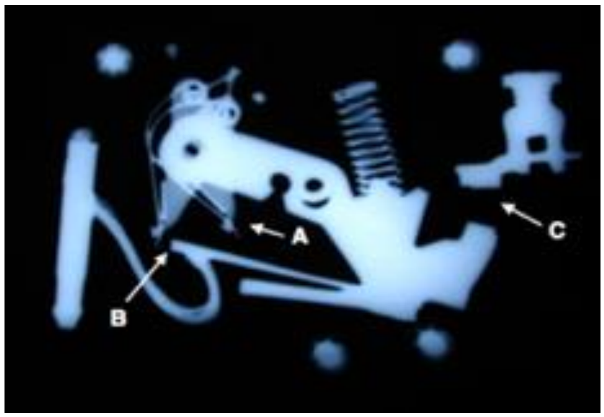

Figure 5: X ray image of a tripped FPE Stab-Lok breaker [3]

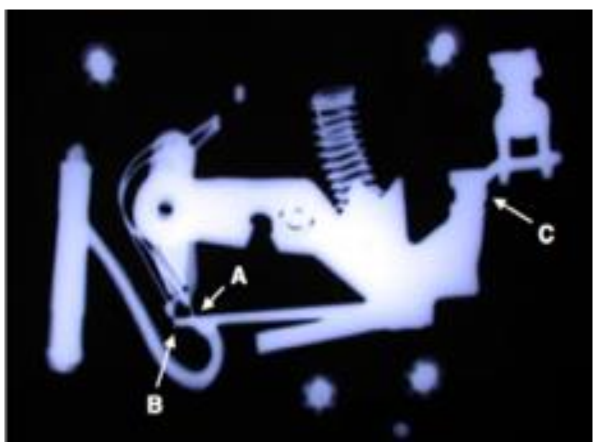

Figure 6: X ray image of a jammed FPE Stab-Lok breaker [3]

2.3 Design Impacts

The Circuit Breaker Failure Analysis System has the following specifications:

2.3-1 Safety

The power supply is designed to handle a large amount of current, which can jeopardize the safety of the user. More specifically, the power supply will output between 0 to 60 amps RMS to the circuit breakers. Thus, the user must be protected from the potential harm caused by excess current. Typically, 50 milliamperes of electric current or more can lead to respiratory arrests, severe muscle contractions, and even death [4]. To ensure safety, the power supply is equipped with a step-down transformer that isolates the AC source from the load. Thus, there are no physical or electrical connections between the primary and secondary windings of the transformer, which means that the connection is done through magnetism. As a result, the user can easily troubleshoot the power supply with no risks of electric shock. The final design will be constructed on a metal base grounded to AC ground to provide short and shock protection.

2.3-2 Potential Users

The Circuit Breaker Failure Analysis System is fully automated, meaning that anyone can use it without any prior knowledge of electrical systems. However, a designer who wishes to recreate the system must have some level of proficiency in Arduino programming and MATLAB. A lack of familiarity with tools and components such as oscilloscopes, function generators, and transformers may be a limiting factor for a more general audience.

2.3-3 Additional Tests: Mechanical and Short-Circuit Tests

To ensure a proper operation of the circuit breakers, whether domestic or industrial, a thorough test procedure should involve additional testing requirements such as mechanical and short-circuit tests. The mechanical test guarantees the reliability of the circuit breakers through "the repeated opening and closing of the breakers to ensure that their trip mechanisms are released at a proper speed without failure" [2]. Circuit breakers should also be checked for their abilities to respond to short-circuit conditions.

2.4 Ethical Considerations

The system is designed such that the user has limited interactions with the power supply as a test cycle is being conducted. The overall system is automated, thus the user's only interaction with the power supply is through the use of a computer-controller for the initiation of a test cycle. Once the test cycle is initiated, the power supply regulates the RMS current delivered to the circuit breaker through an Arduino program that controls the firing angle of the TRIAC, which in turn regulates the RMS current. The power supply is also equipped with a 4:1 step-down transformer that isolates the system from a 120V AC input. Overall, the automated system is designed to ensure maximum safety, therefore, the power supply is constructed on a metal base grounded to AC ground to provide shock and short circuit protection.

3. Design Requirements

3.1 General Specifications

The input to the power supply is a commercial outlet rated at 120VAC and 60 Hz. The power supply also contains three essential circuits, which are a zero-crossing detector, an isolation circuit that separates the voltage source from digital pin 13 of the microcontroller, and a computer-set current controller that regulates the RMS current applied to the circuit breakers. Since the power supply is powered by a 120VAC outlet, a 4:1 step-down transformer is used to step-down the 120VAC source to 30.5V RMS, which is a more desirable voltage level for the components used in the power supply.

The automated system essentially works as a feedback loop and a test cycle is initiated by setting the test current to 100% of the circuit breaker's current rating. Then, the zero-crossing detection circuit identifies the points where the input sinusoidal waveform crosses the time axis to send a hardware interrupt to the input pin of the microcontroller. More specifically, the hardware interrupt is a pulse applied to digital pin 2 of the microcontroller as soon as the zero-crossing points occur. Upon seeing the interrupt, the Arduino program temporarily alters the execution of the current instruction to run the Interrupt Service Routine or ISR, which contains specific instructions regarding the start time-delay and width of the output pulse that determines the TRIAC's firing angle. The firing angle of the TRIAC is adjusted in the Arduino program based on the current value set by the computer. Additionally, the RMS load voltage at the output of the TRIAC circuit can be calculated using the equation

$\mathbf{V_{load} = \sqrt{\ (v_{peak} *(2\pi-2\varphi + \sin(2\varphi)/4\pi))}}$ where V_{load} is the voltage across the load, V_{peak} is the peak voltage of the TRIAC's conduction waveform, and φ is the firing angle

of the TRIAC. For instance, if the computer-controller sets a current value that is proportional to a 90-degree firing angle of the TRIAC, the Arduino program would adjust the previous firing angle such that the load voltage is equivalent to 21.7V RMS at 90 degrees.

Since the circuit breaker under test is thermal, its trip mechanism is triggered by heat dissipation, and the RMS current that causes the heat ranges between 0 to 60 amps at the output of the power supply. The circuit breaker is attached to a shunt that has a small resistance of 0.0033 ohms resistance, and the voltage at the secondary side of the toroidal transformer is 0.2V RMS. Thus, a small voltage and resistance value enable the power supply to output up to 60 amps, RMS. Lastly, an A/D converter is used to measure the current across the shunt, and those current values are stored in a MATLAB file to generate current vs. time plots that allow the user to categorize the circuit breaker as operational or defective.

3. 2 Computer-Controller

A computer is used to initiate a test cycle by applying 100% of the circuit breaker's current rating. The computer must be able to send commands to the Arduino to adjust the firing angle of the TRIAC so that the power supply outputs the desired current to the circuit breaker and shunt. Moreover, a MATLAB file is used to store the current values measured at the shunt to generate current vs. time plots that follow the test curves derived from the UL 489 test standard (see figures 1-4).

3.3 Power Supply

The power supply must be capable of producing a variable RMS current between 0 and 60 amps.

3.4 Computer-Set Current Controller

The test current set by the computer must be maintained between 0 and 60 amps, and the RMS current at the primary side of the toroidal transformer must be +/- 0.5 amps. A TRIAC is also used to implement current control at the primary of the toroidal transformer. Moreover, the current across the shunt must be measured by an analog-to-digital converter such that the current values stored on the computer allow the Arduino program to change the firing angle of the TRIAC.

3.5 Circuit breakers

The variable RMS current at the output of the power supply generates heat to trigger the circuit breakers.

3.6 Safety

To prevent electric shock, a 4:1 step-down transformer is used to bring down the 120VAC supply to 30.5V RMS, allowing the user to troubleshoot the power supply if needed.

3.7 Affordability

The parts needed to build the power supply are inexpensive. Thus, multiple power supply modules can be manufactured to test several circuit breakers

simultaneously. However, each circuit breaker requires its own power supply, meaning that the circuit breakers cannot be connected in parallel because they draw current from the same source. Since the power supply is relatively cheap to manufacture, multiple modules can be produced to test the desired number of circuit breakers. See table 3 for a cost analysis of the automated system.

4. Design Alternatives

4.1 Using Direct Current Instead of Alternating Current in The Power Supply

Since thermal circuit breakers are triggered by heating, the input AC source has an RMS value that generates enough heat to activate the breakers' trip mechanism. The RMS current, which stands for Root-Mean-Square, is the DC equivalent of alternating current, which also means that DC power can be used in the power supply. To use DC, solid-state transistors with high levels of heat dissipation are needed to control the variable current (0-60A) and to trigger the circuit breakers. These solid-state transistors are expensive, which contradicts the affordability criterion of the automated system. The alternating current, on the other hand, has an RMS value that creates enough heat to trigger the circuit breakers, and a TRIAC is used to control the positive and negative half cycles of the AC sinusoid at the primary of the step-down transformer.

4.2 TRIAC Trigger Circuit

The computer-Set Current Controller can implement current control through a TRIAC/DIAC circuit configuration. While the TRIAC is excellent for AC switching

applications, it fires asymmetrically due to its internal construction, which involves two thyristors connected in reverse parallel. The TRIAC does not fire at the same gate voltage for both polarities, resulting in harmonics being generated. The more harmonics a TRIAC produces, the less symmetrical it fires. To fix the asymmetrical firing of the TRIAC, a Diode AC Switch also known as a DIAC is placed in series at the TRIAC's gate to even out the positive and negative half-cycles of the AC sinusoid [5]. It is difficult to trigger the TRIAC with the resistor and capacitor shown in figure 7. As a result, an Arduino code is used in the final design to ensure a correct firing angle of the TRIAC, which turns OFF only when its gate voltage is 0V. Figure 7 depicts the proposed TRIAC/DIAC output circuit for implementing current control:

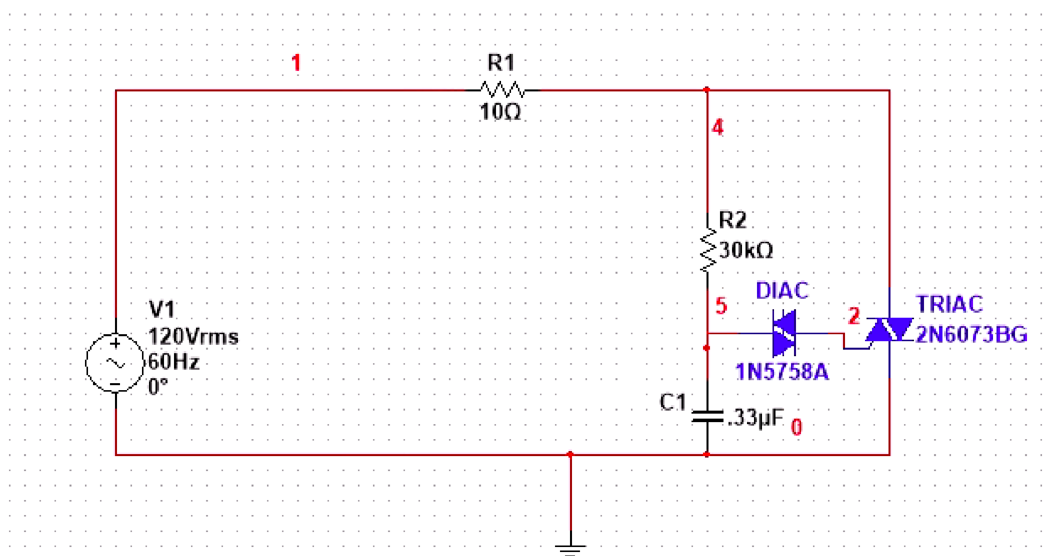

Figure 7: Circuit Diagram of TRIAC trigger circuit with DIAC configuration

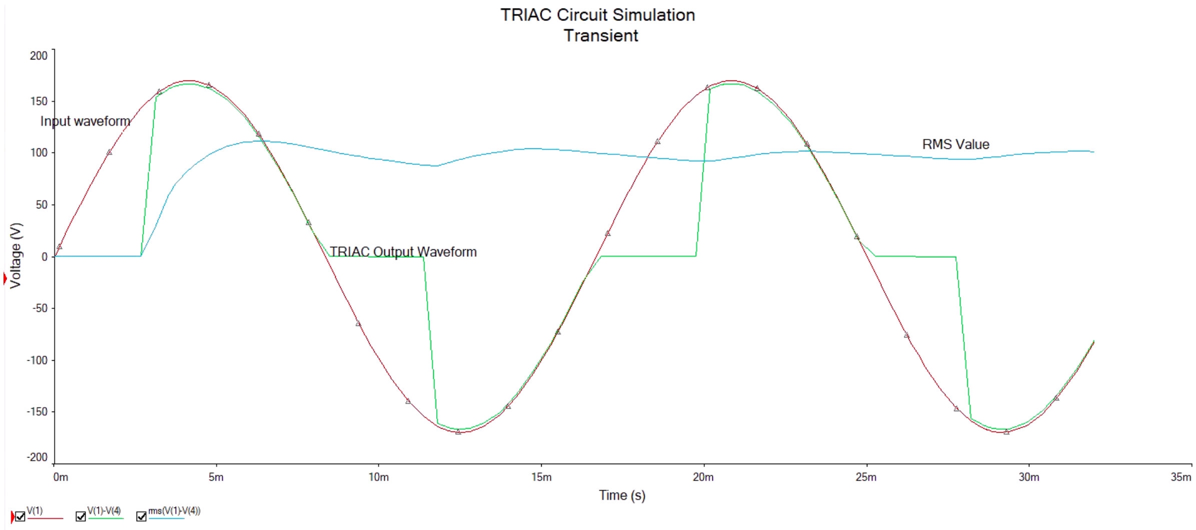

Figure 8: Simulation results for TRIAC/DIAC circuit depicting the input AC Waveform, the TRIAC conduction waveform, and the RMS waveform

