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An Overview about the Fire Risk Management Culture in the Brazilian Utilities

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Abstract: Professional fire safety practice today in the Brazilian electric sector is dominated by traditional regulatory codes, standards and insurance considerations that are based on our past experience, i.e. failures. These methods should be suffice in a simple workplace producing simple and unchanging products or services. However, today´s substations are rarely simple and unchanging. Their complexities require a more effective approach to fire safety. A new way of thinking is essential. It should enable us to use the wisdom of past experience and state-of-the-art knowledge in foreseeing fire hazard interactions. The analysis present in this paper focus on the difficulties that transmission sector (i.e. transmission lines and substation) in Brazil has in tackling fire protection. It is hoped that analysis carried out will help designer and engineers shift from a prescriptive fire safety approach to a performance-based one. The intention is also remind the engineers of some idiosyncrasies of fire safety so that they can better plan for them in design.
Key words: Fire; Explosion; Substation; Performance

INTRODUCTION

In the last decade in Brazil the consumption of electric energy has increased more rapidly than the Gross National Product. Electricity is produced in the electric generating plants from several energy sources. 84% of the electricity produced in Brazil come from hydroelectric power plants. We have around 75,000km of transmission lines. Our transformation capacity is about 171GVA in the next eight it will increase 50%.

The production of electricity does not have the characteristic as those of the process industry. In the process industry, combustible and toxic material will usually react under a process involving high pressure and temperature to form a specific product. In the production of electricity there is no physical end-product and, due to consumer demand, varies with time.

The transmission sector in Brazil is under increasing pressure to demonstrate that their installations and operations are reliable and safe. In response and in an effort to improve their safety culture, the transmission sector has been using a number of techniques taken from the process industry to aid the assessment of risks and the consequences of possible failures. However, due to the distinct characteristics of the two processes, these techniques cannot be applied without certain adaptations. On the other hand, without the experience of using these methodologies the fire risk management in our substations has neglected important aspects inherent in those techniques.

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The transmission sector in Brazil does not traditionally quantitative fire risk analysis as part of their basis for decision making. This is probably due to the fact that many managers rely largely on experience to learn to manage fire risk. These managers, however, may have little or no experience of serious fires causing major damage, injuries or fatalities. It is fortuitous that they have not had these experiences, but their good fortunes leave them unprepared and vulnerable to such accidents.

The fire safety culture throughout the substations is fragile. Individuals who have little knowledge of fire and fire defence behavior make decisions affecting the substations performance throughout their life cycle. Some of the aspects of these decisions are discussed and analysed in the following sections.

1. BRAZILIAN EXPERIENCE WITH SUBSTATIONS AND TRANSFORMER FIRES

For the last 20 years blackout have been included in the list of major disaster that includes storms, hurricanes, earthquakes and floods. Therefore, consumers have become increasingly aware of fires and explosions involving oil-filled transformers located in power plants or substations. Owing to several fires in transformer, the summer of 1997 became known to the people of Rio de Janeiro as *The Summer of Blackouts*.

In the fire design of our substations, the usual focus is compliance with national and international codes and standards. Although during construction the plans and specifications are duly followed, what is rarely done is a considered harmonization of fire defenses by trained and skilled fire safety professionals in order to provide identifiable performance criteria: damage indicators and goals based on those involved in the project design, construction, operation and maintenance, considering both the organizational viewpoint as well as outside needs and desires. Meanwhile, differences in opinion concerning code interpretation and the understanding of fire and fire defense behavior by engineering design teams lead to very different performances among substations. The vast inventory of existing substations that have been constructed under different codes and conditions enables us to recognize the fire risk variability that exists in the electrical power industry. Even though the design theme and organization may produce a substation compliant with codes, standards and good practice, these credentials do not assure safety from fire. The prevailing assumption among many employees, regulators and the organizational culture has been that fire safety can be achieved through a combination of common sense and enforcement of prescriptive codes and standards.

