Managing Electrical Fire Risks in Substations: A Framework to Protect Lives and Assets

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Abstract

Substations, which are part of electric power systems are ubiquitous, versatile and serve virtually all sectors and industries. These are essential high voltage units utilized to power and reliably operate facilities in the Oil and Gas industry. However, this available electricity also poses several electrical hazards to personnel and assets such as arc flashes, electric shocks, fires and explosions. Managing electrical fire risks is of growing significance since as per NFPA it is the leading cause of fire accidents costing personnel to suffer from severe injuries to fatalities and asset damages in a multi-million-dollar business. This study examines the numerous substation electrical fire risks. In addition, it explores the current management practices within ADNOC by conducting a gap assessment to identify the major gaps for managing these risks and in turn, benchmark to adopt the best practices being implemented internationally (such as NFPA and IEEE). Therefore, assisting in developing a framework that will outdo and optimize the current management practices. The designed framework primarily proposes establishing an Electrical Safety Committee and conducting a Failure Mode and Effect Analysis to manage these emerging electrical fires risks within the organization.

Keywords
Fire protection, Electrical fire hazards, electrical fires, Arc flash fires, substation protection.

1. Introduction
Nowadays, most if not all industrial and manufacturing facilities operate utilizing an electrical substation using electricity thanks to its discovery by Benjamin Franklin in 1752. Substation is a high-voltage electric power system facility which are essential elements in any industry. They are the location points in the power network where transformers and busbars are connected via switch gears and circuit breakers for the purpose of power transmission and distribution. The IEEE National Electrical Safety Code (NESC) defines a substation as “an enclosed assemblage of equipment, e.g., switches, circuit breakers, buses, and transformers, under the control of qualified persons, through which electric energy is passed for the purpose of switching or modifying its characteristics” (NESC 2021). A similar definition is provided by IEEE Energy Development and Power Generation Committee (EDPG) as “an area or group of equipment containing switches, circuit breakers, buses, and transformers for switching power circuits and to transform power from one voltage to another or from one system to another (NESC 2021). There are various types of substations based on its main function: step-up transmission substation, step-down transmission substation, distribution substation, and underground distribution substation. Each design type has numerous functions such as stepping up or down the voltage from on level to another, regulating voltage, switching within the grid system the transmission and distribution circuits, measuring electric power flowing in the circuits, connecting signal communication to the circuits, eliminating electrical surges and lightning from the system and as interface connection between the electric generation plant and the system (Bottrill 2005). Figure 1 below presents the main building blocks of a standard electric power system which are real-time electrical energy delivery systems where the power is generated, transported, and distributed to the users. Unlike gas and water system, electric power systems are not storage systems (McDonald 2016). The system starts with a power plant where the electrical energy is produced

(called generation) then this energy is transformed to a High-Voltage (HV) power station for efficient transportation in long distances. These HV power lines transport the electrical energy to substations which are responsible for typically stepping down the HV electrical energy to a low voltage power lines (called feeders) and distribute it to the users (Steven 2017).

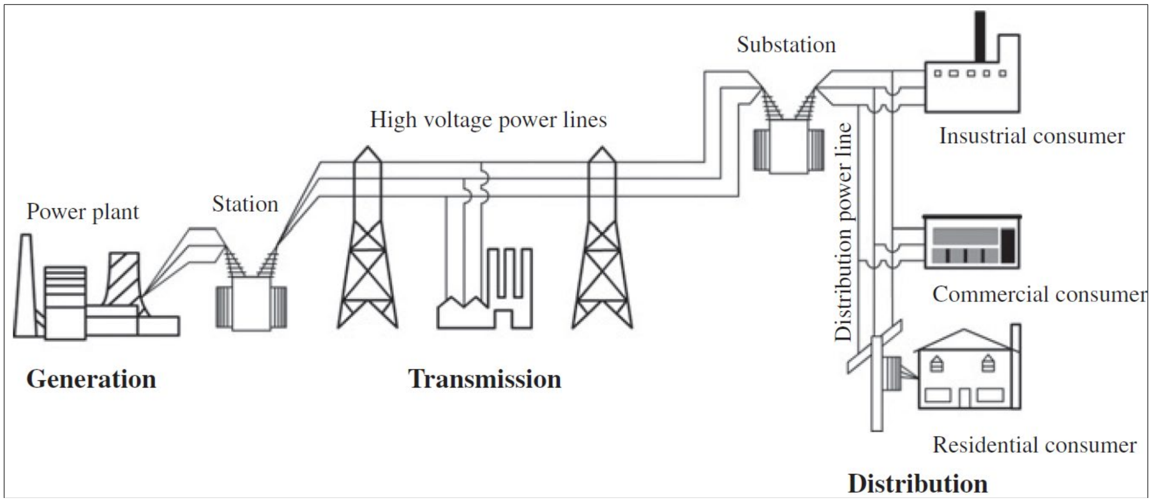

Figure 1. Basic building blocks of an electric power system

The area of focus of this project is fire electrical hazards in substations operated within the UAE Oil & Gas industry. There are various sources of ignition within a substation relevant to electricity that include arcs from motors and switches and electric igniters. This project aims to develop a pragmatic and integrated framework to manage electrical fire risks in substations. It aims to address the major challenges faced daily by electricians, engineers and contractors while operating or maintaining an electrical substation. It is crucial to protect people and assets from the frequent electrical fire incidents in substations within the O&G industry that are leading to injuries, fatalities and asset damages. It is therefore the aim of this study to explore and recommend a framework to improve the current fire protection control measures/practices within the organization.

1.1 Objectives

The design project adopts a design thinking and goal-centered approach rather than being merely technological. The goal that is aspired to be achieved is to control electrical fire risks in substations that will in turn save personnel from injuries and fatalities and protect assets from damages. Therefore, to reach this goal, a top-down approach is being conducted with a set of objectives defined for this project which are broken down into the following:

1. Identify the major causes of electrical fire incidents in substations and conduct a Gap Assessment
2. Benchmark and adopt international codes, standards and best practices to the organization's needs and requirements
3. Design a framework to protect personnel and assets from arc flash fire incidents
4. Investigate the applicability of self-diagnostic mechanism in smoke detectors, and design it accordingly

2. Literature Review

An extensive review of numerous scholarly sources on managing electrical fire risks in substations has been conducted and the approach is thematic and methodological which are detailed in the following sections. The motivation of this work and description of this issue is that even with over 100 years of electricity utilization in the industry, we are still facing major fire incidents attributed to electrical fires. Hence, a holistic strategy for managing electrical fire risks in substations is the optimal and recommended approach to be adopted.

2.1 Electricity and General Perception

Electricity in its most simple terms is one of the fundamental physical forces of the universe, like gravitational force. It is a form of energy, comprising of oppositely charged electrons and protons that produce heat, light, magnetic force and chemical changes. Everyday electricity is being harnessed in virtually all kinds of industries to run operations especially in O&G. It is one of the biggest humankind achievements which has led to industrial revolution and economic prosperity (Vasily 2018). Electricity utilization is by itself a hazard and its operation in hazardous and critical areas requires even more attention and awareness about the risks involved during design, installation and maintenance of such systems (Shoemaker 2017). Most often, the victims of these accidents are personnel not observing the electrical appliance and equipment needing replacement or that energized live parts are exposed in the work vicinity. Electricity is a serious workplace hazard, yet workers usually recognize electricity as a safe energy and assume that it is not an occupational hazard. Typically, electrical hazards are unfortunately seen to workers as merely an electrical shock hazard. However, hardly do they view it as an electrical fire hazard that is exposing personnel and assets to fire and explosions which in turn will result in detrimental fatalities and property damages in such industries (Bayliss 2012).

