Tank depressurisation

Successful operation during short circuit on a 400 MVA transformer during operation and comparison of parameters recorded during transformer internal arcing event with computational simulations

ABSTRACT

This paper analyses the activation of two mechanical depressurisation devices, the transformer protector (TP), a leading example of a fast tank depressurisation technique (FTDT) and the pressure relief valve (PRV) during an internal arc on a transformer installed at the JSC RusHydro Boguchanskaya Hydro Power Plant, located in Krasnoyarsk Krai, Russia. The incident occurred on a 400 MVA three phase transformer on the 3rd May, 2013. Using all the available data, including SCADA records, dissolved gas analysis and voltage/current measurements, computational simulations were performed to study the dynamic pressure evolution and static pressure build up inside the tank. Simulation results on tank protections were analysed in the context of general arcing events. This incident demonstrates that the first dynamic pressure peak due to the arc quickly activates the FTDT, while the PRV activates with static pressure only.

KEYWORDS

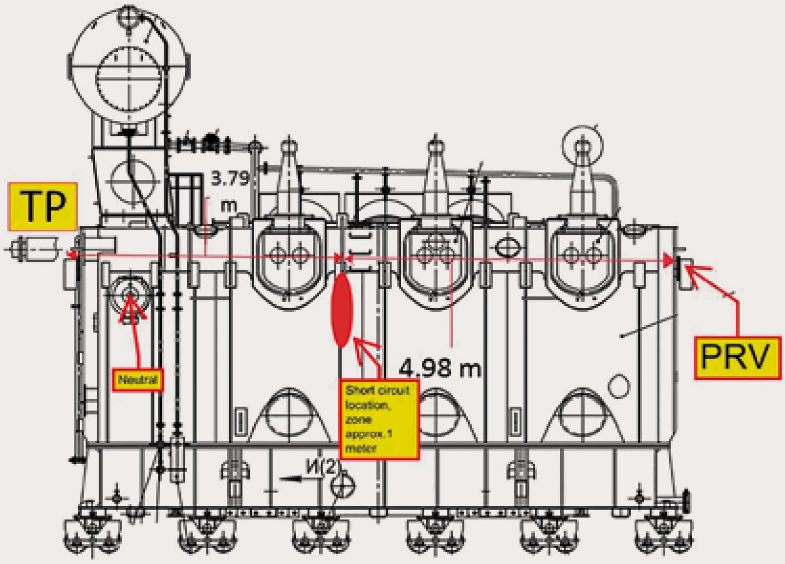
tank depressurisation, transformer protector, pressure relief valve, computational fluid dynamics (CFD)

Introduction

On the 3rd May, 2013, a fault occurred on a transformer installed at the JSC RusHydro Boguchanskaya Hydro Power Plant, located in Krasnoyarsk Krai, Russia. The incident occurred on phase B of the transformer T2 which is a three-phase transformer manufactured on the 26th June, 2008, and in operation since the 11th May, 2012.

T2 has a nominal capacity of 400 MVA but was operating at 360 MVA. A schematic of the transformer can be observed in Figure 1. Transformer T2 was equipped with a TP and a PRV. During the investigation, it was observed that the transformer differential protection, the Buchholz relay, the PRV, and the TP were activated.

> **During the investigation, it was observed that the transformer differential protection, the Buchholz relay, the pressure relief valve and the transformer protector were activated**



Analysis of the event

A) SCADA

According to the SCADA data in Table 1, the transformer differential protection registered a signal at 19:08:57.110 through a warning associated with its 220 kV windings. However, the transformer protector activation signal was first registered 27 ms prior. Because the TP activation must succeed the fault, the fault is estimated to be at 19:08:57.078, roughly 5 ms prior to the TP activation. Therefore, the transformer differential protection signal was registered 32 ms after the estimated fault origin. The PRV activation signal was detected 71 ms after the estimated fault origin. Finally, the circuit breaker fully open signal was detected 97 ms after the estimated fault origin.

Due to some contradictory data between the oscillograph voltage and current measurements and the SCADA described in the 'Short circuit energy' section of this paper, we have doubts regarding the ability of the SCADA to timely follow all events.

