Design of Arc Fault Temperature Detector in Low Voltage Switchboard

Kuan Lee Choo¹* and Pang Jia Yew²

¹Infrastructure University Kuala Lumpur, Selangor, Malaysia; lckuan@iukl.edu.my
²Asia Pacific University, Selangor, Malaysia; jia.yew@apiit.edu.my

Abstract

This paper presents an arc fault temperature detector that is used to detect the overheated condition in the low voltage switchboard prior to the occurrence of an arcing fault. The behavior and characteristics of arcing fault in low voltage switchboard are studied prior the design of the arc fault temperature detector. The simulation and experimental results show that the proposed arc fault temperature detector is able to detect the overheating enclosed in the switchboard and therefore reduce the possibilities of arc occurrences.

Keywords: Arc Fault Temperature Detector, LM 335 Temperature Sensors, Low Voltage Switchboard.

1. Introduction

Arc is defined as flow of electric current in nonconductive/insulating media such as air. Generally, arc is an electrical discharge flowing between two electrodes through a gas or vapor¹. An arcing fault is the flow of current through a higher impedance medium, typically the air, between phase conductors or between phase conductors and neutral, ground or even a non-conducting medium². There are various reasons that cause the arc to occur such as connection that is loosed, connection that is corroded, object falls onto the bus bar, insulation failures and etc³. Schneider-electric worldwide expert has concluded that joint fault is the main reason for low voltage switchboard to have failure⁴. Joint fault is the series arc occurs at the joint.

A low voltage switchboard is an essential piece of equipment used to receive electricity from the utility company and distribute electricity to various loads⁵. The International Electrotechnical Commission (IEC) defines low voltages as any voltages in the range of 50-1000 VAC or 120-1500 VDC⁶. Technically, a low voltage switchboard is a panel with one or more low voltage switching, control, measuring, signaling, and protective and more devices. An arc fault is not a short across a circuit. It is a high impedance fault with the fault current in the range of the rated current. Hence, circuit breakers or other protective devices could not detect the existence of the arc fault and isolate it before serious damages occur.

Overheating in low voltage switchboard is not limited to the arc fault but also other failure causes such as overloads, harmonics and malfunction of ventilation. Since arc faults can cause vast damages and fires besides they are hazardous to equipments and humans, arcing fault occurrences should be avoided and prevented. Arc faults should be detected and isolated prior to their occurrences. The aim of this paper is to design of arc fault temperature detector to protect not only human lives, but properties and equipments. In addition, it reduces fires and explosions caused by the arcing faults, preventing arcing faults occurrences and preventing the destructive effects of arcing faults.

This paper is organized as follows: Section II presents the behavior and characteristic of the arc fault. Section III
subsequently describes the system description of the arc fault temperature detector. Section 4 provides the experimental and simulation results of the arc fault temperature detector and lastly, Section 5 concludes the findings of this paper.

2. Behavior and Characteristic of Arc Fault

An arc fault is the discharge of electricity through the air between two conductors which creates huge quantities of heat and light. It is a high resistance fault with resistance similar to many loads and it is a time varying resistor which can dissipate large amount of heat in the switchboard.

Circuit breakers are tested by bolting a heavy metallic short across the output terminals to determine their capabilities of handling an essentially zero resistance load. The zero resistance fault is named as bolted fault. Bolted fault current is the highest possible current supplied by the source and a protective system is designed according to the value of bolted fault current. The protective system must be able to detect the bolted fault and the protective devices must be capable of interrupting this value of current.

Due to the high resistance loads, an arcing fault will result in much lower values of current. Thus, the protective devices such as circuit breakers, fuses and relays, which are designed to operate for bolted fault, may not detect these lower values of current. As a result, the arcing fault will persist until severe burn down damage occurs. The magnitude of the arc current is limited by the resistance of the arc and the impedance of the ground path.

Arc faults are categorized into series arc faults and parallel arc faults. Series arc faults happen when the current carrying paths in series with the loads are unintentionally broken whereas parallel arc faults happen between two phases, phase to ground or phase to neutral of the switchboard.