2.1 Electrical Heat Energy and Ignition

Chemistry between electricity and fire exists and a thorough understanding of how it develops is imperative. There are myriad sources of heat generation in any O&G industry, electrical energy is one of the most notable as it converts into heat energy. NFPA defines fire as a rapid oxidation process, which is an exothermic chemical reaction, resulting in the release of heat and light energy in varying intensities. It is a combustion reaction that features four pillars classically represented by a 4-sided geometric shape called a fire tetrahedron as exhibited in Figure 2 (NFPA 921 2021). These four components are fuel, heat, oxidizing agent and the chemical chain reaction. Removing or controlling any of these four elements in the fire tetrahedron would assist in preventing or suppressing fires. A fuel in a substation is the material in a state of solid, liquid or gas that sustains the combustion whether organic (plastics, oils, refrigerants, alcohols) or inorganic (combustible metals). Electrical equipment in substations such as transformers, capacitors, switchgears, circuit breakers, batteries, lamps, and fuses, contain flammable and combustible fuels that are also hazardous (e.g. acid, alkaline, heavy metals, combustible metals, and Polychlorinated Biphenyl 'PCB') (Cote 2008).

The combustion process typically occurs above the fuel surface in the vapors region which is created by fuel heating. This heat is a major element that is part of the fire tetrahedron, which comes from the presence of an ignition source from various heat energies ranging from chemical, electrical, mechanical and nuclear. Electrical heat energy (the ignition source) can develop by multiple means through resistance heating, dielectric heating, induction heating, leakage current heating, arcing, static electricity and lightning (Steven 2017). In a substation, the predominant heat elements include systems, appliances, and equipment once misused or malfunctioned. Heat transfer is a phenomenon that occurs when there is a temperature difference between two materials causing transport of heat energy from one area to another. Hence, this heat energy (ignition energy) once absorbed by the material is the heat per unit area that causes materials to pyrolyze, ignite and burn. Moreover, it promotes and maintains a continuous cycle of fuel production, ignition, fire growth and flame spread once the heat produces fuel vapors. Atmospheric oxygen is the most common oxidizing agent abundantly available and only 16% oxygen is required to initiate the combustion process where air contains about 21% oxygen (NEC 2020). Other oxidizers include Sodium Nitrate and Potassium Chlorate.

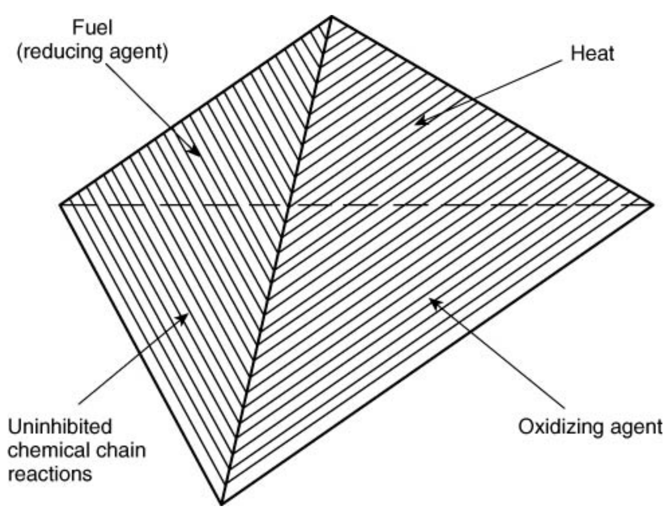

Figure 2. Basic elements of a fire tetrahedron

2.3 Substation Hazards and Causes of Electrical Fires

Substations are high value and critical facilities that operate critical equipment hence they are classified as a special hazard occupancy. Building a substation cost on average $50-100 millions in the O&G industry. The classification of fires in substation as per NFPA is Class C fire hazard that is fires involving energized electrical equipment with Class A and Class B fire hazards. There are many hazards in a substation, however the primary hazards are: **a. fire** caused by overheating and damage of insulation which can be either due to overcurrent or short circuiting; **b. arc flash** which results from an arcing fault, where the electric arcs and resulting radiation and shrapnel cause fires, severe skin burns, hearing damage, and eye injuries, **c. electric shock** resulting from current flowing through the body interfering with muscle and central nervous functions; **d. electrical burns** resulting from the heating effect of the current which burns the body tissue; **e. explosion** caused by an arc flash and an arc blast (Hurley et al. 2015). The sources of ignition in a substation classically comes from arcs or spark which is an electric discharge that arises when the air or gas becomes highly ionized between the two charged conductors, adequate to breakdown, conducting current through a distinctive, luminous channel. The other is hot component that releases enough energy to ignite a combustible mixture surrounding it. These occur in the electrical systems, appliances and equipment such as circuit breakers, switches, relays and many others. Failure of switchgear may lead to fires, and with oil-filled switchgear, this can result in a major incident. This not only poses potential fire and smoke risks to people in the vicinity and to the building fabric, but may also affect other locations, thus escalating the primary event. There are several techniques that can be used singularly or in combination to mitigate the effects of a fire and limit smoke spread (NFPA 70E 2021).

It is paramount to note that arc flashes are one of the most frequent and dangerous situations personnel are exposed to while working with electricity in the industry and the primary cause of electrical fire accidents. An arc flash or electrical flashover is a phenomenon where electric current in one conductor breaks leaving its intended path and travels through the air causing an electrical arc to appear. This arc is characterized by an explosive release of energy when the electrical current passes through ionized air in less than a second an arc flash is initiated. It can result from accidental contact with live electrical systems, build-up of conductive dust, corrosion, dropped tools or improper work procedures. The plasma arc has virtually unlimited current carrying capacity once it is established, the energy of an arc flash converts primarily to heat and light within a millisecond. Temperatures at the epicenter of an arc flash can reach 35,000 degrees Fahrenheit (over 19,400 oC) that is four times hotter than the surface of the sun. These high temperatures along with the heat energy are sufficient to cause ignition, capable of explosively vaporizing metals such as aluminum and steel (NFPA 70E 2021). This extremely high temperatures cause metals to burn, releasing toxic fumes, liberating hydrogen, which is flammable and explosive. The presence of copper can help sustain the plasma arc causing a single-phase arc to propagate into a three-phase arc. An arc flash lasts until the fast-acting overcurrent protective devices such as a circuit breaker or fuse opens the circuit in several milliseconds. Nonetheless, by that time the damage has already been done (Stacho et al 2019). Arc blasts which follow the occurrence of an arc flash, is a dynamic pressure wave created by the instantaneous expansion of gas and this pressure wave can cause panels to rupture creating flying debris, acoustic injuries and physical trauma. The pressure of an arc blast is caused by the expansion of the metal as it vaporizes and the heating of the air by the arc energy. This accounts for the expulsion of molten metal up to 10 feet away. In addition, the sudden expansion of an arc blast creates loud sounds that can cause hearing damage (IEEE 979 2012).

The principle causes of electrical fires in a substation are (NEC 2021):

- Arc flash caused by working with live and energized electrical equipment or electrical installations
- Wiring with defects such as insulation failure due to age or poor maintenance
- Aged electrical equipment and electrical installations
- Overheating of cables or other electrical equipment through overloading with currents above their design capacity
- Incorrect electrical protection selection or settings
- Poor connections due to lack of maintenance or unskilled personnel
- Poorly maintained or defective motors, heating and lighting
- Flammable materials covering electrical equipment which may become hot in normal operation
- Improper design, construction, installation, maintenance and testing of electrical equipment or electrical installations
- Design change or modification without Management of Change (MOC)
- Inadequate or inactive electrical protection

2.4 Past Electrical Fire Incidents and Major Consequences

Electrical fire hazards are the most prevalent hazard in substations. In fact, personnel rarely associate electricity with fires and hence taken for granted as electricity is commonplace. However, in a recent comprehensive study conducted by the NFPA in April 2018 for US fires in industrial and manufacturing facilities concluded that the leading cause of fires are due to electrical systems and appliances amounting to 24% and 55% of these electrical fires are attributed to arc flashes (Campbell 2018). Workers perceive arc flash as isolated or infrequent events while estimates from NFPA reports that workers are exposed to 10 arc flash accidents each day. The equipment involved in the ignition were electrical distribution equipment, wiring, transformers, power supplies, lamps, bulbs, lighting, cords and plugs. Furthermore, the US municipal fire departments responded to approximately 37,910 fires at these facilities every year, which is well over 100 fires every day in these industries. Consequently, these fires have resulted annually in 16 personnel fatalities, 273 work-related injuries and a staggering $1.2 billion in direct asset damage (Campbell et al. 2016 and 2018).

