ARC FLASH ANALYSIS

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ABSTRACT

I chose to do my senior design project on the topic of Arc Flash Analysis. The last few years have developed a great increase in the awareness of arc flash hazards. The analysis is applied to the overall electrical system of utility companies. The purpose of the study is to develop the best way to limit the amount of an arc flash a lineman can be exposed to while doing maintenance in the field. The National Electric Safety Code (NESC)-2007 Rule 410 states "employers shall ensure that an assessment is performed to determine the potential exposure to an electric arc for employees who work on or near energized parts or equipment. If the assessment determines a potential employee exposure, greater than 2 cal/cm² exists, the employer shall require employees to wear clothing or clothing systems that have an effective arc rating not less than the anticipated level of arc energy." Electricity has proposed a serious hazard since its discovery by Benjamin Franklin. Why though, after over a hundred years, is the awareness of this hazard drawing so much attention?

Arc flash analysis can propose a serious problem to utility companies. Most injuries that occur out in the field with lineman who work for power utility companies don’t result from electrocution, but rather from an arc flash. Over the years, these companies install protective devices all throughout a system. However, much effort, time and cost is involved to ensure these protective devices coordinate with other devices and are used to their best efficiency. These protective devices cannot be changed instantaneously to help arc flashes. One job of a consulting engineer is to calculate the arc flash incident energy at the point of contact. It then can be determined if the up line
protective device is adequate, or if a recommendation to their protective devices needs to be applied.

This study has shown that a procedure can be implemented for utility companies. Steps and procedures were developed to perform an accurate arc flash analysis. However, is this the best method that can be used? How accurate are these calculations? Although it has been learned that there isn’t a 100% right solution, an accurate and reliable analysis can be created. Future work for this study will be to come up with the most accurate and reliable method.
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Introduction:

With the development of technology, society has seen an increase in benefits. Things have become easier, more precise, and satisfying. Technology has brought a significant increase to the world of power and electricity. Arc Flash injuries have been a concern since the discovery of electricity. So why is it that these hazards are only drawing high attention over the past few years? A primary reason is the high increase in magnitude and volume to electricity being generated over the world. Many companies are requiring more power and higher voltages. Probably the most important reason is the increased need to perform work on energized equipment. If a line has to be de-energized in order to perform maintenance, then buildings and homes must go without power. This provokes not only a loss in revenue for the Power Company, but can upset many customers. The exponential increase in technology has made it difficult for companies to keep up with training standards to keep employees aware of the risk of arc flash hazard. The last important reason arc flash hazards have become a concern is the increase in liability from lawsuits. Companies are adopting procedures and methods relating to arc flash hazards not only to provide safety to their employees, but the company as well.

The focus of this study will be on the distribution side of the power utility system. This is the final stage of delivery of power to end consumers. A distribution system carries power from the transmission system and delivers it to its consumers. The diagram below shows how power is developed starting at a power plant, traveling to transmission lines where it feeds into a power substation. The power substation downsizes the voltage (typically from 69k volts to 12.47k volts). Here power is traveled
throughout the town until it reaches the transformer drum and downsized (typically from 12.47k volts to 480 volts). Here power is supplied to houses and commercial industries.

According to the NESC an arc flash is the result of a rapid release of energy due to a short between two conductors, or conductor and ground. The arc flash is not the direct short between two conductors but rather it is the arc created in the air after a short circuit occurs. During an arc the air acts as a conductor. This develops problems for utility companies who have lineman working on energized equipment. Majority of accidents that occur in power utility companies are not from the result of electrocution, but instead from an arc flash. Why is an arc flash important to understand? It can kill you!
Arc Flash Characteristics

**How might an arc flash occur?**

Arcing fault current can be easily created through poor electrical contact, failed insulation and carelessness. There is no way to eliminate arc fault hazard when working on an energized line, but we can decrease the amount of energy dissipated from an arc and the injury it can create to a lineman.

**What are the results from an arc flash and why is it such a great concern?**

Injury is the primary reason we are focused on studying the system analysis of arc flashes. Temperatures up to 35,000 degrees Fahrenheit are created at the point of contact (4 times greater than the sun)! Upon contact molten metal is blasted forward from terminal material resulting in serious burns to victims. A large shockwave is produced that could throw a human off ladders or against walls. The light developed from a flash contains UV rays that can cause blindness. The sound pressure from a blast is enough to cause serious ear injury. If an arc occurs and a worker is in close proximity, the survival rate of the worker is dependent upon the following:

**Dependents of Survivability from Arc Flash**

1. **Clearing time**—time of the over current protective device to operate. It determines how fast the device will create an open in the circuit and clear arc fault.