It is not difficult to identify substations or hydroelectric power plants in which, despite both active and passive fire protection barriers, a fire has caused extensive destruction. In Figure 1, an autotransformer of 150 MVA protected by a spray system caught fire as a result of a bushing failure. The spray system did not operate when the fire began. Due to the oil leakage through the base of the bushing, this delay caused the fire to spread. NFPA 15 describes water spray design for transformers. Even if suppression systems are available, there are many uncertainties concerning their success or failure in controlling the fire. The questions that arise include: Can water be discharged from the spray system? Can water extinguish the fire? Water will be discharged from the spray system if all water supply valves are open, but when the sensor fuses, will enough water reach the spray head? Moreover, the violent nature of a transformer fire could render an automatic spray system useless. Although this has happened on a number of occasions, the automatic spray system survived the explosion and was credited with controlling the fire, limiting damage and minimizing system downtime. As the system in which the transformer is inserted has a dynamic behavior, the various fire scenarios are subject to many uncertainties.

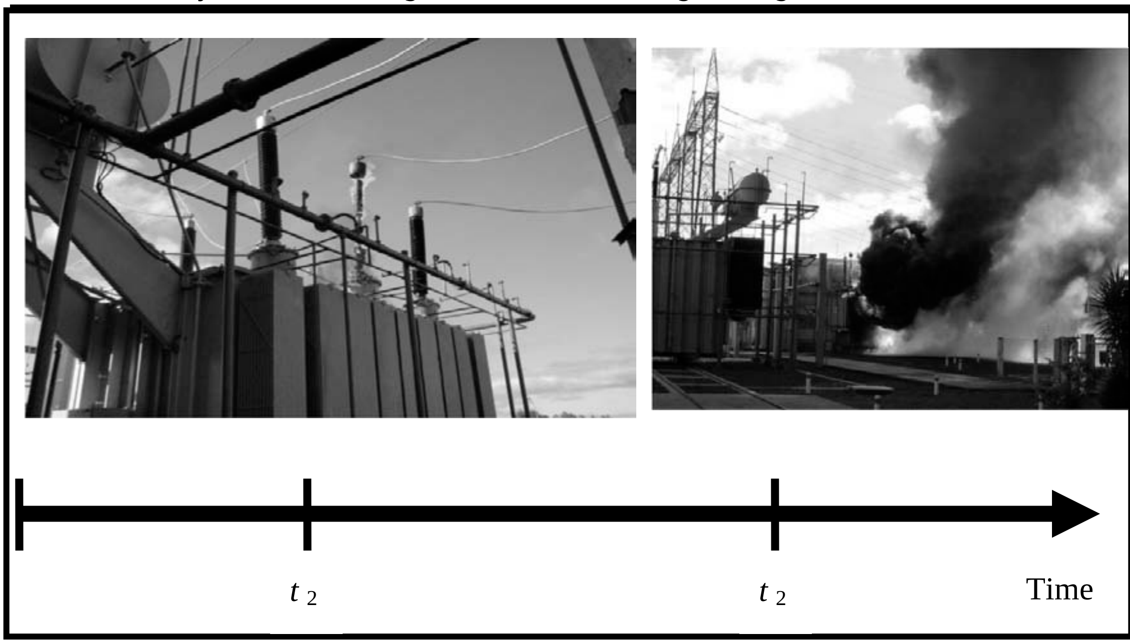

Figure 1. Escalation of a Transformer Fire

Traditional fire defenses provide a tool kit for protecting the substation. Their installation and maintenance have an important influence on substation performance in the event of a fire (see section 4). Evaluations should involve an understanding of individual component (micro) behavior and an interactive (macro) behavior of the complete electrical system.

Figure 2 shows the result of a transformer fire. It left the substation unavailable and about one million people on the dark during several hours. Radiation from the fire exposed the steel overhead bus structured to temperature above the yield temperature, causing failure.

The location of a transformer in the context of a power plant may affect its mission and business objectives if a fire occurs. Some organizations ignore the fire risk in the hope that such an unfortunate event will not happen. Others assume that if a fire does occur, the decision on what to do will be taken at the time. Figure 3 shows the transformer location in the context of a power plant: if a transformer fire occurred in this case, the combustible products could flow into the turbine inlet system.

