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ABSTRACT

Arc flash happens when current passes between two separated electrodes through air, and it can occur in any electrical installation. Arc is a heat source that can lead to fire and explosions.

Switchboards are a key element for the protection and reliability of the power supply, and their design must be tailor-made for each system. The protection devices that connect the switchboard to the end loads must be carefully rated to achieve protection, coordination and selectivity.

The relation between personal safety and switchboard design can be measured in terms of the thermal incident energy that a worker is exposed to when near electrical installations. The way that a switchboard is designed and the protection device is set, have a direct impact on the incident energy. Thus, nine cases were simulated using ETAP software for three different electrode configurations, with reduced enclosure dimensions, shorter gaps between electrodes and different fault clearance times. The calculation methods are based on IEEE 1584 2018 [1].

The main findings were that arranging the electrodes vertically reached the lowest incident energy levels while the horizontal configuration the highest. Moreover, the longer it takes to clear the fault, the more the incident energy increases.

Furthermore, the case study was assumed to be located where a flammable gas was likely to occur during normal operation. Thus, the base case results were re-evaluated to verify if the heat generated was enough to auto-ignite the H_2S if in sufficient concentration in the air.

The result was that the temperature reached way above the H_2S minimum ignition temperature at closest to the arc source. Therefore, the switchboard must be tested and certified for use in explosive atmospheres to ensure that the energy transferred outside the enclosure is not sufficient to ignite a fire or an explosion.

DEDICATION

Thanks to my son for many Oslo-Trondheim trips from 5 weeks old. Thanks for being quiet during classes and to be always by my side.

Thanks to my husband for being patient and supportive even when I had to study in our wedding, honeymoon and mostly every night.

Thanks to my family for always motivating me to study more and more.

Thanks to my friends for understanding my absence.

Thanks to my employer for the valuable work experience.

Thanks to my supervisor for the very good support and relevant feedback.

Thanks to God for giving me the strength to go all the way through this master while raising a baby and working full-time.

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Abbreviations

AC	Alternate current
ACB	Air Circuit Breaker
AFB	Arc-Flash Boundary
ATEX	Equipment for Potentially Explosive Atmospheres
cal	Calories
CB	Circuit Breaker
CBM	Condition Based Maintenance
CSA	Canadian Standards Association
EPL	Equipment Protection Level
FCT	Fault Clearing Time
H_2S	Hydrogen sulfide
HCB	Horizontal Conductors/Electrodes in a Metal Box/Enclosure
HOA	Horizontal Electrodes, Open Air
ID	Identification
IEC	International Electrotechnical Commission
IED	Intelligent Electronic Devices
IECEx	International Electrotechnical Commission for Explosive Atmospheres
IEEE	Institute of Electrical and Electronic Engineers
ISA	Ignition Source Assessment
J	Joules
kA	Kiloamperes
LBS	Load Break Switch
LV	Low Voltage
MCC	Motor Control Center
MIC	Minimum Igniting Current Ratio
MESG	Maximum of The Experimental Safe Gap
mm	Millimeters
MV	Medium Voltage
NFPA	National Fire Protection Association

NTNU	Norges Teknisk Naturvitenskapelige Universitet
PPE	Personal Protection Equipment
RLV	Redline Mark-up Version
RRRV	Rate of Rise of the Recovery Voltage
SF_6	Sulfur Hexafluoride
TBM	Time-based Maintenance
TCC	Time Current Characteristics
TRV	Transient Recovery Voltage
UL	Underwriter Laboratories
V	Volts
VCB	Vertical Conductors/Electrodes in a Metal Box/Enclosure
VCCB	Vertical Conductors or Electrodes Terminated in an insulating barrier inside a Metal Box or Enclosure
VOA	Vertical Electrodes, Open Air

1 Introduction

1.1 Motivation

This thesis aims to contribute to a safer design of switchboards against arc flash, by presenting its related hazards, besides preventive and corrective measures.

Switchboard design variations within enclosure dimensions, material types, relay settings and electrode configuration impact the thermal incident energy released. Therefore, a correct design is the first step toward minimizing the risk of an arc flash.

In the example shown in Figure 1-1 courtesy of BW Offshore, an explosion in a motor control center occurred and investigation showed that a potential contributing factor was the cubicle being undersized.

Figure 1-1: Arc flash in a contactor, courtesy of BW Offshore.

However, even when the design is properly made, electrical arcs may still occur due to certain conditions, such as poor insulation, ageing, loose terminals, or contamination (by dust, moisture, or chemicals). A short circuit because of poor insulation in a 440 V low voltage air circuit breaker from the 1980s, caused an arc which fortunately did not harm anyone, but the black stain in Figure 1-2 courtesy of BW Offshore, indicates that high temperature was generated which could auto ignite flammable gases if presented. Before the arc, temperature ranging from 160 °C to 200 °C during normal operation was detected during thermography inspection, while ignition temperature of the gas present outside this room is 260 °C [2].

This arc could potentially be avoided, if more periodic inspection and testing were performed to early detect eventual high temperature and poor insulation conditions in the switchboard.

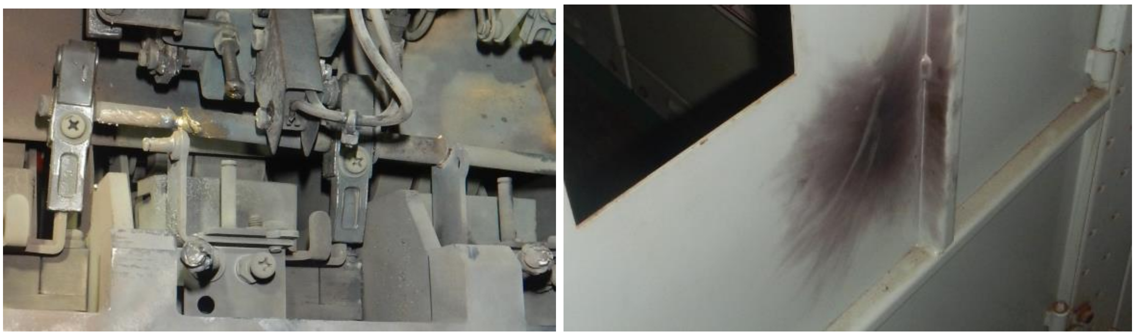

Figure 1-2: Arc flash in air circuit breaker contacts, pictures courtesy of BW Offshore

In case an arc occurs, the closest protection device should detect and clear any abnormal high current values as a corrective measure. If a fault happens during service with opened door, then personal protection equipment (PPE) acts as a barrier to protect the worker when at working distance from the switchboard.

The main motivation for this topic comes from work experience within oil & gas, where electrical installations are exposed to common electrical hazards, in addition to exposure to flammable gas, which can be ignited by the spark itself or by heating above the gas minimum auto-ignition temperature. Thus, the location of the switchboard shall be optimal, with good access and preferably in a safe area free from flammable substances. If an electrical device has to be installed where flammable gas may occur, special design enclosures are required to minimize explosion risk or to internally withstand it. Therefore, the concept of explosive atmosphere is also included in the scope.

The arc flash impacts will be simulated based on the incident energy calculation guideline from the Institute of Electrical and Electronics Engineers IEEE 1584 2018 [1] in the ETAP software version 20.0.2, where is possible to analyze the impact of different dimensions and electrode configurations. The purpose is to highlight the importance of good design as the first step toward safety and how the arrangement directly affects the incident energy levels.

1.2 Scope

The scope is divided into six sections:

Section 1 defines the motivation, introduces the power system protection, the simulation model and presents relevant findings from previous research.

Section 2 introduces the arc flash technical background, in addition to the hazardous area classification definitions and parameters.

Section 3 describes the calculation methods used by the ETAP software for the arc flash module results based on IEEE 1584 [1].

Section 4 presents the model configuration and the simulation incident energy results for different electrode arrangements in the switchboards, with fixed and variable FCTs.

Section 5 discusses the results from the case studies. In addition, the cases are re-evaluated to cover the consideration of the switchboards installed in hazardous area.

Section 6 reports the main findings of this scope.

This research focuses mainly on electrical arcs on the busbar side and its relationship with circuit breakers (CB) fault clearance time and arc flash incident energy in switchgears, besides addressing additional risks related to explosive atmosphere exposure.

1.3 Methodology

Despite the wide scope within electrical installations, the case study model represents a simplified version of an offshore power system, during a normal production scenario with one turbine generator supplying a 6,6 kV medium voltage (MV) switchboard and a 690 V low voltage (LV) switchboard via a stepdown transformer. The goal is to verify how reduced dimensions and various fault clearance times affect the incident energy by simulating three switchboard internal design: vertical electrodes in a metal box enclosure (VCB) as in Figure 1-3, vertical electrodes terminated in insulation barrier in a metal box enclosure (VCCB) as in Figure 1-4, and horizontal electrodes in a metal box enclosure (HCB) as in Figure 1-5.

Figure 1-3: VCB - Vertical electrodes inside a metal enclosure [1]

Figure 1-4: VCCB - Vertical electrodes terminated in an insulating 'barrier' inside a metal enclosure [1]

Figure 1-5: HCB - Horizontal electrodes inside a metal enclosure [1]

The results were based on the normal production scenario as illustrated in Figure 1-6, simulated in ETAP through four modules with the respective purpose:

- Load Flow: power distribution, equipment rating and operability.
- Short Circuit: peak current values for fault in the bus side, calculated as per IEC 61363 [3].
- Arc Flash: three-phase arcing current and incident energy for different enclosure characteristics.
- Protection and Coordination: overcurrent and short circuit protection settings for achieving coordination and selectivity, as showed in Figure 1-7.

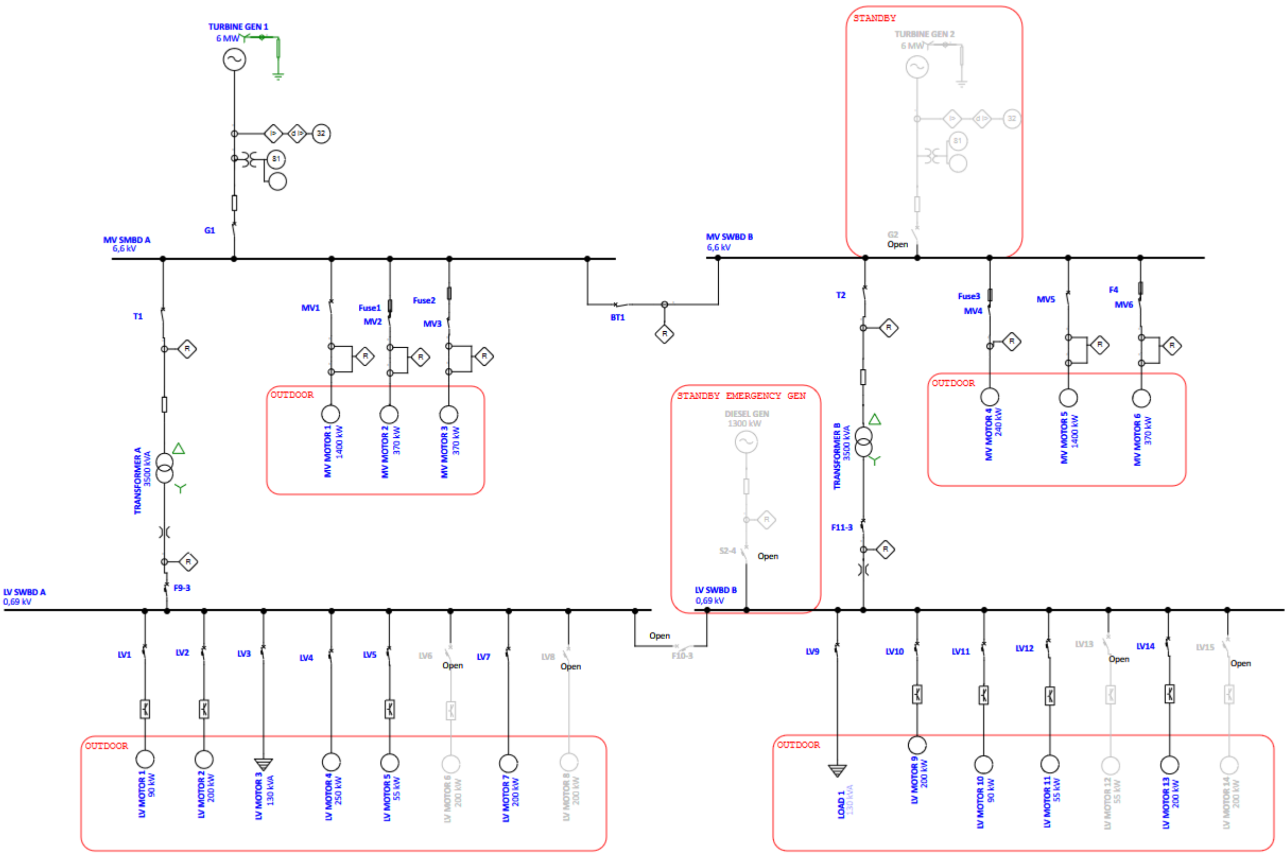

Figure 1-6: ETAP model for the case study

Additional considerations:

- Power supply redundancy is represented by a standby 6,6 kV steam turbine, in addition to a 690 V emergency diesel generator, in case of unwanted blackouts or planned maintenance scenarios.
- Both switchboards are considered to be installed in a location where Hydrogensulfid (H_2S) is likely to occur, but not continuously present in normal operation. H_2S auto ignition temperature is at 260 °C [2].

1.3.1 Power system protection

The continuity of power supply during normal and fault situations, the integrity of the system and protection against safety hazards are the main goals of any substation. Therefore, power networks are equipped with devices such as circuit breakers, fuses with switch contactors, disconnector switches and relays, to protect the system against abnormalities such as overload, short circuit, low frequency, earth fault or other eventual failures. In addition, earthing switches are used for maintenance as well as surge arrestors for overvoltage protection [4].

Different types of switching devices are available in the market, such as circuit breakers (CB) or load break switches (LBS) depending on the desired interrupting duty against short circuit or overload, system voltage and the component maximum rated interruptible current. Besides, disconnector switches and earthing switches can link different parts of the circuit to the ground, but with very limited interruption capability. For short circuit interruption, the most suitable device is the CB, as it can be used to protect equipment also in high voltage systems. LBS can be used in connection with a disconnector switch and with a fuse in series for short circuit protection in addition to the overload above the rated current [4].

Circuit breakers (CBs) are the most reliable device for continuity in power supply for high voltage systems. Since CBs protect against overload and short circuit range, unlike fuses which are widely used for similar purpose, but are not able to withstand the voltage and current stresses of networks beyond 36 kV [4].

Nevertheless, CB can also be used to start or stop a load during normal operation, maintenance and in the event of a fault. Open or close command can be done locally direct in the breaker switch or via an external command if integrated to a control system.

Circuit breaker insulating mediums can vary from air, oil, vacuum or Sulfur Hexafluoride (SF_6). The last has been the most used medium for high voltage (HV) systems, but its use is decreasing due to environmental concerns. Siemens who plays a big role in the HV CB market indicates in an assessment from 2012 that based on extensive experience, the leakage rate of this greenhouse gas to the atmosphere is less than 0.1% per year [5], within the IEC [6] limits of a maximum of 0,5% per year.

Multiple CBs within one circuit can be used to increase the reliability of the power supply. If one fault happens, the closest CB shall respond promptly and isolate the fault, preserving the upstream and downstream healthy parts of the circuit. Thus, the importance of protection coordination study ensuring that the closest CB to the fault acts prior to the next CB in line, avoiding further disturbance in the system until the fault is cleared.

Moreover, each CB must be rated and tested to withstand the equipment full load current during normal operation and start-up, as well as the short circuit current for the specific system voltage. The equipment damage curve and the maximum cable ampacity must also be considered when adjusting CB and relay parameters, to preserve the equipment and cables from exposure above their capabilities.

Protection coordination example from ETAP in Figure 1-7 simulating a case of a 6,6 kV turbine generator supplying to a 6,6 kV, 1400 kW induction motor. In this case, if a fault happens on the motor (MV5) side, the relay (R6) would be the first to trip and isolate the circuit until the fault is cleared, so the rest of the switchboard, generators and other loads would not be affected by this fault.

If the closest CB to the fault does not actuate due to bad adjustment or calibration but instead the next upstream device does, more parts of the system would be exposed to abnormal conditions than if the closest device had actuated as supposed to.

One possible consequence could be that the generator's most upstream breaker (R15) trips and causes an unnecessary shutdown to the unit, because of a fault in one circuit.

Therefore, each protection device should be adjusted above the equipment full load current, below the equipment damage curve and actuate faster than the next trip unit.

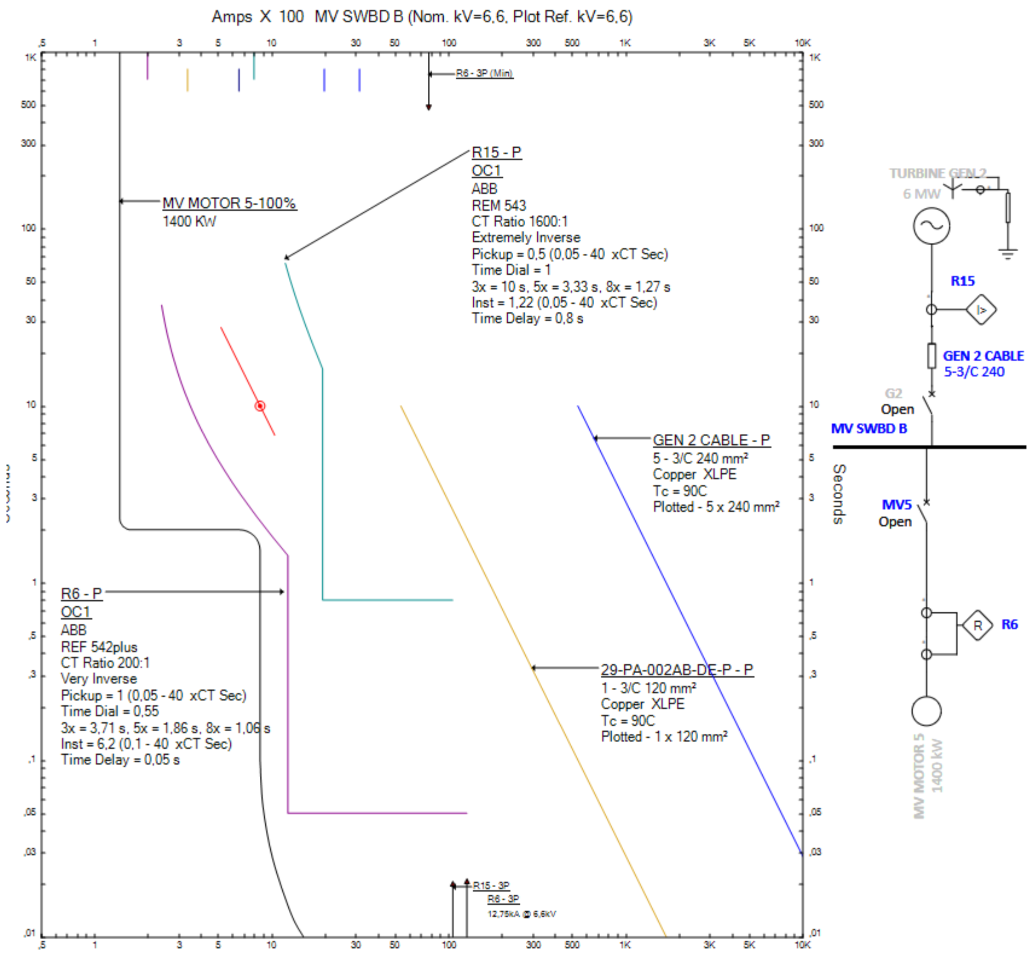

Figure 1-7 Protection Coordination Curve

1.4 Relevant research

Two books [4, 7] were very pertinent for the technical aspects related to arc flash and switching devices required as a base for the discussions and investigation, as well as international standards [1, 8]. Just couple of articles [9, 10] refer to this phenomenon in explosive atmospheres. The article [11] referring to different electrode configuration and its relation to arc flash was relevant to the discussion of the case results.

The effects of electrical arcs inside an enclosure can be represented by incident energy values in cal/cm², or by a rise in temperature and consequent pressure. Since the arc blast heats the surrounding air, causing it to expand, it creates such a great pressure inside of an enclosure that can cause particles to reach outside and be a hazard to workers and installations nearby. In addition, if the enclosure is installed in an area where flammable gas or vapors are present, just the excess of heating itself can be sufficient to ignite a flammable gas. Thus, special enclosures are designed to ensure additional protection techniques to increase safety against an explosion or to even withstand one.

The incident energy is a parameter used to quantify the arc flash hazard that a person can be exposed to, since the protective personal equipment (PPE) to perform tasks in the switchboard are classified in levels based on range of incident energy values. This parameter calculated by the Arc Flash Collaborative Research Project formed by IEEE [1] and National Fire Protection Association (NFPA) [12] is based on over a thousand tests for VCCB, VCB, HCB, vertical electrodes in open air (VOA) and horizontal electrodes in open air (HOA). The gap between electrodes and the enclosure dimensions are variables, so their impact on incident energy can be calculated for different electrodes arrangement [1].

Comparing the three configurations inside an enclosure (VCCB, VCB, HCB), it is expected that at the same working distance the HCB will have the highest incident energy while the VCB the lowest. However, VCCB might present lower incident values than VCB when varying the fault clearing time and arcing current fault for multiple cases [11].

Moreover, a research with a focus on heat and pressure rise has shown that the smaller is the enclosure, the faster the pressure rises. The pressure rise inside a switchboard has shown no difference whether the fault is in the load or in the bus side, while incident energy is higher in the bus side than the load side. Thus, for an optimal switchboard design and tensile strength of bolts at the front door of the cabinet, the calculated arc fault energy and cabinet maximum pressure for a specific project shall be taken into account [10, 13].

In addition, electrical arcs cause voltage drop in the range of 75 and 100 V/inch in low voltage (LV) systems, hence just the difference between the arc and the source voltage remains available. While in HV, the arc length can be of 1 inch per 100 V of the supply voltage prior to the regulation or limit of the fault current. As the arc in HV can reach great lengths, it can act as bridge from energized parts to ground [14]. Despite the longer arc length for HV, it is possible to achieve higher arc energy in a LV system than in HV system under special conditions [7].

Arc flashes can cause unwanted trips, production downtime and damage to equipment, but the most important is safety and health risk to personnel. The safety hazard that electrical circuit, such as arcs, expose humans to are reported by the American Burn Association, showing that 61% of the fatalities connected to electric caused burn, happened at workplace in the period of 2004 to 2013 [15]. Less severe injuries as burn in the arms or eye exposure to arc should not be underestimated since it causes long term conditions as blindness and chronic pain [16].

