PREVENTING TRANSFORMER EXPLOSIONS: EXPERIMENTS, ANALYSIS AND SIMULATIONS

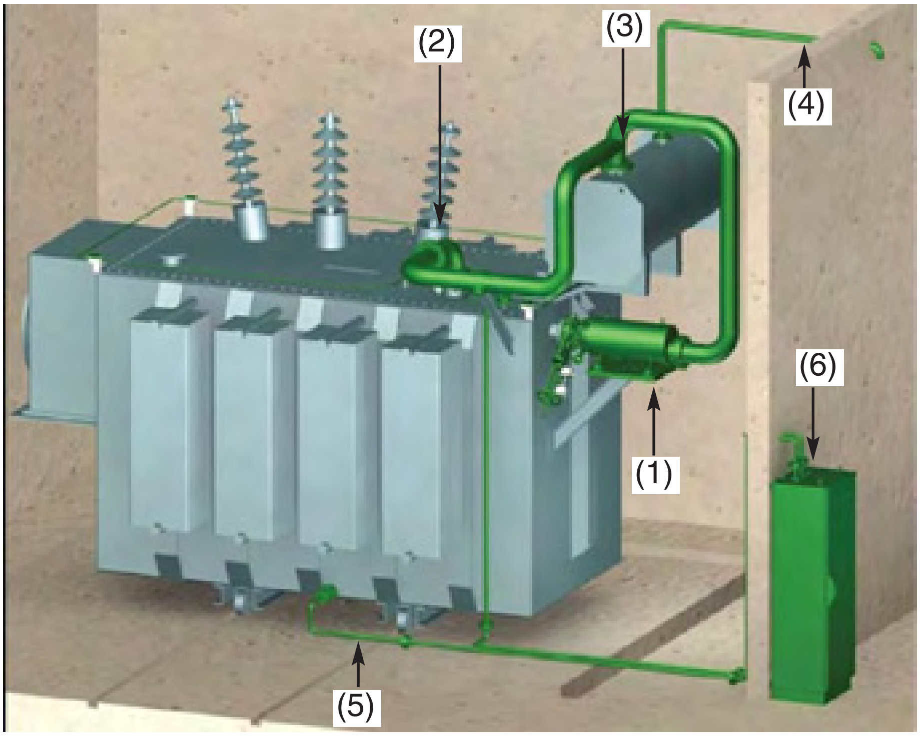

Figure 1: Transformer equipped with a TP comprised of two decompression sets.

1. INTRODUCTION

Transformer explosions are caused by low impedance faults that result in arcing once the oil loses its dielectric properties. Oil is then vaporized, and the generated gas is pressurized because the liquid inertia prevents its expansion. The pressure gap between the generated gas bubbles and the surrounding liquid oil generates pressure waves, which propagate and interact with the tank structure. They cause the pressure rise that leads to the tank explosion. These explosions result most of the time in very expensive damages for electricity facilities.

Realizing that the transformer explosion prevention is the sole effective solution to avoid such financial losses, SERGI designed and patented worldwide the Transformer Protector (TP).

2. TRANSFORMER PROTECTOR (TP) DESCRIPTION

The TP is a passive mechanical system that can only be activated by the level of transformer internal pressure reached during short-circuits. The TP has therefore a very high reliability, making false activation impossible. The TP is designed to protect the main transformer tank, the On Load Tap Changers (OLTC) and the Oil Cable Boxes (OCB).

In Figure 1, the CTP Model protects the transformer tank and the OLTC; this arrangement consists of 6 main components:

1. Transformer tank Depressurization Set (DS), item 1;
2. OLTC Depressurization Set, item 2;
3. Transformer Conservator, which is used here to separate the oil from the explosive gas produced during the short-circuit, item 3;
4. Gas Evacuation Pipe, which channels the flammable gases to a remote and safe area; item 4;
5. Nitrogen injection system, which injects Nitrogen for security purposes to avoid the bazooka effect provoked by the explosive gas when in contact with air (oxygen) and to confine the oil capacities under a safe atmosphere so that maintenance can be executed safely, item 5;
6. The TP Cabinet, where all cables are connected and the Nitrogen Cylinder is stored, item 6.

When an electrical fault has occurred, at the exact time of the electrical arc creation, an enormous amount of explosive gas is created. The first Mega Joule produces 2.3 m3 (80 feet3) of explosive gas, while 100 Mega Joule produces only 4,3 m3 (150 feet3). This huge amount of gas created during the first millisecond provokes a dynamic pressure peak which travels at the speed of the sound inside the transformer oil, 1,200 meters per second (4,000 feet per second). This first dynamic pressure peak of the shock wave, generated by the electrical fault, will activate the TP before static pressure is built up. Then the TP depressurizes the transformer within milliseconds before inner tank pressure reaches its designed limit pressure. It thus prevents the tank from exploding.

As soon as the TP activates, the mechanical energy is evacuated and the transformer protected even if the electrical arc is fed for one or two seconds. Oil and gas are then quickly expelled from the transformer tank through the Decompression Chamber (DC) to the Conservator. In the Conservator, gases will be separated from the oil and channeled away to a remote and safe area. Then, nitrogen will be injected to have the whole transformer safe, cool and ready for repairs.