Figure 2. Impact of A Transformer Fire on A High Voltage Bus Structure

Figure 3. Detail of Thermoelectric Power Plant Layout

Many transformers have been fitted with water-spray systems to combat the effects of fire, but these systems only serve to limit collateral damage in the substation and cannot prevent initial fire. The fire safety aspects of the installation are also neglected at the design stage. Fire risk analysis of the layout of several substations has unequivocally shown that, when there is some fire protection, its effectiveness is questionable, because it was introduced in isolation from the rest of the system. Figure 4 shows details of the layout of a 230/69 kV substation. This substation was initially designed, constructed and operated for some years without firewalls. Firewalls were constructed at a later stage, probably because a transformer fire in another substation without firewalls destroyed the transformer adjacent to the one on fire. As firewalls exist to protect adjacent transformers in the event of one catching fire or exploding, firewall failure may result in the loss of additional transformers. Although the firewalls were designed to resist fire for 4 hours, studies conducted by Duarte et al [1] showed that they can start to collapse after just one hour. In Figure 5, the grey area shows that the structural integrity of the firewall was compromised, since compressive and tensile stress exceeded the values of $150kg/cm^2$ and $15kg/cm^2$ respectively.

Figure 4. Detail of Substation Layout

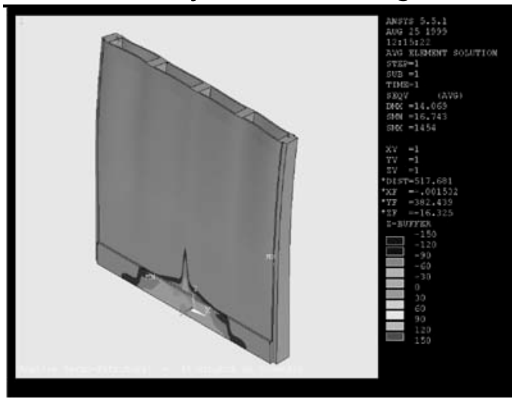

Figure 5. Von Mises Tension Test on Firewall after 60 Minutes

Why did the engineers who designed the firewall believe it had a fire resistance of more than 4 hours? They did not take into account the energy released by a fire or explosion. They did not ask the following question: what will the energy release be if a fire or explosion occurs in one of the transformers? The answer involves the quantification of the physical phenomena involved in a fire or explosion. What is surprising is that the design team thought that all the transmission transformers were protected against a possible fire. About a hundred firewalls of the same design were constructed in other substations of the transmission network managed by this company. However, since the transmission transformer specifications are not the same for the entire network, the energy released during a fire or explosion differs among transformers in operation. The energy release depends on such things as the transformer capacity, distance between the transformer and the firewall, type of fire resulting from the transformer failure, oil characteristics, wind velocity and direction. As a result, some of the firewalls of this particular transmission network are over-dimensioned and others under-dimensioned.

For the substation shown in Figure 4, it is also important to note the relay houses. Some of the protection, bypass and control circuits that control the transformers and other substation equipment are installed in the relay house. In this particular substation there are two relay houses whose structure is masonry with glass windows. A structural thermal performance simulation of one of the relay houses during a transformer pool-fire was carried out using the finite elements method. The distance between the transformer and the relay house was 3.50 meters. Ninety minutes after the fire started, the wall temperature distribution showed some wall temperatures to be above 300^{o}C. Although such high temperatures can cause wall failure, the structural integrity of the walls, pillars and beams was maintained for 117 minutes after the fire started. 45 minutes after the fire started, the glass windows would break, so there would be a rapid increase in the gas temperature inside the relay house. The heat impact would cause irreversible damage to the electronic panels. Analysis of gas temperature distribution inside the house showed that temperatures higher than 70^{o}C would be reached in approximately 30 minutes.