Therefore, employees working or transiting nearby electrical installations must be educated to follow the arc flash standards and safe procedures as earthing, isolating the circuit and lock-out to prevent someone from turning the circuit back online while job is ongoing. In addition to the correct PPE suitable to the class required according to the arc flash energy calculation for each switchboard.

Moreover, maintenance of the CB itself is also important for achieving the device optimal performance, lifetime and avoiding surprise costs related to corrective measure required when an unplanned shutdown or accident occurs because of equipment mal function. Thus, a preventive maintenance plan is essential, and it can be either time-based (schedule maintenance where continuous monitoring it is not available) or condition assessment based.

Condition based maintenance (CBM) shall be preferred since it is tailor-made according to results from real-time events, related to the CB continuous electric parameters trend from a specific installation [17]. While time-based maintenance (TBM) is purely based on a schedule with periodically assessments established by company procedures and minimum standard requirements. TBM can result in too rare maintenance and eventual expensive corrective measures, or even too often using resources and shutdown operation more than necessary.

The CB internal components can be divided in two systems, mechanical drive system and control auxiliar system. The control auxiliar system most common issues are bad contact, switch failure, electromagnet lag/block, maloperation due to low voltage in the coil [18]. Those issues are easier to track if intelligent electronic devices (IED) are already installed to collect and monitor CB parameters and immediately detect abnormal values [17].

2 Technical Theory

2.1 Electrical Arc

Electrical spark or arc happens when there is a passage of current between two electrodes physically separated by a normally nonconductive media. An arc is composed of plasma - a mixture of atoms, neutral particles, free electrons, and ions - produced by gases or metals when exposed to very high temperatures [4]. The arc's property is dependent on the gap size between two electrodes, the terminal material, arc voltage and media conductivity.

Multiple factors can lead to an internal arc, as in Figure 2-1:

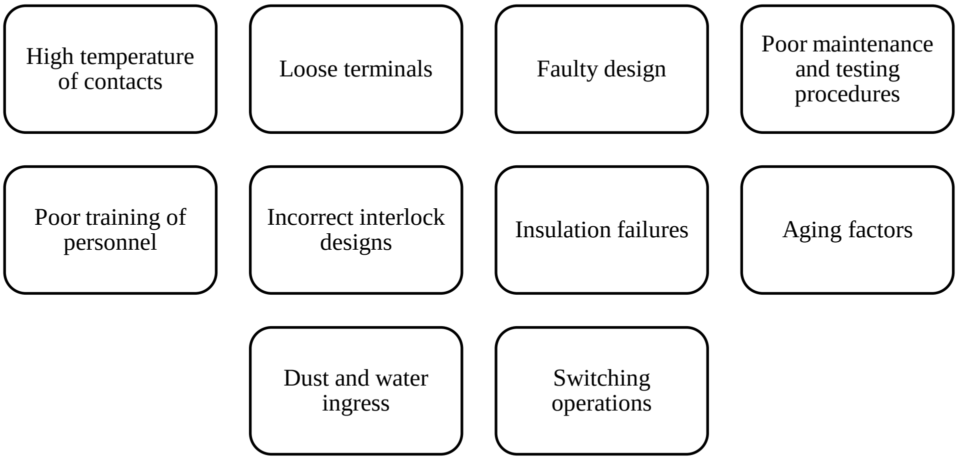

Figure 2-1: Example of arc causes [7]

However, the likelihood of an unexpected internal arc is reduced if personnel is qualified, well-trained and follows relevant standard and regulation guidelines during design, operation, maintenance and testing [8, 19].

Arcs can relate to two power sources: alternate current (AC) and direct current (DC). This scope is based on AC power supply. In DC systems, the concept of arc extinguishing at 'current zero crossing' does not happen as in AC, but the arc is extinguished only if the current is interrupted externally or if electrode consumption is too high [20].

2.1.1 Electrical arc inside metal switchboard cubicle

The first phenomenon observed when an arc is formed inside an enclosure is overheating due to the high energy release. Consequently, overheated gas tries to make its way out of the enclosure, through any eventual opening until pressure reaches its maximum value. Then, the pressure starts to gradually decrease as the hot air is released. The arc continues until the escaping overheated air approaches a constant temperature. Finally, the temperature remains as high as it was at the formation of the arc and it only normalizes once the arc is extinguished [7, 13].

Metal-clad switchboards where switching equipment is of draw-out type, should be preferred if the electric arc probability is to be kept at a minimum, since their design allows to physically disconnect the cubicle from the system with a shutter automatically covering the busbar when in an open position [7]. In addition to no opening or gap (excepted cable entry) between the compartments, beside grounded metal compartments and bus connections covered with insulating material [7].

2.2 Safety hazards

The amount of energy released during an arc exposes personnel to danger for the reasons mentioned in Figure 2-2 [7].

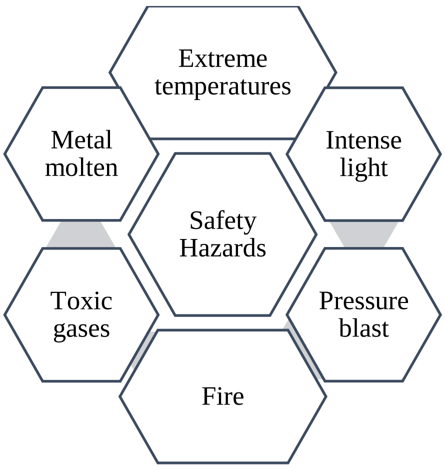

Figure 2-2: Arc flash safety hazard [7]

2.3 Safety measures

Safety measures shall be followed to protect workers exposed to arc flash hazards near electrical installations.

In the design phase, incident energy and arc flash boundary must be calculated according to the applicable standard to identify the suitable personal protection equipment (PPE) certified and tested to withstand the worst-case scenario for each equipment or system. Arc flash labels, as in Figure 2-3, shall be visible on each switchboard containing information such as voltage, PPE category, calculated energy released, working distance limit and equipment ID. During operation, personnel must be trained to understand the arc flash hazards and PPE is to be regularly inspected.

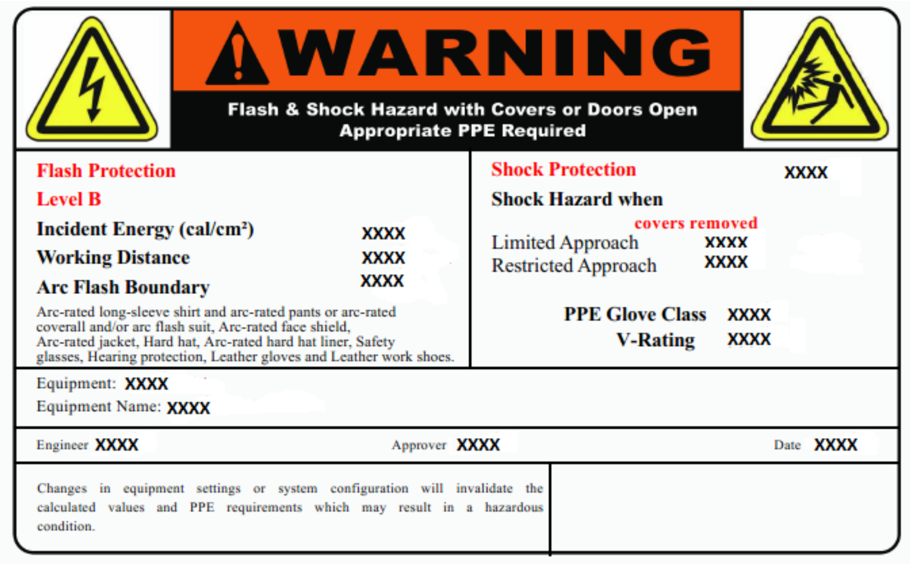

Figure 2-3: Arc flash label template type Avery - 6579 from ETAP report library.

Moreover, a selection of electrical protection components is used to restrict the current to desirable levels in the event of overload and faults. Electrical arcs do not always happen due to malfunction or error, for example, an arc is expected during normal switching operation so circuit breakers design counts with a specific chamber where the switching arc burns and it is extinguished [4].

Electrical arc and hot surfaces are considered as ignition sources and can lead to fire or explosion if in contact with flammable gas or vapor. Power systems within oil & gas, mining and installations where dust can be accumulated are in increased risk of fire and explosion, so special considerations have to be followed as summarized in Section 2.4.

2.3.1 Circuit breaker mechanism

Circuit breakers (CBs) are widely used as a protection device in electrical systems to ensure that current values for a certain period are within the system and equipment's electrical capability. CBs are switching components supposed to be ideal electrical conductors when in close position and an ideal insulator when in open position.

The switching operation principle is based on two pairs of energized contactors moving away from each other whenever an opening signal is received. The current which was flowing through the contactors are not immediately interrupted but continues flowing through an electric arc until its available charge carrier is fully extinguished [4].

Since arcs happen during normal switching operation, the device has to be capable of dealing with the energy losses caused by the voltage drop (at a significant lower level than the network) and extinguishing the arc near its zero crossing so to fully interrupt the current [4].

2.4 Equipment certified for use in hazardous area (Ex rated equipment)

Equipment referred as 'Ex rated' or 'Ex equipment' is tested and certified according to the explosion risks of the hazardous location where the equipment is installed, further details in Section 2.4.2 to 2.4.6. The IEC general guidelines for equipment installed in explosive atmospheres classify Ex equipment in four main parameters: group, maximum surface temperature, protection level and protection type [8] .

The first preventive measure is to classify the facility in areas according to the release risk of a specific flammable gas or vapor to occur during normal operation and fault events. Then, the equipment protection level (EPL), group, temperature and protection type must be suitable for installation as per the hazardous classification area. Electrical equipment susceptible to hazardous conditions must follow the applicable standards and rules for design, operation, maintenance, and testing procedures.

Some countries or regions follow local guidelines instead of (or in additional to) the international IEC 60079 [8] standard. For example, Brazil requires INMETRO certification in addition to IEC [8], Europe uses its own local directive called ATEX [21], while North America has UL and CSA as local certification standards. Despite some differences among the worldwide guidelines, all intend to reduce the risk of an explosion and provide a safer environment in areas surrounded by flammable gas, dust or in mining industry.

2.4.1 Ignition Source

Hazardous area refers to installations where flammable substances in form of gases, vapor or dust are present and can ignite a fire or explosion. Therefore, any type of identified ignition source must be prevented or retained to the greatest degree.

Examples of ignition source are [22, 23]:

- Hot surfaces.
- Hot gases and flames.
- Mechanically generated sparks.
- Electrical apparatus.
- Electromagnetic waves.
- Ionization radiation.
- Ultrasound.
- Adiabatic compression and shock waves.
- Static Electricity.
- Lightning.
- Stray electrical current, cathodic corrosion protection.
- Exothermic reaction, including self-ignition of the powders.

Despite fire risk being often related to electrical circuits, it is not always the case. From the list above it is clear that some items can occur in non-electrical equipment, such as mechanically generated sparks from a rotating machine, or tankers containing fluids causing hot surfaces, that must also be taken into the ignition hazard assessment (IHA). The IHA [23] identifies all potential ignition sources, evaluates their likelihood and frequency throughout equipment lifetime and establishes mitigation measures. The IHA is then re-estimated, considering the mitigation actions, to specify which Equipment Protection Level (EPL) is required for each area.

