ARC FLASH HAZARD MITIGATION TECHNIQUES IN PRACTICE

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Abstract – This paper presents practical mitigation techniques to reduce incident energy, by graphically visualization of theoretical and empirical studies in order to understand the dynamics of parameters that influence the energy released during an arc flash fault event. The practical use of mitigation techniques is based on the hierarchy of control measures from NFPA 70E [1]. The subjects in focus are; *Substitution* of existing equipment and recommendations for good design practices, *Engineering controls* to reduce the arcing current or the arc duration, increase the working distance and introduce work procedures. All is to make electrical work safer and to ensure high reliability of electrical system performance. For further considerations a method to handle cases of generator near nature in relation to arc flash calculations is proposed.

Index Terms – *Arc Flash, Mitigation Techniques, Regulations & New Standards, Good Design Practice, End User, Awareness, Personal Safety, Hierarchy of Control Measures, Substitution, Engineering Control, Operation & Maintenance, Life Cycle Management*

I. INTRODUCTION

Are you aware of the incident energy in your electrical systems? Have you considered what can bring the incident energy down? Are you aware of the danger an arc flash event can cause in an electrical installation? These are some of the questions that will be answered in this paper.

During the last decade, there has been high focus on arc flash hazards in the electrical industry. It is mainly due to a higher focus on the risks and because EN 50110-1 [2] has had an update on the topic in *Annex B.6 Arc Hazard* that focuses on the consequences associated with an arc flash fault event in electrical installations. Today, it is mandatory for all new electrical installations in the United States (US) to include an arc flash analysis according to NFPA 70E [1] to the project documentation in order to follow US federal law of regulation. This indicates that arc flash is a topic that we will see more and more all over the world in order to increase personal safety.

Statistically, arc flash fault events occur due to:

- Human errors, when someone is working on or near live current carrying parts creating an unintended contact between two or more conductive elements.
- Mechanical wear of equipment, corrosion on electrical parts and contactors.
- Faulty connections, wiring failure.
- Pollution, dust, leakage or other substance that may create an accidental electrically conductive connection.

One of the primary reasons for high incident energies are inadequate settings of protective devices, which earlier have been based on short-circuit studies dismissing considering the influence of an arcing current. This paper focusses on high incident energy and describes the mitigation techniques to be used in practice in order to reduce the risk and maybe even eliminate it through hierarchy of control measures from NFPA 70E [1], starting from most to least effective methods as shown in Fig. (1). This paper reviews practical mitigation techniques within *Substitution* and *Engineering Controls* as highlighted with red in Fig (1).

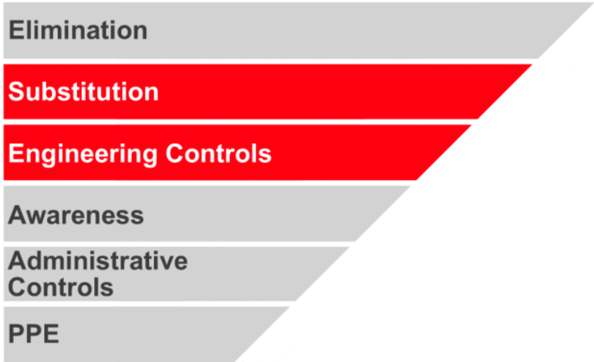

Fig. 1 – NFPA 70E [1] Hierarchy of Control Measures

The intention is to share knowledge, create more awareness and define mitigation solutions to the arc flash hazards by combining the experiences from an engineering perspective as well as a practical approach. Simple techniques such as awareness training and work procedures can reduce or even eliminate the risks by removing the personnel from potentially dangerous situations. It is not complicated to make an analysis and present the risks, but the end users need to know how to use the outputs in relation to incident energy and how to mitigate Arc Flash Hazards via handling, reducing or removing the risk. The important part is to take the action needed to implement control measures by obtaining safety of personnel and to ensure a reliable electrical system at the same time.

A discrepancy has been observed between fault calculations based on remotely located generators and a situation with power generation close by, with higher DC component but faster decay. This paper proposes a method for further considerations of arc flash hazard calculations including current transients and direct current (DC) contribution from a theoretical perspective.

The article ends with a memorandum of advice to the end user of electrical systems who either own or operate systems that could potentially be at risk of carrying high levels of incident energy.

II. ARC FLASH CALCULATIONS IN PRACTICE

Many can do arc flash hazard calculations, even a computer can do it with the right inputs. But to understand the dynamics of the parameters and the equations in a practical relation can be quite abstract. From a practical point of view this is where the engineering work begins.

An arc flash occurs when one or more electrical conductors are located close to each other and with an unexpected fault current passing through, typically in case of a short-circuit. In this situation, an ionization process of the air can take place as a result of various factors, such as high potential differences on electrically conductive devices and the gap between conductors which lead to a low-impedance connection that allows a current named arcing current, to flow through the air gap between the conductors in a plasma channel.

Before starting to use any mitigating techniques to reduce high incident energies, a general understanding of the influencing parameters must be set into relation. Different analysis models have been presented previously to calculate incident energy caused by an arc flash fault event. This section walks through a theoretical derivation known as the Ralph Lee method [3], to understand the dynamics of the parameters and present the empirical determined method known as IEEE std. 1584-2002 method [3] for further demonstration. From an electrical engineering perspective this can be investigated with a simple circuit in order to derive a method of maximum power exposure in case of an arc flash incident. Considered is an arc flash fault event as an electrical circuit containing a power supply with a fixed system voltage U_{sys}, a system impedance Z_{sys} and a variable arc impedance Z_{arc} representing the impedance of the ionized air of an arc flash, as shown in Fig. (2).