2. **Magnitude**—amount of arc fault current created.

3. **Distance**—length worker is away from point of contact (arc).

4. **Personal Protective Equipment (PPE)**—clothing material worker is wearing to protect him or herself.
Units of Measurement

There are two different units in measuring an arc flash. A joule is a standard unit of energy in general scientific application. 1 joule = 1 watt/second of dissipated energy. A calorie is a unit of heat and is a form of kinetic energy. It takes 1 calorie of heat energy to raise one gram of pure liquid water 1 degree Celsius.

1 calorie = 4.1868 joules 1 joule = 0.2388 calorie

Degree of Burns

1<sup>st</sup> degree burns: Affects outer layer of skin. It can be painful, but it is usually not permanent or life threatening.

2<sup>nd</sup> degree burns: Causes tissue damage. Creates blistering to the skin. It also destroys outer skin layer.

3<sup>rd</sup> degree burns: Causes complete destruction of skin. Small areas may be recovered through skin graphs.

Arc flash protection is aimed to limit the injury to no more than a 2<sup>nd</sup> degree burn. Even though this is the goal for a system study, it can still cause a serious burn. 1.2 cal/cm<sup>2</sup> is the threshold of 2<sup>nd</sup> degree burns.

Definitions

Arch Flash Hazard- Dangerous condition associated with the release of energy caused by an electric arc.

Arc Fault Current- Fault current flowing through electric arc plasma.

Available Fault Current- The electrical current that can be provided by the serving utility and facility-owned electrical generating devices and large electric motors, considering the amount of impedance in the current path.
**Bolted fault current**- Electrical contact between two conductors at different potential in which the impedance or resistance between the conductors is essentially zero.

**Arc Fault Current**- Current that flows from a conductor to either ground or another conductor when energized, due to an abnormal condition.

**Flash Hazard Analysis**- Method used to determine the risk of personal injury as a result of exposure to incident energy released from an electrical arc flash.

**Incident Energy**- Amount of energy impressed on a surface, a certain distance from the source, generated during an electrical arc event.

**Shock Hazard**- Dangerous condition associated with the possible release of energy caused by contact or approach to energized parts.

**Voltage (nominal)** - Nominal value assigned to a circuit or system for the purpose of conveniently identifying its voltage class.

**Working Distance**- Distance between possible arc points and the head and body of the worker positioned in place to perform the assigned task

**Arc Gap**- Distance between two contacts where possible arc(s) can arise. When high voltage is applied to the gap, an arc has the possibility of crossing between two conductors.

**Clearing Time**- Amount of time it takes for an over current protection device to clear once fault occurs and protective device settings are past their settings. An example is below.
The previous graph shows a Time Current Curve (TCC) chart. It denotes the time (located on “y” axis) in seconds and the current amount (located on “x” axis) in amperes. The graph shows the curve settings of an 85 “T” fuse. Notice that as the fault current increases, it takes less time for a fuse to clear. The bottom line of the black curve indicates the time a fuse begins to melt. After a short amount of time, at same fault current, the top line is reached. This line indicates the complete melting time of fuses for which circuit is open and arc flash has diminished.
Steps Necessary to Prepare for an Arc Flash Analysis

1. Review the existing data
   a. Existing sectionalizing/fault current study
   b. Substation size/impedance/voltage/grounding configurations
   c. Source impedance of transformers
   d. Breaker/recloser settings

2. Collect new data (by substation area)
   a. Update source impedance
   b. Update substation size/impedance
   c. Update engineering software model
   d. Locate large 3 phase pad mounted transformer locations
      i. Since pad mount transformers are in an enclosed area they
         produce more energy to a lineman compared to an open aired
         transformer where the energy is dissipated to open air.
   e. Update all recloser/breaker settings, TCC opening/closing times etc
   f. Fuse information: manufacturer, type, size/rating, speed
      (standard/slow), and current limit of fuse.
   g. Relays: Are they electronic or mechanical? Need type, manufacturer,
      settings, current transformer rating, and opening/clearing times.
   h. Transformer Data: kVA rating, primary/secondary voltage, impedance
      percentage, connection configuration (Y-Y or Delta-Y)
i. Engineering model: Need all circuit configurations, wire size/section lengths, operating voltages, and circuit configuration

3. Determine Personal Protective Equipment Settings (see above Arc-flash Hazard Category table).

4. Conduct an Analysis Report:
   a. Report should contain data collected from utility companies including: Substation names, transformer sizes, primary/secondary voltages, working distance, available bolted and arcing fault current, incident energy level, and risk category for each scenario.

