IMPROVING THE SAFETY OF DISTRIBUTION POWER TRANSFORMERS

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SUMMARY

Oil-filled transformer explosions are due to electrical arcs occurring in transformer tanks. Within milliseconds, arcs vaporize the surrounding oil and the generated gas is quickly pressurized. The pressure difference between the gas bubble and the surrounding liquid oil generates one dynamic pressure peak which propagates and interacts with the tank. Then, the reflections of the pressure peak build up the static pressure, which rises and leads to the tank rupture since tanks are not designed to withstand such levels of static pressure. This results in dangerous explosions, expensive damages and possible environmental pollution. While protective walls surrounding transformers can contain the explosion and sprinklers can fight the induced fire, the current paper presents a strategy to prevent the transformer tank rupture. Once an electrical fault occurs, the fast depressurization of the tank is induced by quick oil evacuation to a reservoir in order to prevent the tank explosion. To evaluate the efficiency of this strategy, experiments and computer simulations are used. The experiments were performed on large scale transformers equipped with the protection. Besides, simulations of the consequences of an electrical arc occurring in a 200 MVA transformer geometry were run and the pressure maps obtained with and without protection were compared.

Key words: power transformers, protection, arcing, pressure, experiments, simulations.

INTRODUCTION

Despite all the differences between all the European electricity networks, one constant remains: power transformers are the cornerstones of the electricity grid and their safety is crucial for all the transmission and distribution companies around Europe. Indeed, power

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transformer explosions lead to big fire, risk for human life, outage, environmental pollution and huge costs. In many substations, to mitigate the consequences of a transformer explosion, protective walls may surround the transformers to limit the propagation of the explosions while sprinklers extinguish the induced fire. Nevertheless, despite these equipments, power transformers still explode as shown in the examples presented in Figure 1.

a) thermal power plant transformer — b) nuclear power plant transformer — c) distribution transfomer

Figure 1 – Transformers explosion examples

In order to complete the chain of protections, this paper presents a strategy to prevent transformer tanks from rupturing: once a fault occurs inside the transformer, a fast depressurisation of the tank is induced by a quick oil evacuation from the transformer. To evaluate the efficiency of this strategy, experiments and computer simulations are used.
Two experimental test campaigns were performed, first by Electricité de France and second, by CEPEL, Brazil, on large scale transformers. The tests consisted in creating arcing in oil filled transformer tanks equipped with the prevention technology while several sensors could measure temperature, pressure, tank acceleration... Analyse of the recorded data is displayed in the second section of this paper.
Besides, 3D computer simulations run on a 200 MVA transformer geometry (6m long) are presented in the third section. They give a precise insight into the pressure wave propagation within the tank after an electrical arc occurrence and evaluate the influence of mechanical protections design on the depressurisation process.

1. FAST DEPRESSURISATION STRATEGY

The explosion prevention technology studied in this paper is based on mechanical technologies and consists in absorbing the high overpressures generated by the electrical faults, thus preventing the tank rupture and the subsequent fire.
Indeed, when a short circuit occurs in a transformer tank, this electrical arc generates a dynamic pressure peak, which travels at the speed of the sound inside the transformer oil, 1200 meters per second. The dynamic pressure peak mechanically activates the protection. Oil and gas are then quickly expelled out of the transformer tank through the Depressurisation Set (DS, item 1) to an oil gas separation tank placed on the side of the conservator (item 3). The explosive gases are then channelled away to a remote and safe area (item 4 and 5). Then, nitrogen is injected (item 6 and 7) to have the whole transformer safe, cool and ready for repairs. Additional DS can also be placed in order to protect the OLTC or the OCB (item 2).

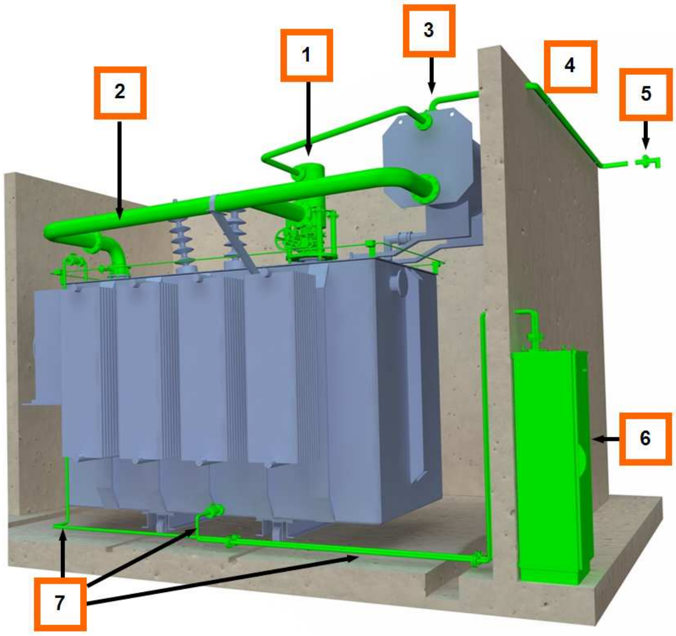

Figure 2 – Transformer equipped with fast direct tank depressurization based method