In figure 7, the capacitor and 30k ohms resistor serve as a time constant. As the capacitor charges and discharges, it causes a phase shift between the input sinusoid and the TRIAC output waveform shown in figure 8. In addition, the RMS waveform is the DC equivalent of the AC sinusoid, and the RMS current produces the same heating effect as a DC power supply to trigger the circuit breakers. For the scenario shown in figure 8, the TRIAC fires at approximately 3ms or 60 degrees and the peak voltage of the sinusoid is 169.68V, and this voltage value is obtained by dividing the input voltage (120VAC) by (1/√2). As a result, the corresponding RMS voltage is 107.61V using the equation

√ (vpeak *(2π-2φ + sin(2φ) / 4π)). The TRIAC conducts at the positive and negative

half-cycles of the AC input but turns off when the gate voltage and current drop to 0. In other words, the TRIAC does not trigger when there is no pulse applied to its gate.

5. Design & Implementation

The proposed design for the Circuit Breaker Failure Analysis System is shown in figure 9. The input to the power supply is a standard 120VAC commercial outlet, and the output is an RMS current that varies between 0 and 60A. The power supply is connected to a computer that determines the test current applied to the circuit breaker. This test current is regulated by the 2N6071A TRIAC whose firing angle controls how much current is delivered to the circuit breaker. An A/D converter reads the current values across the shunt, and these values are stored in the computer, which generates current vs. time plots to illustrate the circuit breaker's trip performance. The RMS current read by the A/D converter allows the computer to adjust the test current, prompting the Arduino program to modify the firing angle of the TRIAC. For example, if the test current is equivalent to a zero-degree firing angle, then the TRIAC will stay in conduction for an entire half cycle of the AC waveform. Upon reading the current values measured by the A/D converter, if the computer changes the test current to a value that is equivalent to 90 degrees, then the TRIAC will conduct for half the duration of a half-cycle (see figures 15 and 21).

The figure below is an overview of the Circuit Breaker Failure Analysis System.

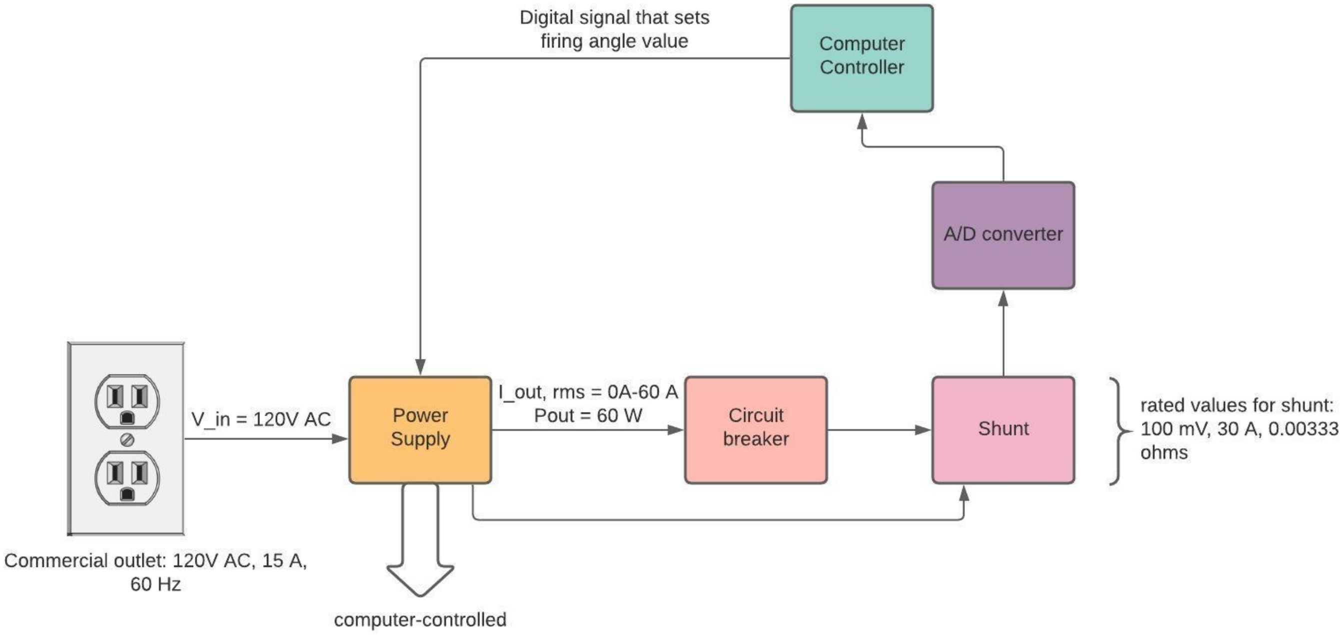

Figure 9: Overview of Circuit Breaker Failure Analysis System

The power supply contains three essential circuits, which are a zero-crossing detector, an isolation circuit, and a computer-set current controller. The internal breakdown of the power supply is shown below:

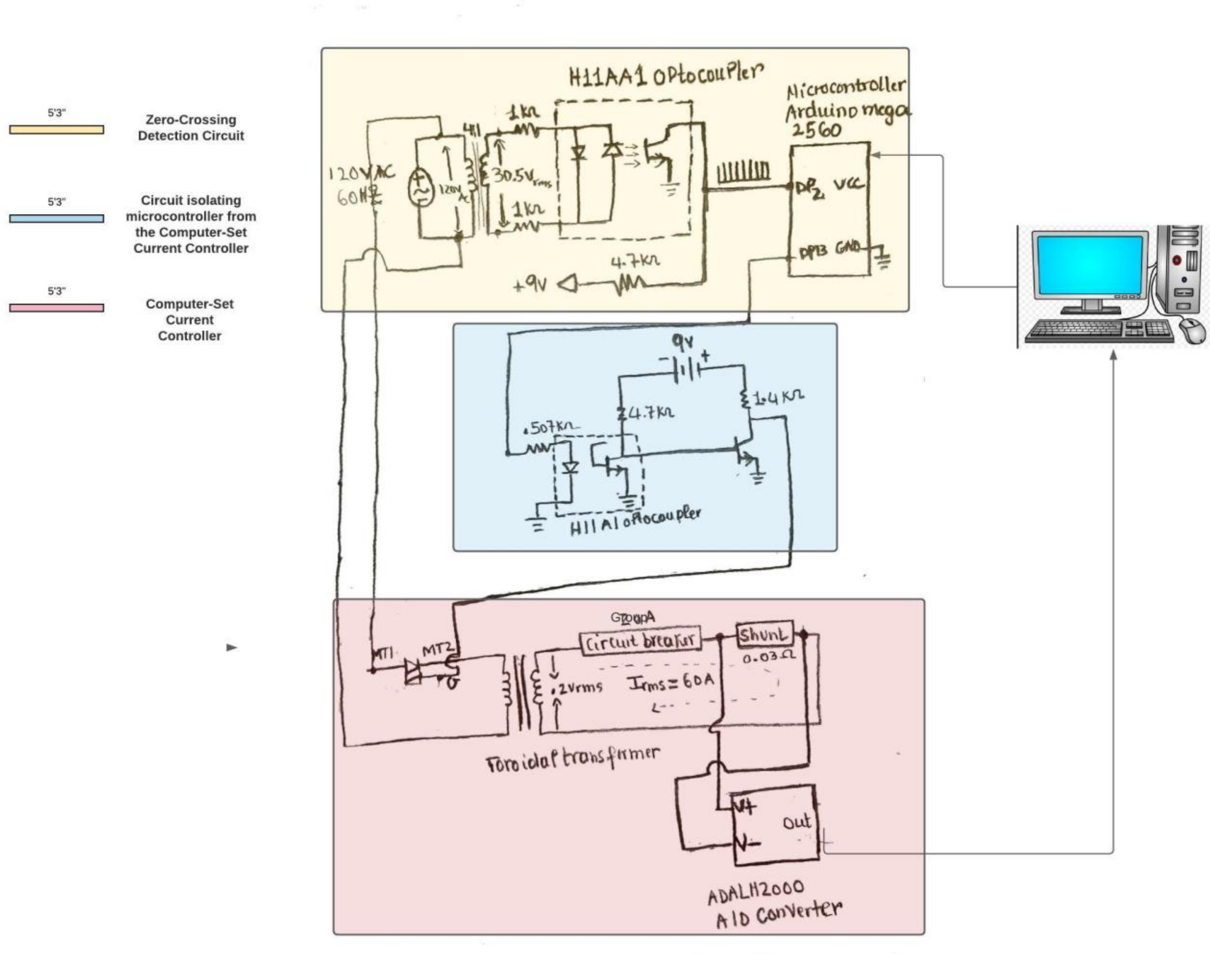

Figure 10: Internal breakdown of the power supply

5.1 Zero-Crossing Detector Circuit

Zero-crossing is the point where a sinusoidal voltage crosses the time axis. In the power supply, zero-crossing detection is used so that the H11AA1 optocoupler can generate a pulse that serves as a hardware interrupt. The interrupt signals the Arduino program to produce an output pulse that triggers the TRIAC. The zero-crossing detector circuit shown in figure 11 is a modified version of the model created by Lewis Loflin [6]. Loflin's model has been adjusted to fit the design requirements of the power supply.

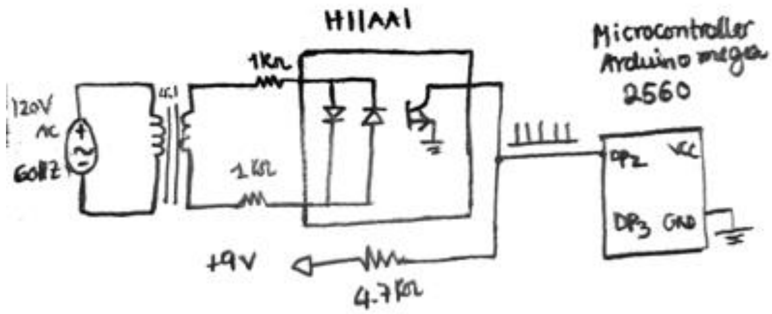

Figure 11: Zero-crossing detection circuit derived from Loflin's model

5.1-1 Step-Down Transformer

A step-down transformer is used in the zero-crossing detection circuit to transfer power from the 120VAC supply to the input of the H11AA1 optocoupler while isolating the AC source to ensure safety. There is no physical or electrical connection between the primary and secondary windings of the transformer and the link is done by magnetism. The transformer works as follows:

1. The input voltage pushes current into the primary coils of the transformer
2. The primary current creates a magnetic flux
3. The magnetic flux induces a voltage on the secondary coils
4. The secondary voltage pushes current out of the secondary coils.