Table 1: SCADA list of events

Time	Events	Pressure Calibration	Time after estimated short circuit origin (milliseconds)
19:08:57.078	Estimated Short Circuit Origin (Currently Under Investigation)		0
19:08:57.083	**TRANSFORMER PROTECTOR ACTIVATION**	**1.2 bar Atmospheric, 17.63 psi**	**5**
19:08:57.110	Transformer Differential Protection		32
19:08:57.149	Pressure Relief Valve Operation	0.8 bar Atmospheric, 11.75 psi	71
19:08:57.175	Circuit Breaker Fully Open		97

> **Observed failure traces helped to locate the short circuit in the B phase of the high voltage windings. The arc length was estimated by the transformer manufacturer to be 1 m long by locating burnt sections of the windings**

B) Short circuit location

The short circuit location was identified, among other factors, by burnt cardboard insulation (Figure 2) as being associated with the B phase of the high voltage windings (Figure 3). The arc length was estimated by the transformer manufacturer to be 1 m long by locating burnt sections of the windings.

Figure 2: Burnt cardboard insulation

Figure 3: Location of short circuit

Dissolved gas analysis

In Table 2, we see the dissolved gas analysis for the transformer T2. Using the data associated with the date 03.05.13, we may characterise the fault.

The DGA suggests that the arc may be classified as D2, which corresponds to a high energy arcing event. Because the lines do not strictly intersect, further validation would be useful. An alternative classification system, known as the Rogers' Ratio, is defined in an IEEE standard, shown in Table 3 [1].

Based on Tables 2 and 3, we determine the following gas ratios:

$$\frac{C_2H_2}{C_2H_4} = R_2 = 0.8326 \qquad \frac{CH_4}{H_2} = R_1 = 0.6089 \qquad \frac{C_2H_4}{C_2H_6} = R_3 = 5.241 \quad (1)$$

Table 2: Dissolved gas analysis for transformer T2

Analysis date	H2 Hydrogen	CH4 Methane	C2H4 Ethene	C2H6 Ethane	C2H2 Ethyne	CO2 Carbon Dioxide	CO Carbonic Monoxide	O2 Oxygen	N2 Nitrogen	Total gas content
Boundary Concentration %	0,01	0,01	0,01	0,005	0,001	0,2	0,05			2
28.1.2013	0,00024	0,00004	0,00002	0,00003	Absent	0,0066	0,0028	0,0147	0,3204	0,34
3.5.2013	0,0777	0,04731	0,0873	0,00818	0,07269	0,0132	0,0161	0,0901	1,749	2,16
Relative Concentration	6,96	4,24	8,49	1,62	68,26	0,02	0,26			
V Relative % Month	9880	36176	133592	8316		31	147	157	137	

Gas Concentration %

Table 3: Rogers' Ratio interpretation method

Case	C2H2/C2H4 (R2)	CH4/H2 (R1)	C2H4/C2H6 (R3)	Suggested Diagnosis
0	R2 < 0.01	R1 < 0.1	R3 < 1.0	Normal
1	R2 >= 1.0	0.01 <= R1 < 0.5	R3 >= 1.0	Low Energy Discharge
2	0.06 <= R2 < 3.0	0.01 <= R1 < 1.0	R3 >= 2.0	High Energy Discharge
3	R2 < 0.01	R1 > 1.0	R3 < 1.0	Low Temperature Thermal
4	R2 < 0.10	R1 > 1.0	1.0 <= R3 < 4.0	Thermal < 973 K
5	R2 < 0.2	R1 > 1.0	R3 >= 4.0	Thermal > 973 K

Interpretation of dissolved gases by Rogers Ratio method and Duval triangle indicated a high energy arcing event

Using Table 3, we may characterise the fault as a high energy arcing event. The IEEE standard defines arcing temperatures as being between 700 K and 1800 K. The confirmation from the Duval algorithm suggests that the temperature is near or in excess of 1800 K, Figure 4.

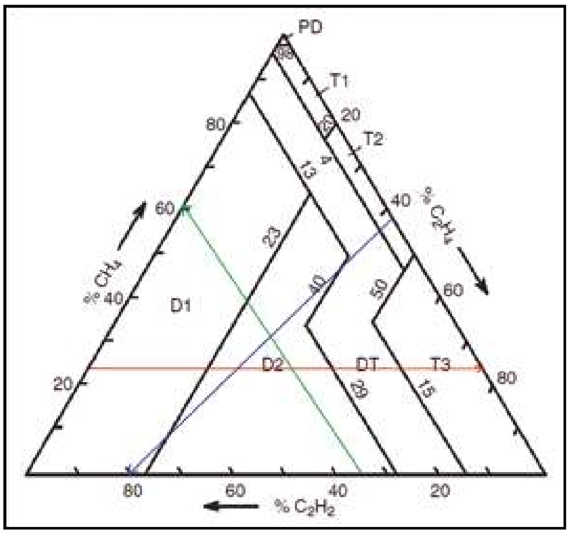


Figure 4: Duval triangle for dissolved gas analysis

Short circuit energy

The arc energy is defined in terms of the voltage (U), current (I), and time (t) as follows:

$$E = \int_0^T UIdt \qquad (2)$$

In Figure 5 we see the electrical measurements taken 2 ms prior to the short circuit. This information will be used as it is the closest set of measurements acquired to the fault.