3. THE EXPERIMENTAL CAMPAIGNS

Up to now, two TP test campaigns have been performed, both under the worst conditions by creating low impedance faults leading to electrical arcs inside the transformer tank dielectric oil. In 2002, Electricité de France performed 28 TP tests. Then, in 2004, a second campaign of 34 TP tests was carried out by

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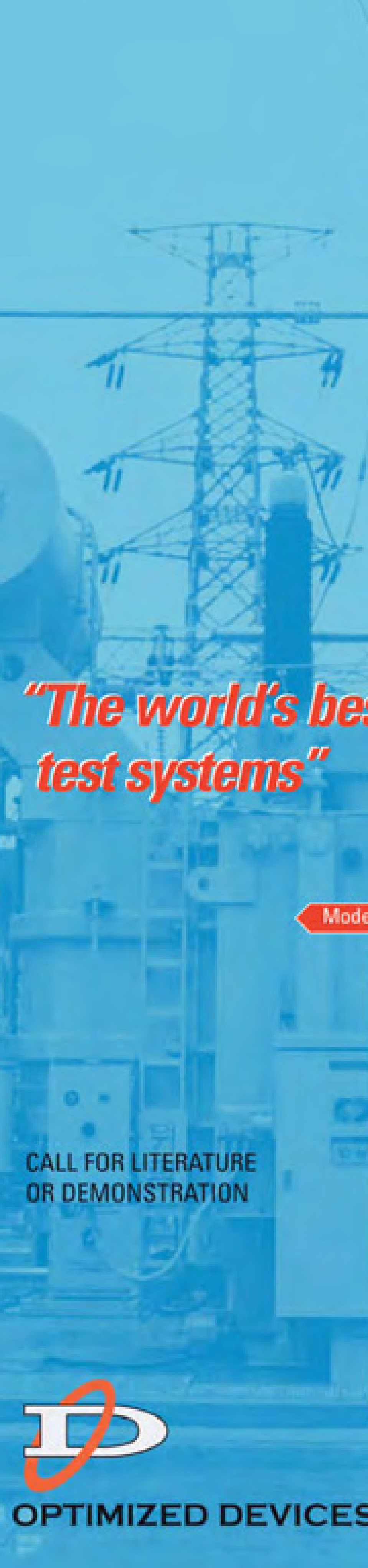

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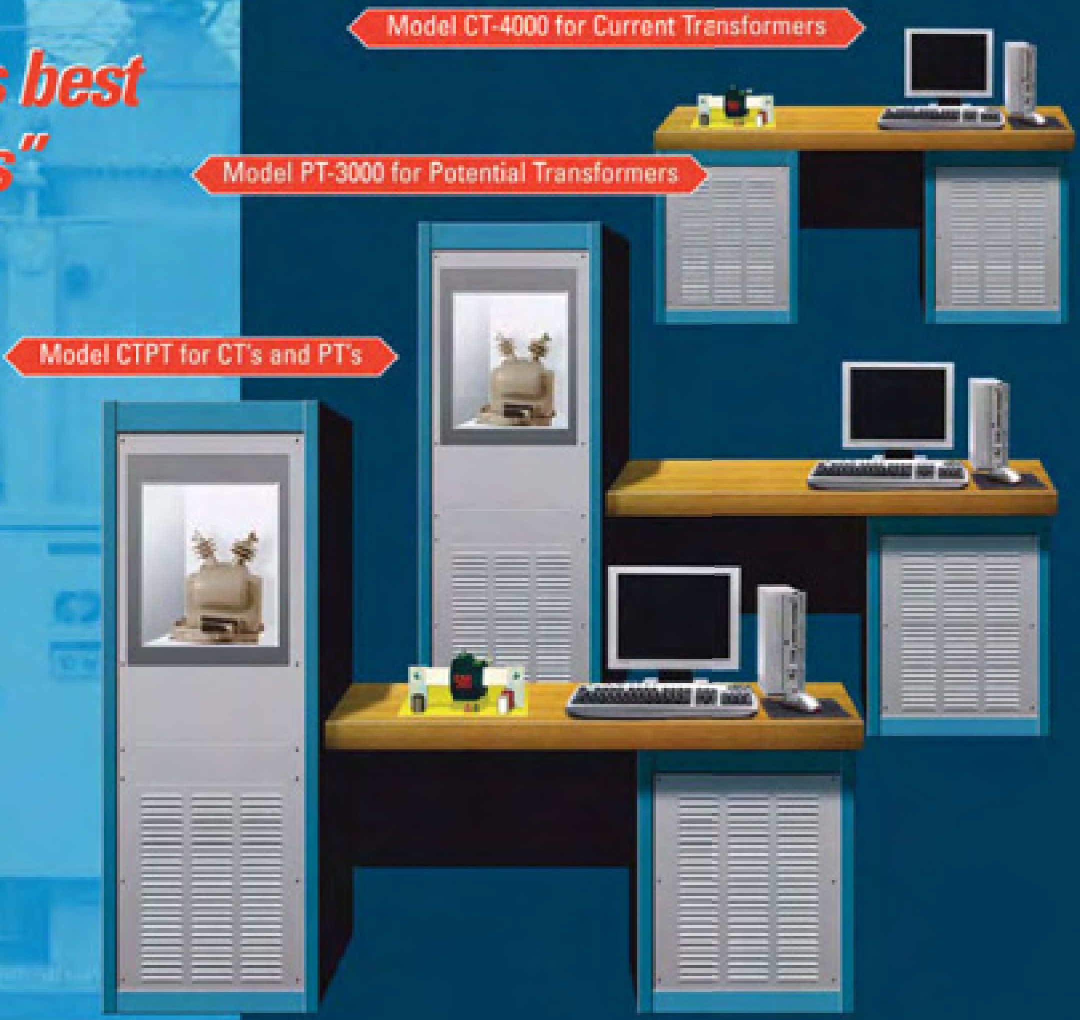

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Transformer Explosions

Contined from Page 14

CEPEL, the Brazilian independent High Voltage Laboratory. For the 62 tests, each transformer was equipped with the TP, which reacts directly to the moving dynamic pressure peak, shock wave, caused by the low impedance fault. This part presents the main conclusions of the last test campaign.