2.4.2 Equipment grouping

Ex rated equipment can be divided into three groups I (mining), II (vapor and gas) and III (dust) depending on the environment of its location [8].

The group II is the only relevant to this scope and refers to non-mining applications under risk of explosive gas and vapor exposure. In summary, the group II is subdivided in IIA, IIB and IIC according to either the minimum igniting current ratio (MIC) or the maximum of the experimental safe gap (MESG) of the respective explosive gas that the equipment is exposed to [8]. A subsequential division also meets the requirements of its previous divisions, for example, IIC is also suitable for IIA and IIB.

The case study requires a minimum group IIB since it refers to a non-mining equipment exposed to H_2S gas.

2.4.3 Ambient Temperature

The case study considers that equipment ambient temperatures are within the standard range of - 20 °C to + 40 °C range [8].

Moreover, the ambient temperature contributes to assess an overheating condition in the circuit breaker, by verifying if the measured temperature in the terminals exceeds the limit of 50 °C temperature rise [24]. As an example, Figure 2-4 courtesy of BW Offshore, shows an extract of an internal inspection report from an offshore platform. The circuit breaker cannot be considered reliable when operating above its maximum testing temperature. Thus, the cause of the overheating should be immediately investigated and resolved.

Figure 2-4: Circuit breaker terminal exceeding maximum allowable temperature, picture courtesy of BW Offshore

2.4.4 Surface Temperature

The maximum surface temperature is based on the equipment group, temperature class and ignition temperature of the respective gas present where the equipment is installed. This parameter is essential to avoid an explosion by ensuring that during operation the equipment surface temperature does not reach above the auto-ignition temperature of the surrounding flammable gas.

The temperature class applicable to group II equipment can be found in Table 2-1 [8].

Temperature class	Maximum surface temperature in °C
T1	≤ 450
T2	≤ 300
T3	≤ 200
T4	≤ 135
45	≤ 100
T6	≤ 85

Table 2-1 Group II maximum surface temperature [8]

The case study requires minimum temperature class T3 since H_2S auto-ignites at a temperature above 260 °C [2]. Therefore, no equipment should reach over 200 °C during normal operation or expected faults.

2.4.5 Equipment Protection Level (EPL)

The EPL parameter assumes that the equipment is not an ignition source during normal operation and rates its capability to remain a non-ignition source through different scenarios. The EPL is subdivided according to the environment characteristics as shown in Table 2-2 [8].

EPL		Mine	Gas	Dust
a	Very high	Ma	Ga	Da
b	High	Mb	Gb	Db
c	Enhanced	-	Gc	Dc

Table 2-2 Equipment Protection Level [8].

Thus, the EPL 'a - very high' indicates that an equipment remains as a non-ignition source even in the event of expected or rare malfunctions. While 'b - high' only covers expected malfunction scenarios. Finally, 'enhanced' (not applicable for non-mining applications) means that an extra protection is in place to avoid the device to ignite in case of faults that are likely to occur on a regular basis [8].

EPL is also presented with the nomenclature Zone 0/Category 1 (Ma, Ga and Da), Zone 1/ Category 2 (Mb, Gb and Db) and Zone 2/Category 3 (Gc and Dc) according to ATEX directive [21].

2.4.6 Equipment Protection Types (Ex Rating)

Various protection types are currently available to avoid or to withstand an eventual explosion.

Each type of protection has their own specific guidelines to be followed from design to operation. The most common rating for electrical and instrument equipment are Ex 'd', Ex 'e' and Ex 'i', combination of methods such as Ex 'de' are also largely used.

A brief summary of the main purpose of equipment protection types, also referred as 'Ex rating', is presented below [8]:

- Ex 'd' flameproof enclosure:

  Enclosure designed to withstand an internal explosion and to ensure that energy released to outside, via the enclosure's flame paths, is not high enough to cause an external explosion.

- Ex 'e' increased safety:

  Enclosure with increased robust design aiming to improve the equipment safety against root causes that could lead to arcs or temperature rise. An example would be to increase the gaps between the conductive parts. Increased safety cannot be used for EPL 'a' (ATEX Zone 0).

- Ex 'i' intrinsically safe:

  Electronic circuit with an associated apparatus located in a safe (non-explosive) area, designed to limit the thermal energy to less than the required to ignite the explosive atmosphere in the event of two simultaneous faults (Ex 'ia'), or during one fault (Ex 'ib') or not during any fault but subject to others onerous conditions (Ex 'ic').

This case study considers that motors located outdoor as hybrid rated Ex 'de', which the motor body is Ex 'd', while the motor terminal box is Ex 'e'.

Whereas the arc flash consideration refers to faults on the busbar side, hence the switchboard rating is the most relevant to this scope.

3 Methods

The arc flash impact is based on the amount of thermal energy produced, in $\mathrm{cal/cm^2}$, on a surface away from the arc source by a specific working distance. The aim is to simulate the exposure of a person working in front or near an electrical installation during an arc flash event, to identify suitable personal equipment and tools to protect them from the energy released.

The simulation was performed in the ETAP software version 20.0.2, the thermal incident energy results were generated by the Arc flash module using calculation method from IEEE 1584 2018 [1]. Therefore, the formulas and definitions presented in this section are based on this source.

The IEEE 1584 [1] calculation method was developed based on arc flash analysis from over thousands empirical tests done by researchers in laboratory for multiple electrode configuration in open air and inside enclosure [1].

In summary, researchers have induced an arc flash by applying the bolted fault current through a wire connecting the electrode ends. The test was repeated multiple times for each setup, and the highest temperature rise detected for each setup was considered. The tests were performed without the enclosure's front door, with sensors and seven copper calorimeters to detect the heat rise in Celsius degrees during an arc event [1].

The absorbed energy measured by the sensors and the incident energy in the calorimeters were assumed to be equal, since the absorbed energy by sensors was equal to or higher than 90 % of the incident energy in the calorimeters [1].

The arc power was found by integrating the multiplication of the current and voltage which were monitored by a digital oscilloscope during the test. Finally, the arc energy was found by the integral of the arc power for the duration of the arc [1].

The raw data obtained was processed and analyzed by researchers using algorithms and mathematical tools as described in detail in Annex G of IEEE 1584 2018 [1].

IEEE 1584 2018 [1] calculation is divided in two model applications, one for the range from 600 V to 15000 V and another from 208 V to 600 V. The first range calculation method was used in this scope, since it is applicable to both case study voltages 690 V and 6600 V.

The empirical tests done in IEEE 1584 provided the calculation methods and coefficients required to achieve the results in Section 4.

The calculation method steps are described in Section 3.1 to 3.8 [1]:

3.1 Electrode configuration

The case studies simulated switchboards with three different electrode arrangement: VCB as per Figure 3-1, HCB in Figure 3-2 and VCCB in Figure 3-3.

Both VCB and VCCB refer to vertical electrode arrangement, but in VCCB the electrodes are terminated in an insulation plate.

Whereas HCB has the electrodes placed horizontally with their end facing the panel door.

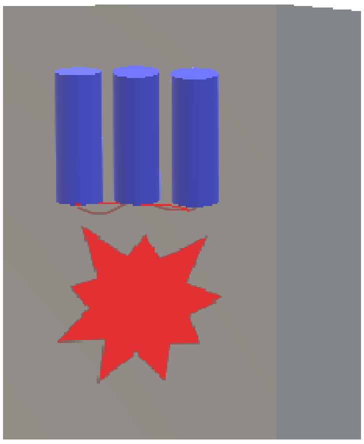

Figure 3-1: Vertical electrodes in a metal box enclosure (VCB) reproduced after [1, 11]

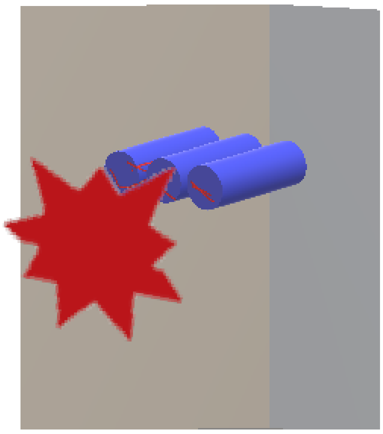

Figure 3-2: Horizontal electrodes in a metal enclosure (HCB) reproduced after [1, 11]

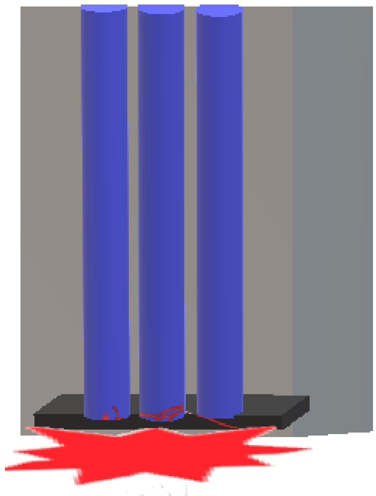

Figure 3-3: Vertical electrodes terminated in a metal enclosure's insulation barrier (VCCB) reproduced after [1, 11]

The configuration design influences the coefficient required in Eq. 3.1 for the arcing current as per Table 3-1.

3.2 Arcing current

Calculation of final arcing current starts with Eq. 3.1 for acquiring the intermediate average arcing current for each 600 V, 2700 V and 14300 V voltage reference levels.

$$I_{arc_{Voc}} = 10^{(k1+k2lgI_{bf}+k3lgG)}\left(k4I_{bf}^{6} + k5I_{bf}^{5} + k6I_{bf}^{4} + k7I_{bf}^{3} + k8I_{bf}^{2} + k9I_{bf} + k10\right) \quad \text{Eq. 3.1}$$

where,

$I_{arc_{Voc}}$ = average rms arcing current at an open circuit voltage (V_{oc}) in kA

I_{bf} = three phase bolted fault current in kA

G = gap distance between electrodes in millimeters

k1 to k10 = coefficient from Table 3-1 according to system voltage and electrode configuration

lg = $\log_{10}$

	VCB			VCCB			HCB		
V_{oc}	**600 V**	**2700 V**	**14300 V**	**600 V**	**2700 V**	**14300 V**	**600 V**	**2700 V**	**14300 V**
k1	-0,04287	0,0065	0,005795	-0,017432	0,002823	0,014827	0,054922	0,001011	0,008693
k2	1,035	1,001	1,015	0,98	0,995	1,01	0,988	1,003	0,999
k3	-0,083	-0,024	-0,011	-0,05	-0,0125	-0,01	-0,11	-0,0249	-0,02
k4	0	$-1{,}557^{-12}$	$-1{,}557^{-12}$	0	0	0	0	0	0
k5	0	$-4{,}556^{-10}$	$-4{,}556^{-10}$	0	$-9{,}204^{-11}$	$-9{,}204^{-11}$	0	0	$-5{,}043^{-11}$
k6	$-4{,}783^{-9}$	$-4{,}186^{-8}$	$-4{,}186^{-8}$	$-5{,}767^{-9}$	$2{,}901^{-8}$	$2{,}901^{-8}$	$-5{,}382^{-9}$	$4{,}859^{-10}$	$2{,}233^{-8}$
k7	$1{,}962^{-6}$	$8{,}346^{-7}$	$8{,}146^{-7}$	$2{,}524^{-6}$	$-3{,}262^{-6}$	$-3{,}262^{-6}$	$2{,}316^{-6}$	$-1{,}814^{-7}$	$3{,}046^{-8}$
k8	-0,000229	$5{,}482^{-5}$	$5{,}482^{-5}$	-0,00034	0,0001569	0,0001569	-0,000302	$-9{,}128^{-6}$	0,000116
k9	0,003141	-0,003191	-0,003191	0,01187	-0,004003	-0,004003	0,0091	-0,0007	-0,001145
k10	1,092	0,9729	0,9729	1,013	0,9825	0,9825	0,9825	0,9881	0,9839

