

ARCING FAULTS AND THEIR EFFECT ON THE SETTINGS OF GROUND FAULT RELAYS IN SOLIDLY GROUNDED LOW VOLTAGE SYSTEMS

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Abstract-In the 1960's excessive burn down damage was documented on 480 (LL)/277 (LN) V systems due to arcing ground faults. To alleviate this problem in the 1970's the National Electrical Code (NEC) began to require ground fault protection in low voltage switch gear with continuous current ratings above 1000 A operating at more than 150 V phase to ground on solidly grounded systems. However, burn down damage and personal injury continues to occur. This paper will revisit the phenomenon of arcing faults on low voltage systems, provide a simplified technique to accurately estimate this arcing fault current, and will discuss the effects on the settings and types of relays, switches, and breakers utilized in 480/277 V switch gear.

INTRODUCTION

The most common type of fault on low voltage power systems involves phase to ground with arcing. Figure 1 shows the results of an arcing ground fault on a 2000 A, 480/277 V fused switch unit.

This switch board was installed in compliance with the National Electrical Code and was protected by a ground fault relay. An arcing fault was initiated when a #10 AWG wire accidentally touched the phase "A" bus and ground. The resulting arc damaged the equipment resulting in considerable downtime. The electrician involved suffered burns over 10% of his body requiring hospitalization and skin grafting.

The protective devices used were inadequate to properly protect either the equipment or personnel. Judicial selection of proper protective devices and correctly adjusting the ground fault relay can greatly reduce the possibility of such equipment damage and injury caused by similar arcing faults in low voltage systems.

*North American Power Symposium
Cleveland State University
Cleveland, Ohio
October 18-20, 1998*

ARCING GROUND FAULT PROTECTION

In low voltage systems, the 3-phase bolted fault (no fault resistance) current (usually the highest possible level)

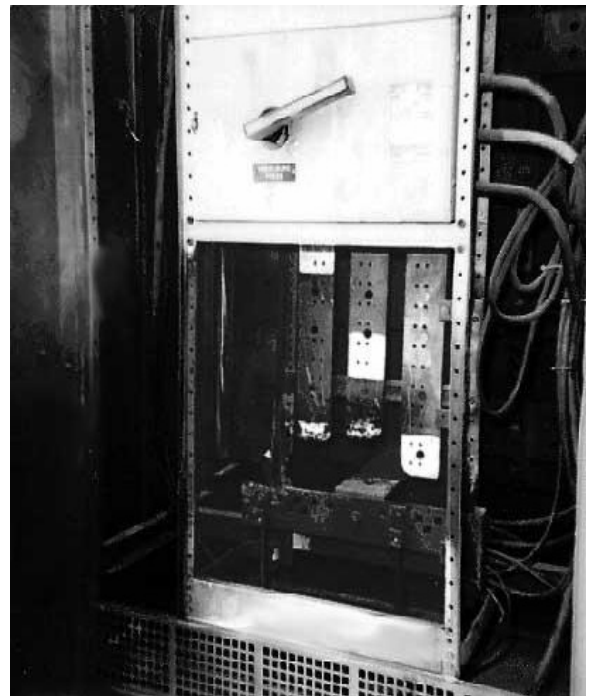


Fig. 1. Arc Damage to Buses on 2000 A Fused Switch Unit

is computed and the system is designed based upon this value. The equipment must be capable of withstanding and the protective devices must be able to interrupt this value of current. However, an arcing fault, in general, will result in much lower levels of current. Fuses and relays designed to operate at 3-phase bolted fault levels may not properly respond to these lower levels of current allowing the arcing fault to persist until severe burn-down damage occurs. It has been observed from years of experience that an arcing fault is usually more damaging than a bolted fault. In the case of a bolted fault the energy of the fault is dissipated by the whole system. However, an arcing fault dissipates the bulk of its energy in the arc, which may be only a few millimeters long.