3.1. Experimental settings

34 live tests were performed by CEPEL on three standard transformers (T1, T2, T3). Their large sizes enabled the detailed study of the pressure wave propagation. In these configurations the maximum distance between an electrical arc and the TP ranged up to 8.5 meters (28 ft). These tests were carried out to study the pressure wave propagation and to demonstrate the TP efficiency during a low impedance fault by measuring physical parameters such as pressure, gas temperature, applied current, arc voltage and tank acceleration.

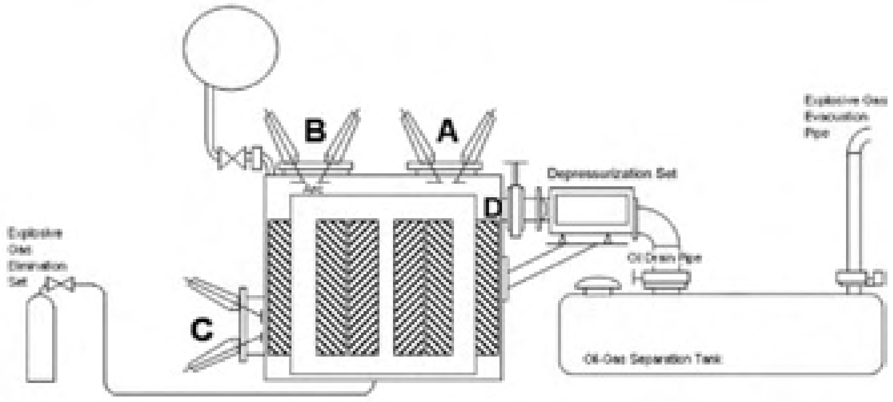


Figure 2: Life Tests Transformer Principle Drawings

3.1.1. Experimental Set

Each transformer was equipped with a standard TRANSFORMER PROTECTOR in which, contrary to what is shown on Figure 1, an Oil and Gas Separation Tank (OGST) was used instead of the conservator to collect the oil and flammable gases expelled out of the transformer after the TP operation (see Figure 2).

3.1.2. Experiments

To study in detail the pressure wave propagation influence, and to show that the TP reliability does not depend on the arc location inside the transformer tank, the electrical arcs were ignited at three different locations, as shown in Figure 2: on the top cover close to the Decompression Set location (position A), on the top cover opposite the Depressurization Set location (position B), and in the lower part of the tank opposite the Depressurization Set location (position C). Position C was the harshest position to test because it was far from the TP and near the windings, which prevented the pressure waves from easily propagating. Note that position D is shown in Figure 2, and is the location where the TP was installed.

Most of the tests were carried out with electrical arcs with currents ranging from 5 to 15 kA, and fed during 83 milliseconds. This duration corresponds to the average response time of an old circuit breaker and was chosen to maximize the generated gas volume.

3.2. Analysis: Generated gas

During the CEPEL test campaign, the electrical arc produced from 1 to 2.3 m3 (35 to 88 ft3) of gas. This volume is plotted as a function of the arc energy in Figure 3. The global trend (dotted curve) is drawn by the following equation:

$$V = 0.44\ln(E + 5474.3) - 3.8$$

where E is the arc energy and V the generated volume.

The gas volume generated during an electrical arc is thus a logarithmic function of the arc energy, which seems in accordance with the vaporization process and especially with the

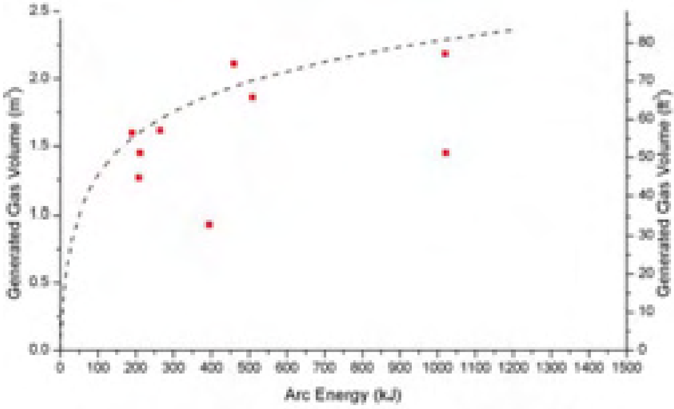


Figure 3: Generated gas volume v. arc energy

saturation of the vaporization for high energy arcs. Indeed, this saturation is due to the fact that, after the arc has vaporized, almost instantaneously an important gas volume, it stays in that volume using its energy to crack the oil vapor rather than continuing to directly vaporize the oil: this results in a smoother vaporization process. The first stage of the vaporization process is almost instantaneous and because of the oil inertia, the gas is very quickly pressurized, generating one important pressure peak that propagates in the oil. The tests showed that the arc energy does not have any clear influence on the pressure maxima detected in the bubble.

3.3. Analysis: Wave Propagation and Fluid/Structure Interaction

At the beginning of the process, when the arc occurs, the tank is sealed and the vaporization causes the bubble growth which generates a shock wave in the transformer.

3.3.1. Pressure

- Pressure Profile Evolution at a Single Location

The pressure in the transformer after an electrical arc has occurred is transient as shown in Figure 4, where an experimental curve is displayed.

