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Tank Rupture Resistance

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SUMMARY

Power transformer and reactor tanks are generally designed to withstand vacuum filling, transportation loads and are occasionally optimized for seismic events. However, they are not designed as pressure vessels. As such, transformer and reactor tanks may rupture from an overpressure inside the tank, often caused by an internal arcing event.

There are multiple consequences resulting from a ruptured transformer or reactor tank. These consequences include environmental pollution from leakage of the insulation oil and irreparable damage to the substation or power plant caused by the subsequent fire. Furthermore, substation or power plant personnel present during a rupture event may be critically injured.

A transformer or reactor tank will generally withstand pressures of between 1.4 bar and 2 bar. However, in case of an internal flashover event the generated gas can raise the internal pressure to above 7 bar, depending on the size of the tank. In such situations only an optimized tank is able to withstand these significant overpressures.

To increase the safety of power transformers and reactors SIEMENS, together with external partner CADFEM, have developed a static method to optimize the geometry of the tank. This optimization is conducted numerically through a finite element analysis. The methodology also accounts for the withstand requirements of each individual unit by relating the arc energy to the transformer or reactor's voltage class. In addition to the static simulation procedure, SIEMENS have also begun developing dynamic simulations based on experimental results from 6.8 MVA distribution transformers. It is anticipated that accurate dynamic simulations will allow for a greater understanding of the tank's dynamic response during overpressure events and may be used to modify and validate the static simulation procedure.

This paper describes the methodology to obtain an optimized tank design and details both static and dynamic simulation procedures. Furthermore, results illustrated in this paper show that employing alternative insulating liquids, such as synthetic ester, adds an additional safety margin to the energy levels required to rupture the tank. This is due to the 20% to 30% decrease in the gas conversion factor exhibited by alternative insulating fluids, which results in an equivalent arc energy level producing less gas and therefore lower pressures within the tank.

KEYWORDS

TANK RUPTURE, FINITE ELEMENT METHOD, DYNAMIC SIMULATION, STATIC SIMULATION

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I. INTRODUCTION

The significant damage and economic costs that result from a power transformer or reactor tank rupture event have led to the development of numerous rupture protection devices. Such devices commonly employed to prevent rupture include real time gas monitors, gas detector relays, rapid pressure rise relays and pressure relief devices. However, these measures are often expensive, require regular maintenance and/or are inadequate.

In order to meet the significant safety demands placed on transformer and reactor designs by customers, SIEMENS together with external partner CADFEM, have created an ANSYS Workbench based simulation to calculate and modify the rupture withstand capabilities of transformer and reactor tanks. The procedure developed allows for the optimal balance between stiffness and flexibility to be achieved. Furthermore, the methodology does not comprise the structural integrity of the tank with regards to vacuum oil filling, transportation and seismic withstand capabilities.

This paper will detail the key theoretical concepts underpinning the tank rupture calculations. Subsequently, both static and dynamic simulation procedures will be discussed in detail. The paper will also illustrate the effect of different insulating liquids on the withstand capabilities of transformer and reactor tanks.

II. SIMULATION BASICS

A. Formula to calculate the arc pressure

Significant overpressures occurring inside a transformer or reactor tank are the result of internal arcing events. A key parameter required to simulate a tank rupture event is therefore the pressure generated by the arc. The principal work carried out to determine the pressure ensuing from internal arcing is provided in the Cigre paper "*Guide For Transformer Fire Safety Practices*", and the relationship is given as [1][2]:

$$P_s = F\left[100\sqrt{\frac{1}{4}+\frac{kE}{100C}} - 50\right] \qquad \text{(EQN. 1)}$$

Where:

- P_S = specified pressure (kPa)
- k = arc energy conversion factor (m^3/kJ)
- E = arc energy to be contained (kJ)
- C = volumetric flexibility of the tank (m^3/kPa)
- F = dynamic amplification factor

B. Choosing the arc energy level

As shown in Eqn. 1, the specified pressure a transformer or reactor tank must withstand to avoid a tank rupture event is directly related to the energy generated by the internal flashover event. The Cigre Working Group A2.33 has therefore established the relationship between the voltage class of a unit and the arcing energy it is likely to produce. Table 1 reproduces the relationship between the voltage class and arc energy as detailed in "*Guide For Transformer Fire Safety Practices*" [1][2].