The most common method of sensing any ground fault in low voltage systems is shown in Figure 2. The phase and neutral conductors are passed through the window of a

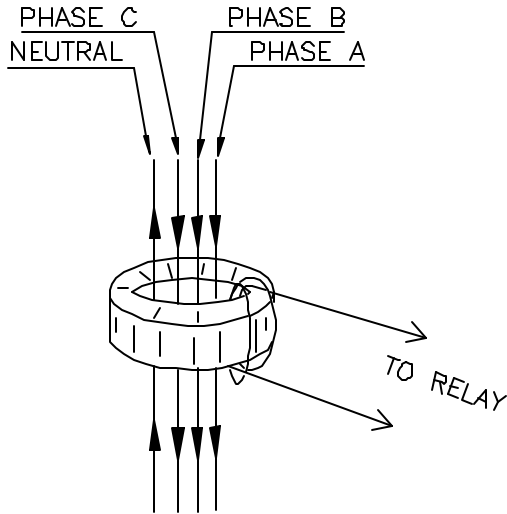


Fig. 2. Method of Sensing Ground Current

current transformer. Under normal operating conditions and for a 3-phase fault the vector sum of the currents passing through the transformer will be zero resulting in zero core flux, and hence no current to the relay. In the case of a ground fault current will flow through ground, resulting in core flux and current flowing to the relay.

The relay may be used to operate one of two types of protective devices: a circuit breaker (that can be shunt tripped) and a fused switch whose contacts can be released and allowed to open by a tripping signal from the relay. A low voltage circuit breaker can clear a fault within 1/2 cycle of receiving a trip signal whereas a fused switch requires 6 to 8 cycles to operate. In the 1000 A range the circuit breaker costs about \$1500.00 less than the fused switch.

The relay has two settings. The current setting, called the "pick-up" value, determines the minimum current that must flow before the relay will activate (the minimum pick-up value recommended by most manufacturer is normally between 100-200 A primary). The "time-delay" setting determines the amount of time the current must persist before the relay will operate. The characteristics are defined by a "time-overcurrent" curve. An instantaneous setting (with no intentional time delay) can be specified. However, the relay is most commonly supplied with a minimum time delay setting of 0.1 seconds. In the case of a relay-operated fused switch many manufacturer do not offer a relay without a minimum time delay of at least 0.1 seconds. In order to determine how these settings should be

adjusted, it is important to understand how the arc behaves during an arcing fault.

THE LOW VOLTAGE ARCING GROUND FAULT

It has been a common practice to model the arc path as a spark gap. The breakdown strength of air in the gap at standard temperature and pressure is approximately 30 kV/cm. Therefore, the spacing between conductors and ground in low voltage equipment should result in an arcing potential of several tens of thousands of volts. This potential must be overcome for an arc to initiate. This can happen when a conducting medium bridges the insulated gap between bare phase conductors and ground. It has been observed that the fault-initiating device will be repelled by the energy of the fault within 1/2 cycle. The arc that develops within this time ionizes the air in the gap and thus greatly reduces the sparking potential voltage of the gap. Vaporized metal from the cathode and anode further decreases the dielectric strength of the gap medium. The net result is that the original sparking potential of several thousand volts may be reduced to a few hundred volts.

At the first current zero the arc will naturally extinguish and the air will begin to de-ionize. If the rate of increase in gap sparking potential exceeds the rate of voltage rise on the next half cycle, the arc will not re-strike. If, at any time, the instantaneous voltage across the gap exceeds the gap sparking potential, the arc will re-strike, ionize the air in the gap, and become sustaining [3].

Figure 3 shows the arc conditions reported for a phase to ground arc on a 480V-system [1][2][3]. After arc

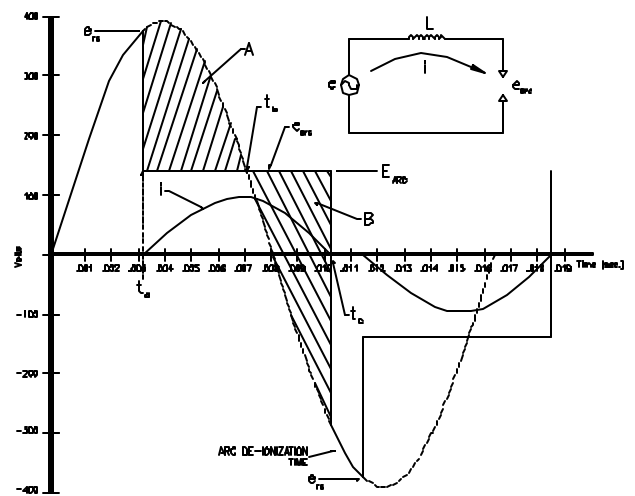


Fig. 3. Voltage and Current Conditions During the First 1/2 Cycle after Arc Initiation