The transformer used in the power supply is shown in figure 12. It has a 4:1 ratio and steps down the 120VAC supply to 30.5V RMS.

Figure 12: Transformer used to step down the 120VAC supply to 30.5V RMS

5.1-2 H11AA1 Optocoupler

An optocoupler is a semiconductor device that isolates electrical circuits. Unlike the step-down transformer that passes electrical signals through magnetism, the optocoupler contains LEDs that emit infrared light, which is detected by a photosensor to produce an AC signal at the optocoupler's output. The light emitted by the LEDs is proportional to the current going through the device, and if the light is obstructed, the optocoupler turns off [7].

The optocoupler used in the zero-crossing detector circuit is an H11AA1 model with an AC input and a phototransistor output. When the AC waveform crosses the time axis, the collector of the phototransistor goes HIGH and gives a brief pulse between 0 and 9V to digital pin 2 of the microcontroller. Under no circumstances should the 30.5V RMS reach the input pin of the microcontroller, thus the optocoupler is used to isolate the voltage at the secondary side of the step-down transformer. The optocoupler has also been tested and there is a 5300V RMS isolation voltage on pins 1 and 2. However,

the isolation voltage does not get transferred to the collector of the phototransistor. Consequently, the isolation voltage will not reach the input pin of the microcontroller. See figure 13 for the H11AA1 optocoupler's internal construction.

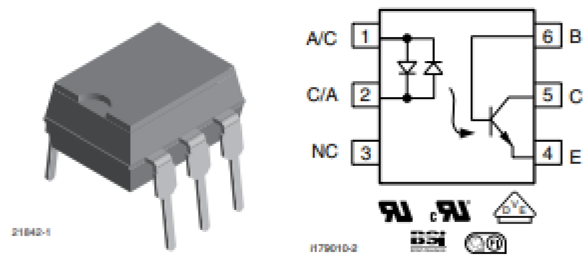

Figure 13: H11AA1 Optocoupler

5.1-3 Interrupt Service Routine

Each time the zero-crossing points occur, the optocoupler applies a pulse to the input pin of the microcontroller. This pulse serves as a hardware interrupt, and it prompts the Arduino program to execute a function called an Interrupt Service Routine or ISR. The ISR contains crucial information regarding the start-time and width of the output pulse that triggers the TRIAC into conduction. The start-time corresponds to the firing angle of the TRIAC, which also regulates the amount of RMS current that goes to the circuit breaker. The output pin of the optocoupler (pin 5) is connected to digital pin 2 of the microcontroller, and digital pin 13 is connected to the TRIAC's gate.

To comprehend how the Interrupt Service Routine controls the TRIAC's firing angle, consider the code shown in figure 14. The TRIAC is set to trigger at 4167 microseconds or 90 degrees from the zero-crossing, and this value can be adjusted using the first "DelayMicroseconds" command located in the *void loop ()* section. The width of the output pulse applied to the TRIAC's gate is indicated by the subsequent

"DelayMicroseconds" command which is set to 1500 microseconds. Once the ISR is executed, the TRIAC fires at 4.16 ms as shown in figure 15, which is equivalent to 90 degrees. The voltage at the TRIAC's output can be calculated using the equation Vload = $\sqrt{}$ (vpeak *(2π-2φ + sin(2φ) / 4π)) where Vpeak corresponds to the peak voltage of the AC input and φ the trigger angle of the TRIAC. For a 90-degree firing angle, the voltage at the TRIAC's output is 21.78V RMS.

```
 void TRIAC(){
// delay start of output from zerocrossing circuit
// pulse from input pulse (which generated IRQ)

   sei();//interrupts are off by default and must be enabled using sei()function
     //delay(5);
     delayMicroseconds(4167);// delay start of the output
     cli();//disable interrupt

   //
    // set output high to trigger triac
    digitalWrite(13,HIGH); //pin 13 equal to the state value
    // pause

       // set on width of output pulse
     sei();//enable interrupt
     delayMicroseconds(1500);//width of the output pulse
     cli();//disable interrupt


    //bring pin low again+
    digitalWrite(13, LOW); //pin 13 equal to the state value
 }
```

Figure 14: Interrupt Service Routine

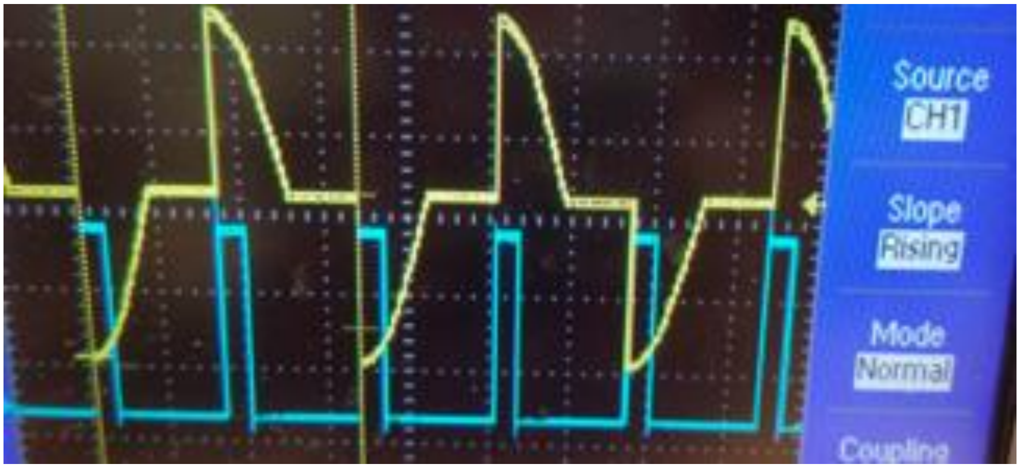

Figure 15: TRIAC Conducting waveform and output pulse triggered at 4.16 ms or 90 degrees

One cycle of the input AC waveform begins at 0 degrees and ends at 360 degrees and the TRIAC can be triggered anywhere along the waveform. The time values indicated on the sinusoid are important for setting up the trigger angle of the TRIAC in the ISR.

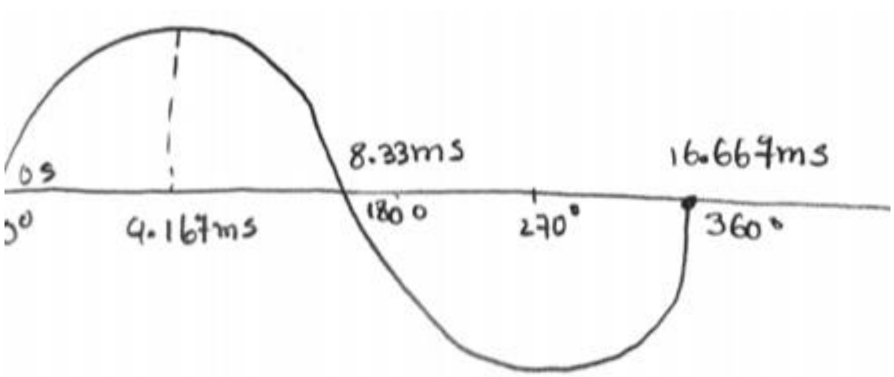

Figure 16: Time values in milliseconds with their respective TRIAC trigger angles

5.1-4 Arduino Mega 2560

The Arduino Mega 2560 is a microcontroller board with 54 digital I/O pins and 16 analog inputs [8]. The microcontroller is powered by a PC through a USB cable, and digital pin 2 is connected to the collector of the H11AA1 optocoupler to receive the interrupt pulse. Meanwhile, digital pin 13 is connected to pin 3 of the 2N6071A TRIAC to apply the trigger pulse. The microcontroller shares a common ground between optocouplers H11AA1 and H11A1, and a 2N3904 transistor. See the figure below for the microcontroller board:

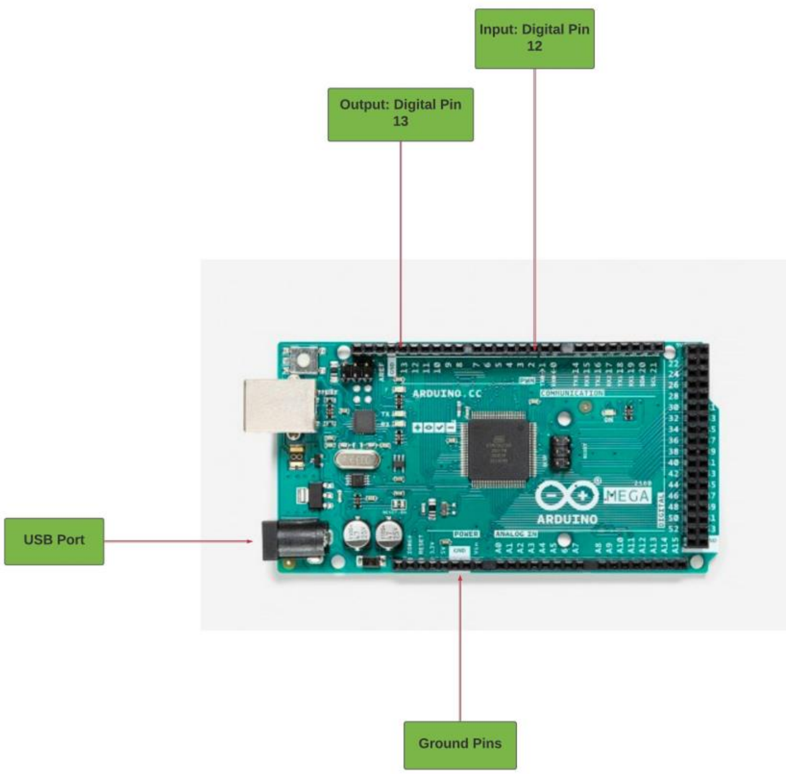

Figure 17: Arduino Mega 2560 microcontroller board with indicated input and output pins used

5.2 Isolation Circuit

The isolation circuit shown in figure 10 separates the 120VAC supply from digital pin 13 of the Arduino board through an H11A1 optocoupler that has an isolation voltage

rated at 4420V RMS. The H11A1 optocoupler contains a single LED that emits light to a phototransistor whose collector is connected to a 9V battery. The isolation circuit also contains a 2N3904 NPN silicon transistor with its base connected to the TRIAC's gate. In addition, there is a 0.507K ohms current-limiting resistor at the optocoupler's input to prevent any unwanted voltages from damaging the microcontroller. See Appendices G and I for the H11A1 optocoupler and 2N3904 transistor datasheets.

5.3 Computer-Set Current Controller

The computer-set current controller is designed to regulate the RMS current provided to the circuit breakers and to allow the PC to store the current values read by the analog-to-digital converter. The computer-set current controller is not fully implemented due to the challenges posed by the toroidal transformer. After connecting the transformer to the TRIAC circuit, the conduction waveforms generated for different trigger angles were different from the ones that we obtained before adding the transformer. However, the TRIAC circuit shown in figure 19 functions properly without the toroidal transformer.

5.3-1 Toroidal transformer

The toroidal transformer has a 10:1 ratio and it is used to step down the 120VAC to a safer voltage level. It contains a single ferromagnetic core around which the primary and secondary coils are wrapped around. I used the shunt's rated values along with the UL 489 test standard suggested by the Underwriters Laboratories to compute the primary and secondary voltage and current values. See Appendix A for a step-by-step calculation of the primary and secondary voltage and current values.

5.3-2 TRIAC

A TRIAC, also known as a Triode Alternating Current, is a four-layer semiconductor device of the order n-p-n-p or p-n-p-n. The TRIAC is used for bidirectional current control because it contains two thyristors connected in reverse parallel, which makes it excellent for AC applications. The main difference between a TRIAC and a Silicon Controlled Rectifier or SCR is that the TRIAC can control both the positive and negative half cycles of an AC waveform whereas an SCR is unidirectional. The TRIAC also contains three terminals which are the gate, Main Terminal 1 or MT1, and Main Terminal 2 or MT2. Lastly, the TRIAC operates by latching, meaning that it turns ON when a single pulse is applied to its gate. Once the TRIAC is in forward conducting mode, it cannot be turned OFF by simply removing the current at the gate. Thus, the current shared between Main Terminal 1 and Main Terminal 2 must be reduced to zero to switch off the TRIAC [9].