In addition, data from the Census of Fatal Occupational Injuries (CFOI) published by the U.S. Bureau of Labor Statistics indicated that in 2020 there were 126 worker deaths attributed to exposure to electricity. It was also reported that 56% (approximately 3 in 5) of the injuries in the same year were due to direct contact with electricity in the form of power sources or working with a live electrical equipment causing an electrical arc flash and fire (Campbell, 2020). Moreover, the Chicago National Safety Council in their Accident Prevention Manual for Industrial Operations reports that Electrical is the number one reason and the leading cause accounting 23% of the ignitions sources of major fires in an industry (Daniel et al 2019).

2.5 Risk assessment and control

Risk management is the logical, systematic process used to manage the risk associated with activities related to electricity which includes hazard identification, risk analysis and control. The first step in managing risks related to electricity is to identify all the hazards present in the substation (elaborated in section 2.4), which could potentially cause harm to people, and/or assets. These hazards can be spotted by regularly inspecting and testing electrical equipment and electrical installations, and most importantly conducting a walk-through assessment of the workplace. A risk assessment shall be performed prior to the commencement of the activity to determine the measures to be taken to implement the control of risk (Sivrikaya et al. 2019). The risk assessment helps to determine the severity of an electrical risk; personnel at risk of exposure; sources and processes causing the risk; proper control measures that shall be implemented; and assess the effectiveness of existing control measures. The risk control measures shall fulfill the hierarchy of controls which is a systematic approach for managing safety in the workplace by providing a structure to select the most effective control measures to eliminate or reduce the risk of certain hazards that have been identified, as being caused by the activities. While undertaking a risk assessment for the activity, the following hierarchy of controls shall be adopted from the most effective to least effective and as appropriate: elimination, substitution, isolation, engineering, organization, procedures, and PPE (NFPA 921, 2021).

2.5.1 General Electrical Safety Requirements

Equipment shall be properly designed, constructed, installed, inspected, tested and maintained so that it does not present a risk of fire when used. Proper design, installation, maintenance of electric power systems (such as in substations) are the key success factors for safe, reliable and efficient operations. Electrical isolation (de-energization) is crucial when operating such equipment. All electrical equipment shall be regarded as being live until properly isolated and proved to be dead (Gordon, et al. 2018). Before carrying out any maintenance, repairs, alterations, cleaning, or testing on electrical equipment the equipment shall be isolated (de-energized) from its power source (El-Mahayni et al. 2017). Isolation is the disconnection from live conductors by an open isolator or adequate physical gap from all sources of supply to prevent electrical equipment being made live in error. Before work is done on equipment that has been isolated, test equipment shall be used to verify that the circuit elements and equipment parts are de-energized. The test shall also determine whether any energized condition exists as a result of inadvertently induced voltage or unrelated of the circuit have been deenergized. The approved test equipment shall be checked immediately before and after use to make sure it is working correctly. These systematic steps are referred to as Lock-Out, Tag-Out, Try-Out (LOTOTO) (NFPA 70, 2021).

Hazard communication is a system to effectively communicate the hazards and related information to personnel. All electrical equipment shall be clearly marked with warnings to safeguard health and safety of the personnel. Specific warnings and markings shall be provided to at least: zero energy state equipment; live conductors; main switchboard etc. (Hughes 2016). Warning posted shall clearly state the nature of risk. Warning signs shall use simple, clear graphics to support the written message. Warnings must also be translated to the suitable languages, where all employees can read/understand. In some cases, it will be required to paint some parts of the machinery/area in a highly visible color to highlight the danger (Simmons 2018). Locking of any electrical equipment shall be accompanied by placing a tag on the isolation point to display information related to the lockout details (DANGER, WARNING or CAUTION).

Training and competence are crucial for enabling people to acquire the necessary skills and knowledge that ensure they are capable to safely undertake tasks that may expose them to the fire hazards of electricity in a substation. The key to effective training is to understand the specific job requirements and individual abilities. Electrical training shall therefore be provided to all personnel which includes awareness training, formal classroom instruction, in addition to on-the-job training and coaching (Pragale et al. 2017). Personnel shall be trained to be thoroughly familiar with the safety procedures for their particular jobs. When working on electrical equipment, personnel shall be capable to identify exposed live parts from other parts of electric equipment. Furthermore, they need to learn how to deenergize the equipment; use lockout and tag procedures to ensure that the equipment remains deenergized. Job briefings to workers are vital before the start of any electrical activity those include nature of the work and hazards associated with the activity; risks associated with the work, control measures implemented, work instructions involved; special precautions; energy source controls; PPE requirements (Martinez et al. 2020).

Substation plant items shall be separated by fire-resisting barriers to limit the extent of any fire to the item of fire origin. Compartmentation needs to be carefully designed so that it can contain a fire but not inhibit any venting required for explosion control. The use of an appropriate automatic fire detection system can provide the electrical plant room or area with early fire detection and alarm features which shall also be linked with a control system to provide fast response fire suppression or control. Use of water is dangerous for extinguishing class C fires in energized equipment such as in substations (Purkiss et al 2013). Hence, the conventional agents that are in practice today suitable for use in fires involving energized electrical equipment are CO_2, Halogenated Hydrocarbons (Halons and Clean Agent Systems), Inergen (N_2, Ar, and CO_2 mixture), Dry Chemicals (such as potassium bicarbonate, potassium chloride) and Multipurpose Dry Chemical (such as monoammonium phosphate). Portable fire extinguishers shall be provided, and procedures for checking these and any permanent systems shall be carried out during the routine inspection of the switch room or substation building (IEEE 979. 2012).

Emergency Response Plans (ERP's) shall be developed, tested and implemented to demonstrate that a fit for purpose Emergency Response set up is in place to act as an effective recovery control barrier for all existing and new activities involving use of electrical equipment. The pre-incident emergency plan shall be made available to all personnel for implementation regardless of their normal local assignments. The emergency plan shall cover emergency procedures, roles and responsibilities of individual; immediate action plan; escape plan and evacuation routes; training and drills and emergency telephone lists (NFPA 70E 2021).

2.6 Laws and Regulations

With the importance of substations and the existance of hazards within, many requirements are needed in order to ensure necessary layers of protection especially against fire. These layers of protection can include prevention, detection and/or control systems. These requirements are detailed in a wide range of standards because substations consist of wide range of equipment; these standards range from local rules and regulations to international standards and best practices. These standards provide the necessary requirements with regards to proper selection, installation and use of equipment; necessary maintenance schedule and frequency; and means of prevention and management. As mentioned in the previous section, electrical equipment can be the cause of catastrophes due to arc flash.

2.6.1 UAE Laws and Regulations

O&G industries within the UAE shall ensure that their activities always comply with all relevant Federal laws and regulations. The relevant UAE legislations applicable to our study on electrical fire risks include but not limited to:

- UAE Federal Law No. 8 (1980), Chapter V: Safety, Protection, and the Health and Social Care of the Employees; Article (91).
- UAE Ministerial Order No. (32), 1982. Specifying Preventive Methods and Measures for Protecting Workers against Work Hazards.
- Federal Law No.: 24 of 1999 for the Protection and Development of the Environment.