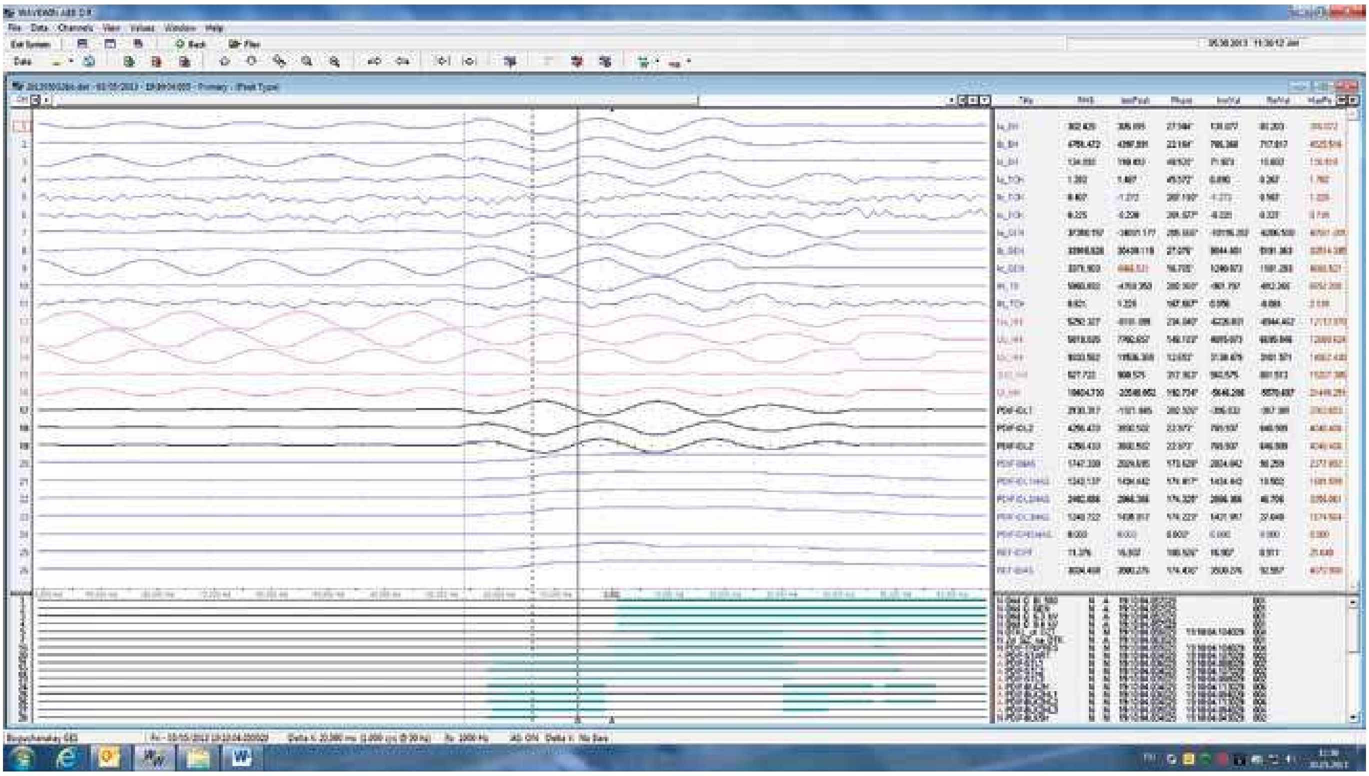
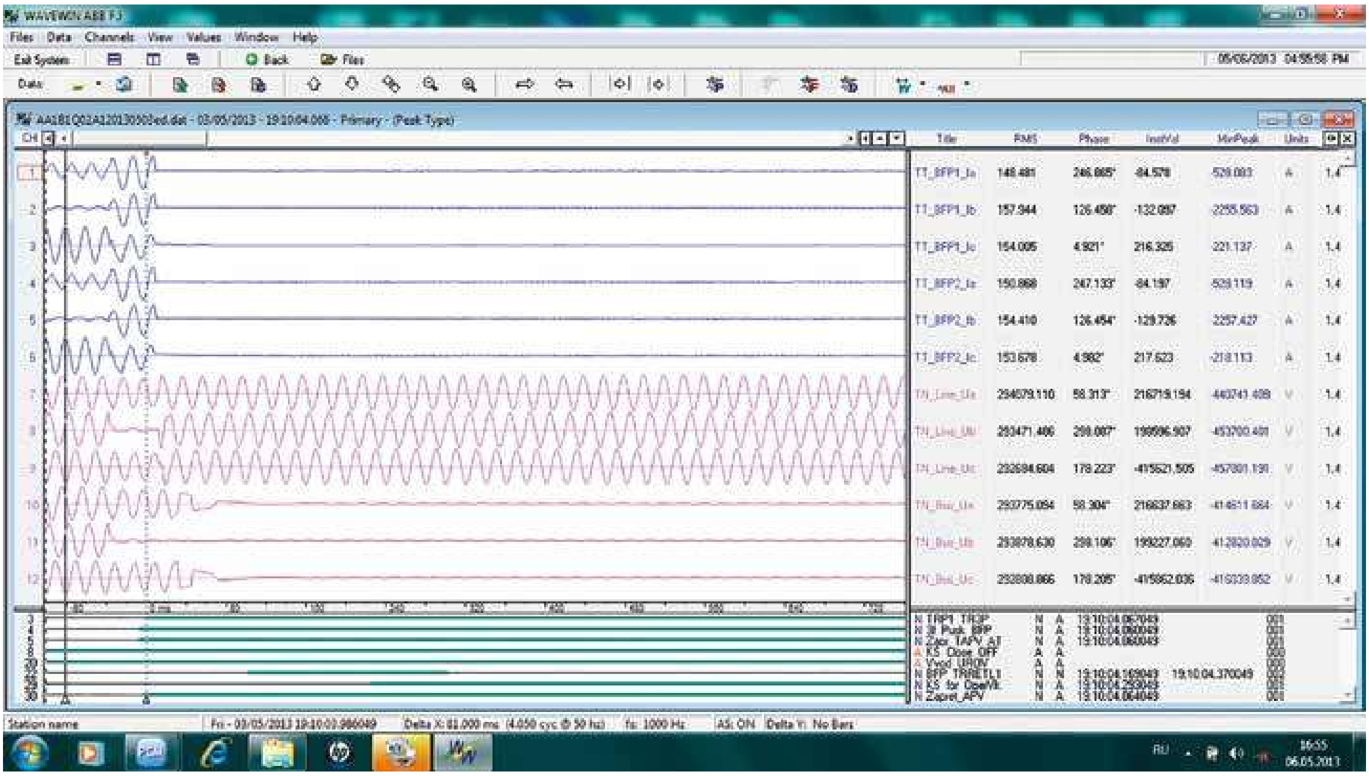