2. EXPERIMENTAL TESTS

2.1. Test Configuration

A complete experimental study was performed by CEPEL, the Brazilian independent High Voltage Laboratory, and SERGI Holding to understand the explosion process in order to establish strategies to prevent it. The experiments consisted of arcing tests on 3 industrial size oil-immersed transformers (up to 5.3 m long) including their internal components (windings, cables…) and equipped with various sensors (pressure, temperature, acceleration…). Their large dimensions enabled the detailed study of the non uniform pressure distribution inside the tank. Furthermore, since transformer explosions are very dangerous and uncontrollable, a transformer protection had to be installed during the experimental tests. This one, shown in green in Figure 2, is based on the direct mechanical response of a Depressurization Set (DS) to the tank inner pressure induced by electrical faults. All the details about the conclusions of the tests can be found in [1] and are summarized in the next paragraphs.

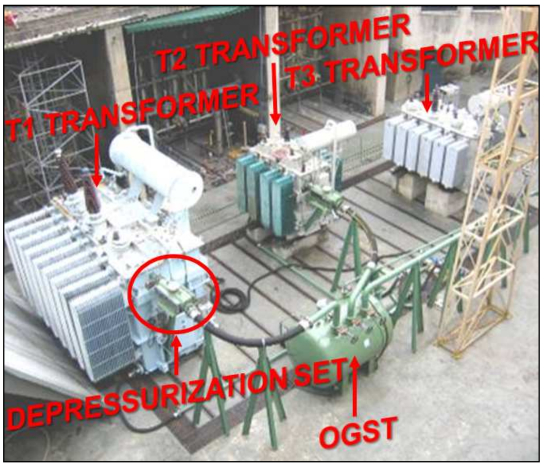

Figure 3 – CEPEL tests configuration

2.2. First Stage – The Vaporization Saturation Process

When an electrical arc is ignited inside the transformer oil, it vaporizes almost instantaneously a significant gas volume (see Figure 4). The generated gas volume was found to be a logarithmic function of the arc energy, which seems to be in accordance with the vaporization process and especially with the saturation of the vaporization for high energy arcs. Indeed, after the arc has vaporized the surrounding oil and created a gas bubble, it stays in that volume, using its energy to crack the oil vapour rather than continuing directly vaporizing the oil: this results in a smoother vaporization process. The first stage of vaporization process is almost instantaneous and because of the oil inertia, the gas is very quickly pressurized, generating one high pressure peak.

t = 3 ms *t = 3.66 ms* *t = 4 ms* *t = 5 ms* *t = 6 ms*

Figure 4 – Gas bubble (3 to 6 ms after the arc ignition)

2.3. Second Stage – The Dynamic Pressure Propagation

In Figure 5, experimental pressure profiles are displayed. Each curve shows the pressure evolution near each sensor respectively located in positions A (at the opposite side of the arc, close to the protection), B (relatively close to the arc) and C (where the arc is ignited).

