Methods of determining safety boundary and PPE by analysing arc-flash incident energy in medium voltage panels

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Abstract. Arc-flash events still occur frequently in industries especially in Indonesia and there are many operators and technicians have got burn injuries caused by it. To avoid this accident, this paper discus about arc flash and its incident energy as well as personal protective equipment (PPE) should be worn by those working with electric panels (switchgears). To demonstrate how incident energy is calculated and the protection boundaries are determined, a 6 kV, 3750 kVA utility panel in a geothermal power plant (60 MW) is used as object. The steps have to be done in this research are bolted fault current and arc fault current calculations, calculation of incident energy and determining both protection boundaries and the relevant PPE. As result, it is found that with protection setting clearing time of 0.12, the incident energy is 4,418 J/cm² and the protection boundary is 1.4 m. The danger will increase with longer clearing time of relay or closer distance to the panel. This paper will hopefully be very help full for the responsible engineers to analyse the danger of any kind of panels and to determine PPE for workers.

1. Introduction
Incident Energy is a term used for energy released when the Arc flash occurs at electric panels.

There are still many workers experience burn injuries or even death caused by arc-flash. For examples, in the US, every day there were 5-10 blast events caused by arc flash, similarly in shipbuilding, 6 electricity vessel fires per year [1], so as in Indonesia. Arc-flash incident energy develops very high temperature that can reach 19,600 °C. It can expand the air and vaporize explosive metals such as copper which can cause a great explosion or arc blast. Conventional protection systems such as relays, breakers are considered unable to guarantee the safety of human beings around the point of faults.

Many paper discussed about this mater, but there is still very rare that discuss comprehensively to define incident energy in a particular situation or condition. This paper will discuss comprehensively how to analysis arch flash incident energy in a particular panel (switchgear) and network system.

1.1. Arc-flash and incident energy
Arc-Flash is an undesirable discharge of electrical energy through the air in a closed switchgear panel. There are two types of Arc flash: series and parallel. The series arc flash is arc flash that is connected in series with loads, while the parallel arc flash is parallel to the load [1]. In the series arc-flash the flowing current is limited by the load. This current is lower than the breaker or fuse settings so, the fault is not detected by protection equipment as an error.
Consequently, the arc will not die and will increase the ambient temperature or cause arc flash on the other parts of equipment which can cause arc-blast. The parallel arc-flash occurs between line to ground/neutral or line-line, therefore, the fault current will be similar to zero impedance short-circuit (bolted fault current) and it can be detected by protection equipment. Arc-fault current is a resistive fault occurring between conductors while a short circuit current is the highest current supplied by the source [2,3]. This study uses the parallel arc-flash type as object of analysis since it can’t be prevented by protection systems and is more harmful.

Incident Energy is the energy released by an electric arc (arc-flash). This incident energy will determine the effect of arc-flash, the higher incident energy, the higher effects. Factors which determine the rate of incident energy are the voltage, the fault current, the distance from the point of faults and the duration of the arcing. To determine the incident energy, it needs to know the arc current or fault current generated by arc flash.

1.2. Bolted fault current calculation
Since the type of arc flash addressed in this study is the parallel arc-flash, therefore, it needs calculation of bolted current as used for short circuit current in networks, using equation:

\[
I_{\text{f3} \Phi} = \frac{V_{L-N}}{Z_1}
\]  

(1)

\( I_{\text{f3} \Phi} \) : 3 – \( \Phi \) short circuit current (A)  
\( V_{L-N} \) : line to neutral voltage(V)  
\( Z_1 \) : positive sequence impedance (\( \Omega \))

1.3. Arc-fault current calculation
There are two methods to calculate arcing fault-current, i.e. for low voltage (\( V < 1000 \) V) and high voltage (\( V > 1000 \) V) system [4].

- For low voltage:
  \[
  \log(I_a) = K + 0.662 \cdot \log(I_{bd}) + 0.0966 \cdot V + 0.000526 \cdot G + 0.5588 \cdot V
  \]
  \[
  (\log(I_{bd})) - 0.00304 \cdot G \cdot (\log(I_{bd}))
  \]

(2)

- For high voltage:
  \[
  \log(I_a) = 0.00402 + 0.983 \cdot \log(I_{bd})
  \]

(3)

where:  
\( I_a \) : arcing current (kA)  
\( K \) : 0.153 for open configuration  
- 0.097 for closed configuration panel  
\( I_{bd} \) : 3 – phase symmetrical bolted fault current (kA)  
\( V \) : voltage (kV)  
\( G \) : distance between conductors (mm)

From this equation it is obvious that the arc-fault current is determined by the bolted fault current.