Eventually a substation fire will be put out and either the company fire brigade or local fire department will have contributed to this outcome. The success of this event is not whether the fire is extinguished; the question is not the overall probability of the fire being controlled, but rather the probability of the fire being controlled when it is 1kW, 5kW, 10kW, 50kW...nkW. The success of the event is to control the fire before it causes further impact on the operational continuity of the substation. An inappropriate layout in the event of a fire (Figures 2, 3 and 4) can spread the impact to other parts of the plant or substation. The time necessary to re-integrate the substation into the network will thus increase, even without considering the other costs involved. The compatibility of the substation layout with fire behavior is important to understanding the substation's post-fire operational continuity.

2. FIRE RECOMMENDATIONS: PRESCRIPTION VS PERFORMANCE

Electricity is taken for granted and it is only when the lights go out and our daily routines seem to go into slow motion that we suddenly become aware of our dependence on power plants, transmission lines and substations. Consumers have become more aware of an increase in fires and explosions involving oil-filled equipment. Fire in substations range from those which have a relatively minor impact, in which there is little or no interruption of the operation to the interconnect network to major catastrophe. While the engineers who design the substation have the knowledge and understanding to recognise the fire hazard throughout the system interactions and take measures, which will reduce the risk of a fire occurring, it is the substation operators who are responsible for its operation on a day-to-day basis. They must be aware, not only of the inherent hazard of the process of which they are in charge, but also of what can go wrong and, perhaps more importantly, *how* it can go wrong.

There is a tendency in Brazil, particularly in the reports following disasters, for a detailed range of prescriptive measures to be laid down to ensure the disaster ***never happens again***. Many of these recommendations tend to become embodied in good practice, which has helped to reduce losses. There is no doubt that the use of standards and codes in the form of good practice helps to avoid hazards of which few people are even aware. The thought process for fire-related decisions is heavily influenced by experience and interpretation of codes and standards. In other words, prescriptive fire regulations developed by consensus committees may be described as a compilation of good practices with a weak technical basis.

Fire regulations are prescriptive for a number of reasons. Fire safety system is far more complex than other discipline and a century ago knowledge base of fire technology was very rudimentary. The professional understanding was that fire protections were not part of the design team because fire was in abnormal rather than normal design function. It is important to recognize that a prescriptive code assumes the responsibility for fire safety rather than a design professional.

In the past as well as in the present the provision of fire safety have been through enactments that have been prescriptive. This may be regarded as the traditional approach to fire safety. There has been a move in recent years from prescriptive to performance based approach. In a prescriptive code environment an installation is required to meet the code recommendation rather than to be a fire safety system. Although a perception exist that good practices contribute to become the installation safe, it is not necessarily the case. Good practices or regulatory practices provide no way to measure the level of fire safety on a complex system as a substation. Therefore, an effective approach to fire safety is needed to deal with the complexities and changes that exist in the electrical sector. What is proposed is that performance analysis recognizes the multifaceted approach to fire safety and it may help the engineers to obtain effective fire safety.

3. A WAY OF THINKING ABOUT FIRE SAFETY IN THE BRAZILIAN TRANSMISSION SECTOR

In Brazil, there is reluctance in the electric sector to review accidents publically. The generating, transmission and distribution organizations are afraid of losing stock value in the market. On the other hand, the need to improve the safety performance and, indirectly, fire prevention on the electric organizations in Brazil, is partially driven by the National Regulatory Agency of the Brazilian Electrical Power System-ANEEL. ANEEL has emphasized that the electric organizations should be punished with high fines whenever they cannot provide electric energy to their consumers. ANEEL will also penalize power utilities if a transmission line, a transformer or any other piece of equipment is not available. These fines, if applied, could compromise the organisation's economic health.

In my opinion, in Brazil one difficulty in preventing substations fires lies in the communicating the responsibility of engineers to consult and apply Recognized and Generally Accepted Good Engineering Practices-RAGAGEP. The objective of the next sections is to address important aspects of substation fire risks. The aim is to help engineers make better decisions and communicate the fire risk more effectively with other.