2.6.2 Local and International Codes and Standards

According to ADNOC Electrical Engineering Design Guide, the first essential element is ensuring the proper placement of substation in the design stage of the project where "a minimum distance of 30 m from any source of hazard shall be considered for locating substations." Another essential element is ensuring that internal temperature and humidity are maintained at 25 °C and 50% ± 10%, respectively. As a result, air conditioning systems must be installed and monitored regularly to ensure proper control of environmental conditions. In addition, substations should be equipped with an automated firefighting system to detect and activate in case of emergencies, and can be easily set to manual setting during shutdown or scheduled maintenance (ADNOC 2019).

The National Fire Protection Agency (NFPA) has provided various standards that support with ensuring the presence of tools for the purpose of life and assets protection. NFPA 70, National Electric Code, is a set of requirements pertaining to "safe electrical design, installation and inspection" that deemed necessary for protection against electrical related hazards (NFPA 70, 2020). In order to ensure that electrical equipment is valid to be used, thorough maintenance routine is to be followed regularly, which is detailed in NFPA 70E, Standard for Electrical Safety in the Workplace. This standard details the "practices to protect personnel by reducing exposure to major electrical hazards" which is accomplished by various measures including but not limited to use of work permits; pre-plan of undertaken electrical activities; use of personal protective equipment (PPE); and de-energize of system prior to start of work (NFPA 70E, 2021).

Another standard studied is IEEE 979, IEEE Guide for Substation Fire Protection. The standard details the various fire hazards that may exist in substations, which could be attributed to the main or auxiliary system, or to the activities undertaken within substations. Also, the standard provides detailed requirements for the different parts of substations with regards to building and structure; personnel and occupancy; and protective system that includes detection and suppression (IEEE 979, 2012).

3. Methods

This section describes the systematic process conducted for the data acquisition and interpretation pertinent to the design project at hand. Multiple case studies have been performed, focusing on previous electrical fire incidents in ADNOC and other facilities. This will facilitate the activities for gap assessment, benchmarking, integration and framework development.

In the 1st case study, observations and past UAE incident data were gathered to obtain knowledge and insights in reference to the current practices for managing electrical fires risks in substations. The type of data collected are qualitative which are utilized to collect, store and process the obtained information. In addition, the qualitative data will be analyzed by interpretations and categorizations. The results and analyses of the data will be elaborated in this section.

4. Data Collection

Electrical fire incidents are one of the most recurrent incidents that takes place in electrical substations of any oil and gas industry. According to Simmons, Jarvis (2018), OSHA and other standards have increased its requirements for companies to reduce electric shock/ arc flash accidents or other accidents caused by direct contact with energized system in electrical equipment for several decades. In order to further emphasize on the importance of such a standard, Table 1 displays several arc flash fire incidents and events that could lead to fire incident if not handled. These incidents and situations have occurred in different substations.

First five incidents that are mentioned in below table happened during the maintenance activities in the substations, and related to electrical fire incidents that are caused by arc flash or flashover. The common root causes that contributed to these events are human errors including behavioral issues, failing to follow the right procedure, and the lack of awareness regarding the hazards associated with working on an energized system.

However, there are some factors or conditions that can escalate the incidents severity or could lead to fire incident directly. One of the discovered cases is the restricted accessibility to smoke detectors for inspection and maintenance activity, which can compromise the fire safety system integrity. The leading causes can be correlated to design issues or administrative failures linked to bypassing or overriding the concerned management and disciplines approval process. Furthermore, detailed findings related to these incidents and cases are highlighted in table below covering incidents immediate and root causes, and proposed recommendations and control measures to avoid the incidents from reoccurring. Below incidents causes represent the gaps identified for most of electrical fire incidents in substations over the world.

Table 1. Summary of incidents/ situations in substations

S.N	Incident Topic	Location	Causes	Controls/Recommendations	Year	Source
1	Arc fault during performing a complete service (Doble testing) of equipment on two 138-kV circuit breakers in substation breaker	Colorado	- Fail to maintain the minimum approach distance to energized parts. - Inadequate procedures for doble testing - Job hazard analysis did not address the minimum approach distance - Inadequate identification of hazards - PPE not used	- Communicate and enforce the working procedure and power system safety manual - Develop job safety analysis and address the associated hazards - Adequate PPE to be used	1999	Substation
2	Arc flash injury during preventive maintenance of transformer	UAE	- Lack of job oversight - Inadequate communication - Inadequate supervision - Inadequate training - Inadequate correction of worksite/ job hazards and Human error	- Develop & communicate work practices - Follow LOTO procedure - Install warning signages - Provide proper training - Provide effective implementation of PM work procedures	2019	Oil & Gas Company
3	Electrical flashover while preparing for the preventive maintenance of 11kV transformer in substation	UAE	- Fail to implement isolation plan - Non-compliance to PTW procedure - Fail to confirm zero energy isolation - Fail to implement LOTO procedure - Human error	- Follow energy isolation (LOTO) procedure - Maintain communication among the work crew. - Comply with PTW procedure	2019	Oil & Gas Company
4	Arc flash during cleaning activity in electrical sub-station	UAE	- Improper isolation of equipment - Servicing of an energized system - Lack of knowledge of hazards present	- Competency assessment - Complete isolation of electrical activity prior starting maintenance activity - Conduct Toolbox talks (TBT)	2020	Oil & Gas Company
5	Electrical Flashover at electrical switchgear room during rack in/ rack out operation.	UAE	- Defective equipment - Lack of knowledge of hazards present - PPE not used - Inadequate communication	- Clearly define the workflow between maintenance & operation team - Perform risk assessment - Comply to PPE requirement - Install warning signages - Lessons learned to be disseminated	2021	Oil & Gas Company
6	Inability to reach smoke detector for inspection & maintenance activity	UAE	- Overriding the approval process - Fail to implement the design specification	- Short-term: design a temporary portable platform - Long-term: conduct review cycle for design acceptance	2022	Oil & Gas Company

5. Results and Discussion

Benchmarking against international best practices was conducted along with utilizing the risk management hierarchy where the aim is to introduce the elimination, substitution, engineering, and administrative controls. Various incidents investigated in Table (1) have been compiled and categorized into five main gaps. Each gap represents several violations or non-compliance that were identified in the previous table. Table (2) below shows the five categories which are lack of behavioral safety, lack of competency, inadequate risk assessment, non-compliance with administrative control and lack of communication.

Table 2. Summary of identified gaps and their descriptions

S.N.	GAP	DESCRIPTION
1	Lack of behavioral safety	- Unable to identify the hazard present - Not wearing PPE - Lack of supervision - Non-compliance with procedure (ex. shortcuts)
2	Lack of competency	- Inadequate training - Lack of hands-on training at site - Non-compliance with procedure (unawareness of existing procedure ex. LOTO)
3	Inadequate risk assessment	- Lack of knowledge of hazards present - Inadequate risk assessment (job safety analysis)
4	Non-compliance with administrative controls	- Overriding the approval process - Fail to implement the design specification - Not maintaining equipment
5	Lack of communication	- Inadequate communication between working crew

Lack of behavioral safety

The O&G industry experiences over 70% of accidents due to human errors (Alkhaldi 2017). The majority of these human errors are caused by behavioral issues, which focus on what people do, how do they think, how and why would they react in a certain way (Behavior Based Safety Guide 2013). A behavioral safety gap can be demonstrated in individuals not wearing Personal Protective Equipment (PPE) when working around potential job hazards. The biggest danger is when an electrician comes into contact with electricity. PPE clothing would be an excellent defense against this danger. Moreover, wearing ineffective PPE may still be a problem and cause risks, as the PPE required for working with Low Voltage (LV) electrical equipment differs from that required for working with High Voltage (HV) electrical equipment according to ADNOC standard (Electrical Safety standard, ADNOC standard 2020). In addition, the inability to identify the hazard present falls under the lack of behavioral safety category. Usually, this is caused by either a lack of knowledge possessed by the electrician, or by complacency, or the fact that the job becomes a routine and is done unconsciously.