1.4. Incident energy normalized
Standard states that to determine the incident energy, it needs firstly, to compute the incident energy normalized [5]. Incident Energy normalized is an empirical formula based on the statistical analysis related to the released energy on an arc-flash event with the duration of 200 ms and the distance between the arc-flash and calorimeter is 610 mm. This energy is calculated by using the equation

\[
\log(E_n) = K_1 + K_2 + 1.081 \cdot \log(I_a) + 0.0011 \cdot G
\]

(4)

where  
\( E_n \) : incident energy normalized (J/cm\(^2\))  
\( K_1 \) : 0.792 for open configuration  
- 0.555 for closed configuration (panel)  
\( K_2 \) : 0 for ungrounded system and high resistance  
- 0.113 for grounded system
1.5. Incident energy

Incident energy is obtained by converting the incident energy normalized. In this conversion it involves some factors, namely: calculation factor \( C_f \), distance factor between the point of fault and human \( D \) and distance exponent \( x \) using equation:

\[
E = 4.184 \cdot C_f \cdot E_w \cdot t^\frac{1}{0.2} \cdot \frac{610^x}{D^x}
\]

where:
- \( E \): incident energy (J/cm²)
- \( C_f \): calculation factor
  - 1.5 for low voltage (< 1kV)
  - 1.0 for medium voltage and higher
- \( D \): distance from faulty point to human (mm)
- \( x \): distance exponent

1.6. Flash protection boundary

Flash protection boundary is calculated by equation as introduced by [ibid] that refers to the magnitude of the incident energy:

\[
D_B = \left[ 4.184 \cdot C_f \cdot E_w \cdot t^\frac{1}{0.2} \cdot \frac{610^x}{E_B} \right]^{\frac{1}{x}}
\]

where \( D_B \): safe distance from arcing point (mm)

NFPA70E-2004, Standard for Electrical Safety in the Workplace, has been performing electrical hazard analysis and has given an illustration about approach boundaries as illustrated in Fig. 1 to understand the electrical shock and electrical arc-flash hazard protection [6].

![Figure 1. Approach boundary.](image_url)

2. Method of analysis

There are 6 steps needed to solve this issue as follows:

- Electrical system and installation data identification.
- Impedance calculation of individual component and networks with respect to point of fault.
- Determination of bolted fault (short circuit) current.
- Determination of arc fault current.
- Incident energy determination.
- Determination of protection boundary and PPE.
3. Results and discussion

3.1. Data of electrical system and installation
Electrical system of the power plant is shown in the single-line diagram in figure 2. The main generator (60 MW, 15 kV) is connected to the 150 kV transmission network through the generator step up transformer 15/150 kV, 85 MVA (EE-MT-1). The generator supplies auxiliary loads of the power plants through three unit auxiliary transformers (UAT’s): EE-TX-1A for auxiliary high power loads, EE-TX-1B: for Motor Control Center (MCC) A, and B; EE-TX-1C: for Motor Control Center (MCC) C, dan D.

![Single-line diagram and components’ specification.](image)

The single diagram shows data impedances of main components (generator, transformers) as well as impedances of loads and cables. Since it will determine the result of analysis, all impedances must be identified carefully and accurately. The short circuit currents are mainly from generator and the utility and some from dynamic loads. The panel used as a research object is a 6 kV (SG-2) medium voltage panel as shown.

3.2. Bolted fault current analysis
According to the standard, the bolted fault current (Ibf) is the same as the three-phase, symmetrical short-circuit current at the point of fault as was stated above [5]. Calculation can be done manually (very tedious) or using application tools. Short circuit analysis by ETAP software is shown in figure 3.
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Figure 3. The point of fault position (bus SG-2).

The short circuit current is addition from mainly the bus transformer EE-TX-1A, the utility (1.638 kA),
generator (0.7 kA), MCC-1A (1.278 kA) and from motor loads (2x0.012 kA), total short circuit current
is 7.181 kA.

3.3. Calculation of arcing fault current
Arcing fault current for 6 kV panel can be determined as:

\[
\log(I_a) = 0.00402 + 0.983 \cdot \log(I_d)
\]

\[
\log(I_a) = 0.00402 + 0.983 \cdot \log(7.181)
\]

\[I_a = 10^{0.046} = 7.011 \text{ kA}\]

The arcing fault current is slightly smaller than the current short circuit current due to the slight higher
impedance.