3.1 Aspects of Transformer Fire in Brazil

Transformers are one of the most critical components on a power system. They have the substation's biggest fire load. Transformers are generally highly reliable and failures are rare. Although most transformer faults do not lead to a fire or explosion, some combinations of latent faults may result in a catastrophic transformer fire. Medina [2] examined a number of case histories and concluded that the following circumstances could lead a transformer fire and explosion.

Failure of inter-turn insulation in the main windings, probably as a result of overheating due to obstruction in oil circulation; mechanical damage during manufacture; moisture penetration between turns; overheating due to overvoltage or overload; and relative movement between turns.

Insulation failure between winding and transformer tanker caused by aging or deterioration of insulation, or moisture entry into oil.

Failure of magnetic circuit, leading to excessive eddy currents in the core.

External causes, such as rapidly fluctuating load, steep-fronted surge voltage and external short circuit on the secondary side.

Miscellaneous faults: Failure at connections or bushing; inadequate design or a design unsuited to the service for which the transformer was installed; inadequate spring tension on tap-charger contact springs; ignition of vapor above the oil level; and inadequate maintenance.

The São Francisco Hydroelectric Company (CHESF) has an installed capacity of more than 10,000 MW. It carried out a survey involving approximately 5,000 transformers with a voltage of no less than 69kV in eight states in Northeast Brazil. CHESF was particularly interested in studying the transformer failure mechanism of larger transformers in service. The failures had their origins in the core, windings, transformer protection components, tap changes and bushings.

The intrinsic protection system includes all accessory protection devices i.e. gas relay, oil and winding temperature sensors, pressure relief devices in the transformer tank and the tap changer protection relay. The main causes of failure are due to environmental conditions such as moisture, rain, sunlight and pollution, which could cause the degradation of micro-switch insulation. Accessory protection devices should be properly housed to prevent environmental damage.

Tap-changer failures are the result of mechanical wear, low dielectric strength or maintenance failure.

The main causes for bushing failures are extremely difficult to determine. The basic obstacle lies in the fact that the explosion leaves little to trace the origin of the fault and provide a reliable diagnosis. The main cause of bushing failure is poor sealing and the resulting reduction of supportability due to contamination by oxygen (oxidation) and humidity (hydrolysis). Sealing failure occurs due to degradation of seals or corrosion. Other causes that should be considered are the bad connection of a capacitive tap, storage in the horizontal position for a long period, pollution effects on porcelain, overheating and very fast transient overvoltages. Figure 6 shows bushing failure due to insulation degradation resulting from manufacturing defects.

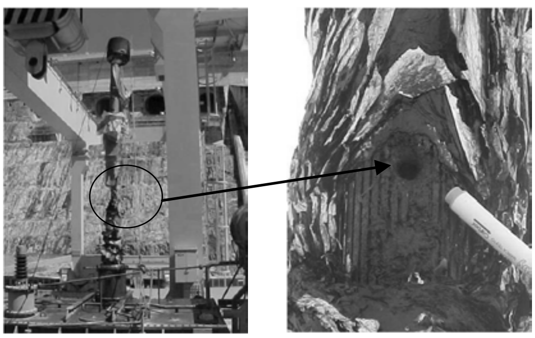

Figure 6. Bushing Failure Caused by Degradation of It Insulation

Transformer fires in Brazil have resulted in unacceptable consequences for companies and society as a whole, such as:

i. A bushing failure resulted in fragments of bushing ceramic being propelled beyond the perimeter of the substation, thereby putting people and buildings at risk.

ii. A transformer explosion created a blast pressure that impacted adjacent properties and structures. The blast waves also destroyed the fire protection measures around the transformer (such as the water spray system).

iii. An insulating oil-pool fire caused ignition of combustible structures inside and outside the installation perimeter.

iv. A transformer oil-spill fire spread because suitable oil containment was not installed. The resulting spill fire impacted other equipment and structures both within the substation and outside the perimeter.

v. Examples of transformer oil-pool fires impacting structures and equipment:

1) The heat flux from a transformer fire ignited exposed combustible surfaces. It also caused the failure of ceramic bushings on adjacent equipment as fireproof walls were not installed.