Since the TRIAC is made of two thyristors as shown in figure 18, the device sometimes fires asymmetrically due to the differences between the two halves. The less asymmetrical the TRIAC fires, the more harmonics are generated in the system [10]. Thus, the TRIAC circuit discussed in the Design Alternatives section contains a DIAC or Diode AC switch that is connected in series with the TRIAC's gate to ensure a more symmetrical firing. Figure 18 and figure 19 depict the internal construction of the TRIAC and the output circuit where the load is replaced by a 470 ohms resistor:

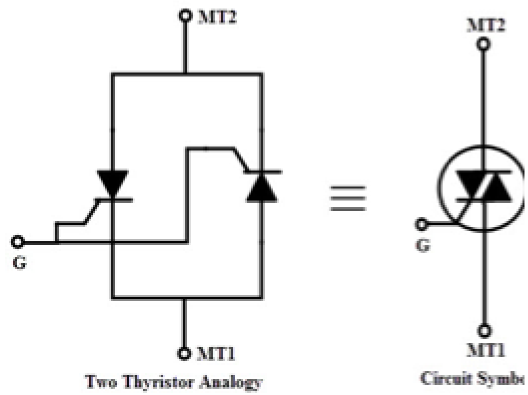

Figure 18: Internal construction of a TRIAC [9]

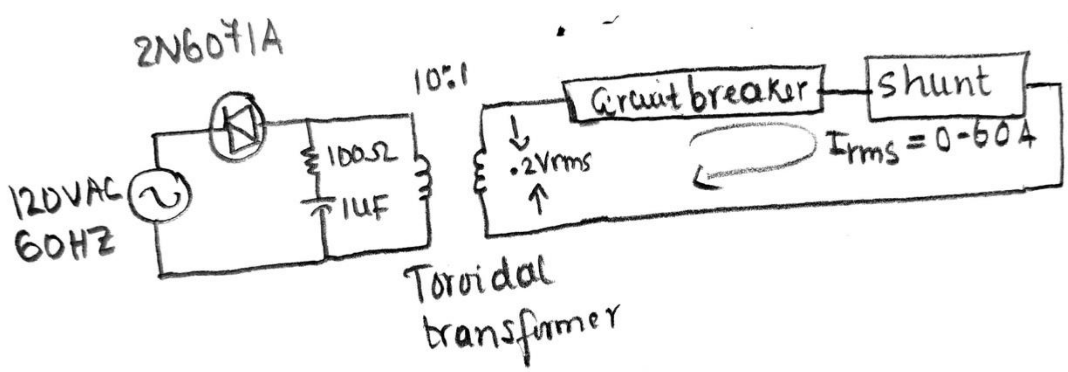

Figure 19: Computer-set current Controller with transient suppression at the primary of the toroidal transformer

The TRIAC used in the power supply is a 2N6071A model with a 10mA trigger current and a 2.5V trigger voltage. The 2N6071A model operates at a 15mA holding current, which is the minimum current needed for the TRIAC to remain in the ON state. Each time the optocoupler detects the zero-crossing points, the Arduino board applies a 9V pulse to the gate of the TRIAC, which turns it ON. Depending on the test current set by the PC, the firing angle of the TRIAC either increases or decreases to regulate the amount of current applied to the circuit breakers. The load voltage at the output of the TRIAC also varies depending on the present firing angle, and this voltage can be

calculated using the equation **$Vload = \sqrt{(vpeak * (2\pi - 2\varphi + \sin(2\varphi) / 4\pi))}$** where Vpeak corresponds to the peak voltage of the AC input and φ the trigger angle of the TRIAC.

5.3-3 Shunt

The shunt and circuit breaker under test are connected in series at the secondary side of the toroidal transformer. I assumed an ideal scenario for the transformer; therefore, the input and output power are both equal to 60 W. We also assumed a zero-resistance value for the circuit breaker, and the wires used throughout the power supply have a small resistance. The RMS current is dissipated across the shunt, which has a 0.0033 ohms resistance. The resistance of the shunt is small to produce a low voltage of 0.2Vrms at the secondary of the transformer. Since the circuit breaker is tripped by heating, then the RMS voltage can be small to create a larger RMS current.

5.3-4 Analog-To-Digital-Converter

The A/D converter used to read the current across the shunt is the ADALM2000, a USB powered tool with a built-in oscilloscope and function generator. The ADALM2000 works with a software graphical tool called Scopy that enables the user to obtain graphical data. The output of the A/D converter is connected to the computer through a USB cable, and it reads the current across the shunt by discretizing the continuous voltage signal. The values are stored in the PC to plot current vs time graphs to illustrate the circuit breaker's performance.

6. Preliminary Testing Results

The H11AA1 optocoupler successfully detected the zero-crossing points of the AC input sinusoid. As shown in figure 20, the optocoupler's output waveform is perfectly aligned with the zero-crossing points, which means that an interrupt is generated each time the input sinusoid crosses the time axis. To ensure a proper operation of the ISR, I manually altered the firing angle of the TRIAC in the code and plotted the corresponding TRIAC conduction waveforms. The sinusoid shown in figure 16 played an important role in determining the firing angles and their corresponding time values. In figure 21, the TRIAC is fired at 0 ms or 0 degrees, which means that 100% of the RMS current is delivered to the load. But in figure 22, the TRIAC is triggered at 3 ms or approximately 60 degrees, thus less current is delivered to the load. Overall, the greater the firing angle of the TRIAC, the lower the RMS current delivered to the circuit breaker and vice versa. See the figures below for the H11AA1 optocoupler's output waveform and the TRIAC conduction waveforms generated at 0 ms and 3 ms, respectively.

Figure 20: AC sinusoid and H11AA1 optocoupler output generated at the zero-crossing points

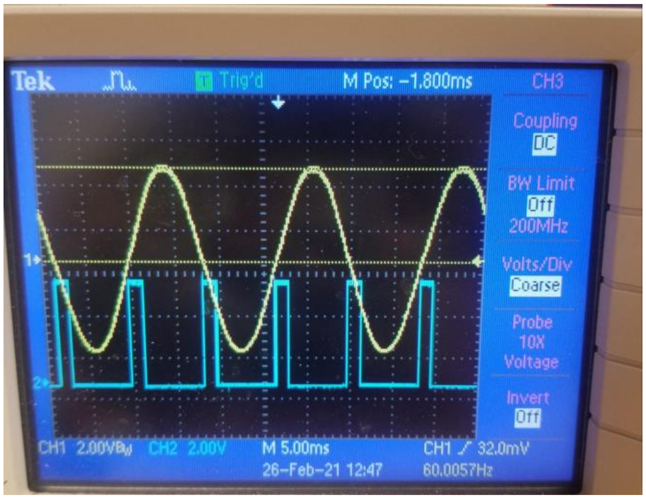

Figure 21: TRIAC waveform and output pulse generated at 0 ms or 0 degrees

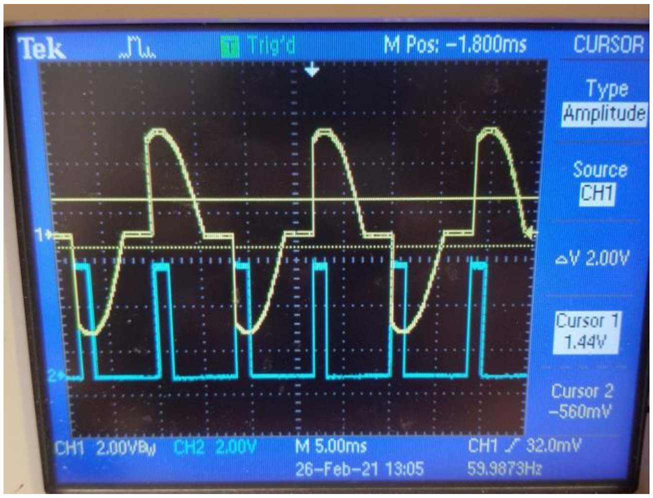

Figure 22: TRIAC waveform and output pulse generated at 3 ms or 60 degrees

6.1 Recommendations & Future Work

The zero-crossing detection and isolation circuits are fully implemented and work as expected. However, the toroidal transformer must be added to the computer-set current controller to complete the construction of the power supply. One solution is to replace the toroidal transformer with another one of the same ratio and add the TRIAC circuit to the transformer's primary side. The TRIAC also needs a heat sink since the current delivered to the load can increase up to 60A RMS. Once the toroidal transformer is added, the ADALM2000 will be connected across the shunt to read the current values,

which will be stored on the computer-controller. Lastly, the UL 489 test procedure will be implemented using the power supply to determine the performance of the circuit breakers. Then, a MATLAB file will be created to plot current vs. time graphs that illustrate the breakers' response to the test conditions. Once the automated system is fully operational, it can be used by consumers who are interested in learning about the trip performance of residential circuit breakers.

7. Production Schedule

In the fall, I spent a great deal of time researching the different components that make up the power supply, with a strong emphasis on the TRIAC and the procedure for testing thermal circuit breakers. I also researched the problem definition and developed a block-diagram containing the main components of the automated system. Between week five and week eight of the fall trimester, I worked with Professor Hedrick to design the alternative TRIAC circuit on Multisim, and the process took longer than expected. While it was important to devise a schedule for the fall trimester, I had difficulty keeping up with the deadlines that were set for each task as a result of being too ambitious. However, I have made significant progress during the winter term and completed the zero-crossing detection circuit and the Interrupt Service Routine. I ran into some difficulties with the ISR since the TRIAC circuit was not responding to the output pulse of the microcontroller. For example, I manually altered the firing angle of the TRIAC in the ISR, but the test curves generated on the oscilloscope showed that the TRIAC was not responding to those changes. Thus, I added the commands *sei ()*; and *cli ();* in the ISR, and each command respectively enabled and disabled the interrupt. I changed the width of the output pulse to 1500 microseconds, and these modifications resulted in a

successful operation of the Interrupt Service Routine. Due to time constraints, the computer-set current controller is not fully implemented, and the toroidal transformer and shunt must be added so that the ADALM2000 analog-to-digital converter can read the current values across the shunt. Lastly, a MATLAB file must be created to display the current measurements stored by the PC and to graphically display the circuit breakers' response to the applied current. Below is a Gantt chart depicting the timeline of the project:

Figure 23: Timeline of the tasks completed during the fall and winter trimesters

8. Cost Analysis

The table below shows a list of the components used to build the power supply including the materials that were already provided by my thesis supervisor and the ECBE department. Note that multiple of the same items were purchased to minimize any delays caused by the lengthy shipment of some of the parts listed. The total cost listed in table 4 excludes the parts that were provided by Professor Hedrick and the ECBE department. Overall, the estimated cost to build a replica of the power supply is $230, and this amount includes the cost of the items that were already provided.

Parts	Quantity purchased	Part Number	Supplier	Unit Cost	Subtotal
Step-down transformer	Provided by ECBE department	-----------	-----------	-----------	-----------
1k ohms resistor	Provided by ECBE department	-----------	-----------	-----------	-----------
H11AA1 optocoupler	5	751-1276-5-ND	Digikey	$ 1.31	$6.55
Arduino Mega 2560	Provided by Prof. Hedrick	-----------	-----------	-----------	-----------
9v DC battery	Provided by Prof. Hedrick	-----------	-----------	-----------	-----------
H11A1 optocoupler	10	751-1273-5-ND	DigiKey	$0.73	$6.44
507k ohms resistor	Provided by ECBE department	-----------	-----------	-----------	-----------
1.4k ohms resistor	Provided by ECBE department	-----------	-----------	-----------	-----------
2N3904 transistor	50	2156-2N3904-ON-	Digikey	$1.76/10 items	$8.80

		ND			
2n6071A TRIAC	20	2156-2N6071A-ON-ND	Digikey	$0.12	$2.4
Toroidal transformer	Provided by Prof. Hedrick	-----------	-----------	-----------	-----------
0.003 ohms shunt	Provided by Prof. Hedrick	-----------	-----------	-----------	-----------
ADALM 2000	Provided by Prof. Hedrick	-----------	-----------	-----------	-----------
Amount Spent					$24.19

Table 3: Cost breakdown of parts purchased

9. User's Manual

9.1 Zero-Crossing Detector Circuit

Connect pins 1 and 2 of the H11AA1 optocoupler to the secondary side of the step-down transformer through two 1k ohms resistors. Pin 4 is the collector of the phototransistor, and it must be connected to a 4.7k ohms limiting resistor, which is connected to digital pin 2 of the microcontroller and a 9V DC supply. Lastly, Pin 5 of the optocoupler or the emitter of the phototransistor goes to common ground. Note that the light emitted by the back-to-back LEDs that are connected to pins 1 and 2 of the optocoupler, is proportional to the current flowing through the device. A light connection is used to isolate the microcontroller from the 30.5Vrms supply since the microcontroller operates at 5V.

