Mitigating Failure Risk in Power Transformers: Eletronorte Case Study

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Power transformers are highly reliable electrical equipment. Still, failures can occur regardless of the application of the best design, production and operation techniques. A global transformer reliability survey conducted by the Cigre working group A2.37 in 2015 [1] concluded that the failure rate of substation transformers was 0.53% per year, and 0.95% per

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year for generator step-up transformers. Such data leads us to estimate that a power transmission company can expect one or two failures per year for each group of 200 transformers in its fleet. This figure becomes more relevant when taking into perspective the potential impacts and external effects of each of these occurrences.

Based on the same Cigre report [1], 76.56% of the failures did not lead to any reported external effects. The remaining 23.44% resulted in the following events:

- Fires: 7.16%
- Explosions: 5.91%
- Leakages: 4.25%
- Collateral Damage: 1.24%
- Other: 4.88%

According to this, for each group of 200 transformers we can expect a failure with significant external consequences to occur once in two to four years. Fires and explosions can lead not only to economic losses and long periods of outages, but also to serious injuries or even casualties, often an unacceptable risk.

(At this writing, the fires in California and the power cut-offs are a significant issue for the entire state, as they were last year and are expected into the future. Editor's note).

Setting the right transformer specifications at the design stage can have a huge impact on the safety and reliability of transformer assets in the long term.

Figure 1. Catastrophic failures at the Tucuruí hydroelectric plant in 2005 (left) and 2007 (right)

Eletronorte Experience

Having an installed generation capacity exceeding 9,000 MW, Eletronorte, a company of the Eletrobras Group, operates over 11,000 kilometers of transmission lines as well as 57 substations to bring electricity throughout Brazil through the National Interconnected System.

Like other companies in the electricity sector, in its daily operations Eletronorte is faced with a possibility of explosions and fires in its assets. The company is therefore continuously searching for alternatives to mitigate the risks and consequences of such events.

Power outages associated with failures can cause huge losses due to lost profit and penalties imposed by regulators. Another aspect strongly impacted by the occurrence of explosions and fires is the company's image.

Often the failure is initiated by an electrical arc resulting from the dielectric breakdown either due to overvoltage or insulation failure, which may be caused by material degradation, manufacturing defect or unforeseen design conditions.

Such failures involve very high energy values and an abrupt rise in temperature and pressure, with insulating oil vaporization and formation of gases whose pressure waves may lead to tank rupture, and consequently, contact of the high-temperature insulating oil with the atmospheric air.

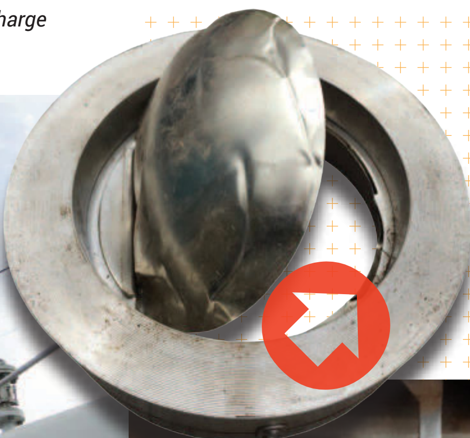
The gas law, PV=nRT, states that the increase in gas volume (V) is followed by an almost instantaneous increase in temperature (T). In the event of a transformer tank rupture, high-temperature gases are released into the atmosphere. This expansion contributes to the increase in the temperature of the gases and may lead to mineral oil self-ignition, at 250°C, causing a pool fire.

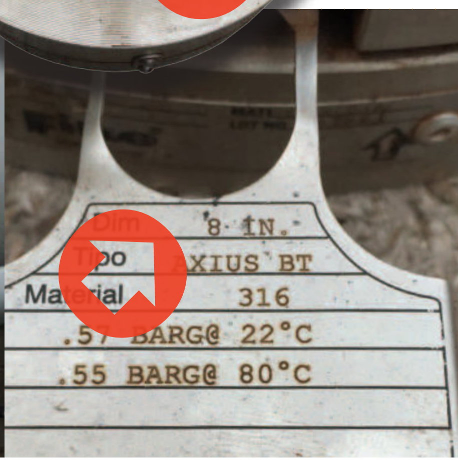
From 1988 to 2008, Eletronorte observed twelve incidents of fire in power transformers whose damage extended to entire GIS substations, neighboring equipment, auxiliary transformers and buses. The four most significant occurrences were at the 8,370 MW Tucuruí hydro power plant located in the state of Pará, in the northern region of Brazil, which has been in operation since 1984 (Figure 1).

