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ELECTRICAL FAILURES NOT RELATED TO WEATHER CONDITIONS

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Executive Summary

Electrical system breakdowns are a leading cause of equipment and business interruption losses. It's a growing problem and the losses can be substantial – electrical systems constitute a major percentage of a property's total value. Insurance companies report increase in fire claims caused by electrical faults.

This paper is intended to provide the reader information about the nature, causes and impact of electrical faults. We discuss the definition of electrical faults and then provide a description of the electrical system and electrical equipment which may experience electrical faults and lead to costly insurance claims.

The scope of this paper is limited to:

1. What unforeseen abnormal conditions cause electric current to flow outside its intended path
2. How this can be caused by a breach of containment system used to manage the flow of electrical current
3. What happens when the fault causes physical damage to equipment that necessitates repair or replacement before it can be returned to normal operations
4. Electrical faults caused by equipment failures (transformers, rotating machines, cables, bus bars, switchgear assemblies, etc), human error (manufacturing, commissioning and testing, operation, etc.) and environmental conditions (lightning, wind, flooding, etc.)

Despite the considerable losses recorded due to weather conditions, this paper excludes electrical failures and/or faults caused by weather conditions.

We also limit our paper to "major" components of the electrical system, while realising that electrical failures/faults can and do exist in all types of equipment that utilise electrical power and have electrical current flowing through them.

There are a wide variety of electricity generation, transmission and distribution systems that are in common use and it is not the intention of this paper to describe all the possible equipment that the insurance industry deals with. Therefore, we will target our analysis towards equipment and systems that most frequently cause issues to insurers and discuss the most common causes of failure in each category.

This paper will therefore focus on the following:

- Electrical Generation
- Transmission Systems
- Distribution Systems

The reader should be aware of other papers published by other IMIA workgroups during previous conferences in which specific pieces of equipment in the electrical system were discussed in details.

We realise that condition monitoring, inspection and testing of electrical systems are all essential techniques to prevent electrical faults. We are aware of another paper published by our colleagues in another workgroup on ageing assets and refer the reader to that paper for detailed analysis of these techniques and how they can be used to detect and prevent electrical faults in equipment.

Definitions

During our research, we came across several definitions of electrical failures, including the following:

- Collins dictionary: "Electrical failure is an instance when an electricity supply stops working"[1]
- IEC: "failure: the termination of the ability of an item to perform a required function"[2]

These, and other sources, define electrical failure as loss of power. This is the general perspective of utilities and IPP's that view reliability of the power system in terms of availability of supply, rather than specific incidents that cause or can lead to physical damage to property. For instance, operator error that results in interruption of power supply (through it does not involve any physical damage) is considered an electrical failure. This broad definition may prove to be irrelevant to insurers whose main concern is events that involve physical damage to property.

To explore a more relevant definition from an insurance perspective, we researched definition of "Electrical Faults" instead of "Electrical Failures".

We identified other resources that define an Electrical System fault "as a condition in the electrical system that causes failure of the electrical equipment in the circuit such as: Generators, Transformers, Busbars, Cables and all other equipment in the system that operate at given voltage level".

Other sources define a fault in electrical equipment or apparatus as an imperfection in the electrical circuit, causing current to deflect from the intended path. In other words, the fault is the abnormal condition of the electrical system that damages the electrical equipment and disturbs the normal flow of the electric current.

When considering the definition from an insurance perspective, we relied on definition of two elements: "accident" and "object" when considering electrical failures/faults.

Accident: In layman's terms, an "accident" means an *unforeseen* breakdown of an "*object*" resulting in *physical damage* to the object that requires that the "object" be either *repaired or replaced* before normal operations can be resumed. It is becoming more common for policies to no longer require the accident to be sudden, as long as it is fortuitous and unforeseen.

Electrical Objects: Electrical equipment or apparatus used for the *generation*, *transmission*, *distribution* or utilisation of electrical power.

We define electrical faults as **any unforeseen abnormal condition (imperfection) in the electrical circuit that causes deflection of current flow from intended path which leads to physical damage to equipment.**

Therefore, we view electrical faults as an event or "accident" that may lead to electrical failures or interruption of power supply. With that in mind, we believe that all electrical faults will lead to electrical failures, even if temporary or short-lived, but that not all electrical failures are caused by electrical faults.

With that in mind, for the purpose of our paper we will study electrical faults and not electrical failures.