Figure 5: Display of electrical measurements during 2 ms prior to the short circuit



Title	RMS	Phase	InstVal	MinPeak	Units	
TT_BFP1_Ia	148.481	246.865°	-84.578	-528.003	A	1.4
TT_BFP1_Ib	157.944	126.458°	-132.097	-2255.563	A	1.4
TT_BFP1_Ic	154.006	4.921°	216.326	-221.137	A	1.4
TT_BFP2_Ia	150.868	247.133°	-84.197	-528.119	A	1.4
TT_BFP2_Ib	154.410	126.454°	-129.726	-2257.427	A	1.4
TT_BFP2_Ic	153.678	4.982°	217.623	-218.113	A	1.4
TN_Line_Ua	294079.110	58.313°	216719.194	-440741.408	V	1.4
TN_Line_Ub	293471.486	298.087°	199596.907	-453700.401	V	1.4
TN_Line_Uc	292694.604	178.223°	-415521.505	-457001.191	V	1.4
TN_Bus_Ua	293775.094	58.304°	216837.663	-414611.684	V	1.4
TN_Bus_Ub	293878.630	298.106°	199227.063	-412820.029	V	1.4
TN_Bus_Uc	292808.866	178.205°	-415862.036	-416033.852	V	1.4

Figure 6: Display of electrical measurements in the short circuit

From this figure, the high voltage phase B current peak, Ib_BH, is 4.526 kA. From information provided by the transformer manufacturer, the maximum current on phase B is 4.492 kA. For the purposes of this paper, the short circuit current is assumed to be 4.5 kA. However, we are also interested in the voltage across the short circuit. These measurements include information on the low voltage side, Ub_HH, but not on the high voltage side.