Incident Energy Calculations (IEEE1584):

To determine the incident energy at the worker location:

- Incident Energy = \( 4.184 \times C_f \times E_a[(t/0.2) \times (610^X/D^X)] \)
- \( \log(E_a) = k_1 + k_2 + [1.081 \times (\log(I_a))] + 0.0011G \)
- \( E_a = 10^{(\log E_a)} \)
- \( E_a \) is normalized for 0.2 sec. and 610 mm gap. For actual Incident energy………..
- Incident Energy = \( 4.184 \times C_f \times E_a[(t/0.2) \times (610^X/D^X)] \)

\( I_a = \) Arcing fault current in kA
\( G = \) conductor gap in millimeters (mm)
\( K1 = \) Open air or in a box factor
\( K2 = \) ground/ungrounded factor
\( C_f = \) calculation factor
\( t = \) arcing time in seconds
\( X = \) Distance exponent
Arc Flash Analysis Calculations:

The following illustration shows a Milsoft model being used to calculate the incident energy that a lineman could be exposed to.

<table>
<thead>
<tr>
<th>Working Distance (mm)</th>
<th>431.80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arcing Fault (amps)</td>
<td>5027.04</td>
</tr>
<tr>
<td>Arc Flash Energy (joules)</td>
<td>57.34</td>
</tr>
<tr>
<td>Arc Flash Clearing Time (sec)</td>
<td>0.89</td>
</tr>
</tbody>
</table>

The previous example shows the calculations for distribution transformers. The substation is providing 12.47k volts to a distribution transformer. Here the 12.47k volts are stepped down to 480 volts, which is supplied to a commercial building. A 30-amp fuse is currently protecting the transformer since the current carrying capacity of transformers is 23.2 amps. The bold black circle simulates a lineman working on the secondary side of transformers. Power remains constant through a transformer. Since the equation for power is P=volts x amps, if the voltage decreases the amperage must increase providing more danger to the lineman. The calculated data box shows results of what happens if a lineman creates a short circuit while doing maintenance. With a distance of 431.8mm (17 inches) between point of contact and worker’s face/body and
arcing fault current of 5.027k amps, there are 57.34 joules (13.704 cal/cm²) of energy exposed to the lineman. The following chart shows the hazard category levels as a function of incident energy. 13.704 cal/cm² has a risk factor of 3.

**Hazard Category as a Function of Incident Energy**

<table>
<thead>
<tr>
<th>Arc-flash Hazard Category</th>
<th>Minimum cal/cm²</th>
<th>Maximum cal/cm²</th>
<th>Risk Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>1.2001</td>
<td>4</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>4.001</td>
<td>8</td>
<td>25</td>
<td>2</td>
</tr>
<tr>
<td>8.001</td>
<td>25</td>
<td>40</td>
<td>3</td>
</tr>
<tr>
<td>25.001</td>
<td>40</td>
<td>No maximum</td>
<td>X</td>
</tr>
</tbody>
</table>

**Improvements/Recommendations**

After reviewing the chart of “Hazard Category as a Function of Incident Energy”, we can see that this provides a risk category of 3. If the goal is to try and maintain a category of 2 or lower some recommendations are applied. The following illustration shows transformers being protected by a 70-4H hydraulic recloser.
It can be seen that the working distance and arc fault current remain constant. However, the incident energy and clearing time of reclosers have decreased substantially, providing incident energy levels of 18.59 joules (4.4441cal/cm²). After reviewing the chart we can see that this puts us at a risk category of 2. Reclosers act differently than fuses in that they can operate on an instantaneous setting where as a fuse has melting time. Reclosers are much more precise in reactance time and helps reduce incident energy levels extremely.

**Arc Flash Boundary**

A perimeter must be set up around an area where maintenance is being done on energized equipment. The perimeter is measured as distance from energized part. Only qualified personnel must cross this boundary. Unqualified personnel may not cross boundary unless escorted by a qualified person. The same PPE is required in this boundary as if direct contact is made with live part. This is done to maximize safety and minimize possible arc flash.