TABLE 1 RELATIONSHIP BETWEEN ARC ENERGY AND VOLTAGE CLASS [1][2]

Voltage Class (kV)	Arc Energy (kJ)
72.5	2,000
145	4,000
170	4,000
245	8,000
330	20,000
765	20,000

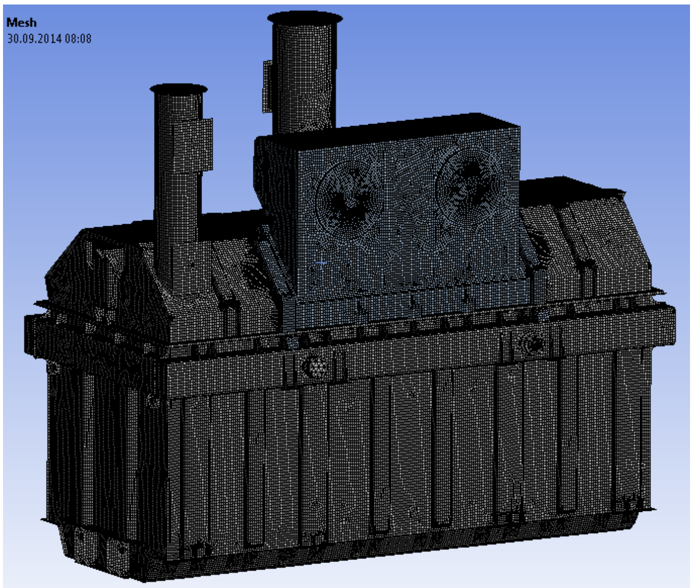
III. SATIC SIMULATION PROCEDURE

A static simulation refers to an analysis under static loading conditions and provides results when the system reaches steady-state conditions. In the static tank rupture simulation the applied pressure is distributed evenly over all the surfaces directly in contact with the insulation oil. This allows for an optimization of the complete tank, disregarding the specific location at which the internal arc is likely to occur. To simulate a local pressure rise in the tank a dynamic simulation would have to be conducted, which is further discussed in Section IV of this paper.

A. Geometry and boundary conditions

The geometry employed in the simulation is a simplified ProEngineer/Creo model with items considered non-essential to the structural integrity of the tank removed. In order to reduce the number of nodes in the finite element model and hence reduce the simulation time midsurface modelling is used as opposed to three-dimensional solid elements. An example of a discretised, simplified transformer tank to be employed within a tank rupture simulation is shown in Figure 1.

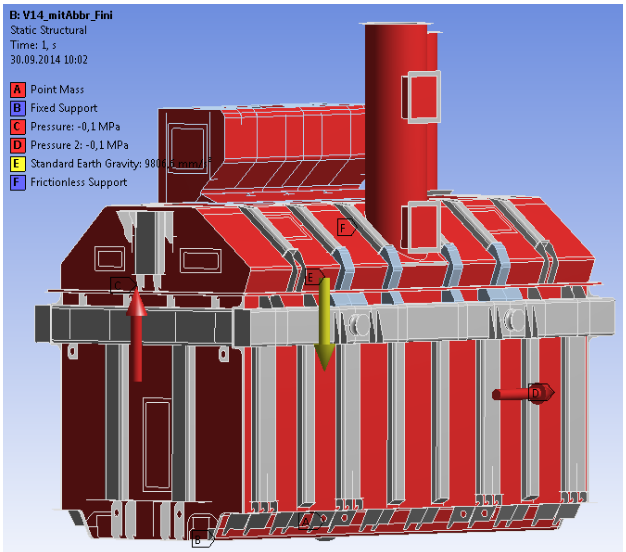
FIG. 1 EXAMPLE OF A MESH FOR STATIC TANK RUPTURE SIMULATION - CONTAINING ABOUT 300,000 NODES



The support of the tank in the simulation is dependent in the physical positioning of the transformer or reactor unit during operation. Such constraints that may be simulated include: welded foundations; bolts; and units standing on wheels. An elastic support may also be employed to simulate an installation on rubber.