9.2 Microcontroller & Isolation Circuit

Connect the microcontroller to common ground by using any of the ground pins of the Arduino Mega 2560. The microcontroller operates at 5V and is powered by a USB cable that is connected to the PC. Then, connect a 500 ohms limiting-resistor to digital pin 13 of the microcontroller and to pin 1 of the H11a1 optocoupler. Moreover, connect pin 2 and pin 4 of the H11A1 optocoupler to common ground. Lastly, the collector of the H11A1 optocoupler is connected to the 9V supply and to the base of the 2N3904 transistor, whose collector goes to the gate of the TRIAC.

9.3 Arduino Code

See appendix D for setting up the Interrupt Service Routine.

9.4 TRIAC and Computer-Set Current Controller

Place the TRIAC at the primary of the toroidal transformer with main terminal 1 connected to the 120VAC supply and the gate connected to the base of the 2N3904 transistor. On the secondary side of the toroidal transformer, place the circuit breaker under test in series with the 0.003 ohms shunt, and connect the ADALM2000 across the shunt and to the PC.

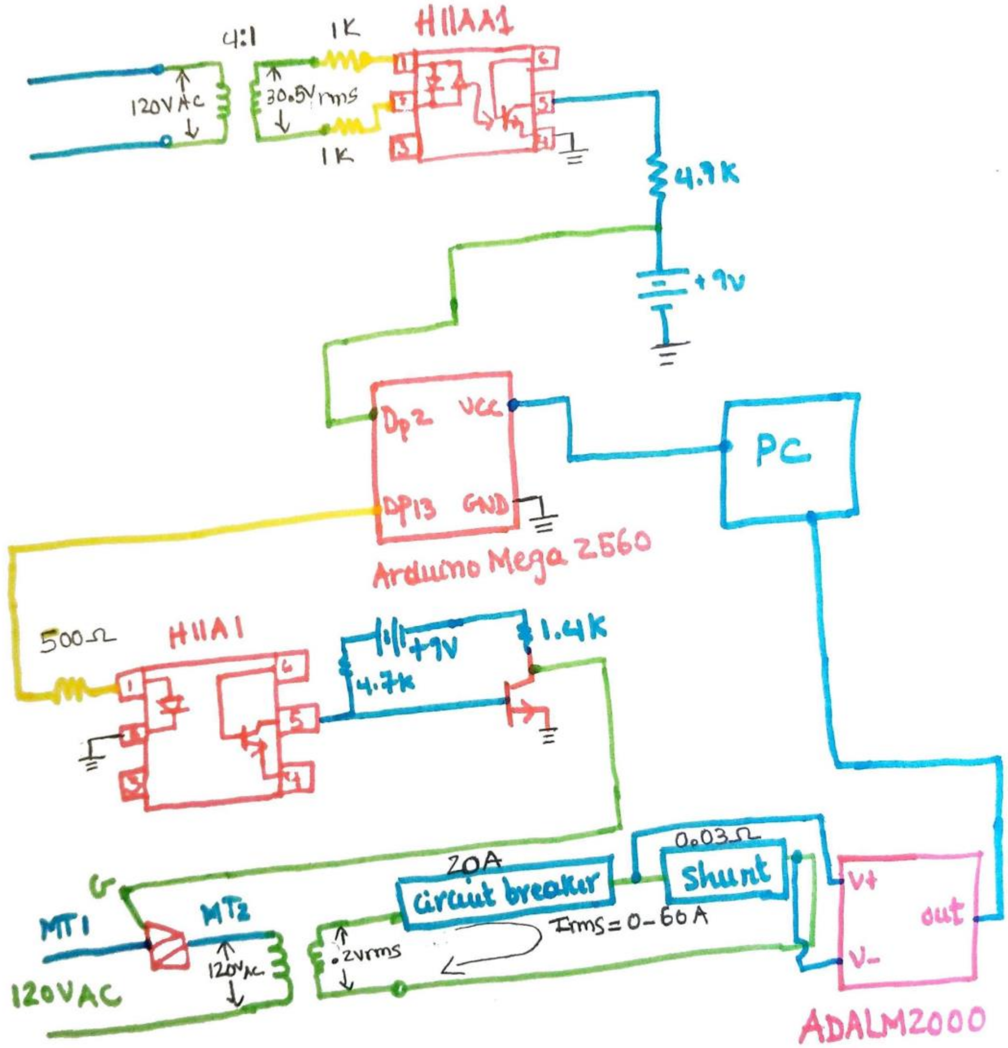

Figure 24: Power Supply

10. Discussion & Conclusion

The National Fire Association reported a considerable number of domestic fires caused by circuit breaker malfunctions between 2012 and 2016. Professor Jesse Aronstein, a consulting engineer who researched the link between circuit breaker failures and estimated fire losses, discovered that FPE Stab-Lok breakers, which are installed in many homes across the United States, failed at an abnormally high rate due to overheating and trip failures. Therefore, the Circuit Breaker Failure Analysis System is a quick and efficient tool for testing domestic thermal breakers that are currently installed in electrical circuits.

The goal of this capstone project is to develop a computer-controlled power supply capable of delivering a variable RMS current to the circuit breakers under test. The automated system will follow the UL489 test criterion, which is a mandated procedure put in place by the Underwriters Laboratories for evaluating residential circuit breakers. The circuit breakers under test will be classified as defective if they trip beyond the 135% threshold whereas operational circuit breakers trigger at 100 % or 135% of the breakers' current rating.

The power supply is expected to output 0-60A RMS to the circuit breakers, thus safety is a major concern. To prevent instances of electrical shock, a 4:1 step-down transformer is used to bring down the 120VAC supply to 30.5Vrms, and the system is fully automated such that the user is only required to initiate a test cycle through a computer-controller. The heat generated by the variable RMS current causes the circuit breakers to trip, and that heat is dissipated across a 0.0033 ohms shunt connected to an ADALM2000 A/D converter. Following the UL489 test procedure, the user can

determine the trip performance of the circuit breaker through the test curves generated on the computer.

The zero-crossing detector and TRIAC trigger circuits are fully implemented and they produced satisfactory results. However, there is more work to be done. The zero-crossing detection circuit successfully identifies the points where the AC input crosses the time axis, as shown in figure 20. The interrupt Service Routine generates an output pulse on the TRIAC’s gate each time the zero crossings occur, and the trigger angles of the TRIAC were manually adjusted in the code to test the efficiency of the TRIAC circuit and the ISR. For every trigger angle, the voltage at the output of the TRIAC circuit can be calculated using the equation **$Vload = \sqrt{(vpeak *(2\pi-2\varphi + \sin(2\varphi) / 4\pi))}$**, and the firing angles are analogous to the time values indicated in figure 16. Lastly, there is an inverse relationship between the TRIAC’s trigger angle and the variable RMS current at the output of the power supply. More specifically, the greater the firing angle, the smaller the current, and vice versa.

In conclusion, the automated system is a useful tool for understanding circuit breaker testing, and it is simple enough to be utilized by engineers or hobbyists who are interested in the topic. To finalize the power supply, the toroidal transformer and shunt must be added to the TRIAC circuit. Lastly, an important question to consider is whether the power supply can accommodate circuit breakers with current ratings that are greater than 40A. Then, heat sinks will be added to the TRIAC circuit to prevent it from overheating.

This capstone project has taught me transferable skills such as time management and the ability to conduct individual research. More important, I learned to document

my research findings, which became useful for revisiting unfamiliar concepts throughout the term.

References

[1] Richard Campbell, “Home Electrical Fires,” in *National Fire Protection Association*, March 2019, pp. 1.

[2] Care Labs, ‘What Is Circuit Breaker Testing and How Is It Done?” https://carelabz.com/what-circuit-breaker-testing-how-circuit-breaker-testing-done/.

[3] Jesse Aronstein, Richard Lowry, “Estimating Fire Losses Associated with FPE Stab-Lok Circuit Breaker Malfunction,” IEEE Transactions on Industry Applications, Jan/Feb 2012, pp 1-5.

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[7] Megan Tug, *What Is an Optocoupler and How It Works*, www.jameco.com/Jameco/workshop/Howitworks/what-is-an-optocoupler-and-how-it-works.html#:~:text=An%20optocoupler%20.

[8] *Getting Started with Arduino Mega 2560*, Arduino cc, 2018.

[9] Administrator, et al. “TRIAC: A Beginner's Guide: Symbol, Working, Applications.” *Electronics Hub*, 31 July 2019, www.electronicshub.org/triac/.

[10] Poole, Ian. "What Is Triac: AC Switch." *Electronics Notes*, Electronics Notes, 11 Feb. 2020, www.electronics-notes.com/articles/electronic_components/scr/what-is-a-triac.php.

Appendices

Appendix A: Calculations for RMS current and voltages at the primary and secondary sides of the toroidal transformer

- The shunt is rated at 100 mV and 30 A. Therefore, we can find the resistance at the shunt using Ohm's Law:

$$V = I * R$$
$$R = V/I = 100mV/30\,A = 0.00333\Omega$$

- The highest current rating of the circuit breaker to be tested is 40 A. According to the UL 489 test standard developed by Underwriter's Laboratory Inc., any circuit breaker that is able to sustain 150% of its current rating is defective. Therefore, taking 150% of 40 A is equal to 60 A. The current at the secondary side of the toroidal transformer is 60 A, RMS.

$$P_{shunt} = P_{circuit\ breaker}$$
$$P_{shunt} = I^2_{RMS} * R_{shunt} = (60)^2 * (0.00333) = 12\ \text{W}$$

- At the secondary side of the toroidal transformer, we have:

$$I_{RMS} = 60A$$

- Since $Pshunt$ = 12 W, then we can compute the power at the secondary side:

$$P = I_{RMS} * V_{secondary}$$
$$V_{secondary} = P/\,I_{RMS} = 12W/60A \approx 1\,V$$

- The power at the secondary side of the transformer is equal to:

$$P = I * V = (60A) * (1V) = 60\,W$$

- Since we are assuming an ideal transformer, the power at the primary side is also 60 W. We know that the input to CSACS is 120V AC. Therefore, we can find the current at the primary:

$$I_{RMS} = P/V_{rms} = 60W/(120V_{RMS}) = 0.5\,A.$$

Appendix B: Image of the shunt placed at the secondary of the toroidal transformer