2) Radiation from the fire exposed the steel overhead bus structure to temperatures well above the yield temperature, causing failure.

3) An insulating oil pool fire created a very large fire plume. Due to high wind speeds, the fire plume tilted significantly and exposed adjacent equipment, buildings and other structures, as well as causing significant soot deposits in the downwind plume area (Figure 7).

Figure 7. Fire Plume from a Reactor Fire

3.2 Brazilian Transformer Failure versus the Globalized Economy

FURNAS Centrais Elétricas has an installed capacity of 10,050 MW. It represents 10% of all electrical energy produced in Brazil. The utility is responsible for supplying energy to the most developed region of Brazil and about 50% of Brazilian homes.

Since 1995 FURNAS has been observing an increase in the failure rate of new transformers and reactors, either during acceptance tests or in the first year of operation. Although these failures have not been catastrophic, they have resulted in equipment becoming unavailable. The failure analysis pointed out deficiencies in the manufacturing process and dielectric design. For example, oil leakage from the main tank was observed to be a result of poor welding leading to the contamination of the mineral oil. This could have caused a transformer fire or explosion.

In other words, the investigation carried out by FURNAS showed that the main cause of failure in new transformers during operation had originated from the active components (including core, winding, etc.) and the bushing. Both the costs and the time attributed to transformer active component failure are normally much higher than those resulting from failure of intrinsic protection devices, tap changers and bushing. All failures are undesirable and a cause of concern to both the electrical power industry and transformer manufacturers. Repair cost and time depend on the affected component.

The Gross Domestic Product (GDP) of any country is proportional to its demand for electrical power. In Brazil, before the 1990s, it was only the Government that invested in the electrical power market. Moreover, the government has not been investing in power plants and distribution utilities for some time, despite electricity consumption having increased over the years. As a result, aging transformers are often overloaded. As the government could not approach the challenge of investing in the industry alone, it decided to deregulate the Brazilian market. As a result, new private utilities were created as well as Public Limited Companies (PLCs) entering the Brazilian Market.

The National Regulatory Agency of the Brazilian Electrical Power System (ANEEL) has been pushing the new stakeholders to optimize the lead time for the design and construction of new facilities. On the other hand, the globalized economy has been putting pressure on manufacturers to reduce their costs. This may be achieved by reducing manufacture time through better tools or manufacturing processes, as well as sophisticated software and better materials.

Operating conditions have become more severe in recent years, and transformers have to operate in conditions of very fast transient or resonant voltage surges. These transient conditions may be the result of switching in the power system. Meanwhile, as manufacturing tools have been improving, there has been the tendency to reduce the safety factor of the transformer's intrinsic protection, active components, tap changers or bushing to compete on the globalized market. In other words, manufacturers have been reducing transformer safety margins, as their intention is to meet only the minimum requirements of the valid standards. Moreover, there are some indications that standardized acceptance tests (type and routine tests) do not reflect operational conditions in the field.

CONCLUSIONS

From the above discussion it is clear that the Brazilian utilities neglect the development of a complete understanding of the actual fire risk. Investment in fire protection appears to be a drain of resources with no immediate returns and no quantifiable results, even in the long term. Uninterrupted operation and cost drive the organizations. Sacrificing the operation in favour of preventing seemingly low probability fire may not seem like a reasonable course of action. In contrast to what occurs in other countries, the route of fire risk management has not gained importance in the last decades in the transmission sector. Additionally, there is a lack of codes and standards to prevent fires.

Fire safety still tends to be analysed in isolation, although fire loss is a result of the interaction of the parts that constitute an interconnected network. Fire loss may seen as

a systematic failure not as a result of single cause or multiple causes. As a result, the organization will usually ignore the warning signs before any serious fire. Managers or engineers will not take pre-emptive measures against future fire. As long as management only pay lip service to the design of fire active and passive barriers and as long as ANEEL does not ensure compliance with fire safety regulations a significant fire could occur. In conclusion, utilities in Brazil have a prescriptive approach to fire. They do not assess the interactions between the various systems, and their impact on the transmission sector overall performance.

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