To account for the active part in the simulation a point mass with a weight equivalent to that of the core and windings is included. This point mass is attached to floor of the unit or to the oil channel, depending on the design of the transformer or reactor being simulated. An example of the boundary conditions applied to the simplified transformer tank during a static tank rupure simulation, including the pressure distribution, is illustrated in Figure 2.

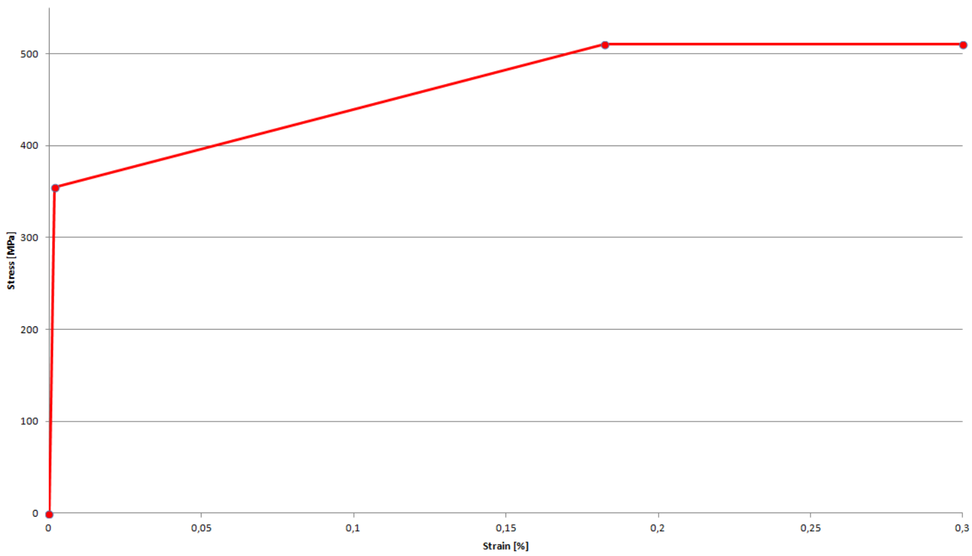
FIG. 2 EXAMPLE OF BOUNDARY CONDITIONS USED IN STATIC TANK RUPTURE SIMULATION



B. Material properties

The rupture withstand capabilities of a transformer or reactor tank are dependent on the materials used to construct the tank. It is therefore necessary to accurately model a tank's mechanical properties within the simulation. To assess a tank's ability to withstand overpressures, the correct values for each component's yield stress, fracture strain and ultimate strength must be employed. Therefore, a *multilinear kinematic hardening plasticity model* is employed within the simulation, as illustrated in Figure 3. This allows for the accurate depiction of both the elastic and inelastic deformation experienced by the structural components as a result of the pressure applied to the tank's inner surfaces.