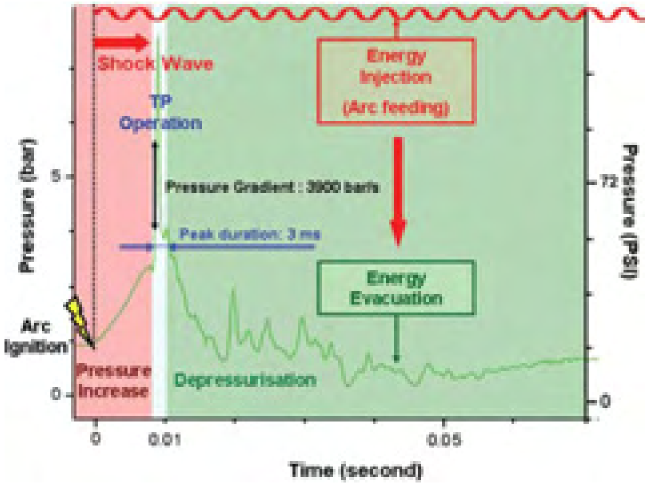


Figure 4: Pressure Evolution Close to the Arc Location after the Arc Ignition

The different phases are also detailed on this figure: after the arc ignition, the pressure locally rises and reaches a maximum level; the waves, generated by the arc, propagate at a finite speed through the transformer and interact with the TP with a pressure gradient of 3900 bar/s (56000 psi/s). Three milliseconds after the TP has activated, the pressure is back to the activation level. Some secondary peaks, much lower than the first pressure maximum, can be observed. They are due to wave reflections off the tank walls and reflected wave interactions.

As soon as the TP has activated, it can be noted that the arc can be fed for a period much longer than the standard opening time of a circuit breaker. Even in this severe condition, the pressure would remain at harmless levels for the transformer tanks.

- Local Pressure and Wave Propagation

The shock wave caused by the electrical arcing propagates in the tank. In Figure 5, experimental pressure profiles are displayed on the right and a simplified associated principle diagram on the left. Each curve shows what happens near each sensor located in positions A, B and C.

The displacement of the shock wave in the tank can thus be followed. The arc ignition located in C causes a high-pressure peak. The pressure waves propagate 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 proven that pressure is not spatially uniform in the tank, and that the pressure waves propagate at a finite speed.

3.3.2. Pressure Peaks and Tank Withstand

- Pressure Peaks

Only one main pressure peak has been noticed for each test. The pressure profiles show variations after that main peak but their magnitude remains low compared to the first pressure peak level.

Indeed, the initial energy transfer is almost instantaneous, and so is the phase change. The created gas has no time to expand and reach the pressure and temperature equilibrium with the surrounding oil. Because of the oil inertia, the gas gets very quickly under pressure, which generates the first very strong pressure waves.

As it is more difficult to vaporize a liquid than to crack oil

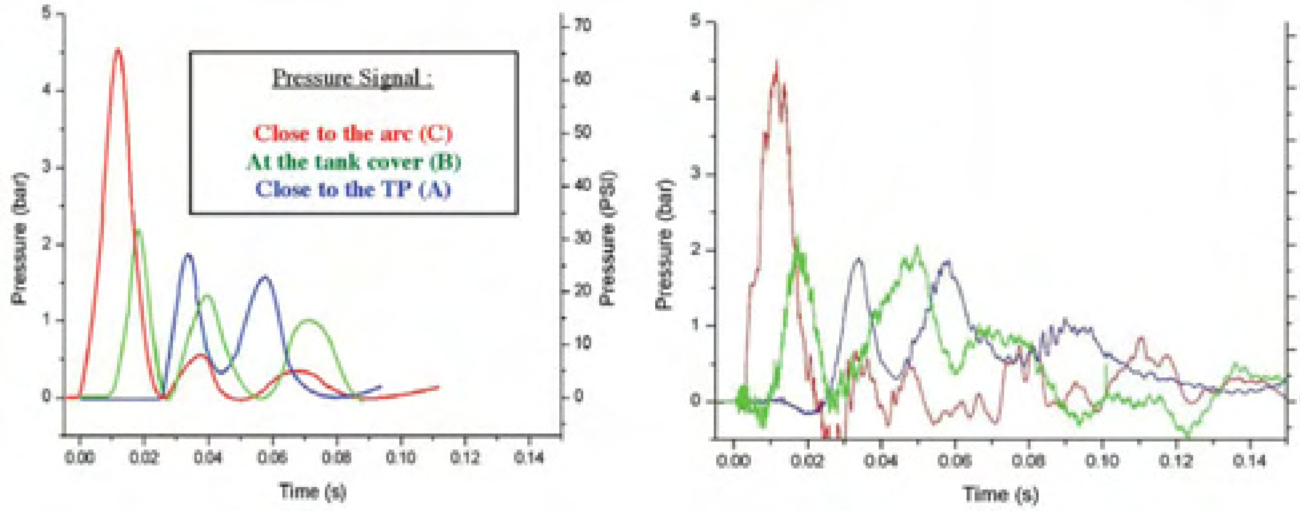


Figure 5: Pressure measurements model

vapor, the arc location would mainly remain in the gaseous phase after its ignition. The vaporization which happens after the gas bubble appearance is smoother and does not really generate physical conditions such as the ones in the very first instance of arc. The secondary pressure variations are thus the result of the overlapping waves and structure influence combined with the smooth gas generation influence on pressure.

Figure 6 shows that even if most of the pressure peaks are higher than the commonly admitted transformer withstand static overpressure limit of +1.2 bar (+17.4 psi), there was no tank rupture.