initiation the first voltage zero crossover occurs at time $t=0$. Beginning at this point the voltage across the arc equals the system driving voltage. When the voltage reaches the value e_{rs} the arc will re-strike and the voltage will quickly decrease to the arc voltage E_{ARC} . Current, i , will begin to flow in the circuit and will increase as long as the driving voltage, e , exceeds E_{ARC} . When $e = E_{ARC}$ the current is at maximum and will begin to decrease. Mathematically [2][3][7] the current is proportional to volt-time area A minus volt-time area B for any time t . Therefore, when the volt-time area A equals the volt-time area B, as shown by the hatch mask, the current will be zero, the arc will extinguish, and the arc voltage will quickly equal the driving voltage again. If the driving voltage at this point is below e_{rs} the arc will not re-strike. When the voltage across the arc reaches e_{rs} once again the arc will re-strike on the negative half cycle which will be a mirror image of the positive half cycle. This results in a current wave and voltage wave across the arc that resembles Figure 4.

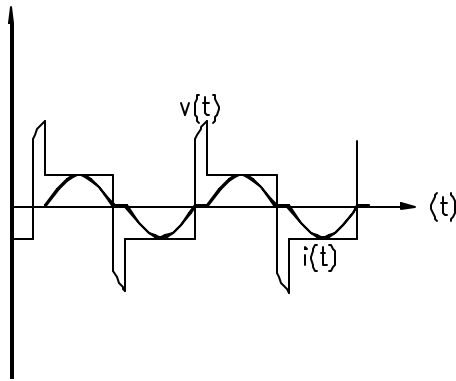


Fig. 4. Arc Current and Voltage Waves

For the arc conditions assumed in Figure 3, if the system voltage is greater than approximately 280 V_{rms} or the gap length is shorter, then the arc may re-strike immediately causing the current wave to become sinusoidal. This will happen when the arc voltage decreases to the driving voltage at the time the arc extinguishes, and the driving voltage immediately exceeds e_{rs} . It can also be seen in Figure 4 that the current is generally, although not entirely, in phase with the arc voltage. Therefore the arc impedance may be viewed, to a first approximation, as resistive in nature.

A mathematical expression for the arc current can

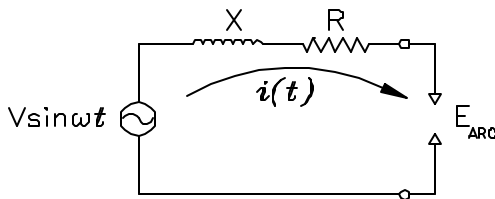


Fig. 5. Thevinin Equivalent Circuit with Arc Included

be derived using a simple mathematical model. A typical electrical system can be modeled by its Thevinin equivalent circuit. With the arc included, as shown in Figure 5, the current $i(t)$ can be calculated for the first half cycle as:

$$i(t) = \begin{cases} 0 & \text{for } t \leq t_a \\ \frac{V}{Z} \left[\sin(\omega t - a) - e^{-\frac{R\omega}{X}(t-t_a)} \sin(\omega t - a) \right] - \frac{E_{ARC}}{R} \left(1 - e^{-\frac{R\omega}{X}(t-t_a)} \right) & \text{for } t > t_a \end{cases}$$

$$\text{Where } a = \arctan \frac{X}{R} \quad (1)$$

$$Z = \text{System Impedance} = R + jX$$

$$X = \text{System Inductive Reactance}$$

$$R = \text{System Resistance}$$

In order to calculate the value of i two parameters are needed beyond the circuit constants: the value of E_{ARC} , the arc voltage, and the value of t_a , the time after the first zero crossover when the arc re-strikes.