Large amounts of heat will be dissipated during an arc event. A portion of this heat is coupled directly into the conductors, a portion heats the air and another portion is radiated in various optical wavelengths. Hasty heating of the air and the expansion of the vaporized metal into gas produces a strong pressure wave which will blow off the covers of the switchboards and collapse the substations. Arcing fault damage increases with the existence of the busbar insulation.

Figure 1 shows the time, current and damage for the 53 arcing tests. When the circuit breakers are tripped within less than 0.25 second, the damage will be limited to smoke damage. The triangle markers represent arcs that left only smoke damages to the side of switchboards. The square markers represent arcs that left surface damage to the side of switchboards whereas the star pointers represent holes of several square inches at the side of the switchboards.

When an arc is ignited, the plasma cloud expands cylindrically around the arc. The expansion of the plasma is constrained by the parallel bus and thus the plasma expands more to the front and the back of the bus. As the plasma reaches any obstructions such as the switchboard, plasma expansion is retarded by the obstructions. Due to the lower velocity of the arc, the plasma becomes more concentrated and its temperature and current will increase.

The root of the arc where the arc contacts the conductor is reported to reach temperatures exceeding 20000ºC, whereas the plasma portion or positive column of the arc is around 13000 ºC. For reference, surface of the sun is reported to be about 5000 ºC. The components in the switchboard can only withstand this temperature within 250 milliseconds before sustaining severe damages.

Figure 2 shows the change of temperature when the joint is loosening at different percentage of the rated tightening torque. It can be observed from Figure 2 that the significant overheating only occurs when the joint is loosening down to less than 1/8 of the rated torque. Figure 2 also reveals that the temperature range just before the occurrence of arc is from 30 ºC to 90 ºC.
Temperature of an arc can reach 20000°C at its root. Before an arcing fault occurrence, the temperature in the switchboard will increase with increasing arc current. The temperature sensor will sense the temperature changes in the surrounding and produce a voltage based output signal. The signal is then sent to the voltage comparator through the buffer to be compared with the reference voltage.

With every 1°C increase in the temperature of the surrounding, 1°K increase will take place in the LM 335 temperature sensor. For every 1°K increase, the output voltage will increase by 10 mV. Under normal condition, the temperature inside a switchboard should not be more than 100°C. As calculated in Equation 2, when the temperature inside a switchboard is 100°C, the output voltage of LM 335 is 3.73 V.

A buffer amplifier provides electrical impedance transformation from one circuit to another circuit. It is used to transfer a voltage from the temperature sensor to voltage comparator. A unity gain buffer is used in the circuit design. The output of the op-amp (buffer) is connected to its inverting input, which is the negative feedback. Therefore, the output voltage is simply equal to the input voltage of the buffer. The output from the temperature sensor is connected to the non-inverting input of the buffer (op-amp), which is the positive feedback and the output from the buffer is identical to the temperature sensor output.

The temperature sensor will generate a voltage based signal with respect to the amount of temperature detected from the surrounding. The signal is then sent to a voltage comparator through a buffer. The voltage comparator is used to compare the signal with a reference voltage and indicate which is larger at its output. The output of the comparator will produce a positive value which will then send a trip signal to the trip indicator if the signal from the temperature sensor exceeds the reference voltage of the voltage comparator. Else, the output voltage of the voltage comparator will indicate a negative value which will not trigger the trip indicator.

Before detect the changes of temperature in the environment and operate the buzzer when the temperature exceeds the predetermined limit. The arc fault temperature detector is modeled to lower values of temperature with respect to the practical temperature.

Figure 4 shows the schematic diagram of an arc fault temperature detector using PSpice program. The input for this circuit is an AC supply. An AC supply is used to represent the output signal from the temperature sensor. The output voltage range of the sensor is used as the input.
Design of Arc Fault Temperature Detector in Low Voltage Switchboard

Figure 4. PSpice schematic diagram of an arc fault temperature detector.

The AC input voltage, $V_{in}$, is ranged from 2.33 V (corresponding to -40°C) to 3.73 V (corresponding to 100°C) as obtained from Equation 1 and Equation 2.

$U_1$ is an op-amp, which represents a buffer in this circuit. The AC supply is connected to the positive feedback of $U_1$ and the negative feedback of $U_1$ is connected to the output of $U_1$ to produce a unity gain buffer. The output voltage of $U_1$ is same as the input voltage since it is a unity gain buffer.