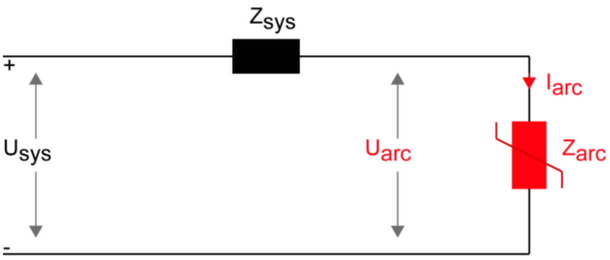

Fig. 2 – Engineering approach to arc flash fault event

The hardest variable to determine in this circuit is the arc impedance Z_{arc} as it depends on the distance between conductors and the surrounding humidity. Using basic circuit theory, it can be derived that the arcing current I_{arc} flowing through the air between the conductors as function of the arc impedance Z_{arc} can be expressed as shown in Eq. (1).

$$I_{arc}(Z_{arc}) = \frac{U_{sys}}{Z_{sys} + Z_{arc}} \; [A] \tag{1}$$

where

I_{arc}	Arcing current [A];
Z_{arc}	Arc impedance [Ω];
U_{sys}	System voltage [V];
Z_{sys}	System impedance [Ω];

Having the arcing current expressed as function of the arc impedance, it can be substituted into a general equation calculating the arc power exposure as shown in Eq. (2).

$$P_{arc}(Z_{arc}) = \left(\frac{U_{sys}}{Z_{sys} + Z_{arc}}\right)^2 \cdot Z_{arc} \; [W] \tag{2}$$

where

P_{arc}	Arc power exposure [W];

From Eq. (2), a plot of the maximum possible power exposure in the arc flash can be visualized by increasing the arc impedance Z_{arc} from 0 → ∞ as visualized on the x-axis in Fig. (3). Plotting this function in a given time interval with an example of a 400 V. system voltage and a system impedance equals 10 Ω, it is possible from Fig. (3), to realize that the maximum power exposure in the arc flash happens exactly when the relation between the system impedance Z_{sys} and the arc impedance Z_{arc} is equal as shown with a dotted grey line.

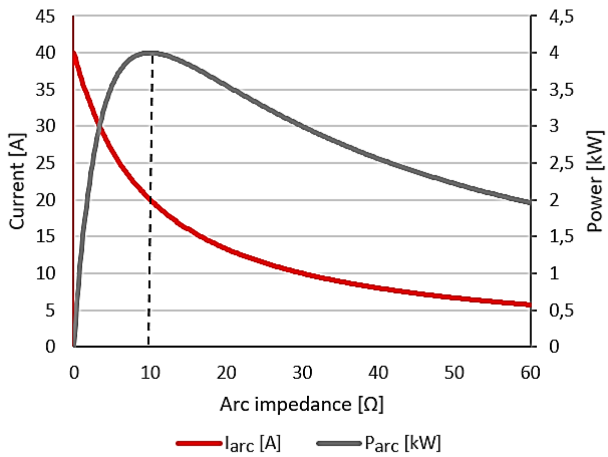

Fig. 3 – Maximum power method derivation

This allows the previous expression from Eq. (2) to be simplified to express the maximum arc power exposure P_{max} in the arc flash as per Eq. (3).

$$P_{max} = \left(\frac{U_{sys}}{2 \cdot Z_{sys}}\right)^2 \cdot Z_{sys} = \frac{U_{sys}^2}{4 \cdot Z_{sys}} \; [W] \tag{3}$$

where

P_{max}	Maximum arc power exposure [W];

Transferring the electrical representation of an arc flash fault event into energy, the maximum power exposure of an arc flash in a given period assuming worst case arc duration conditions to account for current limiting devices, is equal to the total arc energy as per Eq. (4).

$$E_{arc} = P_{max} \cdot T_{arc} \; [J] \tag{4}$$

where

E_{arc}	Arc energy [J];
T_{arc}	Arc duration [s];

Using the total amount of arc energy to assess personal safety would be a very conservative approach, as all vital parts of a human body is at least in a working distance equal to the length of an arm, from live electrical equipment, defined in the IEEE std. 1584-2002 [3] to be 455 mm (typical value). Considering the arc flash as a source of light in an open air environment, the light will radiate radially from the source as shown in Fig. (4). Just as light, the energy intensity from an arc flash will decrease with the distance to the arc flash fault location. By dividing the total amount of arc energy from the arc flash with the surface area of a sphere from Eq. (5), it is clear that the energy intensity from the arc flash, called incident energy E_i will decrease with the working distance squared D^2, as shown in Eq. (6).

$$A_{sph} = 4 \cdot \pi \cdot D^2 \; [cm^2] \tag{5}$$

where

A_{sph} Surface area of a sphere [cm^2];

D Working distance [cm];

$$E_i = \frac{E_{arc}}{A_{sph}} = \frac{P_{max} \cdot T_{arc}}{4 \cdot \pi \cdot D^2} \left[\frac{J}{cm^2}\right] \tag{6}$$

where

E_i Incident energy [J/cm^2];

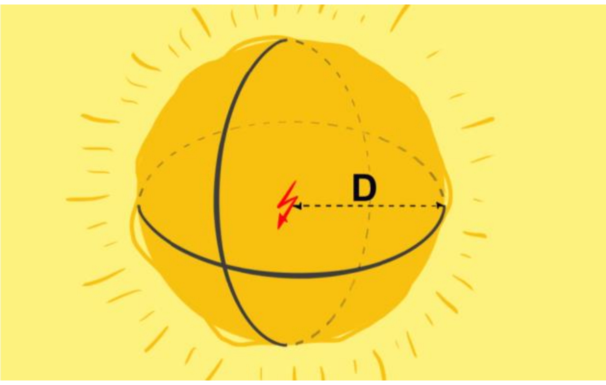

Fig. 4 – Arc flash light consideration

Incident energy is measured in calories per square centimeter (cal/cm^2). The primary choice of energy unit was introduced by the clothing industry. The level of protection is measured in cal/cm^2 and is defined as the maximum incident energy which can be absorbed by a layer of clothing in order to reduce the potential injury to a maximum of a 2nd degree burn, defined as 1.2 cal/cm^2. The conversion between the International system of Units (SI) unit joule and calorie is shown in Eq (7).