Table 3-1: Coefficients for Eq. 3.1 [1]

Then the $I_{arc_{600}}$, $I_{arc_{2700}}$ and $I_{arc_{14300}}$ were used as interpolation equations for calculating the arcing current for each voltage level using Eq. 3.2 and Eq. 3.3.

$$I_{arc_1} = \frac{\left(I_{arc_{2700}} - I_{arc_{600}}\right)}{2{,}6}(V_{oc} - 2{,}7) + I_{arc_{2700}} \quad \text{Eq. 3.2}$$

For the 6600 V (V_{oc}) switchboard, the bus arcing current was given by I_{arc_2} in Eq. *3.3*.

$$I_{arc_2} = \frac{\left(I_{arc_{14300}} - I_{arc_{2700}}\right)}{11{,}6}(V_{oc} - 14{,}3) + I_{arc_{14300}} \quad \text{Eq. 3.3}$$

For the 690 V (V_{oc}) switchboard, the bus arcing current was given by I_{arc_3} in Eq. *3.4*.

$$\mathrm{I}_{\mathrm{arc}_3} = \frac{\mathrm{I}_{\mathrm{arc}_1}(2{,}7 - \mathrm{V}_{\mathrm{oc}})}{2{,}1} + \frac{\mathrm{I}_{\mathrm{arc}_2}(\mathrm{V}_{\mathrm{oc}} - 0{,}6)}{2{,}1} \quad \text{Eq. 3.4}$$

3.3 Fault clearing time (FCT)

The time taken to clear the fault is defined by the Star Protection & Coordination module in ETAP, using the current calculated in section 3.2 and its intersection with the protection device curve based on its design parameters.

The FCT refers to the period from a fault event starts until it is cleared, summing up the time for: [25]

1st. The main protection contacts to close, depending on the fault location and type.

2nd. The trip operation to energize the trip coil.

3rd. The circuit breaker opening contacts.

The duration time for each of these actions are dependent on the fault location, type, and the circuit breaker design.

The maximum FCT for calculations is usually assumed 2 seconds, considering a fair time to someone to move away from the event [7]. However, the standard [1] does not limit this value.

The relation between FCT and incident energy is found to be linear.

3.4 Enclosure size correction factor

First, the equivalent enclosure size (EES) given by Eq. 3.5 was found using the variables and constant from Table 3-2 according to the electrode configuration and enclosure depth to each simulation scenario.

$$EES = \left(\frac{Height_1 + Width_1}{2}\right)^2 \qquad \text{Eq. 3.5}$$

where,

$$Width_1 = 660{,}4 + \left[Width - 660{,}4) \times \left(\frac{V_{oc} + A}{B}\right)\right] \times 25{,}4^{-1} \qquad \text{Eq. 3.6}$$

$$Heigth_1 = 660{,}4 + \left[Height - 660{,}4) \times \left(\frac{V_{oc} + A}{B}\right)\right] \times 25{,}4^{-1} \qquad \text{Eq. 3.7}$$

Electrode configuration and constant	Constant	Enclosure	Depth from 203,2 to 508 (mm)	Depth from 508 to 660,4 (mm)	Depth from 660,4 to 1244,6 (mm)
VCB	A=4 B=20	$Width_1$	20	$0{,}03937 \times Width$	Eq. 3.6
		$Height_1$	20	$0{,}03937 \times Height$	0,03937 × Height
VCCB	A=10 B=24	$Width_1$	20	$0{,}03937 \times Width$	Eq. 3.6
		$Height_1$	20	$0{,}03937 \times Height$	Eq. 3.7
HCB	A=10 B=22	$Width_1$	20	$0{,}03937 \times Width$	Eq. 3.6
		$Height_1$	20	$0{,}03937 \times Height$	Eq. 3.7

Table 3-2: Equivalent height and width in millimeters [1]

Then the corrective factor (CF) was calculated using Eq. *3.8*.

$$CF = b1 \times + b2\ \times EES + b3 \qquad \text{Eq. 3.8}$$

where,

b1 to b3 = coefficients from Table 3-3

Electrode Configuration	b1	b2	b3
VCB	-0,000302	0,03441	0,4325
VCCB	-0,0002976	0,032	0,479
HCB	-0,0001923	0,01935	0,6899

Table 3-3: Coefficients for Eq. 3.8 [1]

3.5 Incident energy

The intermediate incident energy value was calculated for the three reference voltage levels 600 V, 2700 V and 14300 V separately using Eq. 3.9.

$$E_{V_{oc}} = \frac{12{,}552}{50} \times T \times 10^{\left(k1 + k2\log_{10}G + \frac{k3I_{arc,V_{oc}}}{k4I_{bf}^7 + k5I_{bf}^6 + k6I_{bf}^5 + k7I_{bf}^4 + k8I_{bf}^3 + k9I_{bf}^2 + k10I_{bf}} + k11\log_{10}I_{bf} + k12lgD + k13\log_{10}I_{arc,V_{oc}} + \log_{10}\frac{1}{CF}\right)} \qquad \text{Eq. 3.9}$$

where,

$E_{V_{oc}} =$ incident energy calculated for 600 V, 2700 V and 14300 V voltage level in J/cm^2

T = arc duration time in milliseconds

G = gap between conductors in millimeters

$I_{arc,V_{oc}} =$ rms arcing current for a 600 V, 2700 V and 14300 V voltage level in kA

$I_{bf} =$ three phase bolted fault current

D = working distance from electrodes

CF = correction factor for enclosure calculated in Eq. 3.8

k1 to k13 = coefficients from Table 3-4 according to respective electrode configuration and voltage reference level.

	VCB			VCCB			HCB		
V_{oc}	**600 V**	**2700 V**	**14300 V**	**600 V**	**2700 V**	**14300 V**	**600 V**	**2700 V**	**14300 V**
k1	0,753364	2,40021	3,825917	3,068459	3,870592	3,644309	4,073745	3,486391	3,044516
k2	0,566	0,165	0,11	0,26	0,185	0,215	0,344	0,177	0,125
k3	1,752636	0,354202	−0,999749	−0,098107	−0,736618	−0,585522	−0,370259	−0,193101	0,245106
k4	0	−1,557E-12	−1,557E-12	0	0	0	0	0	0
k5	0	4,556E-10	4,556E-10	0	−9,204E-11	−9,204E-11	0	0	−5,043E-11
k6	−4,783E-09	−4,186E-08	−4,186E-08	−5,767E-09	2,901E-08	2,901E-08	−5,382E-09	4,859E-10	2,233E-08
k7	0,000001962	8,346E-07	8,346E-07	0,000002524	−3,262E-06	−3,262E-06	0,000002316	−1,814E-07	−3,046E-06
k8	−0,000229	5,482E-05	5,482E-05	−0,00034	0,0001569	0,0001569	−0,000302	−9,128E-06	0,000116
k9	0,003141	−0,003191	−0,003191	0,01187	−0,004003	−0,004003	0,0091	−0,0007	−0,001145
k10	1,092	0,9729	0,9729	1,013	0,9825	0,9825	0,9725	0,9881	0,9839
k11	0	0	0	−0,06	0	0	0	0,027	0
k12	−1,598	−1,569	−1,568	−1,809	−1,742	−1,677	−2,03	−1,723	−1,655
k13	0,957	0,9778	0,99	1,19	1,09	1,06	1,036	1,055	1,084

Table 3-4: Coefficients for Eq. 3.9 [1]

Then the incident energy is calculated based on three interpolation terms ($\mathrm{E}_1, \mathrm{E}_2$ *and* E_3) using:

Eq. 3.10, for the 6,6 kV switchboard ($\mathrm{J/cm^2}$):

$$\mathrm{E}_{1,J} = \frac{(\mathrm{E}_{14300} - \mathrm{E}_{2700})}{11,6}(\mathrm{V_{oc}} - 14,3) + \mathrm{E}_{14300} \qquad \text{Eq. 3.10}$$

Incident energy converted to cal/cm^2, considering one calorie equals to 4,184 Joules:

$$\mathrm{E}_{1,cal} = \frac{\mathrm{E}_{1,J}}{4,184} \qquad \text{Eq. 3.11}$$

Eq. 3.13, for the 690 V switchboard (J/cm^2):

$$E_{2,J} = \frac{(E_{2700} - E_{600})}{2,1}(V_{oc} - 2,7) + E_{2700} \qquad \text{Eq. 3.12}$$

$$E_{3,J} = \frac{E_2(2,7 - V_{oc})}{2,1} + \frac{E_1(V_{oc} - 0,6)}{2,1} \qquad \text{Eq. 3.13}$$

Incident energy converted to cal/cm^2 considering one calorie equals to 4,184 Joules.

$$E_{3,cal} = \frac{E_{3,J}}{4,184} \qquad \text{Eq. 3.14}$$

3.6 Incident Energy Level

The energy level system based on NFPA 70E [12] determines which personal protective equipment (PPE) should be used for each range of incident energy (IE).

Energy Level	**IE (cal/cm^2)**	**Personal Protective Equipment**
Level A	< 1,2	Protective clothing, non-melting or untreated natural fiber for long sleeve shirt and pants/coverall, Face shield for projectile protection, Safety glasses, Hearing protection and Heavy-duty leather gloves.
Level B	1,2 ≤ IE ≥ 12	Arc-rated long-sleeve shirt and arc-rated pants or arc-rated coverall and/or arc flash suit, Arc-rated face shield, Arc-rated jacket, Hard hat, Arc-rated hard hat liner, Safety glasses, Hearing protection, Leather gloves and Leather work shoes.
Level C	≥ 12	Arc-rated long-sleeve shirt and arc-rated pants, Arc-rated arc flash suit hood, Arc-rated gloves, Arc-rated jacket, Hard hat, FR hard hat liner, Safety glasses, Hearing protection, Arc-rated gloves with Leather work shoes.

Table 3-5: NFPA 70E Incident Energy Level [12]

3.7 Arc Flash Boundary (AFB)

AFB is the distance from the arc where the incident energy is 1,2 $\mathrm{cal/cm^2}$ [26], exposing a person to second degree burn.

The calculation follows the same principle as for arcing current (Section 3.2) where AFB interpolation parameters ($\mathrm{AFB_1}, \mathrm{AFB_2}$ *and* $\mathrm{AFB_3}$) are calculated by:

Eq. 3.15, for the 6,6 kV switchboard ($\mathrm{J/cm^2}$):

$$\mathrm{AFB_1} = \frac{\mathrm{AFB_{14300}} - \mathrm{AFB_{2700}}}{11{,}6} + (\mathrm{V_{oc}} - 14{,}3) + \mathrm{AFB_{14300}} \qquad \text{Eq. 3.15}$$

Eq. 3.17, for the 690 V switchboard ($\mathrm{J/cm^2}$):

$$AFB_2 = \frac{AFB_{2700} - AFB_{600}}{2{,}1} + (V_{oc} - 2{,}7) + AFB_{2700} \qquad \text{Eq. 3.16}$$

$$AFB_3 = \frac{AFB_2(2{,}7 - V_{oc}}{2{,}1} + \frac{AFB_1(V_{oc} - 0{,}6)}{2{,}1} \qquad \text{Eq. 3.17}$$

3.8 Reduced arcing current

A correction factor to cover protection device variations is calculated by returning to Section 3.2 and re-calculating all following steps up to Section 3.7 using the reduced arcing current ($I_{arc\,min}$) for each reference voltage level ($\mathrm{I_{arc_{14300}}}$, $\mathrm{I_{arc_{2700}}}$ and $\mathrm{I_{arc_{600}}}$.) in Eq. 3.18.

$$I_{arc\,min} = I_{arc} \times (1 - 0{,}5\ \times V_{arc}C_f) \qquad \text{Eq. 3.18}$$

$$V_{arc}C_f = k1V_{oc}^6 + k2V_{oc}^5 + k3V_{oc}^4 + k4V_{oc}^3 + k5V_{oc}^2 + k6V_{oc} + k7 \qquad \text{Eq. 3.19}$$

where,

$V_{arc}\mathrm{C_f}$ = arcing current variation correction factor.

