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Arc Fault Pressure Detector in Low Voltage Switchboard

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Abstract- This paper focuses on the study of the behavior, characteristics, causes and effects of arc faults in low voltage (LV) switchboard. A pressure sensor is designed to have an early detection on the fault by means of detecting the arc pressure. By monitoring the pressure of supply the current, the possibility of arc occurrence is minimized. From simulation results of the proposed circuit, the pressure sensor is able to detect an arc fault, send a signal to the fault protector circuit which in turn alerts the breaker control circuit to trip the appropriate circuit breaker, thus avoiding damages to the switchboard, buildings and personnel injury caused by arc flash.

Index Terms- Arc Fault Pressure Detector, Low Voltage Switchboard, Circuit Breaker, Proteus

I. Introduction

Over the years arc faults have posed a huge threat in the safety and operation of low voltage (LV) switchboards. Electric arcs are a destructive electro physical phenomenon which generates internal over pressures, heat which results in mechanical and thermal stressing of the equipments. Electric arcs may cause instant and severe burns to persons happening to stay close to the fault, when it arises.

Arc incidents occur due to various reasons such as, poorly installed equipment (human mistakes), natural aging of equipment, bad connections, faulty connection due to corrosion. Statistics have shown that 80% of electrically related accidents and fatalities involving qualified workers are caused by arc flash or arc blast. A true arc fault will rapidly increase energy level up to 20MW cycle, increase in pressure up to 3 atm, and in heat up to 3000 degrees Celsius [1]. An electrical switchboard of seven feet high, three feet wide, four feet deep, containing several hundred pounds of metal conductors and supports can, in a few seconds be reduced to an empty shell. Arc faults are tricky in the sense that they do not behave like short circuits and therefore are often difficult to be detected by normal circuit breakers. This is because, unlike short circuits, arc faults have high impedance and thus arcing current is insufficient (low) to operate the over-current equipment, therefore the breaker will not open. Because of this, systems require enhanced protection schemes to detect arc faults early and counter stop them before they occur to minimize, if not eliminate, the damages caused to switchboards, buildings and working personnel.

Protection schemes for arcing include use of temperature, current, light and pressure sensors. Pressure in the ambient of burning arc achieves its maximum approximately after 10 ms the arc origin in the switchboard. And the temperature in the arc ambient achieves maximum value after next 5 ms [2]. From the energy balance point of view 50 % of arc energy shares on the increase pressure and persons exposed to severe pressure from proximity to an arc are likely to suffer short-time loss of memory, not remembering the intense explosion of the arc itself [3]. This paper focuses on the design of a pressure sensor to have an early detection on the arc fault to reduce the possibility of the arcs occurring.

This paper is arranged as follows: Section II focuses on the types, behavior and characteristics of arc fault as well as the causes and effects of arc fault. Section III provides the circuit design of the arc fault pressure sensor. Section IV presents the simulation results of the proposed circuit. Section V concludes the findings of this paper.

II. Arc Fault

A. Types of Arc Fault

An arc fault is defined as a high impedance discharge of electricity through the air that creates light and heat [4]. It occurs when two corroded or loose wires make intermittent connections thus causing sparking (arcing) between connections. Generally, we have two types of arcing, natural and unsafe arcing. Natural arcing is the normal, harmless arcing which occurs when mostly a motor driven appliance, for example, it happens when a vacuum cleaner is switched on. Unsafe arcing, as the name suggests is the hazardous type which causes fires, destroys building and loss of lives.

Unsafe arcing is further divided in to two types, series and parallel arcing. Series arcing is caused by a loose connection in series with the connected load. Peak current in series arcing is never greater than the rating of the circuit breaker, and the magnetic sensor in the circuit breaker will never respond to such low amplitude currents. This makes series arcing much more difficult to detect than parallel arcing because the arc current remains well below the rating of the circuit breaker.

Parallel arcing occurs when there is a direct short between two power wires and the current is limited only by the resistance of the wire in the distribution circuit. Peak current of parallel arcs is much higher than the breaker rating, so protection circuits can detect it easily and trip the relevant breaker in a fraction of a second. Though easy to detect, parallel arcing is generally more dangerous than series arcing because the energy in the sparks is much higher and more likely to cause an explosion.