$$\frac{1 \; Calorie}{1 \; Joule} = 4.184 \tag{7}$$

Converting to calories and subtracting all constants to one single constant C in front of the fraction, this leaves only 3 influencing parameters left, as shown in Eq. (8).

$$E_i = C \cdot \frac{P_{max} \cdot T_{arc}}{D^2} \left[\frac{cal}{cm^2}\right] \tag{8}$$

where

C Constant;

Since the theoretically derived equations for calculation of the incident energy have been proven very conservative, IEEE has developed a Guide for Performing Arc-Flash Hazard Calculations, IEEE std. 1584-2002 [3], which is based on an empirically derived model. This method has limitations as it has only been validated within the test ranges. From the IEEE std. 1584-2002 [3] the empirically derived model (Clause 7.5 and 9), based on statistical analyzes and curve fitting programs, is applicable for systems with:

- Voltages in the range of 208 V–15.000 V, three-phase.
- Frequencies of 50 Hz or 60 Hz.
- Bolted fault current in the range of 700 A–106.000 A.
- Grounding of all types and ungrounded.
- Equipment enclosures of commonly available sizes.
- Gaps between conductors of 13 mm to152 mm.
- Faults involving three phases.

Note; The IEEE defined bolted fault current corresponds to IEC defined symmetrical root-mean-square (RMS) short-circuit current.

The model is derived to predict the 3-phase arcing current in order to find the protective tripping time and determine the total arc duration. For system voltages below 1000 V. Eq. (9) is to be used and for system voltages above 1000 V. Eq. (10) is to be used.

$$\begin{aligned} \lg(I_{arc}) = K + 0.662 \cdot \lg(I_{bf}) + 0.0966 \cdot V \\ + 0.000526 \cdot G + 0.5588 \\ \cdot V \cdot \lg(I_{bf}) - 0.00304 \cdot G \\ \cdot \lg(I_{bf}) \end{aligned} \tag{9}$$

where

lg $\log_{10}(x)$;

K -0.153 for open configuration
-0.097 for box configuration;

V System voltage [kV];

I_{bf} Bolted fault current [kA];

G Gap between conductors [mm];

$$\lg(I_{arc}) = 0.00402 + 0.983 \cdot \lg(I_{bf}) \tag{10}$$

As the arcing current calculation so far has been calculated on a logarithmic basis, this is converted into a numeric current value using Eq. (11).

$$I_{arc} = 10^{\lg(I_{arc})} \; [A] \tag{11}$$

A second arc is to be calculated too for low-voltage (LV) systems, corresponding to 85% of the arcing current to account for current variations.

Calculating the incident energy, a normalized calculation is made as per Eq. (12). It is based on an arc duration T_{arc} of 0.2 s. and a working distance D equals 610 mm, with influence from the surrounding configuration and grounding system.

$$\lg(E_n) = K_1 + K_2 + 1.081 \cdot \lg(I_{arc}) + 0.011 \cdot G \tag{12}$$

where

E_n Normalized energy (J/cm^2);

K_1 -0.792 for open configuration
-0.555 for box configuration;

K_2 0.000 for ungrounded and high-resistance grounded systems
-0.113 for grounded systems

Although grounding systems previously have been used as a mitigation technique, the new empirically derived IEEE 1584-2018 states: *Contrary to how the IEEE 1584-2002 model interpreted the effect of system grounding, the new IEEE 1584 arc-flash model will not utilize the system grounding configuration as an input parameter. The IEEE/NFPA Collaboration test results did not show any significant impact of the system grounding or bonding on the incident energy released by the arc*. Due to this statement system grounding has not been considered further.

Like the arcing current, the normalized incident energy is converted from a logarithmic basis to a numeric value using Eq. (13).

$$E_n = 10^{\lg(E_n)} \left[\frac{J}{cm^2}\right] \tag{13}$$

Finally, the calculation of incident energy E_i is adapted to the correct conditions for the given fault configuration using Eq. (14).

$$E_i = 4.184 \cdot C_f \cdot E_n \cdot \left(\frac{t}{0.2}\right) \cdot \left(\frac{610^x}{D^x}\right) \left[\frac{J}{cm^2}\right] \tag{14}$$

where

E_i	Incident energy [cal/cm^2];
C_f	1.0 for voltages above 1 kV.
	1.5 for voltages at or below 1kV.;
t	Arcing time (equals T_{arc}) [s];
x	Distance exponent, from [3] Table 4;

Although there is a difference between the theoretically and the empirically derived method, there are two core relationships that remain unchanged. Comparing Eq. (8) with Eq. (14) it can be concluded that the arc duration T_{arc} is directly proportional to the amount of incident energy E_i and that the amount of incident energy is inversely proportional to the working distance to the power of respectively 2 for the theoretical method and the distance exponent x from IEEE std. 1584-2002 [3] Table 4. for the empirical model.