For example, a latent defect in the insulation of an XLPE cable is a form of an abnormal condition that can exist for some time even after the cable is energised. At some time in the future, that defect can lead to partial discharge (explained further below) that in turn would lead over an unspecified amount

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[1] Collins English Dictionary. Copyright © HarperCollins Publishers

[2] International Electromechanical Commission. Copyright © IEC 2018.

of time to insulation breakdown, and ultimately to an electrical fault or deflection of current outside the confines of the insulation around the conductor.

In this case, the cause of the insulation imperfection is a latent defect that existed for some time before it led to physical damage in the form of an electrical fault (arc). As such, it is important to understand that though the defect was dormant, at some point the defect has changed from being a mere defect to something worse.

Electrical System

The electrical power system is a network of electrical components deployed to supply, transfer, and use electric power.

The system can be divided based on voltage level to three main sections:

Generation

Electricity is an energy currency, rather than an energy source, meaning electrical generation needs to start from a primary energy source like a fuel or a flow. These fuels and flows are usually turned into electric current that transmits electric power to the grid. The part of the electric power system where electric energy is generated (typically in a power station) includes the civil engineering works, energy conversion equipment and all necessary ancillary equipment needed to convert energy from a different form to electric energy.

Power plants are the most commonly used energy conversion technology to create electricity from primary energy. Common types of power plants include coal, nuclear, and hydro. While it is possible to have both AC electrical generation and DC electrical generation, almost all electricity that is produced with a generator is alternating current.

Transmission

Electric energy cannot always be generated where it is needed. Instead, energy needs to be transmitted long distances between the power stations and consumers. Transmission grids are the interconnected networks that deliver electrical energy from producers to consumers.

An important part of this process includes transformers that are used to increase voltage levels to make long distance transmission feasible. Another equally important part of a transmission network is power lines or transmission lines, used to transport electricity from place to place. There are 3 types of lines:

1. **Overhead lines** are very high voltage (between 100 kV and 800 kV) and do the majority of long distance transmission. They must be high voltage in order to minimize power losses to resistance.
2. **Underground lines** are used to transport power through populated areas, underwater, or pretty much anywhere that overhead lines can't be used. They are less common than overhead lines due to heat-related losses and a higher cost.
3. **Sub transmission lines** carry lower voltages (26 kV - 69 kV) to distribution stations and can be overhead or underground.

Transmission substations are the “nodes” of the transmission system that are usually connected via overhead line systems. This is where the transmission transformers, circuit breakers, bus bars and electrical protection and control systems are located. The majority are located outdoor and are designed to operate without issues in all types of weather conditions. They usually have good resistance to hurricane, earthquake and lightning storm conditions. The overall designation of this type of switchgear is Air Insulated Switchgear (AIS).

Photograph 1: Transmission substation in East Amman, Jordan - Courtesy CEERISK Consulting Ltd

Distribution

Distribution grid refers to the final stage of the electrical grid, where electricity is distributed to homes, industry, and other end use products. Distribution is the process of reducing power to safe customer-usable levels and delivering the electric power to the grid.

Overhead transmission and distribution lines are usually excluded from insurance policies and therefore won’t be covered in this paper. AC/DC transmission systems that are sufficiently different in technology from traditional AC transmission are not covered, either, as they warrant further independent analysis.

Major Electrical Equipment

It is not the intention of this paper to provide a detailed description of major electrical equipment that can be subject of an electrical fault. Instead, we refer the reader to the numerous WG papers published by IMIA to learn more about various types of equipment. The following sections provide a brief description of some of the major equipment in the electrical system to provide the reader with basic understanding of electrical faults.

Generators

The electrical generator is the item of equipment that converts the primary source of energy into electrical energy via a rotating magnetic field.

These generators consist of two major components:

- **The rotor,** which is directly coupled to the prime mover. This is fed with current through many turns of copper, and at speed will create a rotating magnetic field. This field spins inside the generator stator. The construction of the rotor (with low voltages) usually means that the insulation may be only paper-thick. However, it must be able to operate through a range of operational environments (no speed, to high speed and turning gear) and through large amounts of differential thermal expansion between the copper and steel.

- **The stator** is made of copper circuits wound into a large laminated iron core. As the rotor spins in the stator, magnetic “flux” in the rotor passes through copper conductors and creates a voltage. This voltage drives the current which is fed to the grid system. The high AC currents mean that the stator winding is subjected to very large electromagnetic forces. The high voltage requires a thick and mechanically robust insulation system.

Apart from the rotor and stators, the generators can have a large complicated auxiliary system, which may include large excitation systems, heat exchangers, hydrogen systems and water cooling (possibly direct water cooling of the stator and even the rotor windings).