The pressure peaks' amplitude is determined by the created arc. The peaks range from +1.5 to +13 bar (+21.75 to +188.55 psi) for arc energies from 0.01 MJ to more than 2.4 MJ as shown in Figure 6. The maximum pressure seems to strongly increase with the arc energy while the energy remains in the low range. This dependence tends to weaken as the energy increases. The pressure rise is indeed the result of the strong oil vaporization that takes place in the arc very first moments, the energy transferred afterwhile having less impact on the pressure build-up. As an illustration, Figure 6 shows that when comparing tests for which pressure peaks respectively equal +8 bar (+116 psi) and +8.8 bar (127 psi), the maximum pressure only varies in 0.8 bar (11.6 psi) while the corresponding arc energies vary within on order 10 of magnitude (0.1 MJ and 1 MJ respectively). This is a very important statement when trying to extrapolate the pressure maximum for high energy arcs: according to the above data, the local pressure should remain in the pressure range experienced during the CEPEL tests.

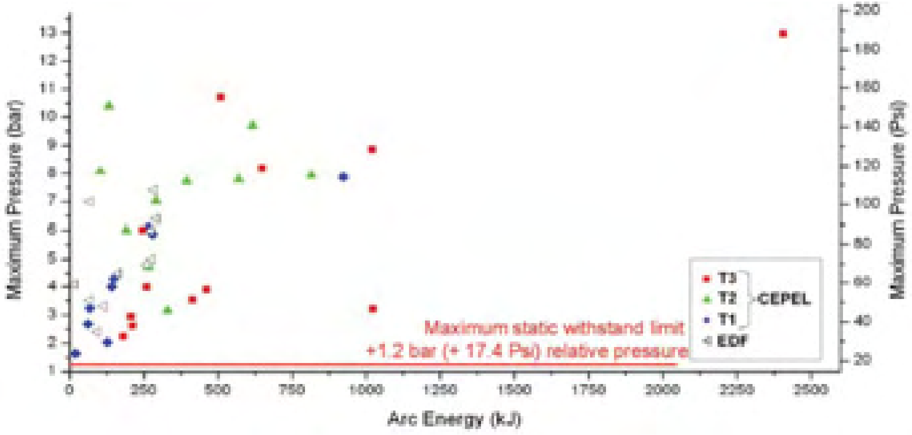


Figure 6 : Maximum relative Pressure close to the Arc v. Arc energy (reference pressure: atmospheric)

- Tank Withstand

To static pressure: To check the mechanical properties of the transformers, static tests were performed before applying any low impedance fault. The withstand limit was found to be +0.7 bar (+10.15 psi) for the biggest CEPEL test transformer, T3. Therefore, this limit (+0.7bar-+10.15 psi) has been used in this analysis as a threshold for the tank depressurization during the dynamic tests. As long as the average static pressure inside the transformer remains under this limit, the transformer is safe.

To dynamic pressure: Despite the fact that the local pressure measured during the dynamic tests is, on average, 6 or 10 times higher than the static withstand limit (Figure 6), no tank damage and no tank permanent deformation occurs because the pressure peaks are very short. In fact, the structure can locally withstand high dynamic pressure increases due to the elasticity of its walls and the TP small inertia to operate. If the pressure had remained above the static overpressure limit, the tank would have exploded.

3.4. TP Influence on the Pressure Evolution

3.4.1. Activation Time

The "activation time" is the addition of the following times:

- The "pressure wave transit time" is the time required from the arc ignition, for the shock waves to propagate and reach the TP;
- The inertia of the TP to operate;
- And the TP burst indicator signal delay.

On average, the TP has activated after about 20 milliseconds (minimum: 4.64ms, maximum: 45.7 ms) after the arc was ignited. Because the pressure wave propagation speed is finite, the maximum distance between the arc location and the TP is the parameter that matters the most for the TP to activate. In the worst situation, the arc occurs in the transformer's lower part opposite the Depressurization Set (location C, figure 9).

3.4.2. Depressurization Time

The depressurization time is the time between the TP Opening and when the pressure is definitely under the level of +0.7 bar (+10.15 psi). It is important to remember that the level of +0.7 bar corresponds to the static pressure limit where leaks appeared on the T3 transformer during the static pressure tests. On average, the TP depressurizes the tank in 116ms, with a minimum value of 19.7ms, and a maximum of 347ms. This experimentally proves the TP's ability to depressurize the transformer tanks within milliseconds and prevent the explosion. The previous experimental data and their analysis are very important in the numerical tool validation, which is the subject of the following sections.

4. NUMERICAL SIMULATIONS

4.1. Mathematical, Physical, and numerical Modeling

The set of equations used to theoretically and numerically describe the phenomena is a model for compressible two-phase flows that is based on a set of Partial Differential Equations (PDE), which governs the hydrodynamic behavior of mixtures. One of the major and most interesting model's charac-

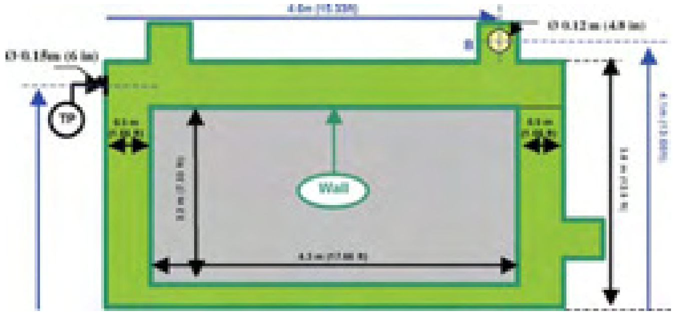


Figure 7: Boundary and Initial Conditions – T3 Transformer

teristics is its ability to accurately depict the pressure wave propagation inside liquids and gases. Physical effects such as gravity, viscosity, and heat transfers are added in the modeling in order to be as close as possible to reality. For the model to be complete and consistent, each phase is described by an equation of state that leads to theoretical sound speeds in agreement with the experimental ones.