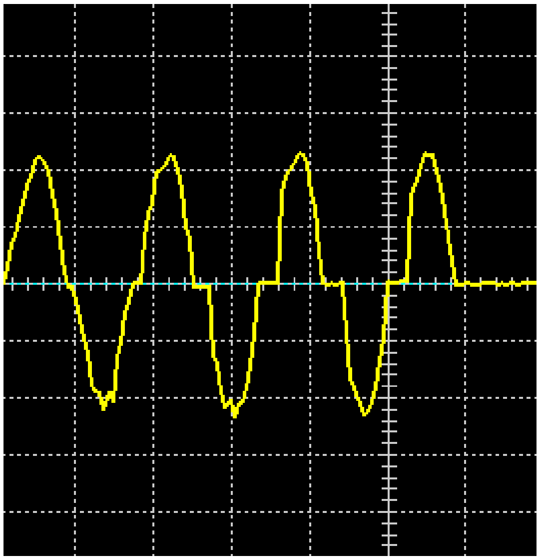
B.Behavior and characteristics of arc fault

Arc faults have been observed to have high thermal energy due to high temperatures of over 19500 degrees Celsius and high pressures of thousands of Pascal's. The pressure of arc fault can be calculated by using its relation to arc current. Ralph Lee's IEEE paper addresses arc blast phenomenon and provides the formula for calculating initial impulse force [5]:

$P = 11.58 \times I_{arc} / D^{0.9}$

where P is pressure in lbs/ft^2
I_{arc} is arcing current in kA
D is distance from arc in feet

Another characteristic of arc fault is its unique current waveform. Arc current waveform has a flat shoulder as it approaches zero crossing for every half cycle. This waveform is used to distinguish normal system current from arc current. Figure 1 shows a typical arc current waveform [6].



C. Causes and Effects of arc fault

Arc faults are a result of many factors, some of which include:

- Insulation failure
- Natural aging of wires
- Human errors in handling of equipment
- Punching of wire insulation from hanging pictures/cable staples
- Furniture pushed against plugs in an outlet
- Cord exposure to heat vents and sunlight
- Poorly installed outlets or switches
- Damaged power supply cord due to door continual pinching
- Loose wiring connections at outlets or switches
- Loose wires twisted together and held by a wire nut
- Frayed cords on appliances

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Arcs if go on undetected result in buildup of temperature and pressure. Pressure causes mechanical stressing of switchboard enclosures and explosions while temperature results in thermal stressing, melting and fire. Overall, the effect of an arc fault is the loss of electrical equipment and lives.

III. CIRCUIT DESIGN OF ARC PRESSURE DETECTOR

Arc faults tend to have high pressures, therefore a pressure sensor is needed to be installed in LV switchboards to detect any change in pressure conditions created by an arcing. A signal is sent to the fault protector circuit which in-turn sends an alert to the breaker control circuit, to trip the appropriate circuit breaker. Figure 2 below shows a simplified diagram of how the pressure sensor circuit works.

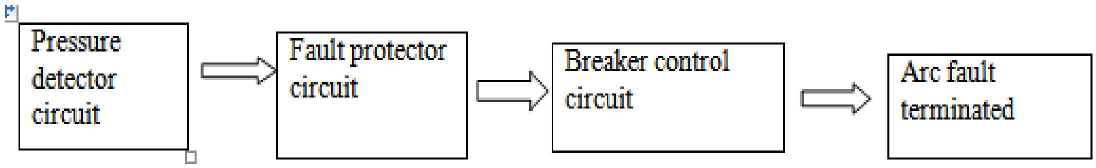

Figure 2. Simplified Block Ddiagram of the Proposed Circuit

The proposed circuit is simulated using “Proteus for professionals software”, version 7.7. It is divided in to three parts. The first part of the circuit is the sensor circuit, second part is the fault protector circuit and the last part is the breaker control circuit.

Part I: Pressure Sensor Circuit

The pressure sensor circuit incorporated with the use of a PIC16F877A micro-controller. When pressure sensor senses arc fault (at voltage>0.5V), it produces voltage which is fed into pin 2of the microcontroller. The microcontroller then processes the voltage and triggers the relay at pin 21 so that fault protection circuit is turned ON to protect the load 10kΩ in the fault protection circuit. When the load 10kΩ is protected, the ammeter current immediately shows zero.