Transformers

The primary function of a power transformer is to transform system voltage from one nominal level to another. Increasingly often, dry type or air-cooled transformers are being used in moderate power applications. These transformers do not utilise oil/paper (OIP) technology to provide the basic insulation but instead use resin encapsulation and air insulation. Though limited in power application, such designs have the inherant advantage of being physically lighter than their OIP equivalent and have a lower fire hazard rating. Such transformers are the norm in wind turbine designs, medium-sized commercial and industrial sites, and high hazard areas.

Generator Step Up Transformer

The generator step-up transformer (GSU or GSUT) is the main connection from the power plant to the grid systems. Most large GSUs will be oil-cooled, with the oil-cooled either by water-cooled exchangers or more commonly finned radiators (usually with forced air fans).

Depending on the country grid requirements, it is quite likely that the GSU will have a “tap changer”. The tap changer can connect to different points (or taps) throughout the winding to change the ratio of the transformer. This has the advantage of allowing the power plant to generator or absorb reactive power as the grids requirements change.

It is however, a common failure point as it has moving parts and must connect and disconnect large amounts of current.

Bushings

One element that is often overlooked in the assessment of the reliability of transformers are the bushings. The bushings connect the external bus bar or cable to the internal windings of the transformer and are a separate but integral part of the transformer design. However, some failure modes of bushings are separate from the processes of the transformer. Therefore, the maintenance assessment and management of bushings is linked but separate from that of the transformer. This is key as nearly all bushing failures lead to a complete replacement of the transformer.

Cables

Cables are an integral part of electrical systems, whether they are related to the bulk transfer of electrical power or in the connection of low voltage supply and instrumentation and control systems. For the purposes of this paper we will concentrate on traditional types of “power cable” application.

Power cables do present a particular problem in that they can have a life expectancy of over 60 years. Therefore, it is highly likely that installations using older technologies such as Paper Insulated Lead Covered (PILC) or Oil Impregnated Paper (OIP) are still in use. Such cables represent an inherently higher hazard than newer XLPE designs but can still give useful service.

Cables can either have a single core or multiple cores. A typical modern design of cable is the integral four core cable that consists of stranded copper conductors encapsulated in various layers of insulating material and metallic armouring that provide mechanical protection and a barrier against moisture ingress.

Mechanical impact of cables is the most common form of damage. To lessen this risk cables are often installed in designated cable trenches as shown. However, cables are often placed in earth ditches that offer less protection against unauthorised excavation. Cable faults do occur mainly at “cable joints,”—an inherently weak part of the overall cable design.

Switchgear

Switchgear is the collective term for all the electrical components that make up a typical electrical (substation) system. It includes the circuit breakers, transformers, voltage and current transformers and reactive power equipment.

Switchgear serves the same system function that may include main power switching or interrupting devices, disconnecting switches, buses, instrument and control power transformers, and control and auxiliary devices, as well as other devices.

Photograph 2: Typical switchgear in a transmission substation - Courtesy CEERISK

In some instances (such as when physical space is at a premium or in the case where there is excessive pollution, like close to the sea) it is more prudent to install equipment indoors. Often these installations utilise Gas Insulated Switchgear (GIS), which are inherently smaller than their outdoor counterparts. GIS switchgear utilises the insulation properties of pressurised SF_6 gas in metallic cylinders to provide the basic insulation. Whilst such switchgear is of comparable rating to AIS designs, they are much more expensive that equivalent AIS designs.

Photograph 3: GIS switchgear in Aqaba, Jordan - Courtesy CEERISK Consulting Ltd

Circuit Breakers

By definition, a circuit breaker is a device that closes and interrupts (opens) an electric circuit between separable contacts under both load and fault conditions, as prescribed in the C37 series of ANSI Standards. Circuit breakers must be capable of connecting and disconnecting both under normal and abnormal (fault) conditions. Therefore, like other substation equipment they are designated by voltage, current and fault condition ratings.

By far the most common technology of circuit breaker used at high voltage and many medium voltage applications are Sulphurhexa Fludide type breakers, or SF_6. The development of this technology has delivered improved capacity and reliability of operation as opposed to the older bulk oil and air blast technologies.

Circuit breakers now are very modular in design, compact in space and have simple and reliable breaker cans and mechanisms.

There is however more variety of types of technology at the medium voltage and low voltage applications where SF_6, vacuum, air break and minimum oil types can be found. However, a common feature in most indoor and outdoor designs regardless of the circuit breaker technology are metal clad designs. Again, these designs have been simplified in operation to improve reliability and range of ratings.