Figure 25: Shunt used as a load. The shunt is rated at 10 mV, 30 A, 0.0033Ω

Appendix C: Toroidal transformer placed in computer-set current controller

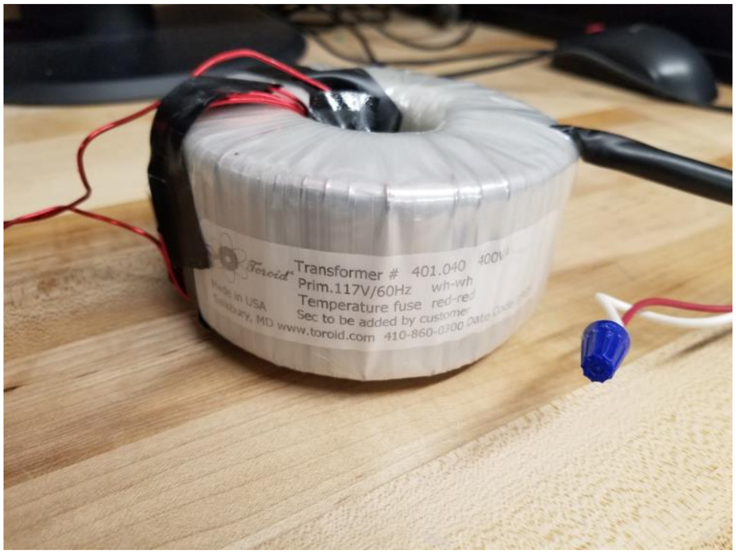


Figure 26: Toroidal transformer

Appendix D: Full Arduino Code containing Interrupt Service Routine

```
byte pin = 2; //define interrupt to pin 2.
volatile int state = LOW; //to make sure that variables shared between the ISR and the main program are
updated correctly, we declare them as volatile.
```

```
void setup() {
  // put your setup code here, to run once:

  attachInterrupt(digitalPinToInterrupt(pin),TRIAC,RISING);
  /*Note that the attachInterrupt command tells the processor which pin to monitor, the ISR, and when to
trigger the interrupt
   digitalPinToInterrupt(pin)= attach the interrupt at pin 2.
  The Interrupt Service Routine (ISR) is defined as TRIAC.
   the Mode is defined as Rising (to trigger the interrupt when pin 2 goes from LOW to HIGH)
   */

  pinMode (13, OUTPUT); //Define pin 13 as output

  digitalWrite(13,LOW); /*Write a low value or a 0 to the output pin.
                        Recall that pin 3 is configured as an outpin pin. Then the voltage on pin 3 will be set to 0v
because pin 3 was assigned a low value.
                        Since there is no voltage on pin 3, then the TRIAC is not triggered
                        */

}

void loop() {
  // put your main code here, to run repeatedly:

}

/*
 * ISR function triggered on zero crossing
 *
 */

 void TRIAC(){
// delay start of output from zero crossing circuit
// pulse from input pulse (which generated IRQ)

   sei();//interrupts are off by default and must be enabled using sei()function
     //delay(5);
     delayMicroseconds(4167);// delay start of the output
     cli();//disable interrupt

   //
    // set output high to trigger triac
    digitalWrite(13,HIGH); //pin 13 equal to the state value
    // pause

       // set on width of output pulse
     sei();//enable interrupt
     delayMicroseconds(1500);//width of the output pulse
```

```
   cli();//disable interrupt


  //bring pin low again
  digitalWrite(13, LOW); //pin 13 equal to the state value
}
```

Appendix E: ADALM2000 pinout

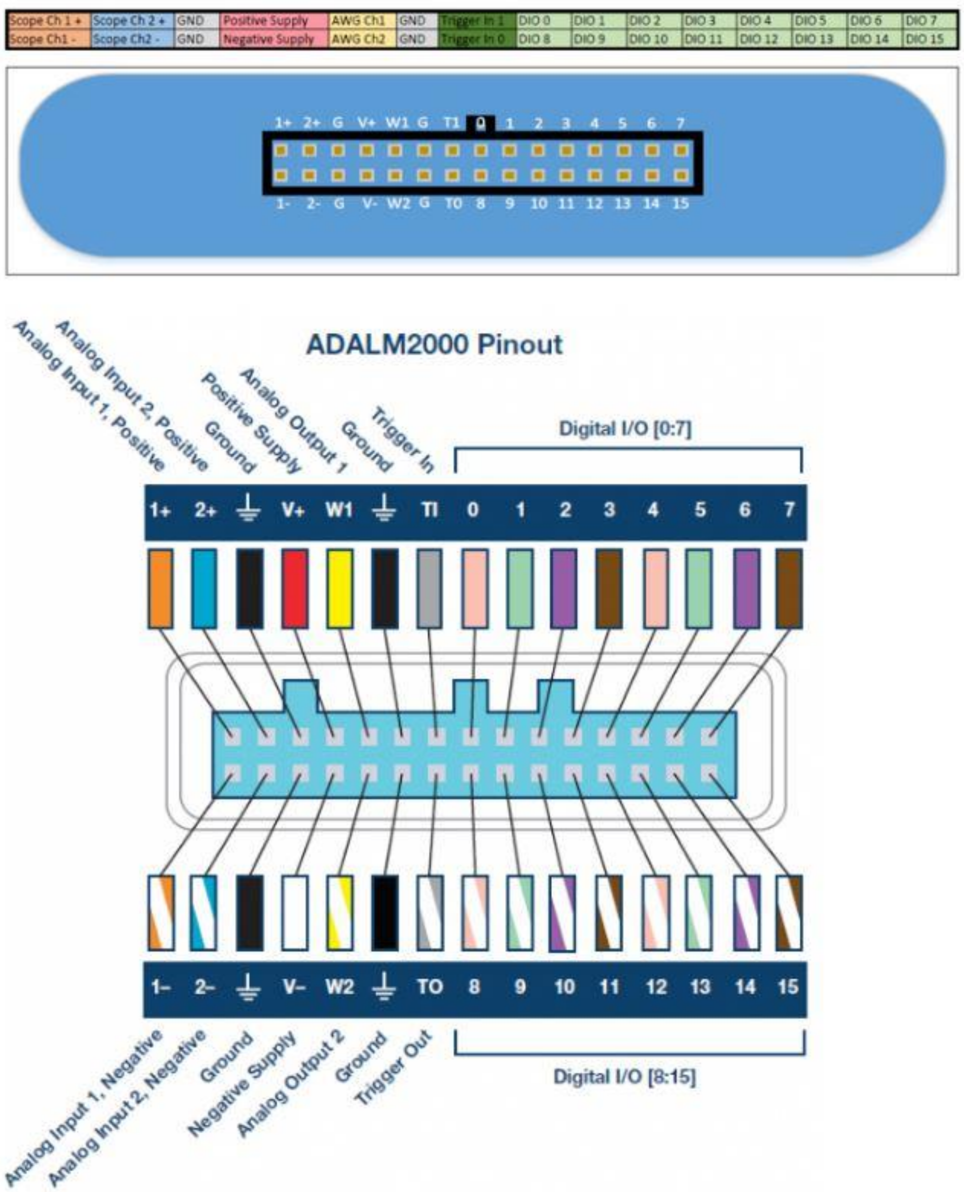


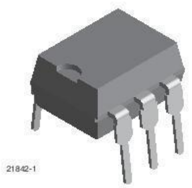
Figure 27: ADALM200 A/D converter pinout

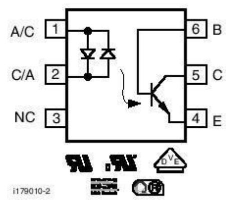
Appendix F: H11AA1 Optocoupler datasheet

H11AA1

Vishay Semiconductors

Optocoupler, Phototransistor Output, AC Input, with Base Connection





FEATURES

- AC or polarity insensitive input
- Built-in reverse polarity input protection
- I/O compatible with integrated circuits
- Industry standard DIP package
- Isolation test voltage: 5300 V_{RMS}
- Compliant to RoHS Directive 2002/95/EC and in accordance to WEEE 2002/96/EC

RoHS COMPLIANT

DESCRIPTION

The H11AA1 is a bi-directional input optically coupled isolator consisting of two inverse parallel gallium arsenide infrared LEDs coupled to a silicon NPN phototransistor in a 6 pin DIP package. The H11AA1 has a minimum CTR of 20 %, a CTR symmetry of 1:3 and is designed for applications requiring detection or monitoring of AC signals.

APPLICATIONS

- Telephone line detection
- AC line motor
- PLC
- Instrumentation

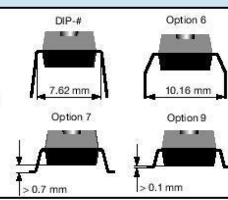
AGENCY APPROVALS

- UL1577, file no. E52744 system code H, double protection
- CSA 93751
- BSI IEC 60950; IEC 60065
- DIN EN 60747-5-2 (VDE0884)/DIN EN 60747-5-5 (pending), available with option 1
- FIMKO

ORDERING INFORMATION

H 1 1 A A 1 - X 0 0 # T

PART NUMBER (H11AA1) — PACKAGE OPTION (X00#) — TAPE AND REEL (T)



AGENCY CERTIFIED/PACKAGE	CTR (%)
UL, cUL, BSI, FIMKO	**≥ 20**
DIP-6	H11AA1
DIP-6, 400 mil, option 6	H11AA1-X006
SMD-6, option 7	H11AA1-X007T [(1)]
SMD-6, option 9	H11AA1-X009T [(1)]
VDE, UL, cUL, BSI, FIMKO	**≥ 20**
DIP-6	H11AA1-X001

Note

- Additional options may be possible, please contact sales office.

(1) Also available in tubes; do not add T to end.

Document Number: 83608
Rev. 1.7, 23-Feb-11

For technical questions, contact: optocoupleranswers@vishay.com

www.vishay.com
1

H11AA1

Vishay Semiconductors Optocoupler, Phototransistor Output, AC Input, with Base Connection

ABSOLUTE MAXIMUM RATINGS (T_{amb} = 25 °C, unless otherwise specified)				
PARAMETER	**TEST CONDITION**	**SYMBOL**	**VALUE**	**UNIT**
INPUT				
Forward continuous current		I_F	± 60	mA
Power dissipation		P_{diss}	100	mW
Derate linearly from 25 °C			1.3	mW/°C
OUTPUT				
Power dissipation		P_{diss}	200	mW
Derate linearly from 25 °C			2.6	mW/°C
Collector emitter breakdown voltage		BV_{CEO}	30	V
Emitter base breakdown voltage		BV_{EBO}	5	V
Collector base breakdown voltage		BV_{CBO}	70	V
COUPLER				
Isolation test voltage (RMS)	Between emitter and detector, referred to standard climate 23 °C/50% RH, DIN 50014	V_{ISO}	5300	V_{RMS}
Creepage distance			≥ 7	mm
Clearance distance			≥ 7	mm
Comparative tracking index	per DIN IEC 112/VDE 0303, part 1	CTI	175	
Isolation resistance	V_{IO} = 500 V, T_{amb} = 25 °C	R_{IO}	≥ 10^{12}	Ω
	V_{IO} = 500 V, T_{amb} = 100 °C	R_{IO}	≥ 10^{11}	Ω
Storage temperature range		T_{stg}	- 55 to + 150	°C
Operating temperature range		T_{amb}	- 55 to + 100	°C
Lead soldering time at 260 °C		T_{sld}	10	s

Note

- Stresses in excess of the absolute maximum ratings can cause permanent damage to the device. Functional operation of the device is not implied at these or any other conditions in excess of those given in the operational sections of this document. Exposure to absolute maximum ratings for extended periods of the time can adversely affect reliability.

ELECTRICAL CHARACTERISTCS (T_{amb} = 25 °C, unless otherwise specified)						
PARAMETER	**TEST CONDITION**	**SYMBOL**	**MIN.**	**TYP.**	**MAX.**	**UNIT**
INPUT						
Forward voltage	I_F = ± 10 mA	V_F		1.2	1.5	V
OUTPUT						
Collector emitter breakdown voltage	I_C = 1 mA	BV_{CEO}	30			V
Emitter base breakdown voltage	I_E = 100 µA	BV_{EBO}	5			V
Collector base breakdown voltage	I_C = 100 µA	BV_{CBO}	70			V
Collector emitter leakage current	V_{CE} = 10 V	I_{CEO}		5	100	nA
COUPLER						
Collector emitter saturation voltage	I_F = ± 10 mA, I_C = 0.5 mA	V_{CEsat}			0.4	V

Note

- Minimum and maximum values were tested requierements. Typical values are characteristics of the device and are the result of engineering evaluations. Typical values are for information only and are not part of the testing requirements.