One measured potential difference related to phase B of the high voltage windings is 31 kV. It is uncertain across which two points this potential is measured but let us assume that the two points correspond to the two terminals of the short circuit. Two possible situations are that it represents an RMS value or a maximum amplitude. If we assume that it is a maximum amplitude, the arc voltage is roughly 31 kV.

If this value is an RMS value instead, it can be assumed that the voltage across the short circuit is $31\sqrt{2}$ kV = 43.84 kV. Another set of measured potential differences is in Figure 6, where a line voltage associated with phase B has a maximum amplitude of 45.37 kV. This is consistent with the interpretation of the value being an RMS voltage. Let us therefore average these two values: 44.6 kV.

In this paper, we will consider both values, 31 kV and 44.6 kV. We remark that an empirical measure for the arc voltage in terms of arc length has been proposed [2]. This is shown in Figure 7.

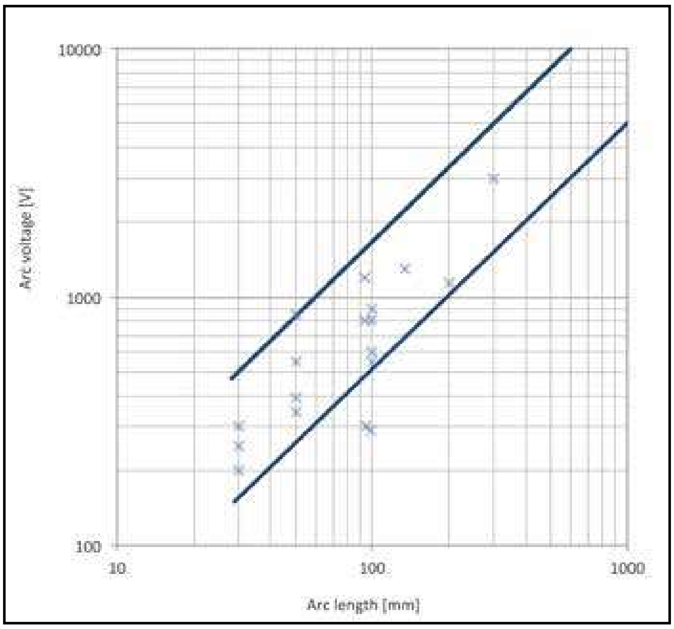


Figure 7: Relation between arc voltage and arc length

> **Data from SCADA system show the arc duration of 97 ms and oscillographs of the voltage and current measurements show the arc duration of 65 ms. The oscillograph data is considered much more reliable, hence the estimated arc duration was 65 ms**

Kawamura uses the upper bound as the more appropriate estimate for the arc voltage. For an arc clearance of 1 m, this implies a voltage of up to 16.66 kV. This is within the same order of magnitude of our values, however more consistent with the 31 kV value.

The SCADA is the electrical output detailing diagnostic events for the transformer. In Table 1 we see a subset of the SCADA data pertaining to critical events. Using this data, we identify the arc duration, the difference between the circuit breaker fully open signal and the estimated fault origin to be roughly 97 ms long. However, the oscillograph of the voltage and current measurements indicate that the arc duration is 65 ms. Because the sampling frequency of the SCADA will be of much lower resolution than the sampling frequency of the oscillograph data, the oscillograph data is considered much more reliable. Therefore, we will use the 65 ms figure to represent the duration of the arc.

We will assume that the stated values for the peak amplitudes of the arc current and voltage are constant across this arc duration and that the voltage and current oscillate at a 50 Hz frequency (f).

The AC current and voltage can be described as proportional to sin ($2 \pi f t + \varphi$), where φ is the phase. It is difficult to determine the precise phase of the voltage and current at the beginning of the arc. This paper assumes that both the current and voltage start at a phase of 0.1 radians (therefore, approximately 10% of its maximum value). Using equation 2:

$$E = I_{\max}U_{\max}\int_0^T |\sin(2\pi f t + \phi)|^2 dt \qquad (3)$$

Defining: $T = 65$ ms, $f = 50$ Hz, $\varphi = 0.1$, $I_{\max} = 4.5$ kA, $U_{\max} = 31$ kV, we arrive at the following arc energy:

$$E_{\mathrm{low}} = 4.578\ \mathrm{MJ} \qquad (4)$$

Alternatively, defining: $U_{\max} = 44.6$ kV, we have the following value for the arc energy:

$$E_{\mathrm{high}} = 6.586\ \mathrm{MJ} \qquad (5)$$

The arc energy may be somewhat larger or smaller than these values, depending on the phase of the current and voltage. We will use the higher energy of 6.586 MJ for all presented simulations as it is the worst case scenario, therefore the most problematic.