$\mathrm{I_{arc}}$ = final intermediate rms arcing current in kA, applied to $\mathrm{I_{arc_{14300}}}$, $\mathrm{I_{arc_{2700}}}$ and $\mathrm{I_{arc_{600}}}$.

$\mathrm{I_{arc\_min}}$ = reduced rms arcing current after correction factor.

Finally, the reduced and the original arcing current values are compared and the one that results in the highest final incident energy is then used as the final result.

4 Results

The simulation's aim was to analyze the thermal energy, which a worker is exposed when working in electrical power installations. The risk is not just restricted to jobs performed in the panel with opened door, but also during non-invasive activities, such as checking a reading in the front door instrument or manually switching off a load.

The base model is a simplified version of an offshore platform electrical system with one steam turbine running while another is in standby, supplying power to 6,6 kV loads and to 690 V via two step-down transformers. Inductive motors and static loads protected by circuit breakers, relays and fuse-switches were added to represent typical offshore loads.

The loads are located in explosive atmosphere classified as Zone 1/Gb, IIB and T3, where Hydrogen Sulfide (H_2S) is likely to occur during normal operation. The H_2S gas auto-ignites when temperature reaches 260 °C, so minimum T3 rated equipment would be required to ensure that no surface exceeds 200 °C.

The case study simulated the base model as illustrated in Figure 4-1, for nine switchboard designs as described in Table 4-1.

The LV and MV switchboards were divided in sections A and B. The 690 V panel was identified as LV SWBD A and LV SWBD B, while the 6,6 kV as MV SWBD A and MV SWBD B.

The system was balanced with similar loads connected to each section, thus similar results were achieved in both sections A and B for the base Cases 1, 4 and 7 when considering the same electrode configuration, panel dimensions and fault clearance time. Therefore, Case 1 (Table 4-2), Case 4 (Table 4-5) and Case 7 (Table 4-8) are used as base case for VCB, HCB and VCCB respectively.

Whereas the Cases 2, 3, 5, 6, 8 and 9 exposed section A (LV SWBD A and MV SWBD A) and section B (LV SWBD B and MV SWBD B) to different enclosure dimensions, conductor gaps and FCTs, for didactic comparison purposes.

The Table 4-1 summarizes the different considerations for each case, further details such as input and results are individually registered in Table 4-2 to Table 4-10.

	Electrode Configuration	Conductor Gap LL (mm)	Enclosure (mm)	Final FCT
Case 1	VCB	Typical*	Typical*	Typical*
Case 2	VCB	Reduced	Reduced	Typical*
Case 3	VCB	Typical*	Typical*	Reduced and Increased
Case 4	HCB	Typical*	Typical*	Typical*
Case 5	HCB	Reduced	Reduced	Typical*
Case 6	HCB	Typical*	Typical*	Reduced and Increased
Case 7	VCCB	Typical*	Typical*	Typical*
Case 8	VCCB	Reduced	Reduced	Typical*
Case 9	VCCB	Typical*	Typical	Reduced and Increased

Table 4-1: Study cases summary

*** 'Typical' refers to the ETAP software default values based on IEEE 1584 [1].**

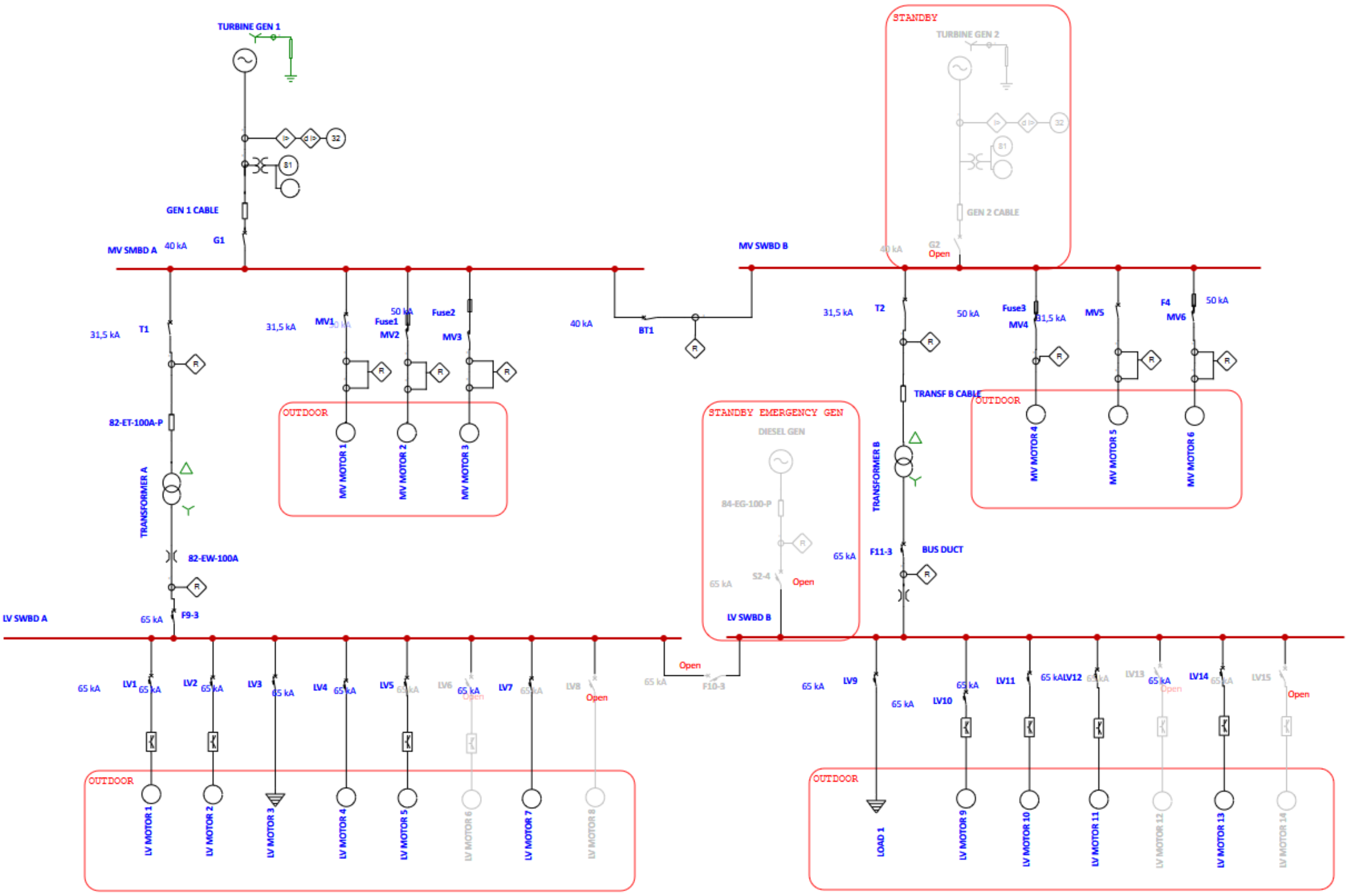

Figure 4-1: Single Line Diagram for base model.

4.1 Case 1 – VCB arrangement base case

The base case for VCB electrode configuration, assuming typical enclosure dimensions, conductor gaps and the calculated FCT (according to Section 3.3). Input data and results are presented in Table 4-2.

	690 V Switchboard		6,6 kV Switchboard	
	LV SWBD A	**LV SWBD B**	**MV SMBD A**	**MV SWBD B**
Electrode Configuration	VCB	VCB	VCB	VCB
Conductor Gap LL (mm)	32	32	152	152
Working Distance LL (cm)	61	61	91,4	91,4
Height (mm)	508	508	1143	1143
Width (mm)	508	508	762	762
Depth (mm)	508	508	762	762
Volume (m³)	0,131	0,131	0,664	0,664
AFB (m)	1,19	1,14	2,38	2,38
Energy Levels	Level B	Level B	Level B	Level B
Ia at FCT (kA)	25,592	24,085	7,215	7,214
Final FCT (sec)	0,08	0,08	0,61	0,61
Total Energy (cal/cm²)	3,5	3,28	5,38	5,39

Table 4-2: Case 1 results from ETAP arc flash module.

4.2 Case 2 – VCB arrangement with reduced enclosure and conductor gap

The second case for VCB electrode configuration differs from Case 1 by assuming reduced enclosure dimensions and shorter conductor gaps. Input data and results are presented in Table 4-3.

The enclosure size was reduced in all switchboard's sections, while the conductor gap was changed only for LV SWBD B and MV SWBD B. The goal was to compare the incident energy impact with and without a conductor gap reduction.

	690 V Switchboard		6,6 kV Switchboard	
	LV SWBD A	**LV SWBD B**	**MV SMBD A**	**MV SWBD B**
Electrode Configuration	VCB	VCB	VCB	VCB
Conductor Gap LL (mm)	32	15	152	90
Working Distance LL (cm)	61	61	91,4	91,4
Height (mm)	355	355	508	508
Width (mm)	305	305	508	508
Depth (mm)	203	203	508	508
Volume (m³)	0,022	0,022	0,131	0,131
AFB (m)	1,19	1,034	2,793	2,68
Energy Levels	Level B	Level B	Level B	Level B
Ia at FCT (kA)	25,592	25,548	7,215	7,287
Final FCT (sec)	0,08	0,08	0,61	0,61
Total Energy (cal/cm²)	3,5	2,8	6,93	6,49

Table 4-3: Case 2 results from ETAP arc flash module.

The incident energy for the LV system decreased when the enclosure dimensions together with the conductor gap were reduced, but it remained unchanged when only the enclosure size was reduced.

Nevertheless, the incident energy increased for the MV system for both sections with and without the conductor gap reduction.

4.3 Case 3 – VCB arrangement with FCT variations

The final case for VCB electrode configuration retains most of the Case 1 setup with exception of the fault clearance time.

The Cases 1 and 2 use the software calculated FCT according to the time current characteristics (TCC) curves for the respective protection coordination device and the circuit current level.

Whereas the Case 3, uses shorter FCT settings for LV SWBD A and MV SWBD A and longer FCT for LV SWBD B and MV SWBD B, as specified in Table 4-4.

	690 V Switchboard		6,6 kV Switchboard	
	LV SWBD A	**LV SWBD B**	**MV SMBD A**	**MV SWBD B**
Electrode Configuration	VCB	VCB	VCB	VCB
Conductor Gap LL (mm)	32	32	152	152
Working Distance LL (cm)	61	61	91,4	91,4
Height (mm)	508	508	1143	1143
Width (mm)	508	508	762	762
Depth (mm)	508	508	762	762
Volume (m³)	0,131	0,131	0,664	0,664
AFB (m)	0,994	2,03	2,095	3,004
Energy Levels	Level B	Level B	Level B	Level B
Ia at FCT (kA)	25,592	24,085	7,215	7,215
Final FCT (sec)	0,06	0,2	0,5	0,88
Total Energy (cal/cm²)	2,62	8,2	4,41	7,76

Table 4-4: Case 3 results from ETAP arc flash module.