Bus Bars

A busbar (or bus bar) is a metallic strip or bar, typically housed inside switchgear, panel boards, and busway enclosures for local high current power distribution. They are also used to connect high voltage equipment at electrical switchyards, and low voltage equipment in battery banks. They are generally uninsulated and have sufficient stiffness to be supported in air by insulated pillars. These features allow sufficient cooling of the conductors, and the ability to tap in at various points without creating a new joint.

System controls

The control systems used on electrical networks are often the least understood and rarely used by the insurance industry. There are two main types of systems: **electrical protection systems** and **site control and data acquisition systems.**

Electrical Protection systems

These are the systems that monitor the electrical parameters of the network, such as voltage level, current and frequency (amongst others). When required, they detect abnormalities on the system and send signals to the circuit breakers to disconnect faulty sections of the system. The way in which the protections systems do this can be complex, but all protection systems should be able to detect faults, then quickly disconnect only those sections of the system to maintain stability.

Often when equipment has catastrophically failed, an analysis of the way in which the protection system detected the fault and cleared the fault gives far clearer understanding of what happened (as opposed to looking at broken and damaged equipment parts that can sometimes be misleading).

Site Control and Data Acquisition Systems (SCADA)

The information for site SCADA systems is now often provided by the electrical protection equipment and centralised control of transmission systems, medium voltage commercial, and industrial systems. Such systems give an excellent overview of operations and give the users the ability to “drill down” into the network to monitor certain conditions if required. Again, when faults do occur, the SCADA systems often contain valuable information regarding the cause and nature of the fault conditions.

Voltage Regulators

Both three-phase and single-phase voltage regulators are used in distribution substations to regulate the loadside voltage. Substation regulators are one of the primary means (along with load-tapchanging power transformers, shunt capacitors, and distribution line regulators) for maintaining a proper level of voltage at a customer's service entrance.

Shunt Capacitors

Shunt capacitor banks at substations improve power factor and voltage conditions by supplying leading KV (kilo vars) to transmission and distribution systems.

Air switches

The general function of an air switch is to act as "a switching device designed to close and open one or more electrical circuits by means of guided separable contacts that separate in air."[3] Air (at atmospheric pressure) is also the insulating medium between contacts in the open position.

Surge Arrestors

Surge arresters are the basic protective devices used against system transient over voltages that may cause flashovers and serious damage to equipment. They establish a baseline of transient overvoltage, above which the arrester will operate to protect the equipment. When a transient overvoltage appears at an arrester location, the arrester conducts internally and discharges the surge energy to ground. Once the overvoltage is reduced sufficiently, the arrester seals off, or stops conducting, the flow of power following current through itself, and the circuit is returned to normal.

Automatic Circuit Reclosers

An automatic circuit recloser is a self-controlled protective device used to interrupt and reclose an alternating-current circuit through a predetermined sequence followed by resetting, lockout, or hold closed.

Reclosers are installed to provide maximum continuity of service to distribution loads, simply and economically, by removing a permanently faulted circuit from the system or by instant clearing and reclosing on a circuit subjected to a temporary fault caused by lightning, trees, wildlife, or similar causes. Unlike fuse links, which interrupt either temporary or permanent faults indiscriminately, reclosers distinguish between the two types of faults (permanent and temporary).

Coupling Capacitors

Coupling capacitors are primarily used for coupling power line carrier communication equipment to a high-voltage power line.

Coupling Capacitor Voltage Transformer

Coupling capacitor voltage transformers, commonly termed capacitor voltage transformers (CVTs), are devices used for coupling to a power line to provide low voltage(s) for the operation of relays and metering instruments. Power line carrier accessories or provisions for future installation of carrier accessories may be included in the base.

Types of Electrical Faults

Most electrical failures are not caused by a major event such as lightning, but by loose connections, moisture, dirt, overloads, ageing, degradation and other common causes. 75% of all electrical system failures can be traced to human error—from carelessness and improperly trained personnel to inadequate maintenance and delayed service. Even modern buildings designed just 10 or 15 years ago are vulnerable to electrical system failures.[4]

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[3] ANSI/IEEE Std. C37.100

[4] Munich RE, A GUIDE To Equipment Breakdown Insurance

There are mainly two types of faults in the electrical power system: symmetrical and unsymmetrical faults.

Symmetrical faults

These are very severe faults and occur infrequently in the power systems. These are also called balanced faults, and are of two types: line-to-line-to-line-to-ground (L-L-L-G) and line-to-line-to-line (L-L-L). Only 2-5% of system faults are symmetrical faults. If these faults occur, system remains balanced but results in severe damage to the electrical power system equipment.