Lack of competency

Incompetence is the inability to apply or use the set of related knowledge, skills, and abilities necessary to perform some type of 'critical work function or task' within a defined work setting. This gap was addressed by inadequate training or lack of hands-on training, and unfamiliarity with electrical safety procedures, such as energy isolation procedures of Lockout Tagout (LOTO). A lack of adequate training refers to any training that does not meet the job description requirements, both in quantity and quality. Both quality and quantity cannot be overlooked when determining your optimal training needs. A lack of knowledge and training leads to lower levels of performance, which can result in incidents and costs to the organization. Performing such work frequently results in errors, quality problems, and wasted time.

Inadequate risk assessment

The most critical part when it comes to risk assessment is identifying the risks associated with the job being conducted. As per ISO 31000 risk management standard, if hazards or risks are not identified properly, no controls will be added to prevent the occurrence of incidents. Gaps found here include unawareness of hazards, which is also related to the previous gap, and inadequate risk assessment, such as the job being inadequately risk assessed in Job Safety Analysis (JSA), Formal Risk Assessment (FRA), or any other risk assessment analyses. In addition, failing to define the purpose and scope of the assessment, and failure to monitor and manage risks can be other forms for the risk assessment inadequacy.

Non-compliance with administrative controls

Administrative controls are among the most effective methods of hazard control. By putting in place policies and rules that reduce the occupational risks faced by workers, they improve safety in the workplace. The term non-compliance with administrative controls can be manifested in various forms. The incidents and cases in Table (1) indicate that management failure is a significant factor in non-compliance. Failure to follow the design approval process, failure to implement the design specification, and defective equipment can be avoided if they are planned and maintained properly, and will not lead to additional incidents. The next section will discuss non-compliance with administrative controls in more detail.

Lack of communication

Workers need to be informed about the risks to their health and safety identified in their risk assessments, and the preventive and protective measures necessary to control those risks. The incidents of serial numbers 2 and 6 in Table (1) illustrate how communication problems can lead to major accidents and incidents. When a task and its associated responsibilities are handed over to another individual or team, effective communication is crucial. During critical times, when the probability of an incident occurring is higher, effective communication is essential. This might include, for example, communication between operations and maintenance when performing any job activity or during process upsets and emergencies (HSE 2013).

5.1 Graphical Results

In this section, we will be focusing in-depth into allocating fundamental methods that will assist in protecting the workers and companies from similar incidents. The general strategy that will be followed to ensure that hazards are eliminated or controlled is the "Hierarchy of Control". The concept of hierarchy of control is built on the basis of eliminating or controlling hazards by means of elimination, substitution, engineering control, administrative controls, and PPE as shown in Figure (3).

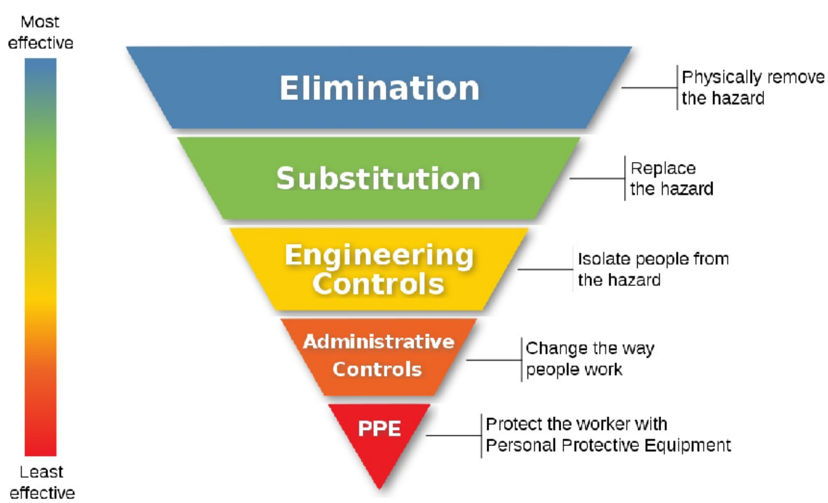

Figure 3. Hierarchy of controls

Elimination and substitution methods are considered very challenging because they are much related to the design stage for any system/project. Elimination is defined as the process of eliminating the hazard physically from the whole designed technology; for instance, eliminating a hazard in a refinery by processing non-flammable/nontoxic material instead of Toxic/flammable crude. The second control measure is Substitution, which is basically defined as consuming less of the hazardous material, and as the elimination method it more involved in the early stages of designing a system/technology. Engineering controls in general are one of the most expensive type of controls that can be used, and this is because most engineering controls installed need frequent maintenance, such kind of controls that we can observe in our daily lives are the distance sensors equipped in our cars, which manages to control accident hazards due to over speeding or being distracted on the phone. Administrative controls are the most popular kind of controls used. They are work methods or procedures designed to minimize exposure to a hazard. In most cases, it uses systems of work to control the risk. And this can be done by, developing procedures on how to operate machinery safely, limiting exposure time to a hazardous task, using signs to warn people of a hazard. The last control measure identified as part of the hierarchy of control is Personal Protection Equipment “PPE”, this control measure refers to anything employees wear or use to minimize risks to their health and safety. PPE includes googles, respirators, portable gas detectors, face masks, gloves, etc. The hierarchy of control is constructed on the basis of most to least effective, as shown in the figure below the top of the triangle highlights Elimination which is considered the most effective method of eliminating hazards, and this goes until we reach the bottom of the hierarchy with the least effective method of controlling a hazard which is PPE.

After defining and understating the concept of Hierarchy of control, the next sections of the report will focus on mapping and developing a detailed framework that will support on minimizing or controlling hazards inside substations. Elimination or substitution is not considered as part of the framework because the need for electricity inside the substation is essential and cannot by eliminated or substituted; therefore, the framework will be developed based on Engineering, Administrative, and PPE controls.

Engineering Controls:

Installation of Cabinet Smoke Detection (CSD) & heat line detectors

Fires in electrical rooms or switchboards are usually caused by short circuits, insulation degradation, poor contact, high temperatures, and overloads of current. It is imperative to detect any equipment irregularities as early as possible to prevent fires or minimize the damage and loss caused by fires. The most common type of detector in an electrical room is point type smoke detectors. These are usually installed under the ceiling (Ava, 2017). However, there are factors that affect the effectiveness of smoke detection such as sensor sensitivity, smoke transport path from fire source to detection, and dilution of smoke during transport. This issue can be resolved by the CSD system where each detector protects only one cabinet. This eliminates the need to search all cabinets one by one in case of abnormal smoke generation, so that fires can be found directly when an alarm is triggered. Furthermore, when a CSD protection system protects only one cabinet, it minimizes smoke dilution, so that the system will have very high sensitivity and can provide very early fire warning signals while the fire is still in an incipient stage. A CSD is an ideal solution, as it provides early warning and locates the cabinet after a fire in an electrical room or panel (Ava, 2017). Figure below demonstrate the Cabinet Smoke Detection (CSD). Cabinet Smoke Detection is a complete pre-engineered system, and is a fully automatic system, which detects and suppresses fire without electricity.

Figure 4. Cabinet Smoke Detection (CSD).

A heat detector (line type) is also recommended to provide the perfect solution for protecting switchgear from fire. In areas that are at risk of overheating such as cable trays or near and around electrical switches, heat sensing cable can be installed to provide fast and reliable localized detection. Any excess heat found along its length can be accurately and precisely located.

Fire detection system (smoke detector) maintenance

According to data collected from one of the oil and gas companies, one of the current models of power substations has smoke detectors that cannot be accessed by technicians to perform their maintenance activities after the construction phase. And this issue was raised because of the incorrect design of the substation which was contradicting with the Design Specification requirements for substations. Figure (5) below illustrate the problem, along with the substation design model in Figure (6);

Figure 5. Cabinet Smoke Detection (CSD).