3.4. Calculation of incident energy normalized and incident energy
The incident energy normalized is calculated using:

\[
\log(E_n) = K_1 + K_2 + 1.081 \cdot \log(I_d) + 0.0011 \cdot G
\]

Since the equipment is in a panel and grounded, so, the \(K_1 = -0.555\) and \(K_2 = -0.113\). The distance
between the bus conductor’s G can be selected from Wellman (Factors for equipment and voltage class)
(IEEE Std 1584-2002) with \(G = 153\) mm. So, the incident energy normalized will be [4]:

\[
\log(E_n) = (-0.555) + (-0.113) + (1.081 \cdot \log (7.011)) + (0.0011 \times 153)
\]

\[= 0.4145\]

\[E_n = 10^{0.4145} = 10^{0.4145 / 2.3026} = 2.597 \text{ J/cm}^2\]

Based on the incident energy normalized, the incident energy can be determined. If the clearing time is
assumed 0.12 s calculated from working time of the relay protection and the new breaker (panel 6 kV)
which are 0.020 s and 0.1s (5 cycles) respectively [5], the incident energy will be:
Thus, if there exists arc-flash in the panel SG-2 the incident energy is 4.418 J/cm². It will be higher if the clearing time is longer.

3.5. Protection boundary calculation
The calculation of safe boundary is [4,5]:

\[
E = 4.184 \times 1.0 \times 2.597 \times 0.12 \times \frac{610^{0.973}}{910^{0.973}} = 4.418 \text{ J/cm}^2
\]

By consideration that the incident energy is at a safe level (minimum) with the highest impact at the second degree burn with 5 J/m² (1.2 Cal/m²), therefore, with the Incident Energy \(E = 4.418 \text{ J/cm}^2\) the best way to avoid the dangers of arc-flash is to take distance 1.38 m from the panel (bus) SG-2. As illustrated in Fig. 1 and known as “flash Protection”.

3.6. Personal Protective Equipment (PPE)
As a last effort in the protection against the dangers of arc-flash is the personal protective equipment that must be worn by workers working in the area around the point of arc-flash. Five categories of hazard levels as presented in table 1 [4,7,8].

| No | Category | Energy(cal/cm²) | Clothing's |
|----|----------|----------------|------------|
| 1  | 0        | 0 – 1.2        | Cotton without treatment |
| 2  | 1        | 1.2 – 5        | Flame retardant shirts and trousers (FR) |
| 3  | 2        | 5 – 8          | Flame retardant shirts and trousers (FR) |
| 4  | 3        | 8 – 25         | Shirts and underwear of cotton, trousers and coverall of fire retardant (FR) |
| 5  | 4        | 25 – 40        | Shirts and cotton underwear, jacket, two-layer trousers of flame-retardant (FR) |

Since the category division is based on cal/cm², the incident energy must be converted into cal/cm². \(E = 4.418 \text{ J/cm}^2 = 1.056 \text{ cal/cm}^2\) (1 cal/cm² = 4.184 J/cm²). It means that at a distance of 1,383 mm the incident energy will be 1.056 cal/cm² which is included in category 0. So, it does not require any special clothing. By the same way the other boundaries can be determined as well as the PPE categories as presented in table 2.

| Protection Boundary | Distance (mm) | Energy (cal/cm²) | PPE Category |
|---------------------|---------------|-----------------|--------------|
| Flash Protection    | 1380          | 1056            | 0            |
| Limited Approach    | 316           | 5               | 2            |
| Restricted Approach | 196           | 8               | 3            |
| Prohibited Approach | 60.8          | 25              | 4            |
4. Conclusion

According to the analysis and discussions above, it can be concluded that:

- Arc-flash incident energy determination needs data of bolted fault current and arc-fault current at the point of arc-flash, technical specification of the panel and the setting of protection clearing time. Longer the clearing time, higher the incident energy.
- If there exist arc-flash in the exercised panel (SG-2), the arc-fault current is 7.011 kA (bolted fault current 7.184 kA) and with clearing time of 0.12s, the incident energy (E) is 4.184 J/cm$^2$ or 1.056 cal/cm$^2$.
- The protection boundary and the PPE category must be followed to avoid the dangers of arc-flash. Flash protection and limited approach at distances from the panel (flash point) of 1.4 m and 0.3 m respectively.

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