Practically, a L-L-L fault is difficult to incite, with the exception of (for example) a foreign object falling onto all 3 phases of a busbar system or an enclosure filling up with water. In most cases a L-L-L fault or L-L-L-G fault start with one L-L fault which produces an arc. The products of that arc (plasma) will then allow the atmosphere to breakdown, connecting the other phases, and potentially earth.

Unsymmetrical faults

These are very common and less severe than symmetrical faults. There are mainly three types: line-to-ground (L-G), line-to-line (L-L) and double line-to-ground (LL-G) faults. Line-to-ground faults (L-G) are the most common fault, with 65-70% of faults being of this type. This is where the conductor to makes contact with earth or ground.

15-20% of faults are double line-to-ground, causing the two conductors to make contact with ground. Line-to-line faults occur when two conductors make contact with each other, mainly while swinging of lines due to winds and 5-10% of the faults are of this type.

These are also called unbalanced faults, as their occurrence causes unbalance in the system. Unbalance of the system means that impedance values are different in each phase causing unbalance current to flow in the phases.

A third event can happen that results in high currents: an out of phase connection. This can either be where a generator is synchronised, or two electrical systems are connected together out of phase. In these circumstances, depending on the phase difference, there can be higher currents than the fault conditions above. It can also lead to high torsional impacts to any rotating electrical machines.

Typical Causes of Electrical Faults

Causes of electrical failure scan be grouped into the following categories:

- **Electrical causes**
- **Mechanical causes**
- **Environmental**
- **Defects**
- **Human errors**
- **Natural catastrophe**

The scope of this paper does not cover natural catastrophes, and therefore this will not be discussed.

There are limited statistics that identify the causes of electrical failures in general, though some sources identify the failure causes for specific types of equipment, such as generators, transformers, cables and switchgear.

Electrical faults generate a significant amount of heat when short circuit current flows through the point at which the fault occurred. This can lead to a number of consequential events, including:

- **Over current flow**: When fault occurs, it creates a very low impedance path for the current flow. This results in a very high current being drawn from the supply, causing tripping of relays, damaging insulation and components of the equipment.
- **Danger to operating personnel:** Fault occurrence can also cause shocks to individuals. Severity of the shock depends on the current and voltage at fault location and may even lead to death.
- **Loss of equipment:** Heavy current due to short circuit faults result in the components being burnt completely, leading to improper working of equipment or device. Sometimes heavy fire causes complete burnout of the equipment.
- **Disturbs interconnected active circuits:** Faults not only affect the location at which they occur but also disturbs the active interconnected circuits to the faulted line.
- **Electrical fires:** Short circuit causes flashovers and sparks due to the ionization of air between two conducting paths that further leads to fire as we often observe in news such as building and shopping complex fires.

Electrical Causes

Electrical causes are those related to electrical energy. They include phenomena such as partial discharge and events such line disturbances.

Partial Discharge (PD)

PD is an electrical discharge that occurs across a localised area of the insulation between two conducting electrodes, without completely bridging the gap. It can be caused by discontinuities or imperfections in the insulation system. PD testing thus gives an indication of deterioration of the insulation and is an indicator of incipient faults. In general PD will occur in systems operating at voltages of 3000 V and above; it should be noted though that in some cases PD can also occur at lower voltages.

PD can occur at various points in the insulation system, for example, voids in the insulation medium, at the interface between insulation layers, or in gas bubbles in liquid insulation.

PD can be observed at the commissioning of new equipment, caused by improper installation or poor design and/or workmanship—particularly in cable joints and terminations that are made on-site. Poor workmanship at the manufacturing stage of an asset can lead to premature failure, with a disproportionately high percentage of insulation failures being observed within the first 1–3 years of service compared to the rest of the working life of the asset.

PD activity can start under normal working conditions in high-voltage equipment where the insulation condition has deteriorated with age or has been aged prematurely by thermal or electrical over-stressing, or due to improper installation.

Line disturbance

Line Surge (or Line Disturbance) is the number one cause for all types of transformers failures. This category includes switching surges, voltage spikes, line faults/flashovers, and other transmission and distribution (T&D) abnormalities.

Electrical Overloading

Electrical overloading normally occurs when the cable is underrated for the application or when too much load is being placed on the cable. In domestic applications this is often a result of plugging too many appliances into the one socket and overloading the wiring to that individual socket, extension adaptor or gang socket.

Overloading causes failure in other equipment such as transformers that fail after being subject to sustained overloading that exceeded the nameplate capacity. Overloading in transformers often occurs when the plant or the utility slowly increases the load in small increments over time. The capacity of the transformer is eventually exceeded, resulting in excessive temperatures that prematurely age the insulation. As the transformer’s paper insulation ages, the strength of the paper is reduced. Forces from an outside fault may cause a deterioration of the insulation, leading to failure.