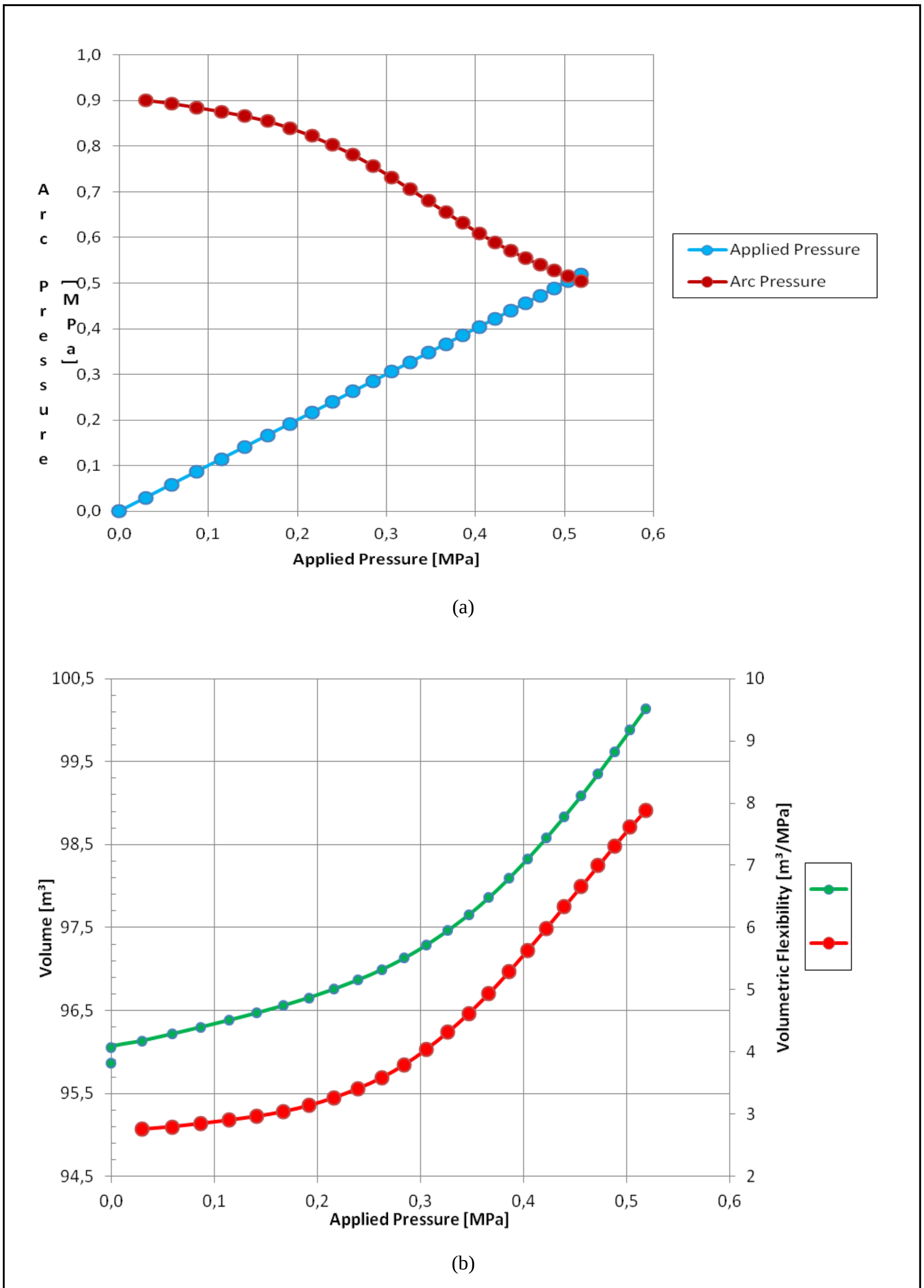
FIG. 3 MULTILINEAR KINEMATIC HARDENING PLASTICITY STRESS-STRAIN CURVE FOR MILD STEEL USED IN THE TANK RUPTURE SIMULATION



C. Pressure, volume and volumetric flexibility

To simulate the rupture withstand capabilities of a transformer or reactor tank the applied pressure is incrementally increased at each iteration step. This results in an expansion of the tank and allows for the volumetric flexibility of the vessel to be determined, which can subsequently be employed in accordance with Eqn. 1 to calculate the specified arc pressure. The pressure is increased in the finite element analysis until the applied pressure is equal to or greater than the pressure ensuing from an internal arcing event. At this point the rupture withstand capabilities of the tank may be assessed. Graphical illustrations of the iteration steps carried out within the finite element analysis are presented in Figure 3.