The results have shown that the incident energy and FCT were linearly proportional.

Thus, longer FCT values resulted in higher energy, while shorter FCT resulted in lower energy.

4.4 Case 4 - HCB arrangement base case

The base case for HCB electrode configuration, assuming typical enclosure dimensions, conductor gaps and the calculated FCT (according to Section 3.3). Input data and results are presented in Table 4-5.

	690 V Switchboard		6,6 kV Switchboard	
	LV SWBD A	**LV SWBD B**	**MV SMBD A**	**MV SWBD B**
Electrode Configuration	HCB	HCB	HCB	HCB
Conductor Gap LL (mm)	32	32	152	152
Working Distance LL (cm)	61	61	91,4	91,4
Height (mm)	508	508	1143	1143
Width (mm)	508	508	762	762
Depth (mm)	508	508	762	762
Volume (m^3)	0,131	0,131	0,664	0,664
AFB (m)	1,428	1,382	3,437	3,437
Energy Levels	Level B	Level B	Level B	Level B
Ia at FCT (kA)	25,104	23,592	7,187	7,187
Final FCT (sec)	0,08	0,08	0,61	0,61
Total Energy (cal/cm²)	6,52	6,11	11,34	11,34

Table 4-5: Case 4 results from ETAP arc flash module.

4.5 Case 5 – HCB arrangement with reduced enclosure and conductor gap

The second case for HCB electrode configuration differs from Case 4 by assuming reduced enclosure dimensions and shorter conductor gaps. Input data and results are presented in Table 4-6.

The enclosure size was reduced in all switchboard's sections, while the conductor gap was changed only for LV SWBD B and MV SWBD B. The goal was to compare the incident energy impact with and without a conductor gap reduction.

	690 V Switchboard		6,6 kV Switchboard	
	LV SWBD A	**LV SWBD B**	**MV SMBD A**	**MV SWBD B**
Electrode Configuration	HCB	HCB	HCB	HCB
Conductor Gap LL (mm)	32	15	152	90
Working Distance LL (cm)	61	61	91,4	91,4
Height (mm)	355	355	508	508
Width (mm)	305	305	508	508
Depth (mm)	203	203	508	508
Volume (m^3)	0,022	0,022	0,131	0,131
AFB (m)	1,428	1,24	3,693	3,545
Energy Levels	Level B	Level B	Level C	Level B
Ia at FCT (kA)	25,104	25,491	7,187	7,274
Final FCT (sec)	0,08	0,08	0,61	0,61
Total Energy (cal/cm²)	6,52	4,92	12,81	11,94

Table 4-6: Case 5 results from ETAP arc flash module.

The conclusion was the same as the Case 2, that incident energy for the LV system decreased when the enclosure dimensions together with the conductor gap were reduced, but it remained unchanged when only the enclosure size was reduced.

Nevertheless, the incident energy increased for the MV system for both sections with and without the conductor gap reduction.

4.6 Case 6 - HCB arrangement with FCT variations

The final case for HCB electrode configuration retains most of the Case 4 setup with exception of the fault clearance time.

The Cases 4 and 5 use the software calculated FCT according to the time current characteristics (TCC) curves for the respective protection coordination device and the circuit current level.

Whereas the Case 6 uses shorter FCT settings for LV SWBD A and MV SWBD A and longer FCT for LV SWBD B and MV SWBD B, as specified in Table 4-7.

	690 V Switchboard		**6,6 kV Switchboard**	
	LV SWBD A	**LV SWBD B**	**MV SMBD A**	**MV SWBD B**
Electrode Configuration	HCB	HCB	HCB	HCB
Conductor Gap LL (mm)	32	32	152	152
Working Distance LL (cm)	61	61	91.4	91.4
Height (mm)	508	508	1143	1143
Width (mm)	508	508	762	762
Depth (mm)	508	508	762	762
Volume (m^3)	0.131	0.131	0.664	0.664
AFB (m)	1,236	2.192	3.057	4.267
Energy Levels	Level B	Level C	Level B	Level C
Ia at FCT (kA)	25.104	23.592	7.187	7.187
Final FCT (sec)	0.06	0.2	0.5	0.88
Total Energy (cal/cm²)	4.89	15.27	9.29	16.36

Table 4-7: Case 6 results from ETAP arc flash module.

The findings were similar to Case 3, that the incident energy and FCT were linearly proportional.

Thus, longer FCT values resulted in higher energy, while shorter FCT resulted in lower energy.

4.7 Case 7 – VCCB arrangement base case

The base case for VCCB electrode configuration, assuming typical enclosure dimensions, conductor gaps and the calculated FCT (according to Section 3.3). Input data and results are presented in Table 4-8.

	690 V Switchboard		6,6 kV Switchboard	
	LV SWBD A	**LV SWBD B**	**MV SMBD A**	**MV SWBD B**
Electrode Configuration	VCBB	VCBB	VCBB	VCBB
Conductor Gap LL (mm)	32	32	152	152
Working Distance LL (cm)	61	61	91,4	91,4
Height (mm)	508	508	1143	1143
Width (mm)	508	508	762	762
Depth (mm)	508	508	762	762
Volume (m^3)	0,131	0,131	0,664	0,664
AFB (m)	1,3	1,249	2,747	2,747
Energy Levels	Level B	Level B	Level B	Level B
Ia at FCT (kA)	27,602	25,889	7,485	7,485
Final FCT (sec)	0,08	0,08	0,61	0,61
Total Energy (cal/cm²)	4,72	4,39	7,94	7,94

Table 4-8: Case 7 results from ETAP arc flash module.

4.8 Case 8 – VCCB arrangement with reduced enclosure and conductor gap

The second case for VCCB electrode configuration differs from Case 7 by assuming reduced enclosure dimensions and shorter conductor gaps. Input data and results are presented in Table 4-9.

The enclosure size was reduced in all switchboard's sections, while the conductor gap was changed only for LV SWBD B and MV SWBD B. The goal was to compare the incident energy impact with and without a conductor gap reduction.

	690 V Switchboard		6,6 kV Switchboard	
	LV SWBD A	**LV SWBD B**	**MV SMBD A**	**MV SWBD B**
Electrode Configuration	VCBB	VCBB	VCBB	VCBB
Conductor Gap LL (mm)	32	15	152	90
Working Distance LL (cm)	61	61	91,4	91,4
Height (mm)	355	355	508	508
Width (mm)	305	305	508	508
Depth (mm)	203	203	508	508
Volume (m^3)	0,022	0,022	0,131	0,131
AFB (m)	1,3	1,145	3,089	2,903
Energy Levels	Level B	Level B	Level B	Level B
Ia at FCT (kA)	27,602	26,823	7,485	7,53
Final FCT (sec)	0,08	0,08	0,61	0,61
Total Energy (cal/cm²)	4,72	3,75	9,7	8,72

Table 4-9: Case 8 results from ETAP arc flash module.

The conclusion was the same as the Cases 2 and 5, that incident energy for the LV system decreased when the enclosure dimensions together with the conductor gap were reduced, but it remained unchanged when only the enclosure size was reduced.

Nevertheless, the incident energy increased for the MV system for both sections with and without the conductor gap reduction.

4.9 Case 9 - VCCB arrangement with FCT variations

The final case for VCCB electrode configuration retains most of the Case 7 setup with exception of the fault clearance time.

The Cases 7 and 8 use the software calculated FCT according to the time current characteristics (TCC) curves for the respective protection coordination device and the circuit current level.

Whereas the Case 9 uses shorter FCT settings for LV SWBD and MV SWBD A and longer FCT for LV SWBD B and MV SWBD B, as specified in Table 4-10.

	690 V Switchboard		6,6 kV Switchboard	
	LV SWBD A	**LV SWBD B**	**MV SMBD A**	**MV SWBD B**
Electrode Configuration	VCBB	VCBB	VCBB	VCBB
Conductor Gap LL (mm)	32	32	152	152
Working Distance LL (cm)	61	61	91,4	91,4
Height (mm)	508	508	1143	1143
Width (mm)	508	508	762	762
Depth (mm)	508	508	762	762
Volume (m^3)	0,131	0,131	0,664	0,664
AFB (m)	1,108	2,077	2,447	3,402
Energy Levels	Level B	Level B	Level B	Level B
Ia at FCT (kA)	27,602	25,889	7,485	7,485
Final FCT (sec)	0,06	0,2	0,5	0,88
Total Energy (cal/cm^2)	3,54	10,97	6,51	11,45

Table 4-10: Case 9 results from ETAP arc flash module.

Finally, the findings were similar to Case 3 and 6, that the incident energy and FCT were linearly proportional.

Thus, longer FCT values resulted in higher energy, while shorter FCT resulted in lower energy.

5 Discussions

The Table 5-1 presents the differences between the base Cases 1, 4 and 7 of the power system model (Figure 4-1) for each electrode configuration. The other variables not mentioned in the Table 5-1 are based on ETAP default values, these input values can be found in Table 4-2, Table 4-5 and Table 4-8.

	LV SWBD A			MV SWBD A		
Electrode Configuration	**VCB**	**HCB**	**VCBB**	**VCB**	**HCB**	**VCBB**
AFB (m)	1,19	1,428	1,3	2,38	3,437	2,747
Ia at FCT (kA)	25,592	25,104	27,602	7,215	7,187	7,485
Total Energy (cal/cm²)	3,5	6,52	4,72	5,38	11,34	7,94

Table 5-1: Base cases summary

The results showed that the incident energy was the highest when the electrode was arranged horizontally (HCB) and the lowest for the vertical arrangement (VCB). Despite the much higher incident energy results, if HCB configuration is used in metal-clad switchboard with draw-out cubicles, the probability of an arc to occur is minimum as mentioned in Section 2.1.1 [7].

The HCB also resulted in the highest arc flash boundary (AFB). Nevertheless, the highest incident energy does not always mean the highest AFB, if considering cases with other variables for arcing current and FCT [11].

The incident energy was also higher in the MV than the LV switchboard.

Moreover, the VCCB presented the highest arcing current, while HCB and VCB results were fairly similar. The reason is that for VCCB, the arc plasma is contained in an insulation barrier very close to the electrode end as shown in Figure 3-3, resulting in a short arc with lower impedance and consequently greater arc fault current [11].

Whereas the plasma moves from the electrode end towards the enclosure's bottom for VCB, as illustrated in Figure 3-1, and from the electrode end to the outside horizontally for HCB, as shown in Figure 3-2. Neither of these setups includes a barrier that could contain the arc plasma, hence the arc expands and reaches a longer length and higher impedance [11].

Additional findings from other scenarios not covered within this scope stated that incident energy decreases at a faster rate for HCB than for the other two arrangements [11]. Furthermore, it is possible to get lower incident energy in VCCB than in VCB by manipulating input parameters according to multiple scenarios [11].

Moreover, the Cases 2, 5 and 8 simulated the impact of using smaller enclosures as well as shorter electrode gaps than the base Cases 1, 4 and 7. Results showed that the incident energy for the LV system decreased when the enclosure dimensions together with the conductor gap were reduced, but unexpectedly remained unchanged when only the enclosure size was reduced. It could be that the reduced input dimensions were within the same calculation range as the base case thus no impact on the calculation, this would need to be further investigated.