Generated gas volume

One paper uses a simplified set of reactions: as oil breaks down, H atoms CH_3 radicals recombine to produce gases such as H_2, C_2H_2, CH_4, and C_2H_4, given a gas temperature T [3]. The simplified model is shown in equations 6-8

$$H + H \rightarrow H_2 \qquad (6)$$

$$CH_3 + H \rightarrow \frac{1}{18}(23H_2 + 7C_2H_2 + 2CH_4 + C_2H_4) \quad if\ T \leq 1500K \qquad (7)$$

$$CH_3 + H \rightarrow C + 2H_2 \quad if\ T \geq 1500K \qquad (8)$$

> **The arc energy was estimated by two methods as 4.578 MJ and 6.586 MJ. As the worst case scenario, the higher value was used in simulations**

At the CEPEL laboratory an experimental test campaign was performed on a series of transformers subject to internal arcs (11). These experiments have determined the following dependence for the relationship between the arc energy and generated gas volume:

$$V = \left(0.44\ln\left(\frac{E}{\mathrm{J}} + 5474.3\right) - 3.8\right)\mathrm{m}^3 \qquad (9)$$

Specifically, a 6.586 MJ arc produces a gas volume of 3.11 m^3 at standard temperature and pressure.

Rupture disc aperture

The top layer of the rupture disc is open at roughly 90% the maximum cross section, Figure 8. This result is consistent with a strong arc.

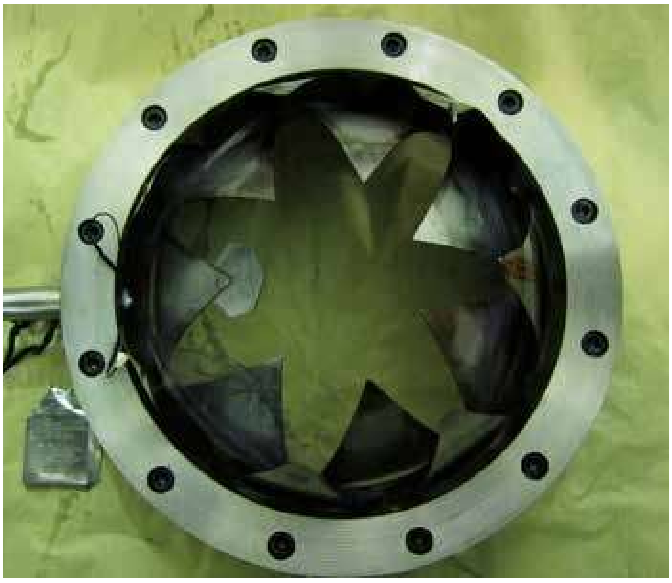


Figure 8: Rupture disc of the transformer protector

Computational fluid dynamics (CFD) simulation background

We are interested in modeling the propagation of pressure waves in transformer oil when subject to internal arcing events. Such phenomena are modeled as a 3D compressible two-phase flow, using a set of partial differential equations based on a 5 equation model developed in [4] and described in equations 10a - 10e. These equations represent the conservation of mass (ρ), momentum (ρv), and energy (E), as well as the advection of the volume fraction (α) for each phase. Source terms relating to gravity (g), viscosity (μ), and heat conduction (T) are added in the conservation equations to adhere to physical constraints.

> **The propagation of pressure waves in transformer oil when subjected to internal arcing events was simulated by computational fluid dynamics**

$$\frac{\partial \alpha_1}{\partial t} + \vec{u}.\vec{\nabla}\alpha_1 = 0 \tag{10a}$$

$$\frac{\partial \rho}{\partial t} + \mathrm{div}(\rho\vec{u}) = 0 \tag{10b}$$

$$\frac{\partial \alpha_1 \rho}{\partial t} + \mathrm{div}(\alpha_1 \rho \vec{u}) = 0 \tag{10c}$$

$$\frac{\partial \rho\vec{u}}{\partial t} + div(\rho\vec{u} \otimes \vec{u} + P) = \Phi_{\mathrm{g}}^{u} + \Phi_{\mu}^{u} \tag{10d}$$

$$\frac{\partial E}{\partial t} + div\big((E + P)\vec{u}\big) = \Phi_{\mathrm{g}}^{E} + \Phi_{\mu}^{E} + \Phi_{T}^{E} + \dot{E} \tag{10e}$$

This model was selected to accurately depict the pressure wave propagation inside liquids and gases. A finite volume algorithm is adopted to transform the system of differential equations into algebraic equations. The fluxes across cell boundaries are determined by the Godunov Riemann solver. The volumes are defined by an unstructured 3D mesh to allow a precise description of complex geometries such as transformer tanks.