The IEEE std. 1584-2002 [3] has already considered a practical solution to ensure personal safety by calculating an arc flash boundary. Solving for the working distance D from Eq. (14) and substitute the incident energy E_i with an incident energy boundary E_B as shown in Eq. (15), a safety distance can be determined, related to the maximum allowable incident energy boundary E_B. This arc flash boundary D_B is the distance of which an incident energy is exactly equal to the incident energy boundary E_B, as illustrated in Fig. (5).

$$D_B = \left[4.184 \cdot C_f \cdot E_n \cdot \left(\frac{t}{0.2}\right) \cdot \left(\frac{610^x}{E_B}\right)\right]^{\frac{1}{x}} [mm] \tag{15}$$

where

D_B	Arc flash boundary [mm];
E_B	Incident energy boundary [J/cm^2];

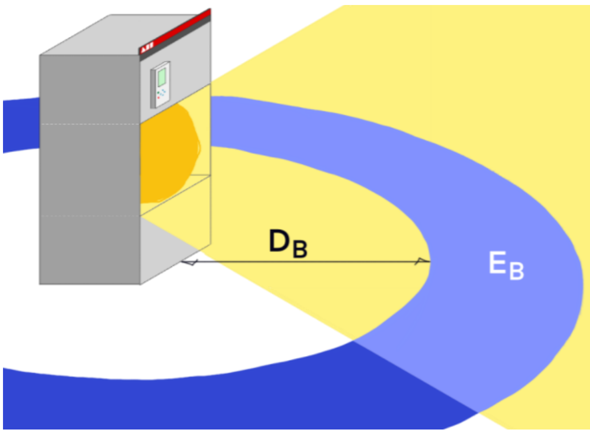

Fig. 5 – Arc flash boundary distance

Recently, IEEE have presented the IEEE std. 1584-2018 [4] with even more and complex input parameters than the version from 2002 including e.g. enclosure dimensions and electrode configurations. The guide is difficult to discuss in a practical perspective as the input parameters are highly dependent on each other, it can be difficult to decode the dynamics of computational relationships. The 2018 version is due to this only discussed further in relation to future recommendation of good design practice in this paper.

III. *MITIGATION TECHNIQUES IN PRACTICE*

Mitigation techniques are available in many formats ranging from simple to complex solutions. As stated in the introduction, mitigation techniques demonstrated in this paper are based on the NFPA 70E [1] with a primary focus on the control measures: *Substitution* and *Engineering controls*.

A. Substitution

Generally, substitution/replacement is often only applicable at the design stage, and therefore it is perhaps more essential to investigate ways to reduce the amount of incident energy in the event of a fault by making some arc flash recommended design criteria/practices which can reduce/eliminate the likelihood of occurrence of an arc flash fault event. However, this does not mean that replacement cannot be used at a later stage. Instead, you may have to distinguish between damage on personnel and damage on electrical equipment.

Examples of reducing the damage to personnel using replacements; If the installation can be operated from an external operative system or if this can be introduced subsequently, the remote switching system can be used to remove the risk of personal injury by moving all personnel outside the arc flash boundary as calculated per. Eq. (15). Equipment replacement can also be activation of protective devices faster acting overcurrent functions or selecting components that limit the available fault current such as; I_{th} limiter, fast earthing switches, arc guard protection, protection and control relays with dual settings introduced e.g. during maintenance mode. In addition, arc flash rated LV switchgear and controlgear assemblies can be used to reduce the risk of injury such as switchboards tested and certified in accordance with IEC 61641 [5] to withstand an arc flash fault event based on 690 V system voltage, 100 kA short circuit current for 300 ms arc duration.

All types of control measures for substitution require supervision of the state of the equipment in order to avoid improper or inadequate maintenance. Therefore, it is always recommended to perform electrical system services which include life cycle assessments, system health checks and system studies. If an installation has a system study it should be validated every time a change in the system occurs, as there might have been changes to the installation such as new equipment, replacements or new operational philosophies that might affect the energy levels and hereby create higher levels of incident energy. Equipment or functionality might change over time, and it might compromise the overall design criteria which then might affect personal safety. It is also important to validate the state of the equipment. The older the equipment is, the more worn out it will become. Therefore, it is important to test functionality and protection of the installation on a regular basis. There are incidents where breakers have failed to trip due to lack of maintenance, and the settings used from previous studies does not fit the purpose anymore or have been changed without validation. A protection relay has a response time to detect a fault and inform the breaker to trip. The breaker also takes time to trip, and if then the springs in the breaker are worn out, the functionality has not been tested or vital parts need lubrication, it will affect the time to clear a fault. As described in this paper, the time is of highest concern, due to the proportionality to the amount of incident energy. In the worst case, poorly maintained equipment can be described as unpredictable and a calculation of this must therefore consider the outer limit value for the absolute worst-case fault event.

Both the arcing current calculations in Eq. (9) and the normalized incident energy in Eq. (12) from IEEE std. 1584-2002 [3], depends on the distance between conductors G shown in Fig. (6). For LV systems, differences in the gap between conductors may result in deviations of approximately 15% within the standard distances defined in the IEEE std. 1584-2002 [3]. For systems with a voltage level exceeding 1000 V, the influence according to the IEEE std. 1584-2002 [3] is less than half, compared to LV systems. For future designs, it is recommended, in particular for LV systems, to increase the distance between conductors G to reduce the amount of incident energy, and in order to eliminate the likelihood of an arc flash initially occurring. From an experience-based point of view, the culprit in the industry is not the companies building electrical distribution boards, but more the component manufacturers who constantly push the terminal sizes of the components and decrease the distance between the conductors. In recent years, it is more frequently seen that LV busbars are insulated which provide flashover protection up to 1 kV.

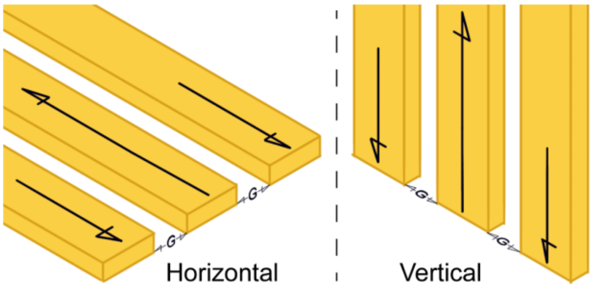

Fig. 6 – Gap between conductors and electrode configuration

In addition to the gap between conductors G, the new IEEE std. 1584-2018 [4] classifies electrode configurations, as it has been discovered that arc flashes typically occur at the end of a 3-phase busbar system. From IEEE std. 1584-2018 [4], Table 9 provides some examples of how equipment conductor arrangements could be classified based on their similarity to the electrode configurations. Fig. (6) illustrates a horizontal- (left) and vertical (right) oriented busbar system. In general, it has been found that incident energy at a given working distance D is increased in cases where horizontally designed busbar systems are used. For future good design practice, a general recommendation is to use vertically oriented busbar systems, both to reduce incident energies but also because experience has shown that horizontal busbars are more dangerous in cases of dropped tools or other foreign objects during work or maintenance.