A Finite Volume Method is thus adopted to numerically solve the PDE's system. It allows describing precisely complex geometries such as transformer tanks.

4.2. Validation against Experiments

In order to validate the presented mathematical method, numerical tests have been performed and compared to the experimental results. For this comparison, we focus on the most severe tests performed on the T3 transformer, which dimensions are similar to those of a 100 MVA transformer manufactured currently.

4.2.1. Experimental Tests for Comparison

Two experimental CEPEL tests (number 31 and 33) are analyzed here to compare numerical and experimental results. For both tests, the transformer is subjected to an 83ms arc occurring in position B, figure 8 with a maximal current peak of 30kA (nominal value 14kA) and a maximum voltage of 1kV. Test 31 considers a TP with a calibrated relative burst pressure of +1.5 bar (+21.75 psi) and with an outer reference absolute pressure of 0.1 bar (1.45 psi) while test 33 is performed using a TP with a calibrated relative burst pressure of +0.8 bar (+11.6 psi) and with an outer reference absolute pressure of 1 bar (14.5 psi).

4.2.2. Geometry, Initial and Boundary Conditions

The outer tank as well as the magnetic core dimensions are detailed in Figure 7.

The TP is numerically modeled and the calibrated burst pressure is set depending on the simulated test.

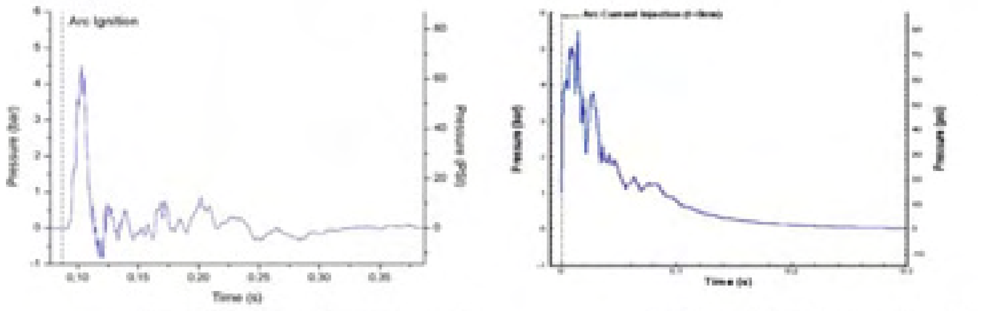
Experimentally, the arc vaporizes the oil and creates gas bubbles under pressure. In the initial state of the simulations we assume the gas bubble has already been created by the arc and the gas is already under pressure.

Thus, the gas bubble generated by the arc is located in the initial state in position B, figure 8. Pressure inside the gas bubble (4.3bar, 62.4psi) and the corresponding density (4.3 kg/m3, 0.27 lb/ft3) are determined according to the arc energy for each test. The arc characteristics are those of the corresponding experimental test.

Moreover, virtual pressure sensors are located in the simulation domain in order to compare the experimental pressure profiles to simulated ones. The results of this comparison are shown in Figure 8.

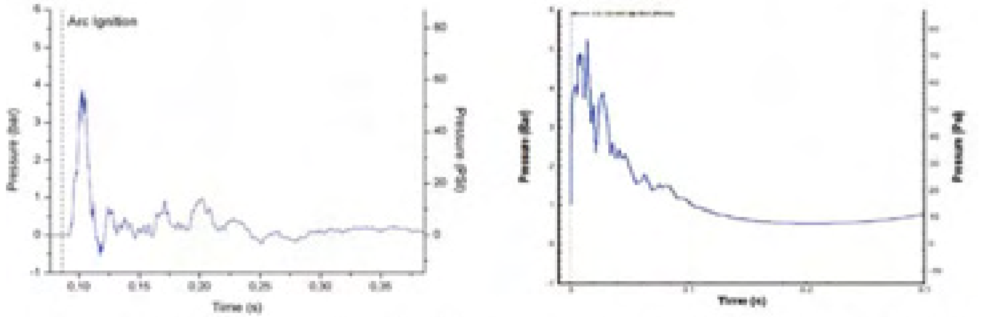
4.2.3. Experiment/Simulation Qualitative Comparison

Experimental and numerical results regarding the pressure time evolution are similar. In both cases, the three same



Test 31: Experiment – Pressure close to the arc

Test 31: Simulation – Pressure close to the arc



Test 33: Experiment – Pressure close to the arc

Test 33: Simulation – Pressure close to the arc

Figure 8: Geometry influence on pressure profiles

phases can be observed: a very sharp pressure rise following the arc ignition, a pressure drop because of the TP activation, and a phase where the pressure alternatively rises and decreases because of the complex wave dynamics due to the wave reflections off the transformer walls (cf. Figure 8). It can be seen that in both cases the pressure returns to the initial reference pressure.

In Figure 8 where numerical as well as experimental results are displayed, the experimental results are in accordance with the tendency exhibited in the previous sections. The simulated pressure profiles are very similar as well: even if the pressure maxima are not exactly the same, the chronology of the phenomena and the profile shapes are identical. These similarities between experiments and theory confirm the geometry influence on local pressure profiles. On each profile, we can also notice that the TP influence causes an inner tank average pressure decrease. The pressure oscillations are due to the pressure waves (rarefaction and compression waves) that propagate back and forth in the tank interacting with the tank structure.