CURRENT TRANSFER RATIO (T_{amb} = 25 °C, unless otherwise specified)						
PARAMETER	**TEST CONDITION**	**SYMBOL**	**MIN.**	**TYP.**	**MAX.**	**UNIT**
DC current transfer ratio	I_F = ± 10 mA, V_{CE} = 10 V	CTR_{DC}	20			%
Symmetry (CTR at + 10 mA)/(CTR at - 10 mA)			0.33	1	3	

For technical questions, contact: optocoupleranswers@vishay.com
Document Number: 83608
Rev. 1.7, 23-Feb-11

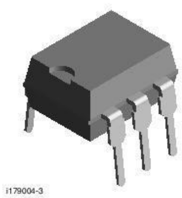
Appendix G: H11A1 optocoupler datasheet

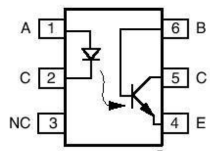
VISHAY. www.vishay.com

H11A1

Vishay Semiconductors

Optocoupler, Phototransistor Output, With Base Connection





FEATURES

- Interfaces with common logic families
- Input-output coupling capacitance < 0.5 pF
- Industry standard dual-in line 6-pin package
- Isolation rated voltage 4420 V_{RMS}
- Material categorization: for definitions of compliance please see www.vishay.com/doc?99912

RoHS COMPLIANT

DESCRIPTION

The H11A1 is an industry standard single channel phototransistor coupler.

Each optocoupler consists of gallium arsenide infrared LED and a silicon NPN phototransistor.

The isolation performance is accomplished through Vishay double molding isolation manufacturing process. Compliance to DIN EN 60747-5-5 partial discharge isolation specification is available is by ordering option 1.

These isolation processes and the Vishay ISO9001 quality program results in the highest isolation performance available for a commercial plastic phototransistor optocoupler.

The devices are available in lead formed configuration suitable for surface mounting and are available either on tape and reel, or in standard tube shipping containers.

Note

- Designing with data sheet is covered in Application Note 45.

APPLICATIONS

- AC mains detection
- Reed relay driving
- Switch mode power supply feedback
- Telephone ring detection
- Logic ground isolation
- Logic coupling with high frequency noise rejection

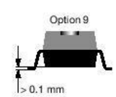
AGENCY APPROVALS

- UL1577, file no. E52744, double protection
- cUL
- DIN EN 60747-5-5 (VDE 0884-5), available with option 1
- BSI EN 62368-1
- CSA 93751
- CQC: GB 8898-2011, GB 4943.1-2011
- FIMKO

ORDERING INFORMATION

H 1 1 A # - X 0 0 # X

PART NUMBER — PACKAGE OPTION — TAPE AND REEL



AGENCY CERTIFIED / PACKAGE	CTR (%)
UL, cUL, BSI, CSA, FIMKO, CQC	**> 50**
DIP-6	H11A1
SMD-6, option 9	H11A1-X009T

Note

- Additional options may be possible, please contact sales office

ABSOLUTE MAXIMUM RATINGS (T_{amb} = 25 °C, unless otherwise specified)				
PARAMETER	TEST CONDITION	SYMBOL	VALUE	UNIT
INPUT				
Reverse voltage		V_R	6	V
Forward current		I_F	60	mA
Surge current	t ≤ 10 µs	I_{FSM}	2.5	A
Power dissipation		P_{diss}	100	mW
OUTPUT				
Collector emitter breakdown voltage		V_{CEO}	70	V
Emitter base breakdown voltage		V_{EBO}	7	V
Collector current		I_C	50	mA
	t < 1 ms	I_C	100	mA
Power dissipation		P_{diss}	150	mW
COUPLER				
Storage temperature range		T_{stg}	-55 to +150	°C
Operating temperature range		T_{amb}	-55 to +100	°C
Junction temperature		T_j	100	°C
Soldering temperature	Max. 10 s, dip soldering: distance to seating plane ≥ 1.5 mm	T_{sld}	260	°C

Note

- Stresses in excess of the absolute maximum ratings can cause permanent damage to the device. Functional operation of the device is not implied at these or any other conditions in excess of those given in the operational sections of this document. Exposure to absolute maximum ratings for extended periods of the time can adversely affect reliability

ELECTRICAL CHARACTERISTICS (T_{amb} = 25 °C, unless otherwise specified)						
PARAMETER	TEST CONDITION	SYMBOL	MIN.	TYP.	MAX.	UNIT
INPUT						
Forward voltage	I_F = 10 mA	V_F	-	1.1	1.5	V
Reverse current	V_R = 3 V	I_R	-	-	10	µA
Capacitance	V_R = 0 V, f = 1 MHz	C_O	-	50	-	pF
OUTPUT						
Collector emitter breakdown voltage	I_C = 1 mA, I_F = 0 mA	BV_{CEO}	30	-	-	V
Emitter collector breakdown voltage	I_E = 100 µA, I_F = 0 mA	BV_{ECO}	7	-	-	V
Collector base breakdown voltage	I_C = 10 µA, I_F = 0 mA	BV_{CBO}	70	-	-	V
Collector emitter leakage current	V_{CE} = 10 V, I_F = 0 mA	I_{CEO}	-	5	50	nA
Emitter collector capacitance	V_{CE} = 0 V	C_{CE}	-	6	-	pF
COUPLER						
Collector emitter, saturation voltage	I_{CE} = 0.5 mA, I_F = 10 mA	V_{CEsat}	-	-	0.4	V
Capacitance (input-output)		C_{IO}	-	0.5	-	pF

Note

- Minimum and maximum values were tested requirements. Typical values are characteristics of the device and are the result of engineering evaluations. Typical values are for information only and are not part of the testing requirements.

CURRENT TRANSFER RATIO						
PARAMETER	TEST CONDITION	SYMBOL	MIN.	TYP.	MAX.	UNIT
I_C/I_F	V_{CE} = 10 V, I_F = 10 mA	CTR_{DC}	50	-	-	%

SWITCHING CHARACTERISTICS						
PARAMETER	TEST CONDITION	SYMBOL	MIN.	TYP.	MAX.	UNIT
Turn-on time	I_C = 2 mA, R_L = 100 Ω, V_{CE} = 10 V	t_{on}	-	3	-	µs
Turn-off time		t_{off}	-	3	-	µs

SAFETY AND INSULATION RATINGS				
PARAMETER	**TEST CONDITION**	**SYMBOL**	**VALUE**	**UNIT**
Climatic classification	According to IEC 68 part 1		55 / 100 / 21	
Comparative tracking index		CTI	175	
Maximum rated withstanding isolation voltage	t = 1 min	V_{ISO}	4420	V_{RMS}
Maximum transient isolation voltage		V_{IOTM}	8000	V_{peak}
Maximum repetitive peak isolation voltage		V_{IORM}	890	V_{peak}
Isolation resistance	V_{IO} = 500 V, T_{amb} = 25 °C	R_{IO}	$\geq 10^{12}$	Ω
	V_{IO} = 500 V, T_{amb} = 100 °C	R_{IO}	$\geq 10^{11}$	Ω
Output safety power		P_{SO}	700	mW
Input safety current		I_{SI}	400	mA
Safety temperature		T_S	175	°C
Creepage distance			≥ 7	mm
Clearance distance			≥ 7	mm
Insulation thickness		DTI	≥ 0.4	mm

Note

- As per IEC 60747-5-5, § 7.4.3.8.2, this optocoupler is suitable for "safe electrical insulation" only within the safety ratings. Compliance with the safety ratings shall be ensured by means of protective circuits

TYPICAL CHARACTERISTICS (T_{amb} = 25 °C, unless otherwise specified)

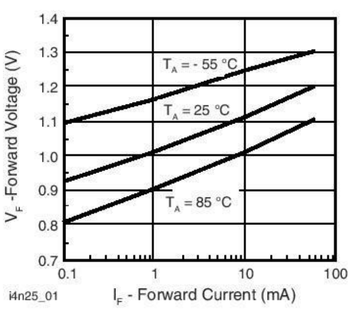


Fig. 1 - Forward Voltage vs. Forward Current

Fig. 2 - Normalized Non-Saturated and Saturated CTR vs. LED Current

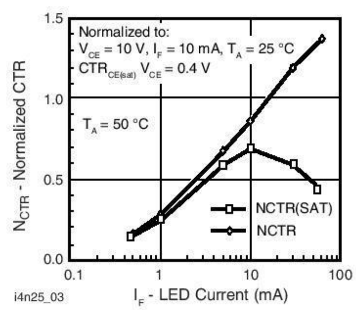
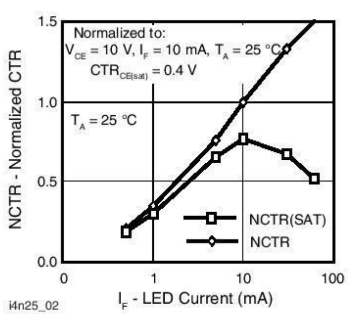


Fig. 3 - Normalized Non-Saturated and Saturated CTR vs. LED Current



Appendix H: 2N6071A TRIAC datasheet

2N6071A/B Series

Preferred Device

Sensitive Gate Triacs

Silicon Bidirectional Thyristors

Designed primarily for full-wave AC control applications, such as light dimmers, motor controls, heating controls and power supplies; or wherever full-wave silicon gate controlled solid-state devices are needed. Triac type thyristors switch from a blocking to a conducting state for either polarity of applied anode voltage with positive or negative gate triggering.

Features

- Sensitive Gate Triggering Uniquely Compatible for Direct Coupling to TTL, HTL, CMOS and Operational Amplifier Integrated Circuit Logic Functions
- Gate Triggering: 4 Mode – 2N6071A, B; 2N6073A, B; 2N6075A, B
- Blocking Voltages to 600 V
- All Diffused and Glass Passivated Junctions for Greater Parameter Uniformity and Stability
- Small, Rugged, Thermopad Construction for Low Thermal Resistance, High Heat Dissipation and Durability
- Device Marking: Device Type, e.g., 2N6071A, Date Code

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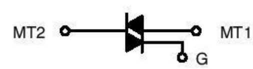
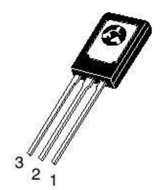
TRIACS
4.0 A RMS, 200 – 600 V



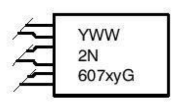


REAR VIEW
SHOW TAB

TO–225
CASE 077
STYLE 5

MARKING DIAGRAM

1. Cathode
2. Anode
3. Gate



x	= 1, 3, 5
y	= A, B
Y	= Year
WW	= Work Week
G	= Pb–Free Package

ORDERING INFORMATION

See detailed ordering and shipping information in the package dimensions section on page 7 of this data sheet.

Preferred devices are recommended choices for future use and best overall value.

*For additional information on our Pb–Free strategy and soldering details, please download the ON Semiconductor Soldering and Mounting Techniques Reference Manual, SOLDERRM/D.

March, 2008 – Rev. 8

Publication Order Number:
2N6071/D

2N6071A/B Series

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

Rating	Symbol	Value	Unit
*Peak Repetitive Off-State Voltage (Note 1) (T_J = − 40 to 110°C, Sine Wave, 50 to 60 Hz, Gate Open) 2N6071A,B 2N6073A,B 2N6075A,B	V_{DRM}, V_{RRM}	 200 400 600	V
*On-State RMS Current (T_C = 85°C) Full Cycle Sine Wave 50 to 60 Hz	$I_{T(RMS)}$	4.0	A
*Peak Non−repetitive Surge Current (One Full cycle, 60 Hz, T_J = +110°C)	I_{TSM}	30	A
Circuit Fusing Considerations (t = 8.3 ms)	I^2t	3.7	A^2s
*Peak Gate Power (Pulse Width ≤ 1.0 μs, T_C = 85°C)	P_{GM}	10	W
*Average Gate Power (t = 8.3 ms, T_C = 85°C)	$P_{G(AV)}$	0.5	W
*Peak Gate Voltage (Pulse Width ≤ 1.0 μs, T_C = 85°C)	V_{GM}	5.0	V
*Operating Junction Temperature Range	T_J	−40 to +110	°C
*Storage Temperature Range	T_{stg}	−40 to +150	°C
Mounting Torque (6-32 Screw) (Note 2)	–	8.0	in. lb.

Stresses exceeding Maximum Ratings may damage the device. Maximum Ratings are stress ratings only. Functional operation above the Recommended Operating Conditions is not implied. Extended exposure to stresses above the Recommended Operating Conditions may affect device reliability.