Mechanical

If the insulation of a cable or winding is damaged either during installation or in subsequent use, the integrity of the electrical device will be affected and reduce its service life and suitability.

Abrasion

Jacket abrasion occurs when the outer jacket of a cable wears through to the underlying layer of conductors or shielding. This failure is especially common when using cables with soft jackets.

However, this problem can also be caused by a thin wall-thickness that can develop during the jacket extrusion process

Vibration

Uncontrolled vibration in generators, motors and other equipment that has heavy and complex structures with electrical windings can lead to damage to the insulation of these windings. Misalignment in large motors have been known to cause scuffing of windings and eventual failure.

Mechanical Impact

Physical damage to insulation of electrical conductors can occur because of mechanical impact with sharp metal objects, including excavators, power and hand tools, construction parts and hardware.

Environmental

Contamination

The outer jacket of a cable swells when it has been exposed to oils or chemicals it was not designed to withstand. Jacket cracking occurs when the jacket breaks and deteriorates down to the cable's shield, normally because of excessively high or low temperatures.

Additionally, contamination in insulating oil in transformers can cause electrical failures in large power transformers. Conductive contaminants on surfaces of components inside switchgear can cause electrical faults.

Moisture ingress

Water intrusion or immersion due to natural disasters or accidents can create instant short circuits, long term insulation damage, and long-term metallic component corrosion, among other complications. Medium-voltage switchgear that is exposed to high humidity conditions will absorb moisture, and voltage stresses will attack the hydrophobic insulation surfaces which were designed to inhibit moisture absorption.

In transformers, failures related to moisture is caused by floods, leaky pipes, leaking roofs, water entering the tanks through leaking bushings or fittings, and confirmed presence of moisture in the insulating oil.

Heating

Excessive heating of the cable will cause degradation of the insulation and sheathing material and premature failure. The heat may come from an external source or may be generated by the resistance to current flow in the conductor—a problem if the cable is overloaded and/or underrated for the application.

Similarly, transformers operating at higher temperature can suffer rapid ageing of the winding insulation that may lead to pre-mature failure. Transformers operating at higher temperature are typically found in confined areas within plants where poor ventilation can raise the ambient temperature around the transformer and prevent it from dissipating heating as designed or intended.

Animals

Rodents frequently attack the outer layers of cables. This damage can be extensive, significantly reducing the sheathing or insulation properties of the cable—another likely source of electrical fires.

Where substations are in open air yards, where wild life roams freely in the area, electrical faults occurred in equipment such as transformers when animals bridge the air gap between bushings of different voltage levels.

In closed spaces, animals gaining access to sections of switchgear with live parts have also been known to cause electrical faults.

Ageing

The service life of a cable can be significantly reduced if it has been expected to operate outside of the optimal operating conditions it was designed for. The ageing process usually results in embrittlement, cracking and eventual failure of the insulating and sheathing materials, exposing the conductor and risking a potential short circuit—a likely cause of electrical fire.

Insulation deterioration was the second leading cause of transformer failure where the average age of the transformers that failed due to insulation deterioration was 17.8 years — a far cry from the expected life of 35 to 40 years!

In 1983, the average age at failure was 20 years.

UV exposure

UV exposure can have a significant influence on electrical cable insulation and sheathing. Cables likely to be exposed to UV light should either be designed with UV resistant materials with a suitable carbon black content or protected from exposure with a protective covering, such as installing inside cable conduit so not in direct sunlight. UV exposure frequently causes cracking of the insulation and therefore potential short circuit failures.

Defect

“Defect” refers to the proximate or immediate preceding cause of a failure. This term covers:

- **Material defect:** a problem in the material used such as incorrect heat treatment
- **Design defect:** including incorrect calculations and assumption that affect ratings and operational conditions
- **Plan Defect:** including using the wrong installation plan (method statements) or not providing measures to protect systems.
- **Installation/manufacturing (Workmanship):** including poor connections, improper joints, contamination during fabrication and other causes.
- **Specifications:** Similar to design defect. Equipment on its own is fine, but was used outside of specifications

Most technicians and engineers recognise a defect that can lead to a failure, either immediately or within a short time. For example, a visually damaged insulation if left untreated, it could lead to short circuit and perhaps a fire. However, this is a rarity as these damages are easily recognizable.

Human factors

Misapplication

If cable selected is not appropriate for the application, it is more likely to fail in service. For example, a cable that is not robust enough for the environment (either mechanically tough enough to wear and abrasion or chemically resistant to the ambient conditions) is more likely to fail than one whose construction is suitable for the installation environment.