The arc pressure transmitted through the sensor can be calculated by using a derived formula:

$$P_R = \left(\frac{I * Voltage}{t * volume} \right)$$

where P_R- pressure

I- current passing through sensor = 3.91mA using ammeter.
Voltage- voltage through the sensor= 5V
t- time taken for the senor to turn on the relay, observed to be approximately 2 seconds
volume- volume of the sensor, standard value is 1cm^3

Substituting these values, P_R = 9775pascals
According to a paper by Ralph Lee [8], a 10kV arc voltage reached a pressure of 2 x 10^4 N/m^2 which is equivalent to 2 x 10^4 Pascal’s (1 Pascal = 1 N/m^2). The difference in pressure values is because, the circuit designed in this paper uses a microcontroller, in which at higher pressures, it could be destroyed or burnt. Ralph H. Lee’s circuit uses pure electronic circuits designed to withstand higher pressures. However in any case, for higher voltage input, the pressure is much higher, which would be the case for industrial circuits with higher voltage input. This is to say that ‘pressure is proportional to input voltage’.

The LM7805 is a voltage regulator used to regulate the voltage from 12V down into 5V and supplies it to the relay and the microcontroller. The capacitors 100µF and 10µF are used to prevent in rush DC voltage and holds a constant 5V across the output of the LM7805. The resistor 1kΩ connected at pin 1 is to limit the current flows into pin 1. The resistor 1kΩ connected at pin 2 is used to draw out the floating voltage where it might disturb the operation of the microcontroller. Pin 21 of the microcontroller is programmed as output pin. This pin will generate HIGH voltage when the sensor senses the pressure. The HIGH voltage is then triggers the relay via the NPN transistor. The diode connected across the relay is to protect the transistor on the reverse current flows.

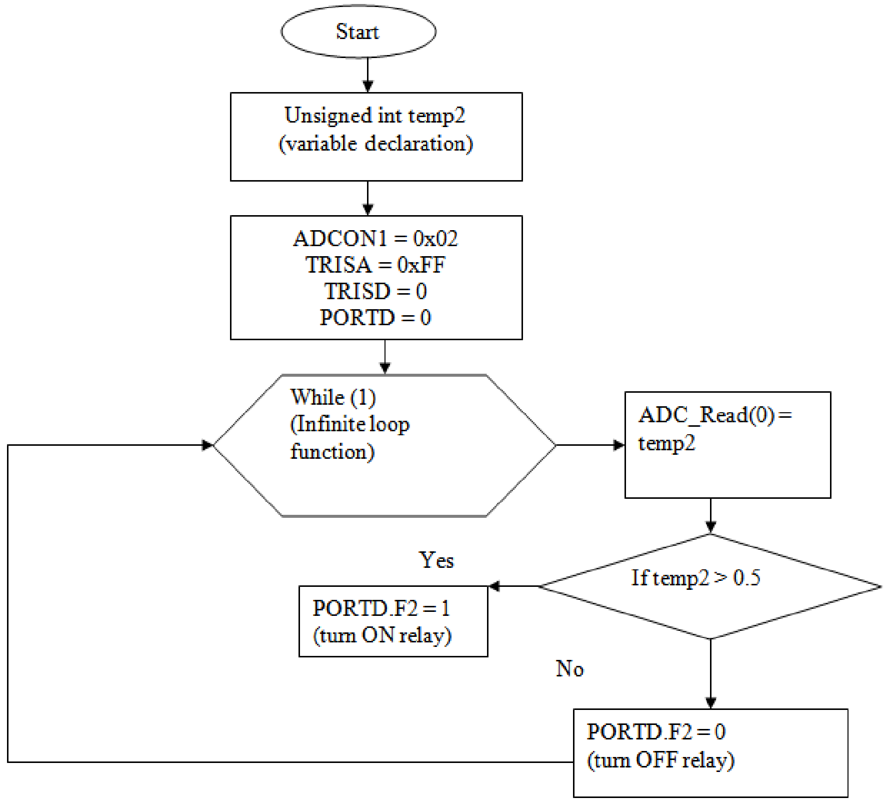

Figure 3: Flowchart of PIC16F877A Microcontroller program

Part II & III: Fault Protection and Breaker Control Circuit

As can be seen in Figure 4, there is an AC source connected in series to the AC load, 10kΩ. Under normal conditions (when no fault or arcing) happens, the ammeter will show some value of current. However, should a fault occur, fault protection circuit is turned ON to protect the load 10kΩ. When the load 10kΩ is protected, the ammeter current immediately shows zero. This means the protection circuit cut off the AC circuit.