ARC VOLTAGE

Figure 6 shows the cross section of a typical arc, which can be divided into three distinct regions.

1. The cathode (cathodic spot)
2. The positive column
3. The anodic region

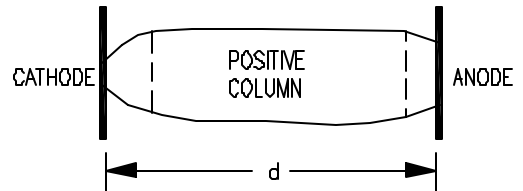


Fig. 6. Typical Arc Cross Section

The arc is slightly constricted at both anode and cathode. This constriction produces a greater voltage drop per unit length than the drop across the positive column. The voltage across the positive column is primarily a function of arc length, whereas the voltage drops across the anodic and cathodic regions are primarily functions of electrode materials. The sum of the anodic and cathodic drops has been found to be [6]:

1. 32 V for Al-Al and Cu-Steel
2. 36 V for Cu-Cu
3. 30 V for Steel-Steel

Once the arc is fully established the total arc voltage is relatively constant and is practically independent of the level

of current through the arc. The positive column voltage gradient has been reported to be between 16 and 24 V/cm. Equation (2) has been suggested as a simple method of

$$E_{ARC} = 36 + 2.4d + 3.2 \times 10^{-3} I_p \quad (2)$$

determining E_{ARC} (V) where d is the length of the arc in millimeters and I_p is the available three-phase fault current (A) at the point of the arc.

RE-STRIKE VOLTAGE

Determination of re-strike voltage, e_{rs} , is often difficult since it depends on many factors, most of which involve the rate of gap de-ionization, such as:

1. Gap length
2. Position and nature of the cathodic spot, and
3. Any outside disturbances that tend to cool the arc.

Circuit parameters such as inductance, resistance, and capacitance values are also important factors that determine the re-strike voltage.

Without knowing the precise conditions under which the arc exists, it is very difficult to accurately determine the re-strike voltage, and therefore determine the current flowing in the circuit. However, from a practical standpoint, it is only necessary to determine the minimum possible value of current that may be expected in the circuit. If the relays and other protective devices can respond to the minimum value of current, they should be able to respond to all higher values, and the system should be protected.

In order to determine the re-strike voltage that will produce the minimum value of current, it may be seen from Figure 3 that the minimum current occurs when the re-strike voltage is at maximum. This would make the value of t_a the 1/4 cycle time, 0.0042 sec. Using this value in equation 1 along with the value of E_{ARC} found by applying equation 2 will yield the arc current. The rms value of the solution to equation 1 determines the current value which protective relays and other protective devices in the system must respond to.

AN ARCING FAULT EXAMPLE

Figure 7 depicts the Thevinin equivalent circuit for the system discussed in Figure 1. The arc length is assumed to be the length of the bus insulators, approximately 50-mm. The maximum 3-phase fault current, I_p , is calculated to be 17,856 A (14.8 MVA). The calculated arc voltage, using equation (2) is approximately 213 V. Assuming a maximum

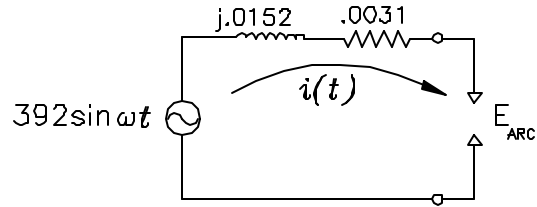


Fig. 7. Thevinin Equivalent Circuit of the System Discussed in Figure 1.

re-strike voltage of $392 (277\sqrt{2})$ V, Figure 8 shows the current wave as obtained from equation (1). The rms value of this current is 4,478 A. In order to properly detect and