**Arc Flash Boundary Formula**

\[ Dc = \left[2.65 \times MVA_{bf} \times t\right]^{1/2} \]

- \( Dc \) = Distance in feet of person from arc source based on limit of having incident energy of 1.2 cal/cm²
- \( MVA_{bf} \) = Bolted fault current in Mega volts at location of maintenance.
- \( T \) = time of arc exposure measured in seconds

Example: *What is the flash protection boundary for the secondary side of a 3,750kVA transformer rated at 480 volts line to line with short circuit current of 50,000 amps and clearing time of 0.1 seconds (6 cycles)?* The utility company provides this
information. 6 cycles is the standard instantaneous time of protective device to operate.

\[
MVA_{bf} = [50,000 \text{amps} \times (1.74)^{1/3} \times 480 \text{volts}] = 41.57 \text{ MVA}_{bf}
\]

\[
Dc = [2.65 \times 41.57 \text{ MVA}_{bf} \times 0.1 \text{sec}]^{1/2} = 3.319 \text{ feet}
\]

**Economic Tradeoff**

As previously stated, it shows no question that a company might want to install a recloser into their system to help the efficiency of arc flash hazards. However, is the economic tradeoff worth the safety? The costs of fuses and reclosers, along with their labor charges, are listed in the table below.

<table>
<thead>
<tr>
<th>Fuse vs. Recloser</th>
<th>Material Cost(per phase)</th>
<th>Material Cost(all three phases)</th>
<th>Cost of Installation</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>FUSE</td>
<td>$150</td>
<td>$450</td>
<td>$150</td>
<td>$700</td>
</tr>
<tr>
<td>RECLOSER</td>
<td>$1,500</td>
<td>$4,500</td>
<td>$450</td>
<td>$4,950</td>
</tr>
</tbody>
</table>

These values do not include the cost to maintain these protective devices. Reclosers have the capability to reclose on their own in the event a fault is cleared, such as a tree branch falls on a power line. A fuse would stay open until a maintenance crew came out to replace the fuse. Also, a recloser has the capability of being installed further up line from the transfer and therefore is able to protect possibly 3 or 4 transformers. So in this scenario we have one recloser protecting 4 transformers vs. 4 transformers being protected by 4 different fuses. The initial cost of installing three reclosers (one recloser per phase) with labor is approximately $5000. The cost of installing three fuses (one fuse per phase) with labor is approximately $700. Since reclosers can reclose on their own, no replacement or labor charges were affected after initial installation.
It can be seen that in order to have the recloser payoff the economic value of the fuses, the fuses would have to blow and be replaced after 7 times. Utility companies have to determine if this is feasible. If a company is looking to improve their system through arc flash incidents, then yes, they might want to invest their money by installing reclosers. If the company wants to invest their money in other areas of the industry, then they may want to pass on this opportunity and replace the fuses.

**Conclusion:**

An arc flash assessment for a power systems utility company can be a complicated process. For recommendations, much more detailed analysis must be provided that is out of the scope of this report. Conducting this report I have learned that you cannot just jump into a project and focus only on the next step. As an example when recommending reclosers, the decision can’t be made just on the arc flash assessment side, but affects on the system as a whole need to be considered. Every protective device in the system needs to coordinate with each other in relation to timing. You don’t want protective devices upline clearing before protective devices down line do. This will
cause unnecessary outages and provide no purpose for the down line protective devices. I also learned that although it may be easy to consider installing reclosers numerously throughout the system, the economic tradeoff is not worth it.

There is room for much improvement when it comes to arc flash analysis. My goal for next year will be to provide better support for arc flash analysis. This will include specific tasks such as:

System evaluation - How does secondary 120/208 volts compare to 277/480 volts during an arc flash?

Transformer design - How does an open-air transformer compare to in-a-box transformer during an arc flash?

Protective Devices - What type of protective devices work most efficiently during an arc flash?

A majority of the injuries that occur in power utility companies are not the result of electrocution, but rather from an arc flash! This is a new problem to the electrical engineering world but something that needs to be resolved or else more injuries will occur. Results from improvements suggested by an arc flash analysis will not only save lives, but also save a company from economic tragedy in the event of lawsuit or equipment damage. Upon final completion of my project I plan to provide a reliable method to conduct an arc flash analysis; a benefit not only to myself, but also to the power industry as a whole.
Sources


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