Electrical cabinets across all voltage levels are required to be designed to withstand a short-circuit, but there is currently no detailed description of protection against arc flash faults. During an arc flash fault event, temperatures of up to 19.500 ºC are achieved, causing copper to be gaseous and expand approximatly 65.000 times the unit of space. The rapid increase in pressure inside a cabinet can result in an explosion like event.

From previous presented PCIC Europe paper EUR19_14 [6], the effect of an arc limiting switchgear based on energy discharge defined as the integral of the arc power per unit of time, converted to pressure discharge, depending on the energy per volume as shown in Eq. (16) has been demonstrated. The pressure discharge is directly related to the intensity of incident energy theoretically decreasing to the power of 2 to the working distance D^2. The message from this is, that it is important to design cabinets which can withstand an arc flash fault event by equalizing the pressure inside the cabinet, as the pressure in many cases will be the most dangerous factor for the human being working in or near the cabinet. Typically systems such as; *pressure relief flaps, gas ducts and pressure blast canals* can be used to solve the problem. Otherwise, there is no point in the first place to make incident energy calculations.

$$p_f = \frac{Energy}{Volume}\left[\frac{J}{m^3}\right] \tag{16}$$

where

p_f Pressure discharge fault event [J/m³];

Comparing an arc flash fault event in an open air environment with a square cabinet as illustarted in Fig. (7), this will increase the radial pointing intensity of the incident energy with a factor of π in front of the faulted cabinet as shown in Eq. (17), due to the relation between the surface area of a sphere A_{sph} with the radius of D and the surface area of a square A_{squ} with side length 2·D.

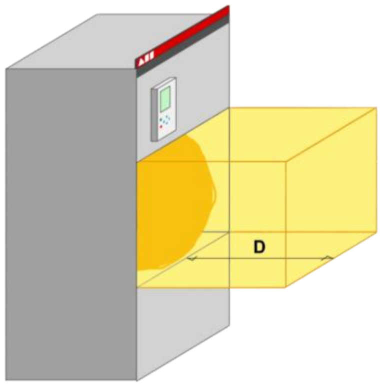

Fig. 7 – Arc flash intensity from a box (el. cabinet)

$$A_{dif} = \frac{A_{Sph}}{A_{Squ}} = \frac{4 \cdot \pi \cdot D^2}{4 \cdot D^2} = \pi \tag{17}$$

where

A_{dif} Difference in surface area;
A_{squ} Surface area of a square [cm²];

B. *Engineering Controls*

Engineering control measures can be different things, but common to all according to NFPA 70E [1], engineering controls may have a substantial impact on risk. They should, where practicable, be considered and analyzed. Typically, engineering controls can be barriers and other safeguarding devices.

Through years of experience, best practice [7] engineering controls with theoretical and practical demonstrated effect is to:

- Reduce the arcing current
- Reduce the arc duration
- Increase the work distance

Or introduce work procedures, which might affect all the engineering controls listed above.

In order to reduce the level of incident energy, parameters presented in the IEEE std. 1584-2002 [3] will set the basis for further demonstration. For low-voltage systems there are 5 variable parameters:

- System voltage (V)
- Arc duration (t)
- Gap between conductors (G)
- Bolted fault current (I_{bf})
- Working distance (D)
- Distance exponent (x)

For high voltage systems, only the system voltage is considered not to have any influence whether it is a 1kV or 15kV system voltage.

The arcing current and the arc duration often have a connection in relation to the protective equipment and they are inversely proportional. The protection coordination philosophies have traditionally been based on short-circuit studies characterized by a minimum and maximum current according to standards such as IEC 60909-0 [8]. For future studies, due to personal safety, the impact of an arc flash occurring should be considered during the construction of protection coordination. Considering the calculation of a 3-phase short-circuit current I_{3p} according to IEC 60909-0 [8], using Eq. (18), only the system voltage U_{sys} and the fault impedance Z_f has to be determined.

$$I_{3p} = \frac{U_{sys}}{\sqrt{3} \cdot \sum Z_f} \tag{18}$$

where

I_{3p}	3-phase short-circuit current [A];
U_{sys}	Nominal voltage [V];
Z_f	Fault impedance [Ω];

Representing the calculation graphically as shown in Fig. (8), the system impedance Z_{sys} can be assumed constant, which makes it easy to determine the 3-phase bolted fault current I_{bf}, while the arc impedance Z_{arc} is variable and makes it difficult to define I_{arc}. The total fault impedance Z_f can be defined according to Eq. (19) as the sum of all impedances from the power source to the faulted location.