1. V_{DRM} and V_{RRM} for all types can be applied on a continuous basis. Blocking voltages shall not be tested with a constant current source such that the voltage ratings of the devices are exceeded.
2. Torque rating applies with use of a compression washer. Mounting torque in excess of 6 in. lb. does not appreciably lower case-to-sink thermal resistance. Main terminal 2 and heatsink contact pad are common.

THERMAL CHARACTERISTICS

Characteristic	Symbol	Max	Unit
*Thermal Resistance, Junction−to−Case	$R_{\theta JC}$	3.5	°C/W
Thermal Resistance, Junction−to−Ambient	$R_{\theta JA}$	75	°C/W
Maximum Lead Temperature for Soldering Purposes 1/8″ from Case for 10 Seconds	T_L	260	°C

*Indicates JEDEC Registered Data.

2N6071A/B Series

ELECTRICAL CHARACTERISTICS (T_C = 25°C unless otherwise noted; Electricals apply in both directions)

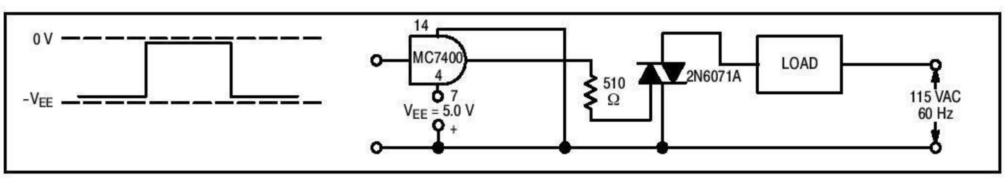
Characteristic	Symbol	Min	Typ	Max	Unit
OFF CHARACTERISTICS					
*Peak Repetitive Blocking Current (V_D = V_{DRM} = V_{RRM}; Gate Open) T_J = 25°C	I_{DRM}, I_{RRM}	–	–	10	μA
T_J = 110°C		–	–	2	mA
ON CHARACTERISTICS					
*Peak On-State Voltage (Note 3) (I_{TM} = ± 6.0 A Peak)	V_{TM}	–	–	2	V
*Gate Trigger Voltage (Continuous DC), All Quadrants (Main Terminal Voltage = 12 Vdc, R_L = 100 Ω, T_J = −40°C)	V_{GT}	–	1.4	2.5	V
Gate Non−Trigger Voltage, All Quadrants (Main Terminal Voltage = 12 Vdc, R_L = 100 Ω, T_J = 110°C)	V_{GD}	0.2	–	–	V
*Holding Current (Main Terminal Voltage = 12 Vdc, Gate Open, Initiating Current = ± 1 Adc) T_J = −40°C	I_H	–	–	30	mA
T_J = 25°C		–	–	15	
Turn-On Time (I_{TM} = 14 Adc, I_{GT} = 100 mAdc)	t_{gt}	–	1.5	–	μs

Characteristic	Type	I_{GT} @ T_J	QUADRANT (Maximum Value) I mA	II mA	III mA	IV mA
Gate Trigger Current (Continuous DC) (Main Terminal Voltage = 12 Vdc, R_L = 100 Ω)	2N6071A 2N6073A 2N6075A	+25°C	5	5	5	10
		−40°C	20	20	20	30
	2N6071B 2N6073B 2N6075B	+25°C	3	3	3	5
		−40°C	15	15	15	20

Characteristic	Symbol	Min	Typ	Max	Unit
DYNAMIC CHARACTERISTICS					
Critical Rate of Rise of Commutation Voltage @ V_{DRM}, T_J = 85°C, Gate Open, I_{TM} = 5.7 A, Exponential Waveform, Commutating di/dt = 2.0 A/ms	dv/dt(c)	–	5	–	V/μs

3. Pulse Test: Pulse Width ≤ 2.0 ms, Duty Cycle ≤ 2%.
*Indicates JEDEC Registered Data.

SAMPLE APPLICATION:
TTL-SENSITIVE GATE 4 AMPERE TRIAC
TRIGGERS IN MODES II AND III

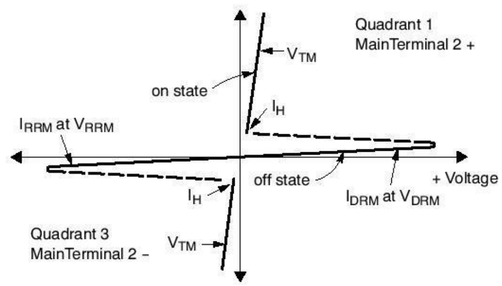


Trigger devices are recommended for gating on Triacs. They provide:
1. Consistent predictable turn-on points.
2. Simplified circuitry.
3. Fast turn-on time for cooler, more efficient and reliable operation.

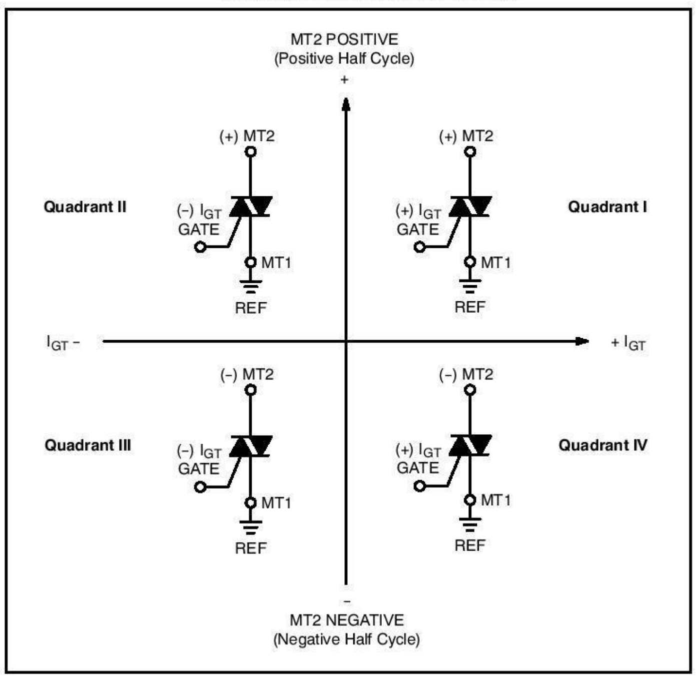
2N6071A/B Series

Voltage Current Characteristic of Triacs (Bidirectional Device)

Symbol	Parameter
V_{DRM}	Peak Repetitive Forward Off State Voltage
I_{DRM}	Peak Forward Blocking Current
V_{RRM}	Peak Repetitive Reverse Off State Voltage
I_{RRM}	Peak Reverse Blocking Current
V_{TM}	Maximum On State Voltage
I_H	Holding Current



Quadrant Definitions for a Triac



All polarities are referenced to MT1.
With in-phase signals (using standard AC lines) quadrants I and III are used.

SENSITIVE GATE LOGIC REFERENCE

IC Logic Functions	Firing Quadrant			
	I	II	III	IV
TTL		2N6071A Series	2N6071A Series	
HTL		2N6071A Series	2N6071A Series	
CMOS (NAND)	2N6071B Series			2N6071B Series
CMOS (Buffer)		2N6071B Series	2N6071B Series	
Operational Amplifier	2N6071A Series			2N6071A Series
Zero Voltage Switch		2N6071A Series	2N6071A Series	

http://onsemi.com
4

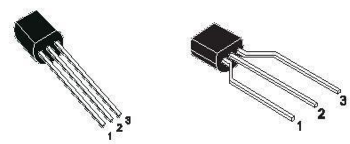
Appendix I: 2N3904 transistor datasheet

2N3904

SMALL SIGNAL NPN TRANSISTOR

PRELIMINARY DATA

Ordering Code	Marking	Package / Shipment
2N3904	2N3904	TO-92 / Bulk
2N3904-AP	2N3904	TO-92 / Ammopack



TO-92 Bulk

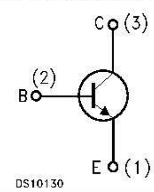
TO-92 Ammopack

- SILICON EPITAXIAL PLANAR NPN TRANSISTOR
- TO-92 PACKAGE SUITABLE FOR THROUGH-HOLE PCB ASSEMBLY
- THE PNP COMPLEMENTARY TYPE IS 2N3906

APPLICATIONS

- WELL SUITABLE FOR TV AND HOME APPLIANCE EQUIPMENT
- SMALL LOAD SWITCH TRANSISTOR WITH HIGH GAIN AND LOW SATURATION VOLTAGE

INTERNAL SCHEMATIC DIAGRAM



ABSOLUTE MAXIMUM RATINGS

Symbol	Parameter	Value	Unit
V_{CBO}	Collector-Base Voltage ($I_E = 0$)	60	V
V_{CEO}	Collector-Emitter Voltage ($I_B = 0$)	40	V
V_{EBO}	Emitter-Base Voltage ($I_C = 0$)	6	V
I_C	Collector Current	200	mA
P_{tot}	Total Dissipation at $T_C = 25\ ^oC$	625	mW
T_{stg}	Storage Temperature	-65 to 150	^oC
T_j	Max. Operating Junction Temperature	150	^oC

February 2003 1/5

2N3904

THERMAL DATA

$R_{thj-amb}$ •	Thermal Resistance Junction-Ambient	Max	200	°C/W
$R_{thj-case}$ •	Thermal Resistance Junction-Case	Max	83.3	°C/W

ELECTRICAL CHARACTERISTICS (T_{case} = 25 °C unless otherwise specified)

Symbol	Parameter	Test Conditions	Min.	Typ.	Max.	Unit
I_{CEX}	Collector Cut-off Current (V_{BE} = -3 V)	V_{CE} = 30 V			50	nA
I_{BEX}	Base Cut-off Current (V_{BE} = -3 V)	V_{CE} = 30 V			50	nA
$V_{(BR)CEO}$*	Collector-Emitter Breakdown Voltage (I_B = 0)	I_C = 1 mA	40			V
$V_{(BR)CBO}$	Collector-Base Breakdown Voltage (I_E = 0)	I_C = 10 µA	60			V
$V_{(BR)EBO}$	Emitter-Base Breakdown Voltage (I_C = 0)	I_E = 10 µA	6			V
$V_{CE(sat)}$*	Collector-Emitter Saturation Voltage	I_C = 10 mA I_B = 1 mA I_C = 50 mA I_B = 5 mA			0.2 0.2	V V
$V_{BE(sat)}$*	Base-Emitter Saturation Voltage	I_C = 10 mA I_B = 1 mA I_C = 50 mA I_B = 5 mA	 0.65		0.85 0.95	V V
h_{FE}*	DC Current Gain	I_C = 0.1 mA V_{CE} = 1 V I_C = 1 mA V_{CE} = 1 V I_C = 10 mA V_{CE} = 1 V I_C = 50 mA V_{CE} = 1 V I_C = 100 mA V_{CE} = 1 V	60 80 100 60 30		 300	
f_T	Transition Frequency	I_C = 10 mA V_{CE} = 20 V f = 100 MHz	250	270		MHz
C_{CBO}	Collector-Base Capacitance	I_E = 0 V_{CB} = 10 V f = 1 MHz		4		pF
C_{EBO}	Emitter-Base Capacitance	I_C = 0 V_{EB} = 0.5 V f = 1 MHz		18		pF
NF	Noise Figure	V_{CE} = 5 V I_C = 0.1 mA f = 10 Hz to 15.7 KHz R_G = 1 KΩ		5		dB
t_d t_r	Delay Time Rise Time	I_C = 10 mA I_B = 1 mA V_{CC} = 30 V			35 35	ns ns
t_s t_f	Storage Time Fall Time	I_C = 10 mA I_{B1} = $-I_{B2}$ = 1 mA V_{CC} = 30 V			200 50	ns ns

∗ Pulsed: Pulse duration = 300 µs, duty cycle ≤ 2 %

Appendix J: Acknowledgement

Professor James Hedrick: Thank you for your continued support and patience during the fall and winter trimesters. I learned a lot from your engineering expertise, and I will continue to apply the skills that I have acquired in my future endeavors.

The ECBE Department and the SRG committee: Thank you for granting me the funds to purchase the parts needed for the project.