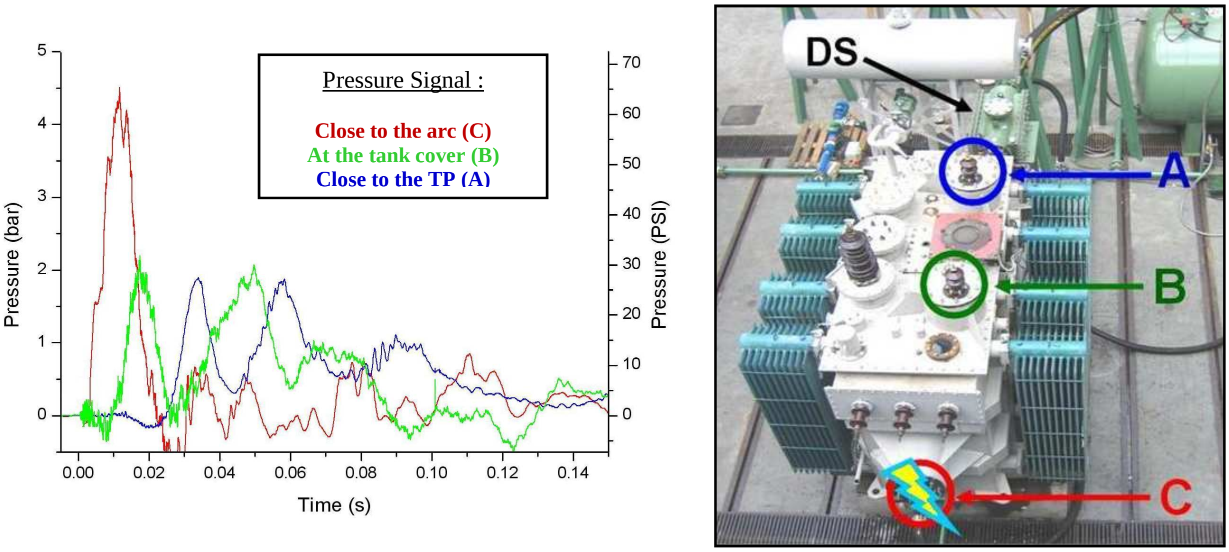

Figure 5 – Pressure profiles at different locations

The displacement of the shock wave in the tank can thus be easily followed in Figure 4. The arc ignition located in C causes a high-pressure peak (as mentioned in 2.2). This pressure peak then propagates leading to a second delayed lower peak in B, ending in A. For each sensor, the other pressure peaks (smaller than the main peak) are due to wave reflections off the walls. It has thus been experimentally shown that pressure increase is not spatially uniform in the tank, and that the pressure waves propagate at a finite speed.

2.4. Third Stage – Tank Withstand to High Dynamic Pressure

The static pressure that transformer tanks can withstand is usually around 2.2 bars (abs.). In other words, if the tank is submitted to uniform and stabilized pressure (hereafter called *static pressure*) over 2.2 bars then the tank ruptures (see for instance [1] or [2]).

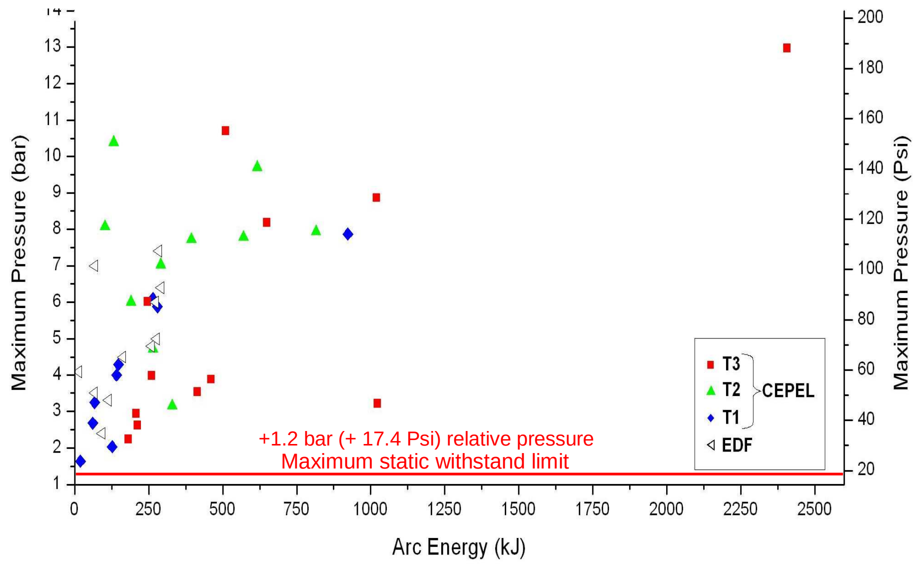

Figure 6 – Max. relative pressure measured for each test vs arc energy

During the arcing tests performed by Cepel and SERGI, the sensors measured pressure peaks up to 14 bars (abs.) and no tank rupture was noticed (Fig. 6). In fact, thanks to the protection operation and as showed in Fig 5, the tank was submitted to localised pressure peaks for a very short period of time (hereafter called *dynamic pressure*) and the tank could withstand these high dynamic pressure peaks. The tests thus showed that if the oil evacuation out of the tank is activated within milliseconds by the first dynamic pressure peak before static pressure increases, the explosion can be prevented.