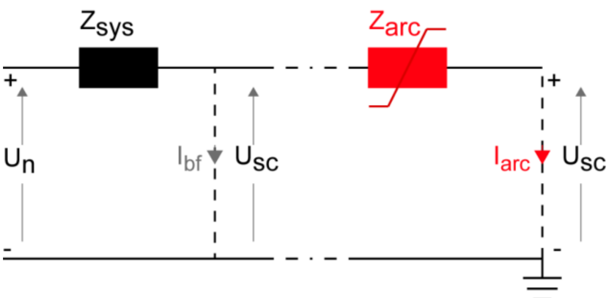

Fig. 8 – 3-phase short-circuit current calculation graphically according to IEC 60909-0 [8]

$$\sum Z_f = Z_{sys} + Z_{arc} \tag{19}$$

For boundary values calculating the arcing current according to IEEE std. 1584-2002 [3], this representation of 3-phase short-circuits calculations in accordance with IEC 60909-0 [8] cannot be asserted. Calculating on a circuit with a system voltage of 999 V in an open air configuration, the arcing current exceeds the 3-phase short-circuit current, when the 3-phase short-circuit current reaches 1.9 kA. This is physically not possible and may be caused due to an approximation in the derivation of Eq. (9), which is based on logarithmic curve fittings.

Representing the short-circuit current with and without the arc impedance in a typical protection time/current curve with a thermal overcurrent curve and a definite setting, as shown in Fig. (9), the difference in between can be considered as the arc impedance Z_{arc}. As per Eq. (14) the arc duration is proportional to the amount of incident energy. This means typically for a given example, the incident energy is increasing with a factor of 10-100 times just by introducing the arc impedance Z_{arc}. From best practices this should be a general protection recommendation in protection coordination- and selectivity studies to include the impact of the arcing current. As it is so difficult to determine, one must make some general assumptions from a conservative point of view. In cases where it is not possible to change the protection settings due to selectivty or limitations of the protective device, an arc time-limitng device can be installed in both existing- and new cabinets. Arc time-limitng device use an optical detection system which together with a current measurement is connected to an external breaker that trips the fault current typically within 10 ms. in the event of a short-circuit. Using an arc time-limitng device, the incident energy will decrease in all cases, without compromising personal safety and system selectivity, as visulized in the protection time/current curve in Fig. (9).

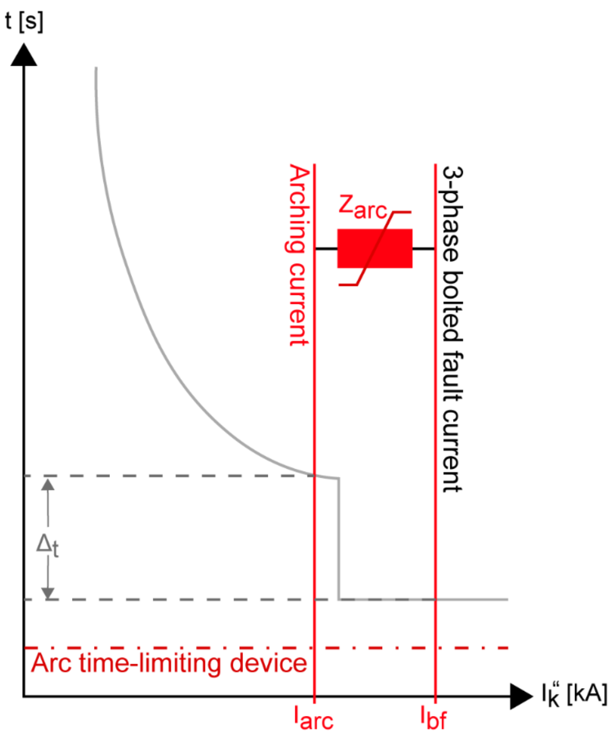

Fig. 9 – Protection characteristic with an Arc time-liming device

An example of various modes of operation is presented to show the relationship between security of supply and personal safety, as well as the importance of proper protection relay settings that account for the arcing current. One important thing to distinguish when considering electrical systems with multiple inputs in the event of a failure is that there is a difference between bus fault current and arcing current that flows through the protective device to limit the arc duration.

By considering a simple busbar system consisting of a generator connected to a distribution panel (3.3 kV.) feeding four MCC panels (400 V.) through each individual transformer with internal bus couplers (BC1, BC2, BC3) as shown from an ETAP [9] model in Fig. (10), for various constellations of bus couplers status (open/closed) one can illustrate the effect. The low-voltage protection relays (LV1, LV2, LV3, LV4) shown in Fig. (11), are assumed being identically set, with a; long time, short time and instantaneous protective settings as shown in Fig. (11).

Traditionally, there has previously been focus on security of supply by parallel mode of operation, but in a perspective of personal safety this may be reconsidered due to the risk of an arc flash fault event. A general recommendation from best practices is to divide busbars into as many sections as possible in order to reduce the bus fault current, increase the tripping current through each LV protection relay and hereby lower the arc duration. In some cases, this is not possible due to requirements of security of supply. In this case, an introduction of a work procedure can be useful.

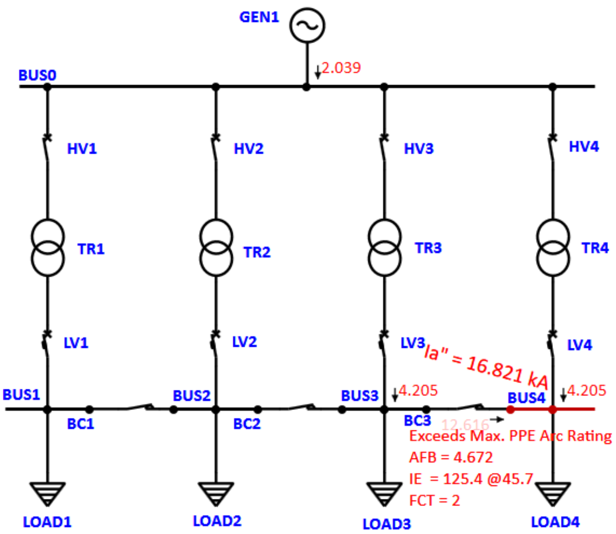

Fig. 10 – ETAP [9] busbar system, parallel mode of operation, fault at BUS4 (arc flash calculation)

From Tab. (1), calculation of 3 different modes of operation is performed, with a comparison to the level of security of supply. In case of a fault at BUS4 shown in Fig. (10), the incident energy can simply be reduced by opening the bus coupler BC2, as the total fault current on the busbar will be reduced and the arcing current flowing through each protection relay will increase, resulting in reduced arc duration as shown represented with read lines for each mode of operation in Fig. (11). This change in mode of operation will practically reduce security of supply but will result in a significant increase in personal safety as the amount of incident energy decrease from 125.4 cal/cm^2 to 17.5 cal/cm^2 which enable the possibility to put on proper personal protective equipment (PPE).