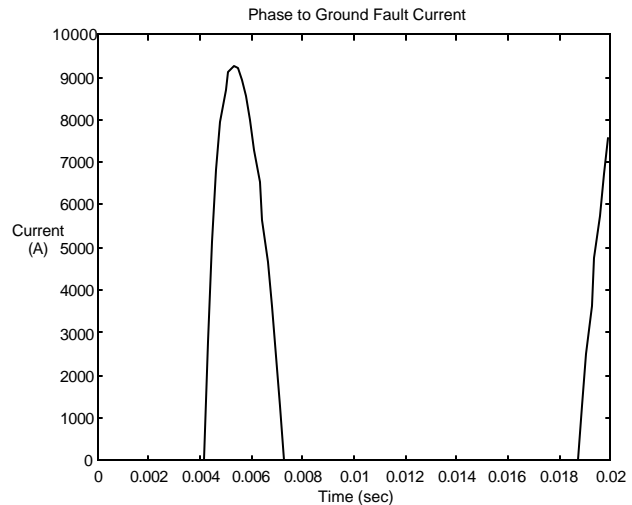


Fig. 8. Current Wave of Arcing Fault Example

respond to this level of fault current, the ground fault relay pickup current setting must be set below 4,478 A.

In order to determine the time delay setting of the relay, it is important to understand the effects the arc flash has on the human body. The greatest hazard of this type of burn occurs in the main service switch gear where the available arcing current is greatest. It is desired to provide a relay setting which will protect a worker from injury, should an arcing fault be accidentally initiated while the equipment is being inspected or serviced.

The following equation (3) has been suggested [13] [14] to determine the length of time at a certain distance a human can be exposed to the heat of an electric arc without

$$t = \frac{D_c^2}{2.65 \times MVA_{BF}} \quad (3)$$

incurable burns. D_c is the distance from the arc (ft),

MVA_{BF} is the maximum 3-phase bolted fault MVA at the point of the arc and t is time in seconds. Assuming a distance of 1 ft from energized busses and using the bolted fault level of 14.8 MVA for the system shown in Figure 7, the calculated maximum time of exposure is 0.025 seconds or about 1.5 cycles. To prevent incurable burns within 1 ft of the arc, the fault must clear within 1.5 cycles. In the system shown in Figure 1, the relay pick-up was set at its minimum current setting of 200 A, which is below 4,478 A.

The fused switch and relay utilized in the design were inadequate in protecting equipment or personnel. The relay used had a minimum time delay of 0.1 seconds and the fused switch required 6 to 8 cycles to operate after receiving the trip signal. The total clearing time, 12 to 14 cycles, exceeds the calculated clearing time of 1.5 cycles. To properly clear the fault a 1/2 cycle circuit breaker coupled with a ground fault relay with a time delay setting of less than one cycle should have been specified.

CONCLUSIONS

To safely clear an arcing ground fault without any injury and equipment damage the correct circuit-interrupting device and ground fault relay must be specified. Proper delay time and pickup current settings must be provided to enable the protection scheme to properly detect arcing faults while not allowing nuisance tripping.

In order to specify and calculate proper settings for ground fault relays used in low voltage systems, the following steps are recommended:

1. Estimate the likely minimum arc length. The bus to ground distance in the panelboard or switch gear may be used.
2. Calculate the bolted 3-phase fault current and MVA.
3. Calculate the arc voltage, E_{ARC} , using the equation (2).
4. Calculate the possible minimum arcing fault current (rms) as far from the service entrance as necessary using equation 1.
5. Set the relay pick-up current to 80% of the current calculated in step 4.
6. Calculate the maximum time duration a worker can be exposed to this level of current without serious injury using equation (3).
7. Set the breaker time delay setting faster than the time calculated in step 6. In most cases, only a circuit breaker coupled with an instantaneous relay will operate quickly enough to protect personnel from arc flash injury.

The requirements for ground fault protection included in the National Electrical Code after 1971 have reduced the burn down damage witnessed on 480/277 V systems before the implementation of the rule. However, the requirements of the NEC are still inadequate in preventing damage to equipment and personnel. The NEC allows a wide latitude in the setting of ground fault protective devices. Also, the general rule of protecting against "excessive damage" due to fault currents is difficult to apply in the case of arcing faults since the withstand ratings of equipment to arcing faults is impossible to determine. It is suggested that the criteria for adjusting the settings of ground fault sensing devices should be based upon the maximum allowable exposure of personnel to the arc flash. This is a stricter guideline than that included in the NEC, but has the advantage of minimizing damage to both personnel and equipment resulting from arcing faults.

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