FIG. 3 (A) ARC PRESSURE VS. APPLIED PRESSURE AND (B) VOLUME VS.APPLIED PRESSURE VS. VOLUMETRIC FLEXIBILITY AT EACH ITERATION STEP

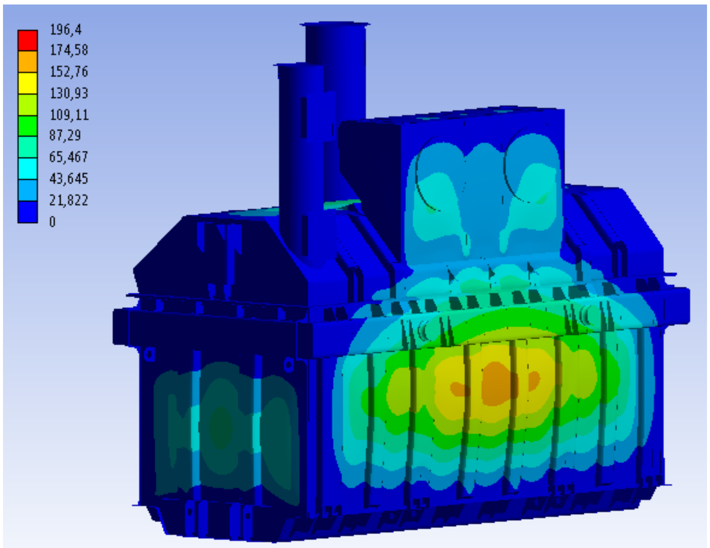


D. Results verification and optimization

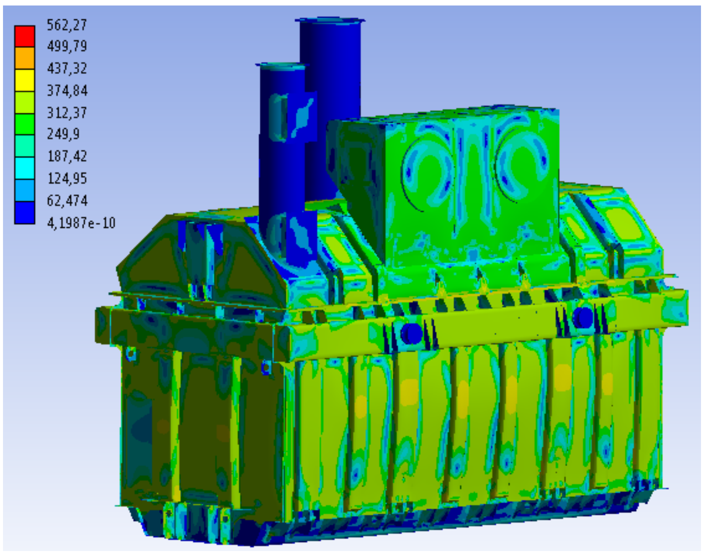
The final iteration of the simulation, at which point the pressure applied to the tank is equal or greater than to the pressure resulting from an internal arcing event, provides the tank rupture withstand capabilities of the transformer or reactor unit. It is therefore at this step in the simulation that the tank must be analysed. Results that may be deduced from the simulations include the deformation and the stress distribution over the tank, as illustrated in Figure 4. However, it is the analysis of the strain on the tank's components, as shown in Figure 5, which is vital to ensuring that the tank is able to withstand the arc pressure. Areas of strain exceeding the fracture strain of the material indicate a unit's susceptibility to rupture during an internal flashover.

If there are areas with higher strain than the fracture strain, the design must be altered and the simulation rerun. This optimization process to ensure that the tank is able to withstand the energy of an internal arc is time consuming. However, the experience gained from these simulations and knowledge of tank geometries susceptible rupture may be utilized in designing future tank, thereby increasing the safety of all units.