In case of maintenance on one of the MCC panels, BC1 or BC3 can be opened, which compromises the security of supply, but reduces the amount of incident energy to 2.1 cal/cm^2 where it is possible to protect all personnel with basic PPE.

Mode of Operation	**Security of Supply**	**Bus Coupler (BC) status**	**Incident Energy**
Parallel	High	BC1: Closed BC2: Closed BC3: Closed	125.4 cal/cm^2
Normal	Medium	BC1: Closed BC2: Open BC3: Closed	17.5 cal/cm^2
Maintenance	Low	BC1: Open BC2: Open BC3: Open	2.1 cal/cm^2

Tab. 1 – ETAP work procedure / reduce arcing current

Another parameter to adjust to reduce the incident energy is the working distance D, which according to Eq. (14) has the greatest impact hence it raises to the power of the distance exponent x. According to IEEE 1584-2002 [3] for low-voltage systems the distance exponent can range from 1,473 to 2, dependent of the type of equipment.

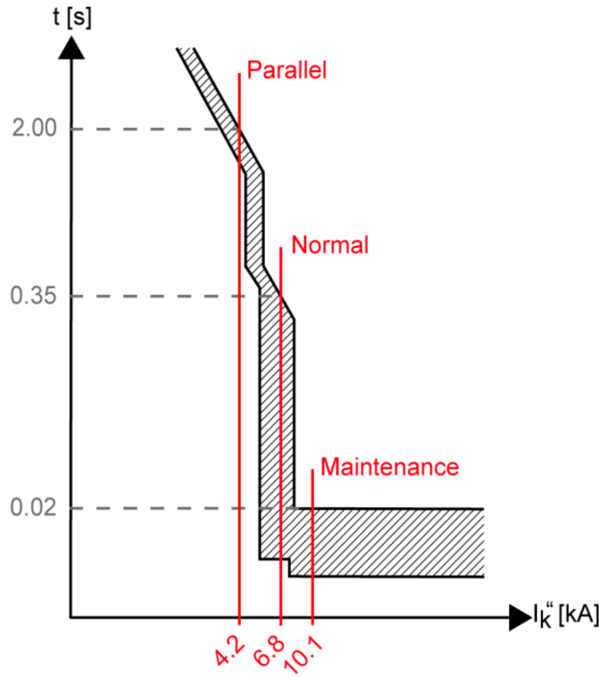

Fig. 11 – Low-voltage protection characteristics for LV1, LV2, LV3 and LV4

There are various approaches to increase working distance from live electrical equipment. Several switchgear manufacturers have developed remote switching devices and others have exchanged electrical equipment with built-in communication modules to operate the electrical system from a power management system. Using Eq. (15) to determine a minimum approach distance for a given level of PPE, energy zones can be introduced. Considering BUS4 from previous calculation example during normal operation, using Eq. (14), as shown in Fig. (12), the arc flash boundary D_B for NFPA 70E [1] defined energy categories can be graphically illustrated and listed in Tab (2). These zones can be used to define, depending on PPE, the observer distance, typically used in the offshore industry.

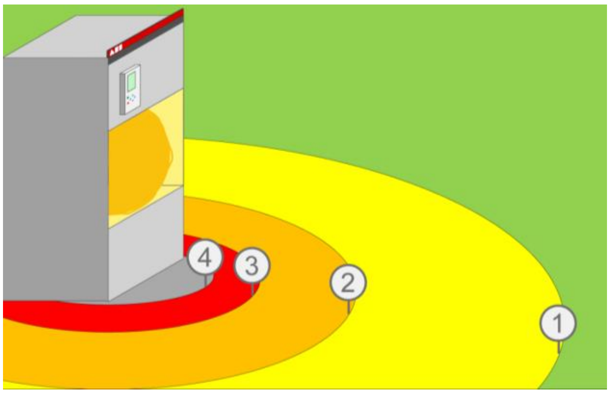

Fig. 12 – Arc flash boundary energy zones

II. Energy zones	Energy boundary E_B [cal/cm²]	Arc flash boundary D_B [cm]
0	<1.2	-
1	>1.2	174.8
2	>8.0	67.7
3	>25.0	38.3
4	>40.0	30.3

Tab. 2 – Arc flash boundary energy zones

III. FURTHER CONSIDERATIONS

There are inconsistencies between the current guide for performing arc flash calculations [3] [4] and the petroleum industry as the generator near nature of the offshore electrical system studies and designs are considered for normal mode of operation as generator near nature. The IEEE std. 1584-2002 [3] is based on symmetrical RMS 3-phase short-circuit current in static conditions reached after approximatly 30 cycles, which implies that current transient and DC components are not considered. This is a fair consideration far from generator, where steady-state conditions can be assumed. This cannot be assumed in cases with a generator near nature, as current peaks of up to 5 times nominal current occur.

From years of experience in the industry, a general model have been developed to handle the issue. Representing the incident energy as energy blocks in a 2-dimensional plot where the arcing current is plotted as function of the arc duration $I_{arc}(t_n)$ as shown in Fig (13), a method can be derived as per Eq. (20).