The reason of using R3=100Ω resistor is to limit the current flows into the optocoupler. The function of the optocoupler is to isolate the AC circuit with the DC circuit. The optocoupler can be treated as a switch where it detects the AC current and ready to activate the protection circuit. At the output of the optocoupler, there are a variable resistor RV1, R4 of 100Ω and R5 of 2.2kΩ. The function of RV1 is to adjust the sensitivities of the protection level. The sensitivity output voltage is determined by the following formula:

$$V_{R1} = \left(\frac{RV1}{R_4 + RV1 + R_5} \right) Vcc$$

From the circuit, Vcc is 12V. Hence the VR1 can be simplified to:

$$V_{R1} = \left(\frac{RV1}{2300 + RV1} \right) 12$$

The zener diode D1 is a 4.7V diode. The zener will turn ON when VR1 > 4.7V. The turn ON of zener diode will cause the transistor Q1 bias and hence produce collector current to charge the capacitor C1 or 4.7µF. The voltage charged by capacitor C1 will then drop across 10kΩ resistor. The 555 timer is connected in monostable mode where it produces single pulse at pin 3 (output) when is activated at pin 2. The 10nF and 10kΩ connected at pin 6 are used to determine the duty cycle of the output pulse. At the output of the 555 timer, there is a LED and transistor. The LED is used as an output indicator whereas the transistor is used to trigger the circuit breaker (relay).

The base current of transistor base can be computed as:

$$I_B = \frac{V_{Pin3} - V_{BE}}{R9}$$

where $V_{pin3=}$ 5V

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$V_{BE} = 0.7V$

$R9 = 4k\Omega$

The collector current of transistor Q2 to trigger the circuit breaker is:

$$I_C = \beta_{DC} I_B$$

When the circuit breaker is activated, the AC circuit breaks down and hence the load is protected. Figure 4 shows the complete arc fault pressure detector circuit.