FIG. 4 EAMPLES OF (A) THE TOTAL DEFORMATION AND (B) THE EQUIVALENT STRESSES OCCURING ON THE TRANSFORMER TANK AT THE CALCULATED ARC PRESSURE

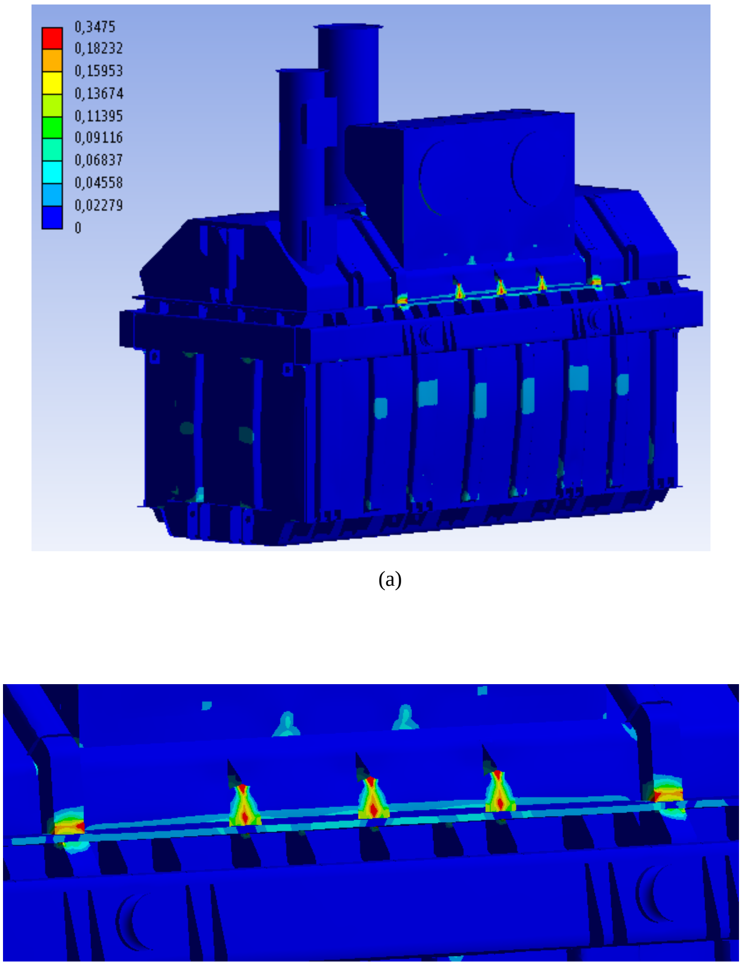


(a)



(b)

FIG. 5 (A) EAMPLE OF THE STRAIN ON A TRANSFORMER TANK COMPRISING OF MILD STEEL AND STAINLESS STEEL PARTS AND (B) DETAIL OF STRAIN ON THE TANK



(a)

(b)

IV. DYNAMIC SIMULATION PROCEDURE

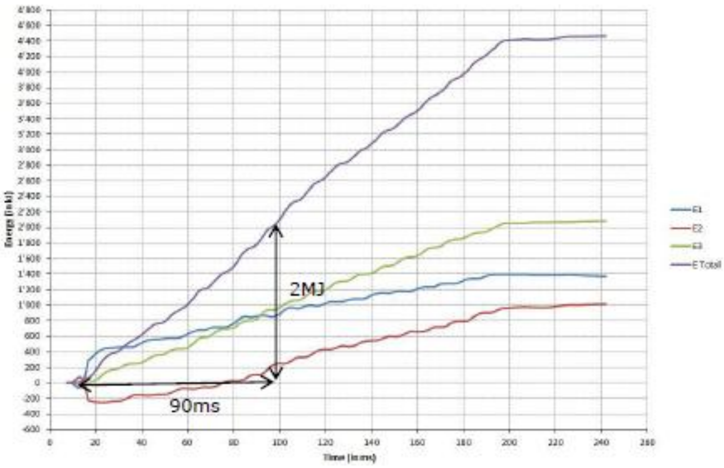
As stated in Section III, a dynamic simulation procedure is required to simulate the local pressure rise in a transformer or reactor unit resulting from an internal arcing event. SIEMENS have recently performed several physical tank rupture tests to understand how this event may be accurately simulated. Both physical and numerical procedures and results are further detailed in the following sections.