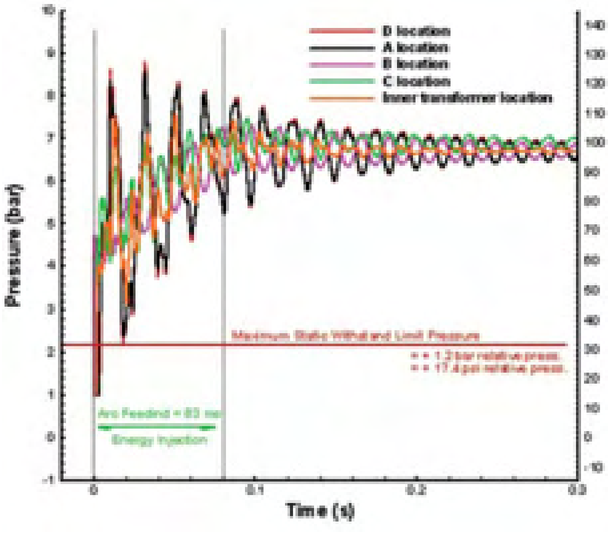


Figure 9: Pressure when the Tank is NOT equipped with the TP

4.3. Numerical simulation results

Simulations manage to give results in accordance with the experimental results, for a relatively low cost and without any danger. They were thus used here to compute the consequences of an electrical arc appearing in a tank not equipped with a TP and also to compute the TP operation on a very large transformer.

4.3.1. What would happen without TP?

Experimental testing would be dangerous if the transformer were not protected by a TP, so numerical simulations were performed instead. Figure 9 shows pressure evolutions computed for a geometry and for arcing conditions similar to those of the CEPEL test 31 (Figure 8). It shows that, after the arc feeding, the average pressure remains close to an equilibrium state equal to 7 bar (100 psi), much higher than the static withstand limit pressure.

Thus, during test 31, if the transformer had not been equipped with the TP, the inner average pressure would have risen up to the static overpressure withstand limit. The transformer would have exploded as soon as the tank wall elasticity limits were over, i.e. as soon as the tank walls could not store any more mechanical energy due to the pressure increase.

Geometry and Numerical Parameters:

The 750 MVA transformer dimensions are displayed in Figure 10. The studied configuration corresponds to the worst case where the electrical arcing is ignited in location C, figure 9, where the gas bubble appears. The maximum distance between the TP and the arc ignition is the key-parameter. In the case of the CEPEL tests, for T3 transformer, the biggest of the three, this distance was 8.5 m (28 ft). In the case of this 750 MVA transformer geometry, this distance is about 15 m (49 ft), twice the distance considered in the case of T3 transformer. In conclusion, the extrapolation is only of an order of 2, instead of an order of 37. The RD calibrated static pressure is set at +1.2 bar (17.4 psi).

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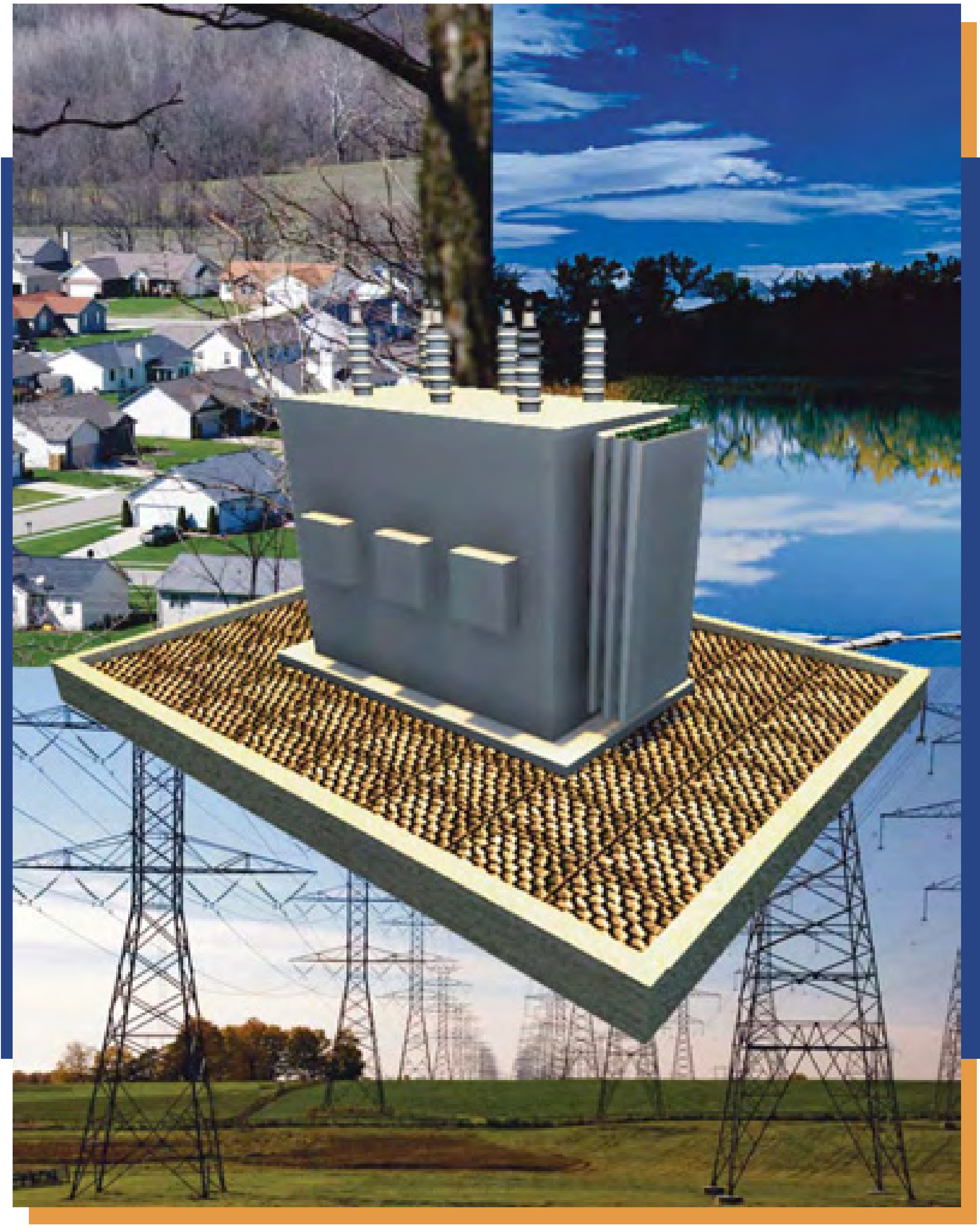