Poor manufacturing/poor workmanship

In the 1998 HSB study, only a small percent of the total claims were attributed to Poor Workmanship or Manufacturer’s Defects. Among the conditions found were such things as loose or unsupported leads, loose blocking, poor brazing, inadequate core insulation, inferior short circuit strength, and foreign objects left in the tank.

A major insurance carrier estimates that 25% of all electrical failures originate from improper connections. Loose connections generate heat, leading to eventual failure. That said, a loose connection can be detected using infrared thermography, whilst the system is in service. Hence it is important that a regular maintenance regime is in place to avoid any surprises. Loose and faulty connections cause an increase of resistance at that localized point. The increased resistance causes increased heat. The increase in heat will escalate until complete thermal failure of the connection occurs or the nearby insulation fails resulting in a fault.

Inadequate maintenance

Inadequate maintenance was the fourth leading cause of transformer failures in a study published by HSB. This category includes disconnected or improperly set controls, loss of coolant, accumulation of dirt and oil, and corrosion. Inadequate maintenance must bear the blame for not discovering incipient troubles when there was ample time to correct it.

Loose connections could be included in the maintenance category, along with workmanship and maintenance in making electrical connections; one problem is the improper mating of dissimilar metals, although this has decreased somewhat in recent years. Another problem is improper torqueing of bolted connections.

Sabotage and malicious mischief

Electrical failures in some electrical system components can be the result of wilful damage such as when metal objects are thrown inside substations with the intent of causing damage to bushings, outdoor buses and transformers. If the objects introduced into the substation are metallic and land between energised contacts of different voltage levels.

Preventing Electrical Faults

The electrical system includes devices designed to provide protection against electrical faults and limit their impact. These devices are designed to respond to limited conditions that may lead to electrical faults such as overloading. Most protection devices are designed to limit the impact of the electrical fault, only after it occurs. To prevent electrical faults, a comprehensive and knowledgeable loss prevention programme is required. Again, focus is related to mitigate the risk or at least minimize the impact of a short circuit or fire.

Preventing electrical faults requires attention to three areas:

- Early detection through appropriate condition monitoring
- Quick release and shut down of electrical equipment through devices designed to detect electrical faults and interrupt the flow of energy through the failed component
- Fast extinguishing of a short circuit/fire

The risk of electric failure can be mitigated when applying recognised standards, performing inspections and maintenance, and through regular testing. Simple checks consist of visual inspections where cabling should be in line with electrical drawings and documentation. Overloaded cable trays make this identification difficult. In addition, they pile up dust and generate heat and inductivity loads.

Preparing for electrical power interruptions means knowing your system. Thermographic inspection during peak-load conditions of all electrical equipment prior to the scheduled outage is mandatory to identifying high temperature excursions that indicate potential problem areas due to lose or dirty connections, load imbalances, or improper installation of equipment.

Oil-filled transformers, circuit breakers and disconnect switches should have samples of the insulating oil screen-tested as a means of identifying potential problems with those components. Transformer oil should also undergo dissolved gas analysis to identify specific adverse conditions present inside the unit. Equipment insulated with gas should be inspected and leak-tested to ensure the integrity of the gas system. It is helpful to identify redundant equipment and available spares and identification of each major component with a unique name. In addition to showing the equipment identifier on the drawing, a permanent equipment label should be mounted onto the component itself.

Insurance Considerations

Cause and coverage

Causes of electrical faults should be investigated forensically to determine the root cause and establish liability. Policies treat causes in different ways and we provide some ideas on what areas should be considered when applying coverage.

Questions that should be discussed when applying coverage include:

- Insulation breakdown (Is it wear and tear?) as a result of wear and tear
    - Can you prove wear and tear? How?
    - Is it foreseeable after a number of years?
    - Do they have the proper condition monitoring?
- Failure due to lack of maintenance – special wording but necessarily.
    - Think fortuity—What would a normal reasonable engineer do?
    - Have not seen policies excluding that, unless
        - It was wear and tear that should include gradual deterioration of the equipment and not normal negligence?
        - Is it breach of due diligence? (e.g. transformer overheating because of lack of cleaning that prevented the transformer from adequately dissipating heat)
- Causes that are typically excluded include:
    - Failures caused by off premises faults
    - Damage caused by cyber activities, unless there is special coverage in place
    - Terrorism/war
    - Negligence

Recovery/Subrogation

Feasibility of recovery or subrogation depends on, among many things, type of policy, warranty, contract, waivers, jurisdictions. Grounds for subrogation may include defect (design, material, workmanship); system inter-dependencies; third party impact; and location of the fault (off-premises: going after suppliers for disturbances that may have occurred off premises).