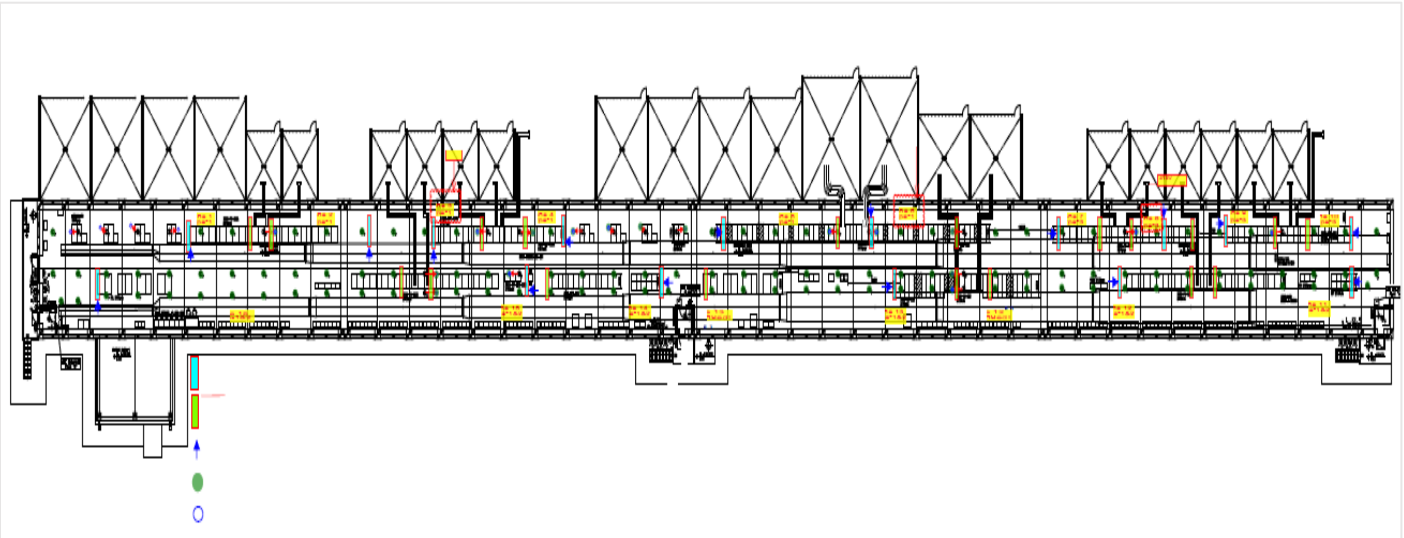

Figure 6. Electrical Substation Design

During a fire, smoke detectors alert all persons in the affected area of toxic smoke gases through an acoustic and visual signal. Maintaining smoke detector functionality should be a priority. As specified in Chapter 14, Inspection, Testing, and Maintenance (ITM) of NFPA 72, smoke detection systems must be;

- Semi-annually inspected.
- Functionally tested annually.
- The device is tested for sensitivity 1 year after installation, then every other year, and every 5 years if it remains within its sensitivity range.
- Maintained in accordance with manufacturer's instructions.

As far as the identified issue is concerned, the above design model failed to meet the NFPA 72 standard due to incomplete data in the Downgraded Situations (DGS) and other administrative reasons. First, DGS did not include information regarding the distance between switch gears/boards, and smoke detectors, and they were not included in the design specifications in response to following section 10.1.17 of the company's DGS, the clearances shall be maintained inside the building;

- Behind Ring Main Units and 415 Switchboard (both Ring Main Units and 415V Switchboard may be installed without any back clearance if back access for cable termination and maintenance is not required) - 750mm Minimum.
- On both sides of Ring Main Unit and 415V Switchboard -1000mm (Min).
- In front of Ring Main Unit and Switchboard -1500mm.
- Top of equipment to substation ceiling -500mm (Min).

While the administrative cause was reflected in the approval process undertaken by the company, it was reviewed only by the civil and electrical departments. On the other hand, the fire & gas department, who is responsible for maintaining the smoke detectors was not included in the approval process. In other words, the design was accepted by the company without a thorough review and approved without proper justification, and without a diagnostic design specification.

There are two possible solutions, a short-term solution, and a long-term solution, to resolve this issue. The short-term solution is to design a temporary portable platform that is a modified version of a step ladder to increase safety and allow access to the top of the platform for smoke detector maintenance (give extra space and functions to access the work at the top level). During maintenance, the platform can be assembled and disassembled, enabling technicians to reach the smoke detectors and perform maintenance activities on them. Figure (7) illustrates the design of the portable platform.

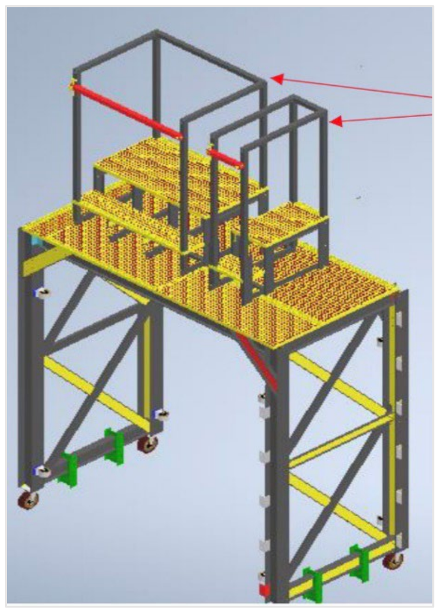

Figure 7. Electrical Substation Design

The long-term solution is to conduct one more review cycle for acceptance of a design (where the approval shall go through the civil department, electrical department, and fire & gas department who are considering access and maintenance of the fire alarms and detectors), and update the design specification, as necessary. The long-term solution will be furtherly explained as part of the administrative control section.

Self-diagnosis Built In-Self Test (BIST) for smoke detectors

Generally, for smoke detectors, many manufacturing companies rely on physical maintenance for smoke detectors. And their reliability in preforming their function in case of an incident is much dependent on the type of technology used which defines the failure frequency of the detector, and the maintenance frequency of how much the respective company is preforming functional test for their smoke detectors. In substations, smoke detectors are considered a major contributor in the detection of fires; moreover, they are also linked with activating thInergen system that will prevent escalation and damage to electrical equipment such as switch gears, control panels etc. inside the substation. As part of Engineering control, to prevent malfunctioning of the smoke detectors inside the substation. We are designing smoke detectors equipped with Built in-Self Test (BIST). BIST is a technique used by designing additional hardware and software into integrated circuits to allow them to preform self-testing. BITS helps into identifying faults into integrated circuits which would alert operators that the respective smoke detector inside the substation is sending a faulty signal, and this would subsequently help in ensuring a proactive approach in maintaining the smoke detectors rather than reactive action after an incident (Peng Zhang 2010).

BIST basic operation is shown in the figure below, this hardware and configuration will be set-up as part of the smoke of the detectors. The Test controller will give signal to the Multiplexer (MUX), which is also known as a data selector, which basically selects between several digital inputs and analog signals. In normal operation, normal input will be signaled to the MUX which will subsequently transfer it to the Circuit Under Test (CUT). However, in case of testing to check the adequacy of the system and absence of faults, the signal will be transferred from the Test controller to the Hardware Tester (H/W), which will produce different codes and signals to the MUX and then to the CUT. The output of the CUT will run all the signals and check that all results are corrected. If there are any faults identified those will be sent to the COMPARATOR which will compare the two digital signals received from the ROM and Output indicating the fault/error in the system (Peng Zhang 2010).