3. COMPUTER SIMULATIONS OF A 200 MVA TRANSFORMER EXPLOSION AND ITS PREVENTION

The here above presented experimental tests consisted in igniting electrical arcs inside protected transformer. Similar experimental tests performed without protections would be far too dangerous. Furthermore, many different transformer geometries and sizes exist and various protection configurations are possible. A huge number of tests should be done. Such systematic experimental tests would lead to huge costs.
On the other side, physical modelling and in particular CFD (Computational Fluid Dynamics) modelling has made some impressive progress during the last decades and computational capabilities have quickly increased. Computer simulations are now able to give a clear insight

into complex 3D phenomena such as transformer explosions and their prevention. Using computer simulations is thus an alternative to costly and dangerous test campaigns.

3.1. Description of the simulation tool and the tests configuration

Experiments showed that the key phenomena in transformer explosions and their prevention are first, the local pressure increase induced by the vaporization of the oil surrounding the arc and second, the pressure waves propagation. The core of the simulation tool then consists of a set of partial differential equations that govern the fluids dynamic while the other physical phenomena (viscosity, thermal effect, electromagnetic effects…) are modelled via the source terms added in the partial differential equations. The partial differential equation set is based on a 5 equation two phase flow model developed in [3]. Both phases (liquid/gas) are considered compressible. The thermodynamics of the two phases are handled carefully to prevent any theoretical or numerical problems. The modelling is dedicated to flows with interfaces so that both phases share a single pressure and velocity at a given point in the domain.
The equations are solved using a finite volume method on 3D tetrahedrical meshes allowing simulating complex 3D transformer geometries. The aim of this tool is to estimate the pressure repartition inside the transformer tank during the first fractions of second after the electrical arc occurs. All the details can be found in [4].

The 200 MVA transformer is 5.75 m long, 3.25 m high and 2.5 m wide and all the components of the transformer, such as bushing turrets or windings are taken into account. An electrical arc (11.5 MJ arc generating about 3.4 m^3 of gas) resulting from a low impedance fault ignites near a winding, generating an 11 bar abs gas bubble.

3.2. Results of the simulations

Figures 7 show the simulated evolution of the pressure inside the transformer tank after the occurrence of the gas bubble generated by the arc. On the right side (Figure 7b), the transformer is equipped with the protection presented previously, while on the left side (Figure 7a), the transformer is not protected.

When the transformer is equipped with the protection, the pressurized gas bubble creates dynamic pressure waves which propagate throughout the transformer, reflecting and otherwise interacting with the tank structure (Fig. 7b). Within 3 ms, a large pressure peak has reached the entry of the first bushing, as shown in Figure 7b. Then the pressure wave triggers the activation of the Depressurization Set within about 10 ms after the gas bubble creation. This produces the rapid evacuation of fluid from the transformer tank which thus generates rarefaction waves spreading throughout the transformer. After only 60 ms, the pressure throughout the transformer stabilizes well below dangerous levels, as shown in Figure 7b.

Otherwise, when the tank is not equipped with any protection system, and if it is subjected to a similar low impedance fault, the tank is exposed to very dangerous pressure levels. For instance, 30 ms after the arc occurs, the pressure in the bushing reaches more than 10 bars abs as shown in Fig. 7a. Moreover, without the tank protection, the static pressure stabilizes around 6 bars abs and the transformer would violently explode (as transformer tanks are designed to withstand static pressure only up to about 2.2 bars abs).