A. Physical testing

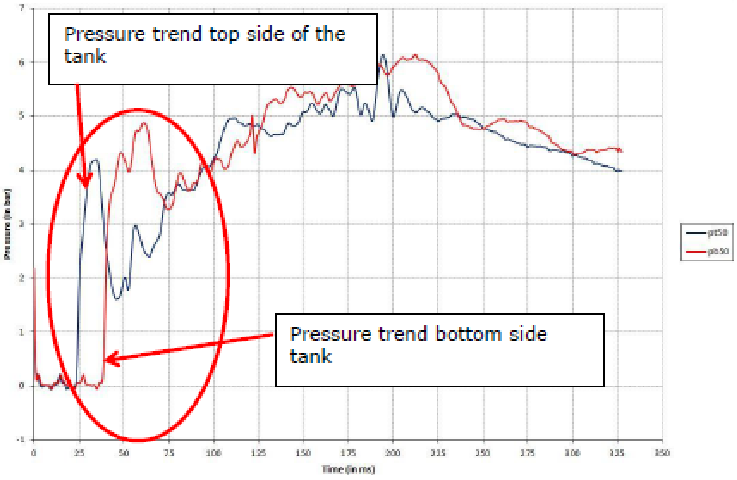
Physical tests to better understand the dynamic behaviour of tank rupture events have been carried out by creating a short circuit between two phases on 6.8 MVA distribution transformers. More recently these tests have also been conducted on larger units. The tests have primarily measured the increase in internal pressure within the tank and the arcing energy required to create this pressure rise. The 6.8 MVA unit on which the majority of tests have been conducted and key results from the physical tests are illustrated in Figure 6.

FIG. 6 (A) 6.8 MVA UNIT EMPLOYED FOR RUPTURE TESTING AND (B) ENERGY MEASUREMENTS AND (C) PRESSURE MEASUREMENTS TAKEN DURING TESTING

(a)



(b)



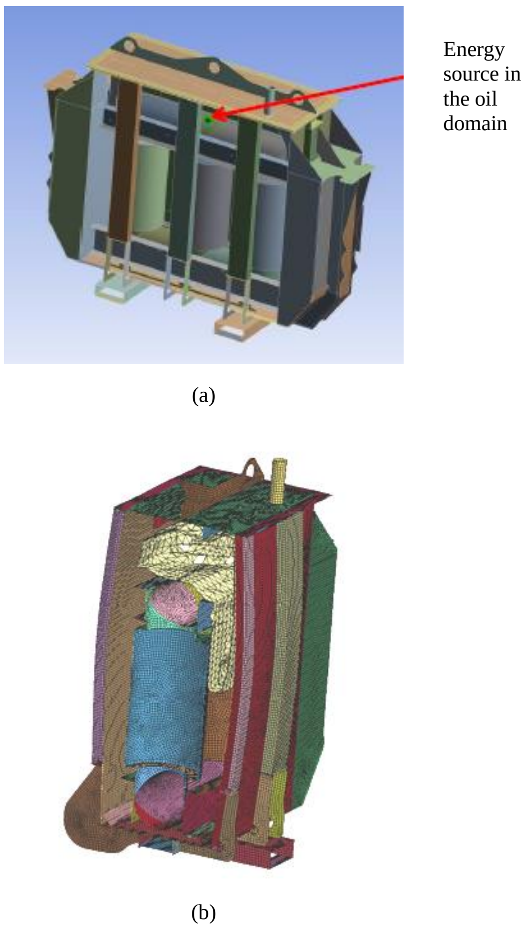
(c)