Photo: Eletronorte

From 1988 to 2008, Eletronorte had twelve incidents of fire in power transformers with catastrophic consequences, four of which took place at the Tucuruí hydroelectric plant.

Figure 2. A ruptured disc in the confined discharge explosion tube in a 245/145-15 kV, 100 MVA autotransformer





From Better Design Standards to Higher Resilience

In 2003, following the occurrence of transformer leakages, explosions and fires at its substations, Eletronorte started a reassessment of transformer designs and their specifications, adopting the following basic assumptions:

- Under normal operating conditions and during the service life, maintain tightness and avoid contamination of oil, active part and the environment.
- In a fault condition, the tank must withstand the internal overpressure without causing the containment rupture and, consequently, occurrence of fire.

As a result of this effort, the transformer and reactor specifications were updated and improved with the following requirements:

- Tank: Design and testing according to ASME code, section VIII; standard design of weld joints; welded main tank cap; 100% inspection of structural welds with LP and ultrasound; use of flats with flat faces.
- Joints: Adopted PTFE – expanded Teflon – for the joints, on flat flanges.
- Load tap changer (LTC): Use only vacuum-type LTCs.
- Natural ester insulating liquid: Fire resistant, with a fire point above 360°C; protects insulating paper and reduces environmental impact.
- Pressure relief: Pressure relief valve opening adjustment considering expansion tank oil column as per NFPA-30 recommendation and use of rupture disc burst tube as per NBR 5356-1 and confined discharge.

Implementing these improvements in the transformer and reactor design and specifications has drastically reduced the risk of explosion and fire, as well as increased the service life, facility availability, and revenue assurance. There was also a reduction in the following items:

With the implementation of improved design standards for transformers and reactors, the company recorded a significant reduction in catastrophic failures, with no failures taking place at the Tucuruí plant in the period from 2008-2019.

Photo: Eletronorte

restoration time of electricity supply, insurance premium and, most importantly, reduction of risk to operating or maintenance personnel and the environment.

With the improvements in the conventional protection of its electrical system and having limiting some operations at generating units, Eletronorte effectively recorded a reduction in catastrophic failures in its assets. Particularly in relation to the Tucuruí plant, there have been no failures in the period between 2008 and the time of writing this article.

Figure 3. A bushing failure in 2018 had minimal impact on the operation of the substation.

Since 2006, when Eletronorte started specifying power transformers and reactors immersed in natural ester, more than twenty units have been installed up to 245 kV voltage class, all of which in continuous operation. The specifications allow use of vegetable insulating oil for all voltage classes, including 550 kV.

Figure 4. An internal failure in an auxiliary service 75 kVA natural ester immersed transformer in 2012 was limited to the tank deformation for pressure relief – no fire occurred.

Thanks to the measures taken, a bushing failure in early 2018 (shown in Figure 3) that would possibly have led to major external effects was reduced to replacing only the components: the bushing and the rupture disc (as shown in Figure 2).

They also faced an internal arcing in a small 75 kVA natural ester immersed transformer from the early days of the assessment of the technology (Figure 4). Although the tank deformation makes clear the amount of energy, possibly reaching temperatures in the level of thousands of degrees in the arcing region (plasma), no fire happened.

These events are good examples of the effectiveness of the adopted measures, which minimize external effects of a real failure.

Conclusion

Safety, reliability and resilience starts at the design phase, a fundamental principle of the Electrical Power Reliability Alliance (EPRA); www.myepra.com and is an essential element within the Body of Knowledge (BoK) of all of the reliability societies and Safety, reliability and resilience starts at the design phase organizations; www.smrp.org and www.reliable-web.com. The Eletronorte experience is a powerful example of how design standards can and do effect safety, reliability and resilience.

References

[1] Cigre Working Group A2.37, "Technical Brochure 642 – Transformer Reliability Survey," Cigre, Paris, December 2015