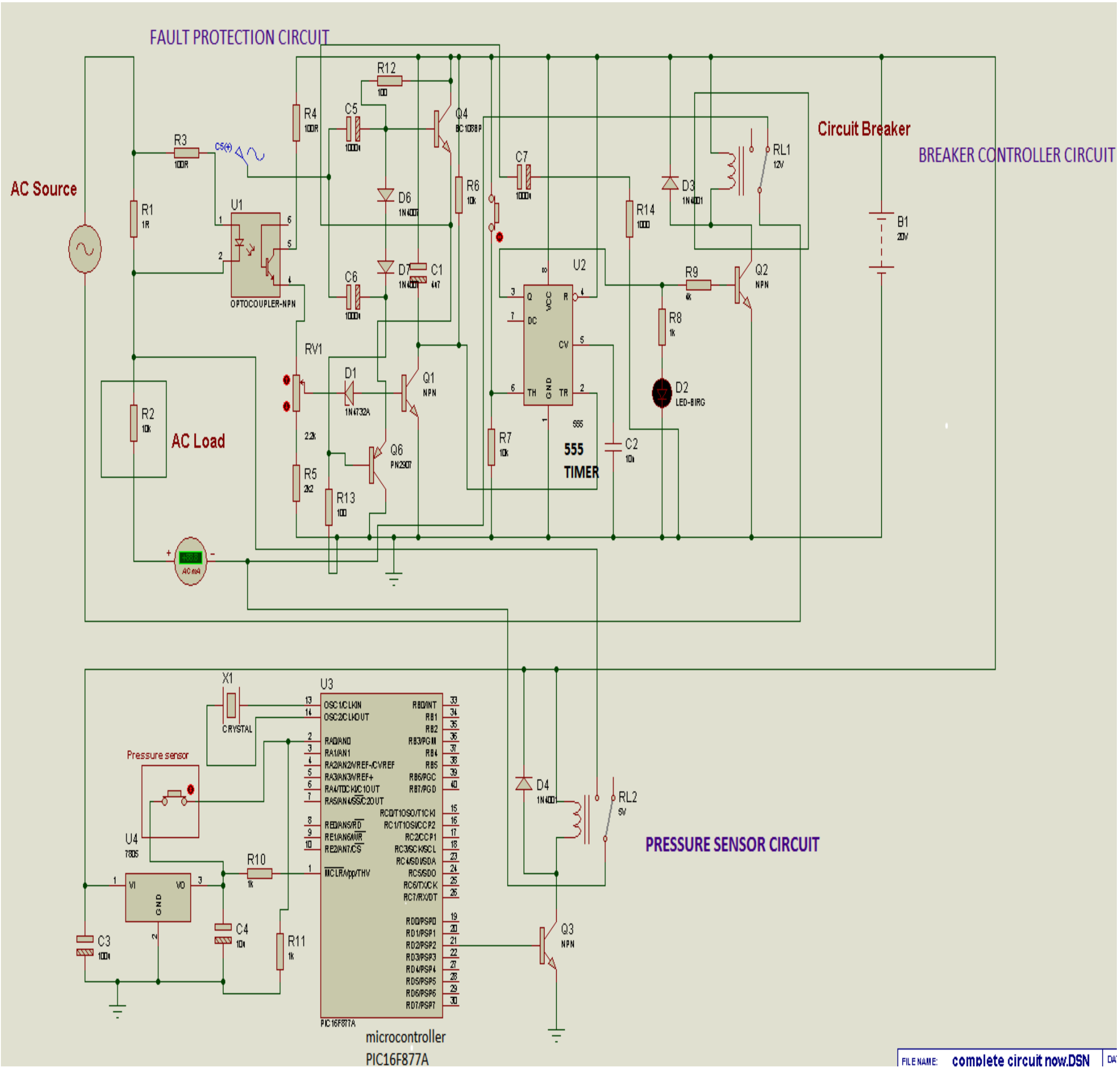

Figure 4: Complete Arc Pressure Detector Circuit

IV. SIMULATION RESULTS

When simulating the circuit under normal conditions, the ammeter reads currents as 24mA as seen in Figure 5.1

Supply voltage = 240V

Load resistance is 10kΩ

This is equal to the calculated value, using ohms law, $I = V/R$

$$= 240V/10k\Omega$$

$$\approx 24mA$$

Meanwhile, at the pressure detector circuit, there is no current going through the sensor and hence the ammeter reads 0mA as in Figure 5.2.

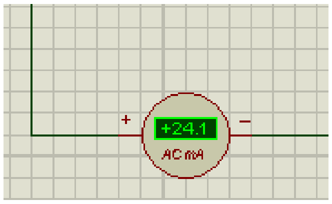

Figure 5.1: Ammeter Reading under Normal Conditions

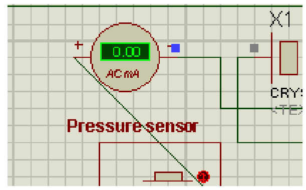

Figure 5.2: Ammeter Reading of Pressure Sensor under Normal Conditions

When arcing occurs, the ammeter immediately reduces to zero amperes as shown in Figure 6.1and trips the circuit breaker. The fault protection circuit is turned ON to protect the load 10kΩ. This means the protection circuit cuts off the AC circuit from the load. Under arcing conditions, current reading from the pressure sensor is 3.91mA as can be seen in Figure 6.2. This value is used to calculate the pressure of the arc.

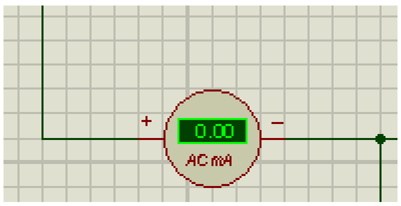

Figure 6.1: Ammeter Reading under Arcing Conditions

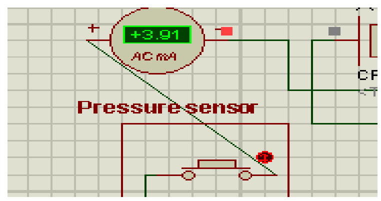

Figure 6.2: Ammeter Reading of the Pressure Sensor under Arcing Conditions

When the fault protection circuit is turned ON, it sends an alert signal via the 555 timer to the breaker control circuits. The relevant circuit breaker trips, LED will light ON to show output as can be seen in Figure 7.

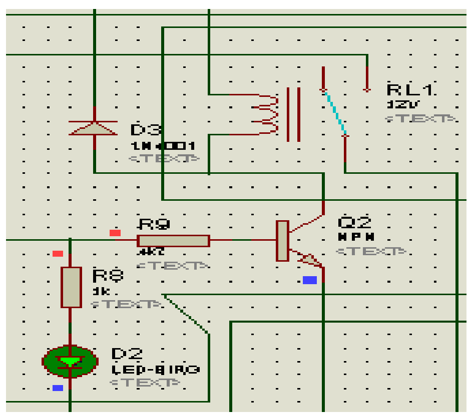

Figure 7: LED light ON after Circuit Breaker Trips

To better compare normal current in relation to load, a plot of load versus current is obtained by varying the load from 1kΩ to 10kΩ for normal conditions. Results are tabulated in Table I.