Whereas smaller enclosures in the MV switchboards, resulted in higher incident energy. It is also expected that pressure caused by an arc increases if the enclosure dimensions are reduced [13].

Finally, Cases 3, 6 and 9 simulated the impact of the fault clearance time (FCT) in the incident energy and showed that the incident energy and FCT are linearly proportional for all electrode configurations. Thus, longer FCT values resulted in higher energy, while shorter FCT resulted in lower energy.

Nonetheless, the software treats the FCT as a fixed value, hence it does not cover the various trip settings of the protection devices connected to the switchboard [11].

Each protection device installed in the switchboard shall have the trip setting adjusted according to the connected load, the switchboard rating, as well as the fault type and its location. Therefore, the importance of time coordination characteristics (TCC) curve to adjust each trip unit to best achieve protection, coordination and selectivity as mentioned in Section 1.3.1.

In addition, even if one device has a very high-speed response, its actuation might have to be delayed allowing a higher current for a short period, as for example in a start-up scenario or to achieve protection coordination. Nevertheless, FCT can be adjusted within the trip unit range to better protect a specific system if not exceeding the maximum time limit of the applicable system.

Moreover, the incident energy increases with time, so a lower arcing current lasting for long time can achieve higher energy than a higher arcing current lasting for a very short period [11]. For example in Case 3, a ‘LV SWBD B’ arcing current of 24,085 kA at 0,2 seconds resulted in about four times higher incident energy than ‘LV SWBD A’ with an arcing current of 25,592 kA at 0,06 seconds, the same was observed in Cases 6 and 9.

5.1 Explosive atmosphere considerations

The results have shown that incident energy levels were within acceptable values below ‘Level C’ [12] for all nine simulation cases. Thus, the recommendation is that the worker shall use the tested and approved personal protection equipment (PPE) to the minimum required level as per Table 3-5, while performing any scope in the switchboard.

The results from Table 4-2 to Table 4-10 present the incident energy in a specific location, away from the arc source by a specific distance representing what would be a working distance in a practical setup. This assumption is appropriate for choosing the correct PPE against human burn in a non-explosive atmosphere. However, it is not suitable for investigating if the arc produces heat enough to auto-ignite a flammable gas, if presented in sufficient concentration in the surrounding air.

The absolute maximum energy and consequent temperature rise are the parameters that determine whether an arc would become an ignition source leading to a fire or an explosion by reaching above the flammable gas auto-ignition temperature if in sufficient concentration in the surrounding air. This scope considers that Hydrogensulfid (H_2S) may occur and its auto-ignition temperature is at 260 °C and in concentration between 4,3 % to 45 % [2].

The maximum temperature is expected at the closest point to the source. Thus, the maximum energy could be calculated if the variable ‘D = working distance from electrodes’, from Eq. 3.9 in Section 3.5, referred to the closest point to the source instead of the working distance.

The Table 5-2 shows the re-calculated results for the nine cases using the same assumptions as the case studies from Section 4 except that ‘work distance’ was changed to ETAP minimum setting 2,54 cm.

	Incident Energy (cal/cm^2)			
	LV SWBD A	**LV SWBD B**	**MV SMBD A**	**MV SWBD B**
Case 1	555,8	520,7	1486,3	1486,3
Case 2	555,8	444,0	1912,9	1792,6
Case 3	416,9	1301,8	1218,3	2144,2
Case 4	3785,6	3547,3	4978,5	4978,5
Case 5	3785,6	2837,5	5624,1	5233,6
Case 6	2839,2	8868,3	4080,7	7182,1
Case 7	1447,4	1346,6	3706,1	3706,1
Case 8	1447,4	1151,1	4530,7	4076,6
Case 9	1085,5	3366,4	3037,8	5346,6

Table 5-2: Incident energy at 2,54 centimeters from arc source.

Whereas the software ETAP does not provide temperature as an output data, but IEEE 1584 [1] mentions that thermal incident energy in $\mathrm{cal/cm^2}$ was converted from Celsius degrees by multiplying the temperature rise detected by the calorimeter during testing by 0,135 [1]. The standard does not explain the mathematic behind this factor of 0,135, but the ASTM 1959 [27] indicates that it originates from the 'Stoll Curve' [26], which shows the heat tolerance of human's tissue to a second-degree burn as a function of time, considering any incident energy over 1,2 $\mathrm{cal/cm^2}$ as a hazard.

The re-calculated incident energy values from Table 5-2 were then converted to a temperature rise in Celsius degrees by assuming the 0,135 energy to temperature conversion ratio, and sum up with an ambient temperature of 40 °C. The final temperature results are presented in Table 5-3.

	Temperature (°C)			
	LV SWBD A	**LV SWBD B**	**MV SMBD A**	**MV SWBD B**
Case 1	4157,0	3897,0	11049,6	11049,6
Case 2	4157,0	3328,9	14209,6	13318,5
Case 3	3128,1	9683,0	9064,4	15923,0
Case 4	28081,5	26316,3	36917,8	36917,8
Case 5	28081,5	21058,5	41700,0	38807,4
Case 6	21071,1	65731,1	30267,4	53240,7
Case 7	10761,5	10014,8	27492,6	27492,6
Case 8	10761,5	8566,7	33600,7	30237,0
Case 9	8080,7	24976,3	22542,2	39644,4

Table 5-3: Temperature at 2,54 centimeters from arc source.

According to the Table 5-3, the heat generated by the arc flash would act as an ignition source if H_2S was present in sufficient concentration nearby the arc source, since the results exceeded the H_2S auto-ignition temperature of 260 °C for all nine cases.

Special enclosures with increased safety against explosion were not included in IEEE 1584 [1], so the impact of the incident energy externally to an Ex rated enclosure was not covered by this scope. Whereas the research [10] results showed that the energy released outside an Ex rated enclosure was 90% less than the incident energy measured internally. This result does not reflect the difference between Ex rated and non-Ex enclosures, hence does not add value to this scope.

Additional measures would be applicable if the switchboards were installed in a hazardous area, to prevent that the energy released by the arc was enough to ignite the H_2S flammable gas outside the enclosure.

A wide range of Ex rated enclosures and equipment exist in the market to mitigate the risk linked to electrical equipment installed in explosive atmospheres, suitable to the minimum requirements of the area classification where the equipment is located as summarized in Section 2.4. For example, an explosion proof switchboard rated Ex ‘d’, IIB, T3 would be suitable for the classification area of this scope.

Even if the switchboard was installed in an indoor room free from flammable gases, special measures would be required to prevent outdoor gases entering the switchboard room via ventilation or cable penetration. Moreover, gas detectors shall be in place and integrated into the control system to early detect and to shutdown all equipment in the room before the gas concentration in the air is sufficient to cause an ignition. Besides the explosion risk, H_2S is a deadly gas, so common practice is that workers should carry a mobile gas detector to monitor concentration levels while transiting by areas with gas exposure, in addition to the permanently installed devices in each room.

5.2 Future work

Investigate the special conditions of scenarios which present less common results, such as incident energy arc being higher in the LV system than in a HV system [7] and VCCB electrode arrangement presenting lower incident energy than the VCB [11].

In addition, further investigation of the impact of enclosure dimensions in LV switchboards would be required, since it did not affect the incident energy result as expected in Cases 2, 5 and 8.

There are few researches available related to arc flash in hazardous areas. Therefore, a simulation covering various types of explosion proof enclosures and the impact on the incident energy would be interesting for comparison against non-explosive enclosures.

Furthermore, internal modifications of Ex rated enclosure are not recommended and it can compromise its certification, hence it would be valuable to simulate non-authorized modifications to verify how the integrity of the equipment is affected in relation to its capability of reducing the risk of an explosion.

This scope focused on faults in the bus side for an AC system, so further work could involve simulations for arc flash in DC system and faults on the load side.

Finally, protection devices are essential to early detect and clear the faults in the system, hence additional research related to various circuit breaker’s ratings and their impact on the incident energy would be pertinent to this scope. As the fault clearance time (FCT) is strongly dependent on the CB and relay settings, as well as playing an essential role in the incident energy calculation, a deeper analysis of the time-current curve and its impact on the system protection, coordination, and selectivity for different system voltage levels would be relevant.

6 Conclusion

The proper design of a switchboard is the first preventive measure to ensure that a power system is safe and reliable during normal operations and eventual faults. Then maintenance, inspection and testing are required to secure the equipment's integrity throughout its operational lifetime by avoiding the factors (examples in Figure 2-1) which can lead to an arc. In addition, protection devices are installed and properly adjusted to protect its load, cables and to clear a fault before affecting the rest of the system.

Nevertheless, the protection personal equipment (PPE) suitable to the switchboard's incident energy level is required while working in electrical installation, as a safety corrective measure in case an arc happens.

The incident energy is a parameter used to quantify the safety hazard that an electrical arc exposes a human to second-degree burn when energy released exceeds 1,2 $\mathrm{cal/cm^2}$ [26]. Therefore, the importance of understanding the factors that contribute to achieve the lowest incident energy during switchboard design.

The results achieved by ETAP software based on IEEE 1584 2018 [1] calculation methods confirmed that variations within the switchboard internal design impact the incident energy levels. For example, just the fact of arranging the electrodes horizontally instead of vertically doubled the incident energy.

Moreover, the total time for a fault to be cleared was proven to have a linear impact on the incident energy, hence the longer an arc lasts, more the incident energy increases.

Therefore, when comparing two cases with different fault clearing times (FCT), lower arcing current lasting longer can result in higher incident energy than a higher arcing current that is cleared instantaneously. For example in Cases 3, 6 and 9, the LV switchboard's section B had a lower arcing current and a longer FCT that resulted in a four times higher incident energy than the section A that had a higher arcing current but a much shorter FCT.

The reduction in enclosure size did not impact at all the results for the LV switchboards, but slightly increased the incident energy for the MV switchboards. Whereas a shorter gap between conductors reduced the incident energy for both voltage levels, but not significantly.

The cases were then re-evaluated to cover the additional risk that the switchboards are located in explosive atmosphere where flammable gas (H_2S) might occur.

The ignition risk is pertinent even when incident energy level is deemed within acceptable safety level at a working distance. The arc flash safety level only purpose is to protect personnel against burn, hence the incident energy is calculated at a certain distance from the electrodes, as to represent where a worker would stand while performing a work in the switchboard.

Nevertheless, the incident energy increases as the distance from the arc source decreases. Therefore, the incident energy for the nine cases were re-calculated at closest to the arc source and converted to temperature. The results showed that for all cases the temperature reached above the H_2S auto-ignition temperature of 260 °C. Thus, the heat caused by the arc could cause fire or explosion if flammable gas was able to enter the switchboard in a sufficient concentration.

Switchboard enclosure and internal components would then have to be tested and certified according to the hazardous area minimum requirements, as specified in section 2.4.

The vertical electrode configuration (VCB) resulted in the lowest incident energy and lowest arcing current. Thus, an explosion proof rated Ex ‘d’, IIB, T3 enclosure with a VCB arrangement would be the most suitable design alternative for this scope’s power system.

The explosion-proof rating Ex ‘d’ certifies that the enclosure can withstand an internal explosion and reduce the incident energy, transferred (and consequent temperature) to outside the enclosure, to non-hazard levels below the gas auto ignition temperature. Whereas the rating ‘IIB’ is suitable for non-mining application with H_2S exposure, while T3 ensures that no component surface temperature exceeds 200 °C.

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