Then, the output voltage of $U_1$, $V_{in'}$, is connected to the positive feedback (pin 3) of $U_2$, which is a voltage comparator. The output voltage of the buffer is used as the input voltage of the comparator. Theoretically, the input voltage of $U_2$ is identical to the output voltage of $U_1$ and is also identical to the output voltage of the temperature sensor, which is represented by an AC source in this circuit. uA741 op-amp is used as the voltage comparator. A DC input voltage, $V_{ref}$, of 3.65 V is placed at the negative feedback (pin 2) of $U_2$ to produce a constant value of reference voltage. The voltage value of 3.65 V is equal to the temperature value of 92°C.

A +9 V DC supply is connected to pin 7 and a -9 V DC supply is connected to pin 4 of $U_2$ to supply voltage for this component. Output voltage from $U_2$ (pin 6), $V_{out}$, is used to indicate the comparison result of the input voltage and the reference voltage.

4. Simulation and Experimental Results

The PSpice simulation result from the schematic diagram of an arc fault temperature detector is shown in Figure 5.

The straight line in green in Figure 5 represents the value of the reference voltage (pin 2) of $U_2$ which is set to 3.65 V. The waveform in yellow color is the AC input voltage of the circuit, $V_{in}$. The waveform in red color, which is the same as the waveform in yellow, is the output voltage of $U_1$, $V_{in'}$. The square wave in blue color is the output voltage of $U_2$, $V_{out}$.

The waveforms in red and yellow colors are the same because the input and the output voltages of the buffer are identical. The AC input voltage, which is indicated by the yellow color waveform, forms a sinusoidal wave and it is in the range of 2.33 V to 3.73 V. The output of the buffer, which is in red, is in the range of 2.33 V to 3.73 V as well. The output voltage of the buffer is then compared with the reference voltage of 3.65 V. From Figure 5, it is shown that for the portions where the yellow color waveform is higher than the straight line in green, the blue color square wave indicates a positive value, which is 4.061 V. Else; the blue color square wave indicates a negative value of -4.061 V. In other words, when the output voltage from $U_1$ is larger than the reference voltage of $U_2$, the output of $U_2$ produces a positive value which will trigger the trip indicator. However, when the output voltage from $U_1$ is smaller than the reference voltage, the output of $U_2$ produces a negative value which will not trigger the trip indicator. The trip indicator is responsible to send a signal to the circuit breaker in order to isolate the arc fault immediately to prevent further damages.

Figure 6 shows the circuit diagram of an arc fault temperature detector. LM335 temperature sensor IC is used to measure the temperature of the low-voltage switchboard environment and to produce the equivalent voltage output to the voltage comparator. Resistor R with value of 10kΩ is inserted between the supply voltage.
and LM335 to lower the current flow into the LM335 temperature sensor IC. The output potential of LM335 is connected to the non-inverting input of a high impedance input operational amplifier U1 to buffer it. Resistor R2 and variable resistor R3 play the role as a voltage divider to set the reference voltage to the inverting input of the voltage comparator U2.

The voltage comparator consists of a voltage divider and an operational amplifier. It is used to sound the buzzer once the LM335 temperature sensor IC detects a temperature more than 60°C which is equivalent to 3.33V (can be obtained using Equation 1 or Equation 2) at the output voltage of LM335. Therefore, the reference voltage for voltage comparator must be set at 3.33V by using the voltage divider resistors. The variable resistor R3 needs to be tuned to an appropriate value according to the calculation as shown below:

\[
V_{\text{ref}} = \frac{R_3}{1000 + R_3} \times V_{\text{cc}}
\]

\[
3.33 = \frac{R_3}{1000 + R_3} \times 9
\]

\[
\therefore R_3 = 587\Omega
\]

In order to obtain reference voltage of 3.33V, R3 must be set at 587Ω. The output voltage of the variable resistor is measured using the multimeter to set the equivalent reference voltage of 3.33V corresponding to 60°C and trigger the buzzer.

There are two transistors which are used to amplify the current signal so that it is sufficient to energize the coil inside the relay to operate the switching mechanism. The relay plays the role as a switch in the circuit. When output voltage of the voltage comparator is equal to Vcc, the voltage will energize the coil in the relay and close the normally open contact. The model of the relay used is HRS4 DC9V which requires 6.75V to operate the switch. The normally open contact is connected to the buzzer in order to sound the buzzer when signal from the voltage comparator energizes the relay coil.