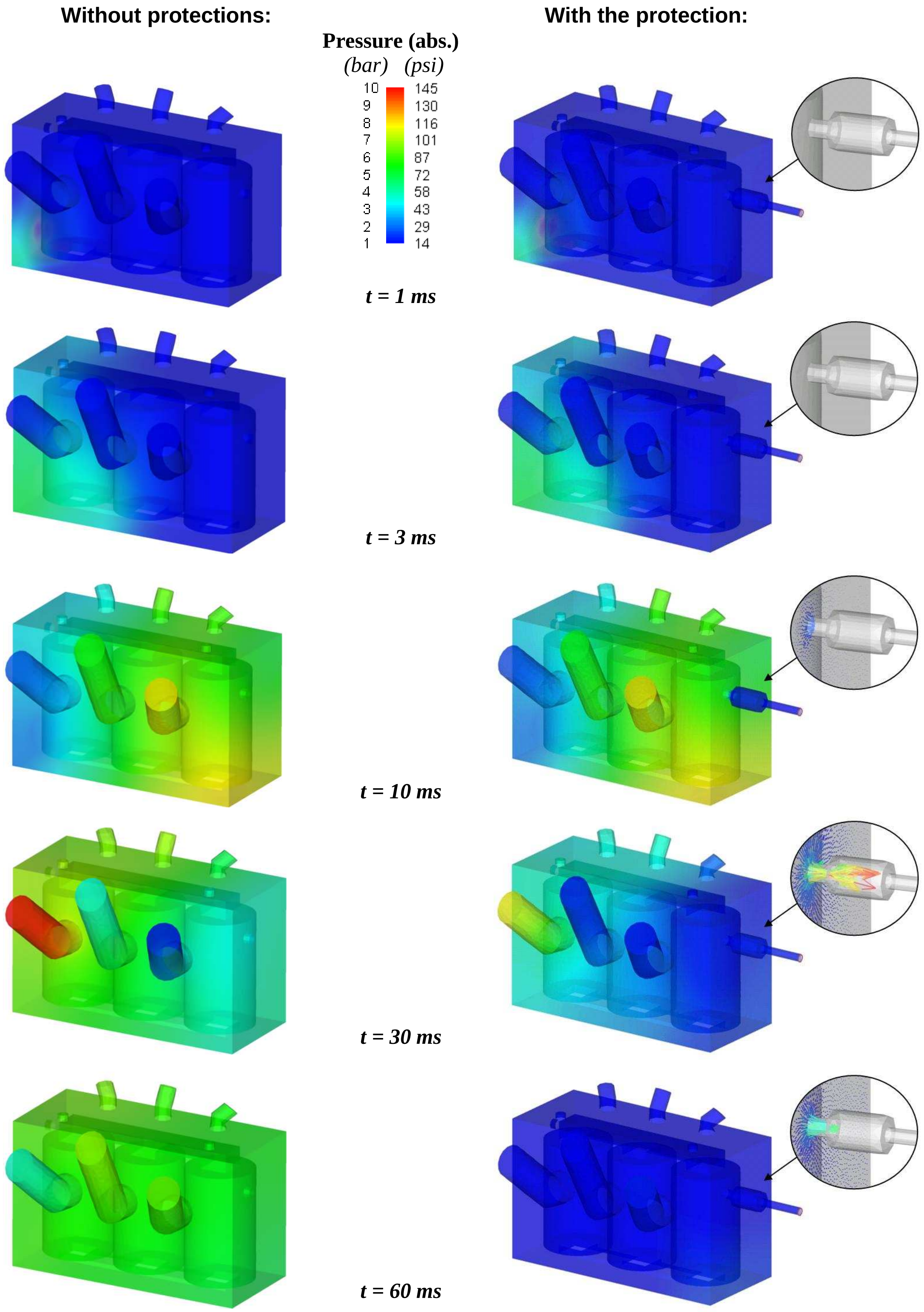

Figure 7a – Pressure evolution in an unprotected tank

Figure 7b – Pressure evolution in an tank equipped with a DS

CONCLUSION

An experimental test campaign was dedicated to the understanding of transformer explosions induced by electrical arcing. The tests consisted in igniting electrical arcs inside oil-filled transformers equipped with an explosion prevention technology that operates at a calibrated pressure level due to dynamic pressure peaks.

The tests showed that when an electrical arc occurs in the tank, the oil surrounding the arc is quickly vaporized and the gas generated is pressurized because the liquid inertia prevents its expansion. The pressure difference between the gas bubbles and the surrounding liquid oil generates pressure waves that propagate within the oil. When the first dynamic pressure peak reaches the protection, it triggers an oil evacuation that quickly depressurizes the tank so that no tank rupture occurs.

During the tests, transformer tanks could withstand high pressure peaks (up to 14 bar abs.) for several tens of milliseconds even if the static limit of transformer tanks is around 2.2 bar abs.

Complementarily, the consequences of arcing inside unprotected transformers can be studied safely using computational simulations. A numerical simulation tool was thus developed to compute pressure wave propagation and to deal with liquid and gas. Simulations were run on a 200 MVA transformer and highlighted the advantages of using an advanced simulation tool. The simulation tool confirmed that when an electrical arc occurs inside a transformer tank that is not protected, the dynamic pressure peak generated by the arc propagates through the tank, reflects on the wall and progressively increases the static pressure inside the tank resulting in its rupture. On the other side, the computational tool is efficient to study the operation of an explosion prevention strategy based on a fast depressurization induced by oil evacuation. Indeed, the results showed that this fast fluid evacuation generates large rarefaction waves that propagate and depressurize the whole tank within milliseconds thus avoiding the static pressure build up that could not be withstood by the tank.

Such strategies based a fast tank depressurization generated by a quick oil evacuation can thus be considered an efficient protection against transformer explosion and they are now recommended by the NFPA Standards 850 and 851 (see ref. [5] and [6]).

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