B. Dynamic simulations

Based on physical test results the ANSYS LS-DYNA software package has been selected as the preferred tool to simulate the dynamic tank rupture event. This software allows for the tank's response to short-duration severe loading, as experienced during an internal arcing event, to be simulated and analysed. It is anticipated that accurate simulations will allow for a greater understanding of the tank's dynamic response during overpressure events and may be used to modify and validate the static simulation procedure.

Figure 7 illustrates the placement of the energy source within the oil domain of the transformer during the dynamic simulation. The calculation simulates only the initial 90 ms of the internal arcing event, which contains 2 MJ of energy as shown in Figure 6 (b), as afterward this point there are only static pressure and energy increases. The resulting deformation of the tank from the supplied energy is seen in Figure 7 (b).

FIG. 7 (A) APPLIED ENERGY SOURCE IN THE TANK AND (B) DEFORMED TANK WITH GAS BUBBLE AFTER 90MS



C. Results from dynamic investigations

It must first be noted that the 6.8 MVA distribution transformer employed to compare physical and numerical results was filled with synthetic ester insulation fluid, as opposed to mineral oil. The flash point of synthetic ester is higher than that of mineral oil, at 260 °C in comparison to 147 °C. However, the gas conversion factor, denoted as k in Eqn. 1, of the synthetic ester fluid was unknown. The static simulation was therefore run with the k factor adjusted such that the simulated pressure at a specified arc energy matched the value recorded during physical testing. This resulted in a reduction of the gas conversion factor from 5.8×10^{-4} m³/kJ for mineral oil to 4.06×10^{-4} m³/kJ for synthetic ester, signifying a significant decrease in the likelihood of critical overpressures in ester filled tanks [3].

The second result of note from the dynamic investigations was that the energy applied to the dynamic simulation had to be reduced from 2.0 MJ, as applied during testing, to 0.5 MJ. This reduction in the applied energy was required in order for the simulated pressure to correspond to the pressure measured during testing. It can therefore be concluded that only approximately 25% of the electrical energy in an internal arc is transformed into mechanical energy that deforms a transformer or reactor tank [4].

The final significant result to date is that a direct comparison of static and dynamic simulations illustrates that the static calculation is the more conservative of the two cases [3][4]. This is likely a result of the uniformly applied pressure to all surfaces of the tank, as opposed to a local pressure rise. It is therefore probable that tanks which have been optimized through the static simulation process will exhibit tank rupture withstand capabilities in excess of those specified.

V. CONCLUSION

The tank rupture of power transformer and reactor units, resulting from an arcing fault, usually leads to significant safety risks and economic loss. The methodologies presented in this paper therefore focus on both static and dynamic simulations that may be conducted to determine and optimize the tank rupture withstand capabilities of specific transformer and reactor units.

Details provided within this paper have illustrated that the static simulation, through the uniform distribution of pressure to all surfaces in contact with the insulation fluid, provides an optimized design of the entire tank. However, such simulations do not account for the duration and the initial location of the arcing event. This is in contrast to the dynamic simulations, which provide extremely detailed results; however, focusing on a specific arcing location makes it difficult to optimize the entire structure.

The direct comparison of static and dynamic simulations has illustrated that the static calculation is the more conservative of the two cases. Therefore, transformer and reactor tanks which have been optimized through the static simulation process will likely exhibit true tank rupture withstand capabilities in excess of those specified. Furthermore, investigations into the dynamic response of transformers and reactors to overpressures have shown that employing alternative insulating liquids, such as synthetic ester, adds an additional safety margin to the energy levels required to rupture the tank. This is due to the 20% to 30% decrease in the gas conversion factor exhibited by alternative insulating fluids.

End of text

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