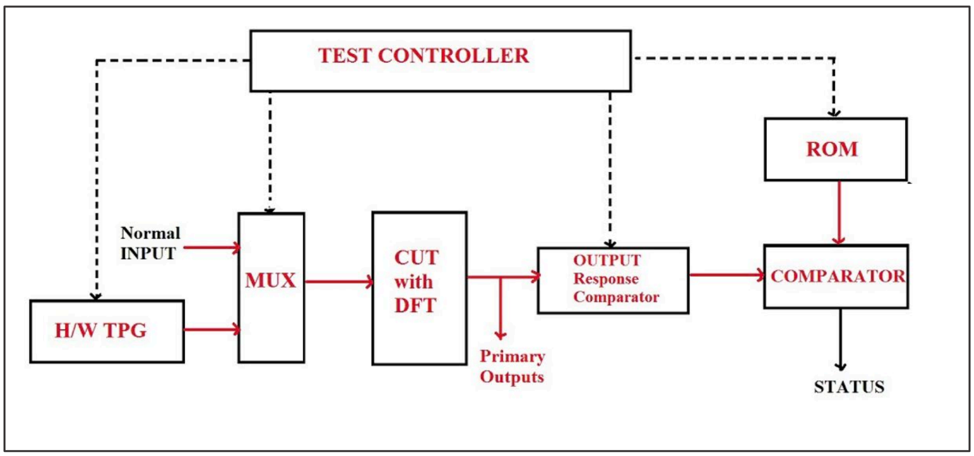

Figure 8. Self-diagnosis Built In-Self Test (BIST)

The system then will alert the operator by showing the specific faulty detector on the panel screen, where he must take action by notifying the Instrument/ Control team to take further action (root cause analysis) either by doing maintenance or replacing the detector (Peng Zhang, 2010).

Administrative Controls:

Perform an arc flash hazard analysis (Risk Assessment)

In the event of an accident, it is crucial to recognize hazards, reduce risks, and minimize the harm. Conducting an Arc Flash Risk Assessment is one of the most important processes to identify, measure, and mitigate arc flash risks. In accordance with NFPA 70E and IEEE 1584, a risk assessment needs to be completed for any process and/or hazard, including arc flash hazard analysis. Steps include:

- Identify a Hazard
- Determine the likelihood and severity of occurrence
- Determine whether additional protective measures are required.

One important factor that needs to be considered is the limit of approach, which is an approach limit at a distance from an exposed energized electrical conductor or circuit part within which a shock hazard occurs. Personnel are safe when they maintain a distance from the exposed energized conductors or circuit parts, including the longest conductive object being handled so that they cannot contact or enter a specified air insulation distance to the exposed energized electrical conductors or circuit parts. This safe approach distance is the limited approach boundary, which is calculated based on a thorough risk assessment study analysis. Figure (9) represents the application of Limit of approach (ADNOC, 2020).

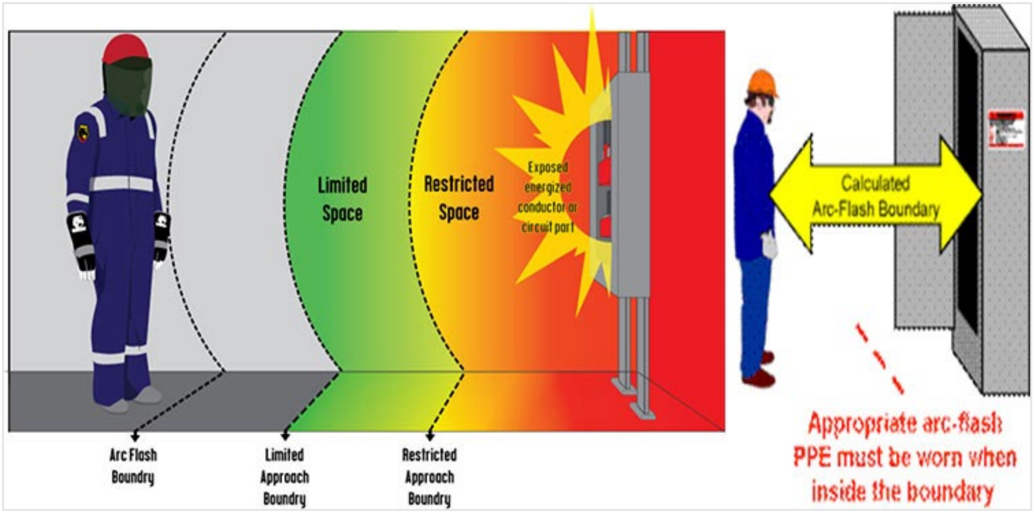

Figure 9. Arc Flash boundary

Conduct a review cycle and formulate an approval process and ensure the involvement of all related/ corresponding disciplines.

The phase gate process is a technique that is used to guide a project from conception to launch. It requires a review of each project stage before moving on to the next. In the phase gate review process, specific criteria must be met to determine the success of a phase and the ongoing viability of a project. A new phase gate will be developed to enforce the review requirement for electrical substation prior to proceeding with construction (EPC phase).

Training

Statistics reveal that improper employee training is the root cause of 7% of major safety incidents in different industries. Additionally, it ranked second to the highest ranked cause, following incorrect procedures. There are several factors contributing to major process safety incidents root causes, where 50% are personal factors, individual competency, and HSE culture (Snyman 2007). This highlights the importance of providing HSE training, which will aid the employees in reducing health risks by becoming extra aware and considerate of their safety. Therefore, to bridge the gaps associated with training inadequacy, lack of hands-on training at site, and non-compliance with procedure due to unawareness of existing procedure, it is recommended to consider the following trainings:

- **On-job Training or physical Training:** using real or close-to-real working conditions to acquire new skills and competencies for a job, typically learning how to operate particular tools or equipment in a live-work setting, a simulated environment, or during a training session.
- **Behavior Based Safety (BBS) Training:** BBS training is a program that focuses a worker's attention on their own and other peers' daily behavior to create a safer workplace. The implementation of this program will serve as a catalyst to create a strong safety culture. The approach will be guided by encouraging individuals to consider the potential for incidents and assess their own behavior as (safe or unsafe). Then agree to behave at their best and to engage others continuously to do the same. This training will be established which will focus on all working groups from management to field operators, where this will influence all work groups to ensure a safe working environment and correct behaviors while preforming their activities (Behavior Based Safety Guide 2013).
- **Risk Assessment Training:** in this training, delegates learn what risk assessments are and how to conduct them successfully based on the specific activity (ISO 31000).

Perform an Electrical HAZOP (e-HAZOP)

The Electrical System Hazard and Operability Study (e-HAZOP) aims to identify all electrical network hazards and operability issues. This assessment will focus on high-voltage distribution systems, with main electrical generation being examined only for interface purposes. When there are numerous similar electrical systems, only one will be examined, but the study results will apply to all identical systems.

An Electrical HAZOP (e-HAZOP) is used to supplement design reviews by providing a structured brainstorming environment. e-HAZOP is carried out with the help of those involved in the design and engineering of the electric system, as well as suppliers and the end user. The method is based on IEC 61882 and includes the necessary instructions and parameters. The system is often divided into nodes according to different bus bar voltage levels (e.g., 24V, 110V, 11 kV, etc.). Aside from the more common current, voltage, frequency, power, earthing, the parameters must also include more common HAZID parameters related to the electric design, such as fire protection, location and housing, lightning protection etc. Over, spike, under, dip, offset, fault, segregation, and load are common guidewords utilized as deviation during the workshop which will develop different hazards (Petro-risk, 2020).

5.3 Proposed Improvements

Failure modes and Effects Analysis (FMEA) is a method for identifying all potential problems in a design, manufacturing or assembly process, product, or service. It is a standard technique for analysing processes. It consists of two parts, which are (Mascia, A. 2020);

- **Failure modes**: refers to the numerous ways in which something can fail. Failures are any faults or defects, whether potential or actual, that have an impact on the customer.
- **Effects Analysis**: The examination of the repercussions of those failures/ consequences.

In Failure modes and effects analysis, categorization of deviations is based on their consequences, and probability of occurrence, and how easily it can be detected. The main purpose of the FMEA is to reduce or eliminate failures and beginning with the highest-priority failures. Below figure shows a typical FMEA spreadsheet which needs to be filled with the involvements of all related disciplines to ensure maximum end results from the analysis (Mascia 2020).