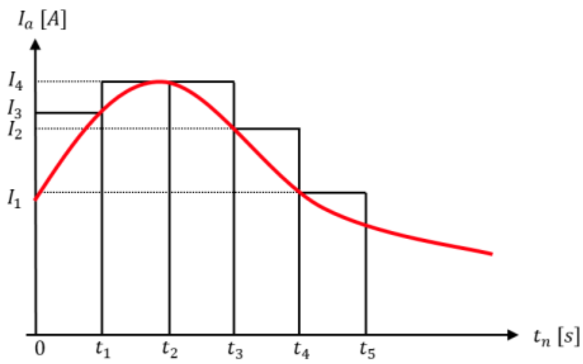

Fig. 13 – Transient arc flash calculation method

This can only be done due to the linear correlation between the incident energy and the arc duration as shown in Eq. (14), whereas the superposition principle can be used. This allows to calculate the incident energy by dividing the calculations into an appropriate number of rectangular energy blocks with time interval $t_{\Delta n}$ as shown in Fig. (13).

From Fig. (13) a theoretical derivation is applicable, in accordance to IEEE std. 1584-2002 [3]. The expression is made to calculate the transient amount of incident energy E_{i*} taking into account current transients and the DC component, as shown in Eq. (20), by taking the integral of each individual energy block for a varying arcing current.

$$E_{i*} = \sum_{n=1}^{N} \int_{t_{n-1}}^{t_n} E_i\left(I_{arc}(t_n), t_{\Delta n}\right) \qquad (20)$$

$$\rightarrow \quad t_{\Delta n} = t_{n-1} - t_n$$

where

E_{i*}	Transient incident energy [cal/cm²];
N	Number of energy blocks;
n	Counter number;
$t_{\Delta n}$	Arc duration time interval at the nth time [s];
t_n	Arc duration time [s];
I_n	Arcing current at the nth time [kA];

In direct relation to Fig. (13) this can be calculated as shown in Eq. (21).

$$E_{i*} = \int_{0}^{t_1} E_i(I_3, t_1) + \int_{t_1}^{t_2} E_i(I_4, t_2 - t_1) + \int_{t_2}^{t_3} E_i(I_4, t_3 - t_2) + \int_{t_3}^{t_4} E_i(I_2, t_4 - t_3) + \int_{t_4}^{t_5} E_i(I_1, t_5 - t_4) \qquad (21)$$

The conservatism in the IEEE std. 1584-2002 [3] is still unchanged using this method. But considering current transients has shown significant reductions in incident energy when comparing the calculation with a worst-case estimate assuming peak currents (0,5 cycle) and long-time arc duration conditions.

IV. MEMORANDUM

Arc flash has been a well-known phenomenon for many years, but in the recent years arc flash has become a hot topic in the industry. This is due to greater focus on electrical safety from standards, regulations and company internal requirements. At this time many calculation softwares in the market can perform arc flash studies and print a sign to hang on the switchboards. But if the author of the study lacks understanding of the data input, analysis output, operation of the electrical system, as well as methods of dealing with high energy levels, it will not increase the level of personal safety. This paper provides guidance to the end user for simple electrical safety solutions so that both internal and external requirements can be met. It is important to understand the full picture of an electrical system to interact with it and protect personnel.

V. CONCLUSIONS

This paper presents graphical visualization of the influencing parameters used for arc flash hazard calculations. From an experienced practical perspective combined with a theoretical approach, mitigation techniques have been proven very effective in the reduction of incident energy to ensure high personal safety and ensure reliable operation of electrical systems in case of a fault event. In addition, recommendations for future good design practices have been presented to keep the amount of incident energy at a manageable level by conventional PPE. Based on the content of this article, the general recommendations to the end user is:

1) *Analyze*. Get to know the level of incident energy of the electrical system through a system analysis
2) *Mitigation*. Perform mitigations as presented in this paper where incident energy exceeds an inappropriate level
3) *Education*. Pay attention to the consequences of an arc flash fault event and do awareness training of all personal working with or near the electrical system.

VI. ACKNOWLEDGEMENTS

We would like to thank PCIC and ABB A/S for being able to contribute to the conference with this paper demonstrating some practical knowledge from the past decade in the oil and gas industry and contribute with new and innovative approaches in arc flash hazard visualization and handling of practical related issues.

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VIII. NOMENCLATURE

A_{sph}	Surface area of a sphere [cm^2];
A_{squ}	Surface area of a square [cm^2];
A_{dif}	Difference in surface area;
C	Constant;
C_f	1.0 for voltages above 1 kV. 1.5 for voltages at or below 1kV;
D	Working distance [cm];
D_B	Arc flash boundary [mm];
E_{arc}	Arc energy [J];
E_B	Incident energy boundary [cal/cm^2];
E_i	Incident energy [cal/cm^2];
E_{i*}	Transient incident energy [cal/cm^2];
E_n	Normalized energy [J/cm^2];
G	Gap between conductors [mm];
I_{arc}	Arcing current [A];
I_{bf}	Bolted fault current [kA];
I_n	Arcing current at the nth current [kA];
I_{3p}	Three-phase short-circuit current [A]
K	-0.153 for open configuration -0.097 for box configuration;
K_1	-0.792 for open configuration -0.555 for box configuration;
K_2	0.000 for ungrounded and high-resistance grounded systems -0.113 for grounded systems;
lg	$\log_{10}(x)$;
n	Counter number;
N	Number of energy blocks;
p_f	Pressure discharge during fault event [J/m^3];
P_{arc}	Arc power exposure [W];
P_{max}	Maximum arc power exposure [W];
t	Arcing time (equals T_{arc}) [s]
t_n	Arc duration at the nth time [s];
T_{arc}	Arc duration [s];
U_{sys}	System voltage [V];
U_n	Nominal system voltage [V];
V	System voltage [kV];
x	Distance exponent, from [3] Table 4.
Z_f	Fault impedance [Ω];
Z_{arc}	Arc impedance [Ω];
Z_{sys}	System impedance [Ω];

IX. VITA

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