According to EN 60439-1:1994 standard, a nominal rise of 60°C or more above an ambient of 40°C is allowed by provided that suitable precautions, such as plating, are taken. In practice, the maximum working temperature is limited to that of the insulation of cables connected to the bar – typically 90°C or 70°C\(^1\). Therefore to prevent the melting of conductors’ insulation and occurrence of arcing fault, the reference temperature of this proposed temperature detector is set below these temperatures, i.e. 60°C.

The hardware prototype of the arc fault temperature detector circuit is implemented to detect a reference temperature and sound the buzzer as shown in Figure 6. The 9V battery provides the supply voltage to the whole temperature detector circuit as shown in Figure 7. Two operational amplifiers are used as a buffer for LM335 temperature sensor IC and a voltage comparator. Electromagnetic relay is used as a switch to trigger the buzzer when output voltage of the LM335 temperature sensor IC is higher than the reference voltage.

### Figure 6.
Circuit diagram of arc fault temperature detector.

5. **Conclusion**

Arcing faults in low voltage switchboards is a serious issue as the effects of the arcing faults are devastating. In...
this paper, a temperature sensor in the propose arc fault temperature detector circuit is able to generate a voltage based signal with respect to the amount of temperature detected from the surrounding. The signal is then sent to a voltage comparator through a buffer to trigger the trip indicator. An early detection of arc fault in low voltage switchboard enable the isolation of the power supply to the consumer side just before the occurrence of arc fault and thereby reduce the danger to personal injury and building. In addition, it improves the system reliability without power interruption which is particular essential to hospitals and certain industries with sensitive loads.

6. References

1. Gammon T, Matthews J. The historical evolution of arcing-fault models for low voltage systems. IEEE Industrial & Commercial Power Systems Technical Conference; 1999 Aug; Sparks NV.
2. Hoyaux MF. Arc Physic. New York: Springer-Verlag; 1968.
3. Bruce Land H, Land HB, Eddins CL, Klimek JM. Evolution of arc fault protection technology at APL. John Hopkins APL Technical Digest. 2004; 25(2):140–53.
4. N’guessan K, Jouseau E, Rostaing G, Francois F. A new approach for local detection of failures and global diagnosis of LV switchboards. IEEE International Conference on Industrial Technology (ICIT 2006); 2006 Dec 15-17; Mumbai; p. 506–11.
5. Wikipedia, the free encyclopedia. 2009 Nov 20. Available from: http://en.wikipedia.org/wiki/Electric_switchboard
6. Wikipedia, the free encyclopedia. 2009 Nov 20. Available from: http://en.wikipedia.org/wiki/Low_voltage
7. Bruce Land H, The behavior of arcing faults in low voltage switchboards. IEEE Transactions on Industry Applications. 2008 Mar/Apr; 44(2):437–44.
8. Malmedal K, Sen PK. Arcing fault current and the criteria for setting ground fault relays in solidly-grounded low voltage systems. Industrial and Commercial Power Systems Technical Conference; Clearwater FL; 2000. p. 185–91.
9. Gammon T, Matthews J. Arcing fault models for low voltage power systems. Industrial and Commercial Power Systems Technical Conference; Clearwater FL; 2000. p. 119–26.
10. Muller P, Tenbohlen S, Maier R, Anheuser M. Artificial low current arc fault for pattern recognition in low voltage switchgear. Institute of Power Transmission and High Voltage Technology (IEH); 2009 Sep 14-16; Vancouver British Columbia Canada; p. 15–21.
11. Baliga BR, Pfender E. Fire safety related testing of electric cable insulation materials. Univ Minnesota; 1975.
12. Bruce Land H, Eddins CL, Klimek JM. Evolution of arc fault protection technology at APL. John Hopkins APL Technical Digest. 2004; 25(2):140–53.
13. Chapman D, Norris T. 2.0 Current-carrying capacity of busbars. 2015 May 28. Available from: http://www.leonardo-energy.org/sites/leonardo-energy/files/Cu0184-rating.pdf