Table I – Experimental test on the load current when load is varies

Loads in kΩ	AC current in Ampere
1	0.24
2	0.12
3	0.08
4	0.06
5	0.048
6	0.04
7	0.034
8	0.03
9	0.026
10	0.024

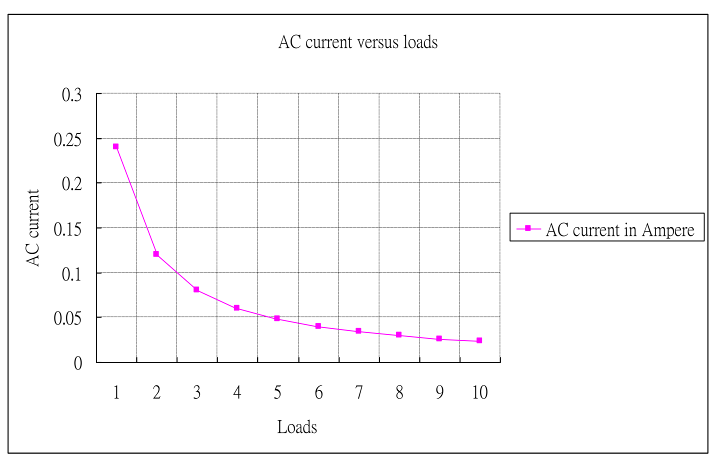

Figure 8 – The Plot for Table 1.

Under normal conditions as load increases, current measured reduces as shown in Figure 8. Resistance is inversely proportional to current, even from ohm's law equation: V=IR. Higher resistance means lower current.

During arcing the circuit at any point should immediately cut of AC circuit from the load and trip circuit breaker. To test this, load is kept constant and arcing is initiated after some time. Results are tabulated in Table II.

Table II – Current Values when Arc Fault is Detected

Time in second	**Loads in kΩ**	**AC current in Ampere**
1	1	0.24
2	1	0.24
3	1	0.24
4	1	0.24
5	1	0.24
6	1	0
7	1	0
8	1	0
9	1	0
10	1	0

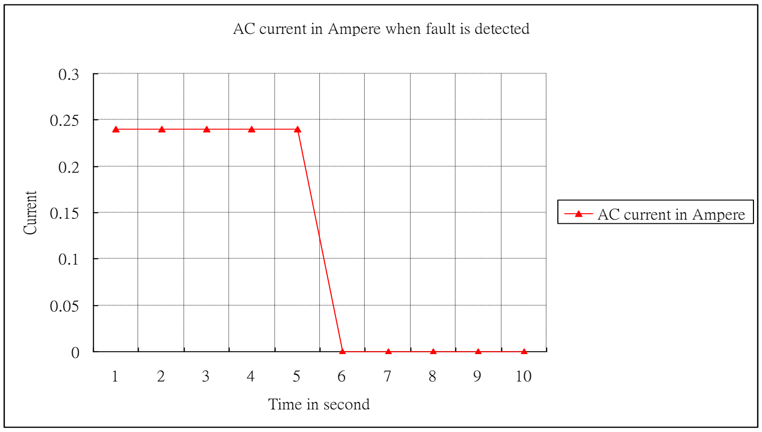

Figure 9 – The plot for Table 2.

From the graph as shown in Figure 9, it reveals that when the arc fault happens at any time, the circuit breaker breaks the circuit and this causes the current to drop to zero. When the current is zero, the circuit is saved from the excess current thus protecting the load and preventing the arc to destroy the circuit.

V. CONCLUSION

The design of an arc fault pressure sensor is presented in this paper. The simulation results, plots and voltage waveforms that were obtained show that the proposed arc fault pressure sensor circuit is able to detect the arc fault, alert the fault protection circuit. Then an alert signal will be sent to the breaker control circuit to trip the relevant breaker and cut the supply to the load. The sensor circuit help to eliminate the possibility of an arc occurring and hence prevents against the effects of arc occurrence. The proposed circuit can be modeled to meet specifications of industry with different supply requirements. It is easy to design and highly reliable.

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