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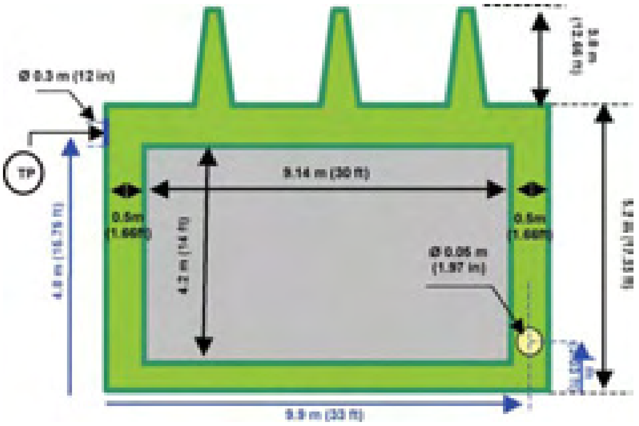

Figure 10: Initial and boundary conditions, pressure sensors locations

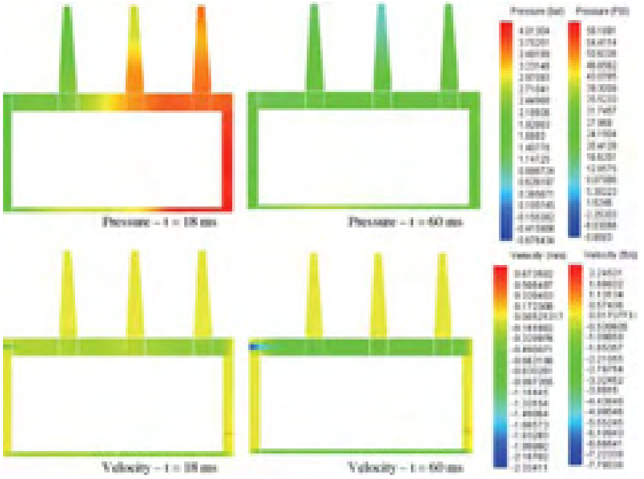

Figure 11: TP behavior – 750 MVA, 70 ms, 70 kA, C

Results:

A 70 kA arc is applied to the system for 70 ms, which is illustrative of harsh fault conditions. The maximum pressure reached and recorded during this simulation is higher than 5.5 bar (80 psi) in one of the bushings and 4.2 bar (61 psi) close to the arc. The major value in the bushing is due to its geometry (wave-guide). The time for the wave to be propagated from the arc to the TP is 13.86 ms.

The depressurization time is 60 ms, which is very acceptable for such a tank size. The pressure repartition informs us about the way the wave concentrated in any locations into the tank. The Figure 11 shows the interaction of the pressure wave with the TP after 14 ms. After 60 ms, the TP almost decreases the pressure under the 0.7bar (10.15 psi) level in the entire tank, even if the electrical arcing is still supplied (pressure rise close to the bubble location). Even with a higher current (70 kA instead of 15 kA for CEPEL tests) applied for 70 ms, the TP succeeds in depressurizing the tank in a few milliseconds since the pressure remains under the average withstand limit of the structure.

5. CONCLUSION

An essential step for SERGI is to show the TRANSFORMER PROTECTOR efficiency for all transformers and all types of rupture of insulation. Its research program philosophy is thus to maintain a strong connection between experiments and the theoretical developments:

- 34 experimental tests under severe low-impedance faults were performed in the CEPEL Laboratory. They showed that during a transformer short circuit, the TRANSFORMER PROTECTOR (TP) is activated within milliseconds by the first dynamic pressure peak of the shock wave, before static pressure increases, thus preventing the transformer tank rupture;
- In addition, a complete numerical tool was developed in order to describe compressible two-phase flows, the pressure wave propagation inside liquids and gases, and to simulate the TP depressurization process. This tool was validated using comparisons with the experimental data.

Furthermore, results from the simulations show that:

- if the same arcing conditions as during the CEPEL tests had been applied to a transformer not equipped with a TP, the tank would have been subjected to static pressure up to 7 bars to which it would not have been able to resist;
- The TP is efficient to quickly depressurize large transformers (up to 10m / 33ft long) subjected to severe electrical fault conditions and to prevent the transformer tank explosion.