The experimental test by CEPEL was simulated in order to verify the mathematical model developed for arc-induced dynamic pressure peak within transformers [5].

Originally developed and presented, HYCTEP (**HY**drodynamic **C**ode for **T**ransformer **E**xplosion **P**revention) is implemented as a hydrodynamic numerical tool for computational fluid simulations [6]. The mesh used to discretise the transformer geometry has up to 139,794 tetrahedral elements, and is shown in Figure 9.

The transformer oil and its vapour are represented as a stiffened gas fitted to the mineral oil dodecane (Table 4).

Included on the geometry are a TP and a PRV. The TP DC is 300 mm in diameter, and the PRV 150 mm. The PRV is set to open at 0.8 bars above atmospheric pressure, and the TP rupture disc opens at 1.2 bars above atmospheric pressure.

The arc parameters used in the simulation are listed in Table 5 and energy is injected using HYCTEP's arc model 4, which guarantees that the total power input is determined by the product of the voltage and current throughout the arc region.

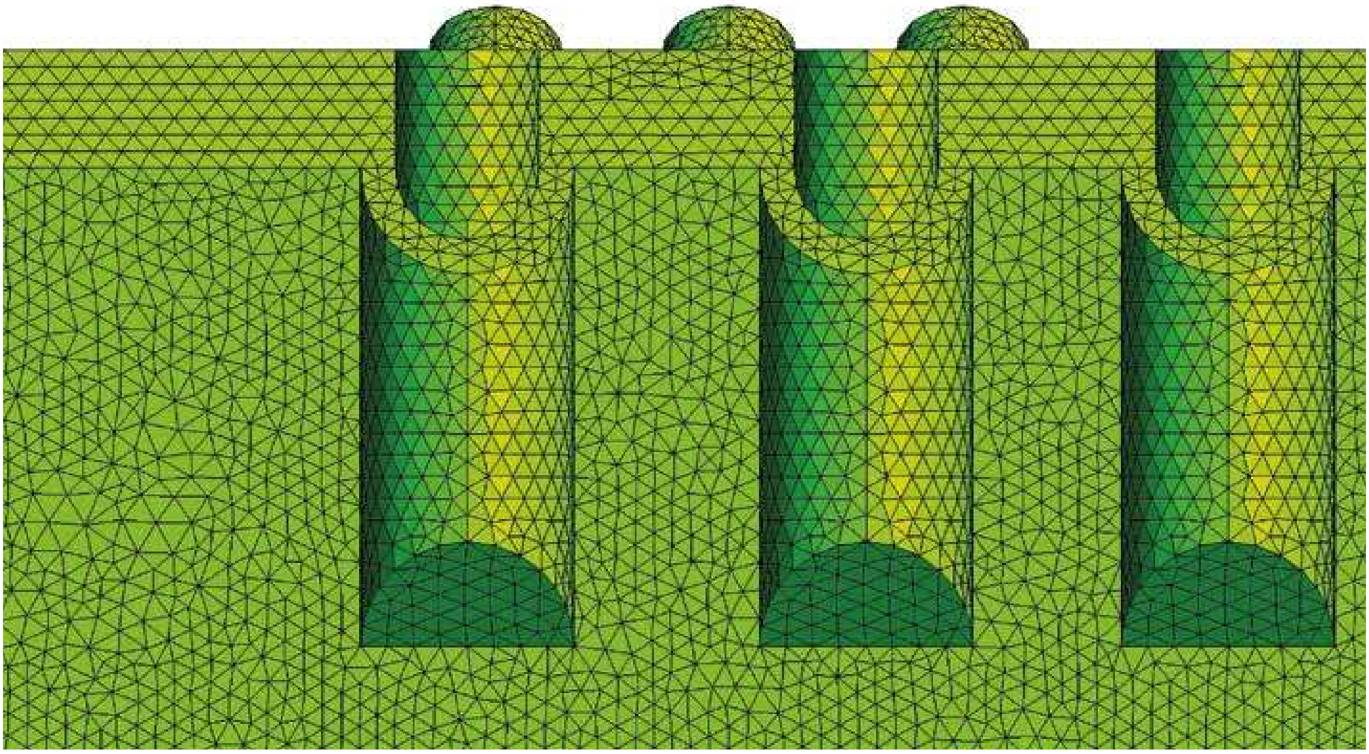


Figure 9: Transformer model in the hydrodynamic numerical tool for computational fluid simulations