When pursuing recovery (subrogation) against responsible parties, it is necessary to consider the following:

a. Understanding causation based on thorough and comprehensive investigation. Need to be clear on the causal link between the loss and the target of subrogation.
b. Third party involvement, responsibility, actions or omissions and failures
c. Non-subrogation clauses. Cannot subrogate against a party insured under the same policy (such as in CAR, where subcontractors, suppliers, manufacturers are covered by the same construction all risk policies.)
d. In operational policies, it is easier to subrogate as the insured is only the owner and not a third party (manufacturer, service provider).

Loss Examples

Electrical Damage and Fire in TR

Location: Asia
Claim Amount: Replacement cost of TR $12,000,000 + LV Connection inspection & repair $3,000,000
Description: An explosion and fire on the GSUT Generator Step-Up Unit Transformer. The plant was on the normal operation without any significant alarm and the generator loading before the incident is around 404 MW and -100 MVar. The failure caused the unit to trip, black out in addition to other equipment damages. Base on the Plant CCTV recording data, the failure came from phase C bushing of the transformer. There was also other plant protection and alarm system that reacted and provided the data that confirmed the incident.

A plant core team tried to extinguish the fire using fire trucks together with the plant deluge system that was activated just after the fire occurred. The plant deluge system was not working to optimal standards at first due to a e loss of power supply to the electric fire during the unit black out. It began to work after the unit got the power source from unit 7 start-up unit transformer through 7DT incoming feeder.

Damages:

- Tank found severe damaged, oil leak from the tank
- All phases of HV bushings found burnt
- LV side connection to the generator step-up transformers found deflected with the worst in phase C, found broken

The cause of GSUT bushing failure has not been able to be identified from the above data so a deep OEM bushing and transformer investigation was required.

The incident was successfully mitigated by plant protection system. The plant protection system (500kV line differential, GSUT electrical protection (transformer differential protection) and mechanical protection (Bucholz and OLTC relay, winding and oil temperature relay) worked simultaneously to ensure that every equipment failure within the plant responded effectively.

Switchgear Fire

The substation was energised successfully, with the first wind turbine starting at 16:27 hours, with 42 of out of the 45 turbines operating by 17:04 hours.

It was concluded that this was an accidental fire. The full extent of the damage became evident after numerous inspections with the main damage sustained by the main switchgear.

The major cost item was the main 33 kV switchgear that was deemed to be a total loss.

Literature review

The following documents give a detailed insight how electric systems inspections must be done:

- Allianz Engineering Inspection Services: Engineering Plant & Inspection Guide
- AGCS: Infrared Thermography: Determining failure or problems in electrical systems

Preventive maintenance should be in line with manufacturers recommendations and standards and should be performed as recommended in the documents below. They can reduce the risk of an unscheduled outage by as much as 66%, according to statistics from the Institute of Electrical and Electronics Engineers (IEEE).

Most important maintenance measures are to keep an electric system clean, cool, dry and tight. (The Hartford Steam Boiler Inspection and Insurance Company, 2015).

Preventive Maintenance:

- Munich Re: Standard for an Electrical Preventive Maintenance (EPM) Program
- Munich Re: How to Prevent Costly Electrical System Problems

Failure examples:

- Munich Re: Common Equipment Failures and causes - How breakdowns can impact the bottom line.
- Munich Re: Electrical Equipment Failures and Causes

A loss of power can mean loss of income and customers. Since the panels, circuit breakers and cables in an electrical system are all interconnected, a short circuit in one part can cause damage to a part somewhere else.

Breakdown of electrical equipment is one of the leading causes of Business Interruption losses.

Electrical equipment includes power transformers, switchboards, distribution panels, circuit breakers, cables, bus ducts, motors, generators, disconnects, and related equipment.

Common causes of failure are burnout of windings; insulator, connector or control failure; bearing burnout in rotating equipment; and casing, rotor or shaft damage.

- Zurich: Machinery Breakdown Failures that go up in smoke!

Power blackout:

- CRO Forum: Power Blackout Risks - Risk Management Options
- U.S. Department of Energy Insurance As a Risk Management Instrument for Energy Infrastructure Security and Resilience
- Cambridge Centre for Risk Studies - Business Blackout
- AGCS: Cyber-attacks on critical infrastructure

Loss example

- Video of a bunker fire in Bielefeld, Germany (www.nonstopnews.de, 2016)
- Video of a bunker fire in Winterthur, Switzerland (TELE TOP, 2014)
- Video of a bunker fire in Ludwigshafen, Germany (Crash24, 2010)

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