Failure Mode Effects Analysis

System Description: Landing Gear
Operation Mode: Flight - Level 2

Item Number	Item Description	Function	FM. Id.	Failure Mode	Local Effect	Next Higher Effects	End Effects	Sev.	Detection Method	Compensating Provisions	Remarks
1.1.1	Main Pump	Provides pressure when requested by Pilot Command	1	Fails to operate	No effect during this phase	No effect during this phase	No effect	IV	Indication to pilot	None	
			2	Untimely operation	Untimely hydraulic pressure in Main Hydraulic Generation Assembly	Untimely hydraulic pressure from Main Hydraulic Generation Assembly to Actuator Assembly	Untimely extension of Landing Gear	I	Indication to pilot	None	
1.1.2	Check Valve (Main)	Prevents reverse flow	1	Stucked closed	Loss of fluid flow through the Main Generation Assembly check valve	No effect during this phase	No effect	IV	Indication to pilot	None	
			2	Stucked open	Permits fluid flow through the main assy check valve when not required	No effect during this phase	No effect	IV	Undetected	None	

Figure 10. Failure Modes and Effects Analysis (FMEA)

<u>Personal Protective Equipment (PPE) Controls:</u>

Personnel working on or near electrical equipment shall have adequate PPE. As a minimum the following shall be considered while selecting the appropriate PPE (Electrical Safety Standard, ADNOC Standard, 2020);

- Head Area (Head, Face, Neck & Chin) Protection Personnel shall wear non-conductive head protection wherever there is a danger of head injury from electric shock or burns due to contact with energized electrical conductors or circuit parts or from flying objects resulting from electrical explosion. Personnel shall wear non-conductive protective equipment for the face, neck and chin whenever there is a danger of injury from exposure to electrical arcs or flashes or from flying objects resulting from electrical explosion.
- Eye Protection Personnel shall wear protective equipment for the eyes danger of injury from exposure to electrical arcs or flashes or from flying objects resulting from electrical explosion.
- Hearing Protection Personnel shall wear hearing whenever there is a potential of exceeding the sound limits (i.e. > 85dBA for 8 hours) as per ADNOC Physical Hazards Standard.
- Body Protection Personnel shall wear arc-rated clothing where exposure to an electric arc flash is above the threshold incident energy based on the Arc Flash Boundary Hazard Analysis**.**
- Hand and Arm Protection Personnel shall wear rubber insulating gloves with leather protectors and rubber insulating sleeves where there is a danger of hand injury from electric shock due to contact with exposed energized electrical conductors or circuit parts. Rubber insulating gloves shall be rated for the voltage for which personnel will be exposed to.
- Foot Protection Where insulated footwear is used as protection against step and touch potential, dielectric footwear shall be required. Insulated soles shall not be used as a primary electrical protection.

The above-mentioned PPE are general PPE when working around electrical equipment in substations. However, based on the most recent NFPA 70E standard, it is mandatory to identify four PPE categories related to incident energy analyses, where each number represents an increased risk of danger and requires a higher level of PPE as shown in Figure below.

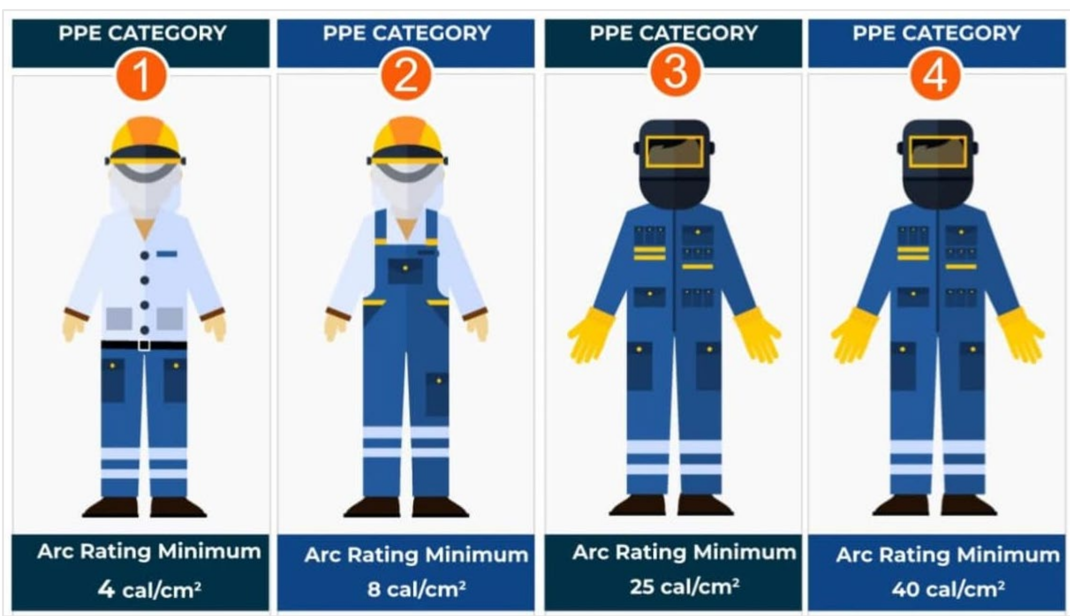

Figure 11. Personal Protective Equipment (PPE) categories

5.4 Validation

An Electrical Safety Committee is proposed to be established taking the responsibilities mentioned below. Those responsibilities will ensure all the identified gaps are managed and monitored in accordance with the hierarchy of control and international standards. The committee will:

- Perform regulatory review and approval of Electrical Risk Assessments, which includes FMEA's, E-HAZOP's, LOTO isolation procedures etc.
- Perform inspections and audits to satisfy its regulatory duty and acquire the required level of confidence on the implementation of the Electrical Safety Standards.
- Execute and implement a holistic training plan which involves Behavioral Based Safety, Competency, and Risk Management training. This will contribute towards enhancing the safety culture, performance, and behavioral awareness.
- Collect information on Electrical Safety performance and implementation progress and monitor established KPIs from Company via routine meetings. Moreover, Alert respective disciplines as/when required on weaknesses in specific electrical safety issues.

This kind of committee came into existence after identifying that Fire incidents inside substations are having very high probability of occurrence. Different incidents were analyzed for existing gaps and causes. Based on the identified gaps, a framework was proposed utilizing the Hierarchy of Control to ensure that those gaps were either mitigated or controlled proactively. The Pillars of the committee emerged after conducting detailed research on what new modifications/initiatives need to be instilled in an organization. Five main Pillars were identified which are behavioral based safety, competency and training, electrical safety risk assessment, engineering and design deviation, and procedures. All these pillars will be overseen by the Electrical Safety Committee (ESC) where they will be responsible of managing and guiding the implementation strategy of those pillars. Figure (12) displays the 5 main pillars of ESP.

Figure 12. lectrical Safety Committee (ESC)

6. Conclusion

In conclusion, the study conducted a system analysis which was a problem and goal-centered approach for managing and controlling substation electrical fire hazards in ADNOC. The team recommended a framework based on a gap analysis and benchmarking to international codes and standards (NFPA and IEEE) to be adopted for ADNOC which are pragmatic and methodical following the risk control hierarchy and benchmarked against the best practices in the industry. Substations are high value and critical facilities that operate critical equipment hence they are classified as a special hazard occupancy. Building a substation cost on average \$50-100 millions in the O&G. In addition, the electricity operated in substation is a serious workplace hazard that exists in substations, exposing employees to fires, explosions, electric shocks, and burns. It is well known that human body conducts electricity, even at levels as low as 3 milliamperes can also cause injuries in which involuntary muscular reaction from the electric shock can cause bruises, bone fractures and even death resulting from collisions or falls. All industries shall commit to ensure that a safe working environment is maintained in all areas (with the proper design, installation, and maintenance), and that all personnel who work on or near electrical equipment, are fully aware of the hazards involved and have the competence, training and awareness to undertake such activities. Otherwise, catastrophic consequences will be incurred in the form of fires leading to personnel fatalities or serious injuries, asset damages, production downtime and reputation damages.

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