Table 4: Fluid parameters for usage in simulations

	p_∞ (Pa)	C_p (J kg^{-1} K^{-1})	C_v (J kg^{-1} K^{-1})	γ	q (J kg^{-1})	q' (J kg^{-1}K^{-1})
liquid	4×10^8	2534	1077	2,35	-755×10^3	0
vapour	0	2005	1956	1,025	-237×10^3	-24×10^3

> **For the case of the transformer with both a transformer protector and a pressure relief valve, the average tank pressure first drops below the approximate static withstand limit of the tank (2.2 bars) after 125 ms**

Table 5: Arc parameters

Max Current	Max volatge	Duration	Phase
4.5 kA	44.6 kV	65 ms	0.1

The simulations were run for up to 900 ms with a time step of 10^{-6} s. Four cases were run:

1) The actual case where transformer T2 has both TP and PRV
2) T2 only has a TP
3) T2 only has a PRV
4) T2 is completely sealed

CFD simulation results

In Figure 10 the average tank pressure is visualised for the four simulated cases in the case of arc energy of 6.586 MJ. It can be observed that for both cases with a TP, the tank is rapidly depressurised. For the case of T2 with both a TP and a PRV, the average tank pressure first drops below the approximate static withstand limit of the tank (2.2 bars) after 125 ms.

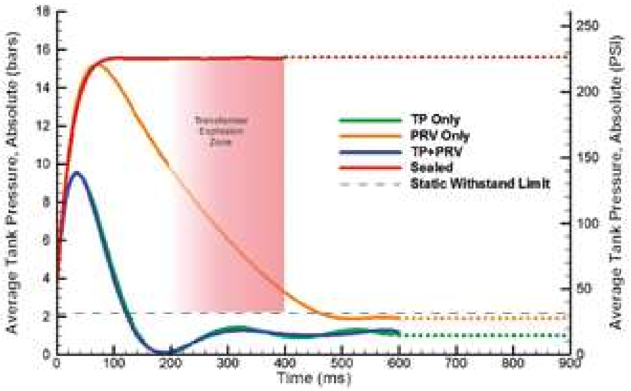


Figure 10: Average tank pressure for simulated cases with the arc energy of 6.586 MJ

In contrast, for the case with only a PRV, the average tank pressure does not drop below the static withstand limit until 461 ms, a duration more than three times as long as the case including the TP. With neither a TP nor PRV, the average tank pressure approaches a steady state of roughly 15.6 bars, more than seven times the static withstand limit.

In Figure 11 we see the pressure evolution under the three most distinct cases. This figure reinforces our observations for Figure 10. The transformer with a TP only is safely below the static withstand limit by 150 ms in contrast to the case of the transformer with only a PRV and particularly the sealed tank.

Conclusion

A fault was identified in transformer T2, with a 400 MW capacity at the Boguchanskaya HPP, equipped with a TP. No permanent damage to the tank was observed.

Due to the dissolved gas analysis, the fault was identified as a high energy arcing event through the insulation. From observations of the current and voltage data, the energy of the short circuit is approximately 6.586 MJ.

Using this knowledge, we attempted to model the sequence of events through a CFD simulation. This in-house simulation tool is designed to model pressure wave propagation in a two phase compressible media. Observing burnt areas of the insulation allowed us to approximate the spatial extent of the arc. Using a schematic of the transformer, a mesh was generated to discretise the geometry.

Four simulation cases were run: 1. transformer T2 with both a TP and a PRV, 2. T2 with only a TP, 3. T2 with only a PRV, and 4. a completely sealed T2. The two cases including a TP behaved similar although the tank with both the TP and PRV depressurised below the static withstand limit by 125 ms. In contrast, the case with only a PRV did not depressurise below the static withstand limit until 461 ms. The sealed tank reaches a steady state of 15.6 bars, likely leading to a rupture.

We observe that the first dynamic pressure peak due to the arc quickly activates the TP while a sustained pressure for a duration roughly 14 times longer is necessary to open the PRV, which therefore activates with static pressure only.

We may conclude that the inclusion of the TP allowed the tank to depressurise very quickly, saving the transformer from explosion. This conclusion has been attested by RusHydro through a TP Successful Activation Certificate [7].

> **With neither a transformer protector nor pressure relief valve, the average tank pressure approaches a steady state of roughly 15.6 bars, more than seven times the static withstand limit likely leading to a rupture**

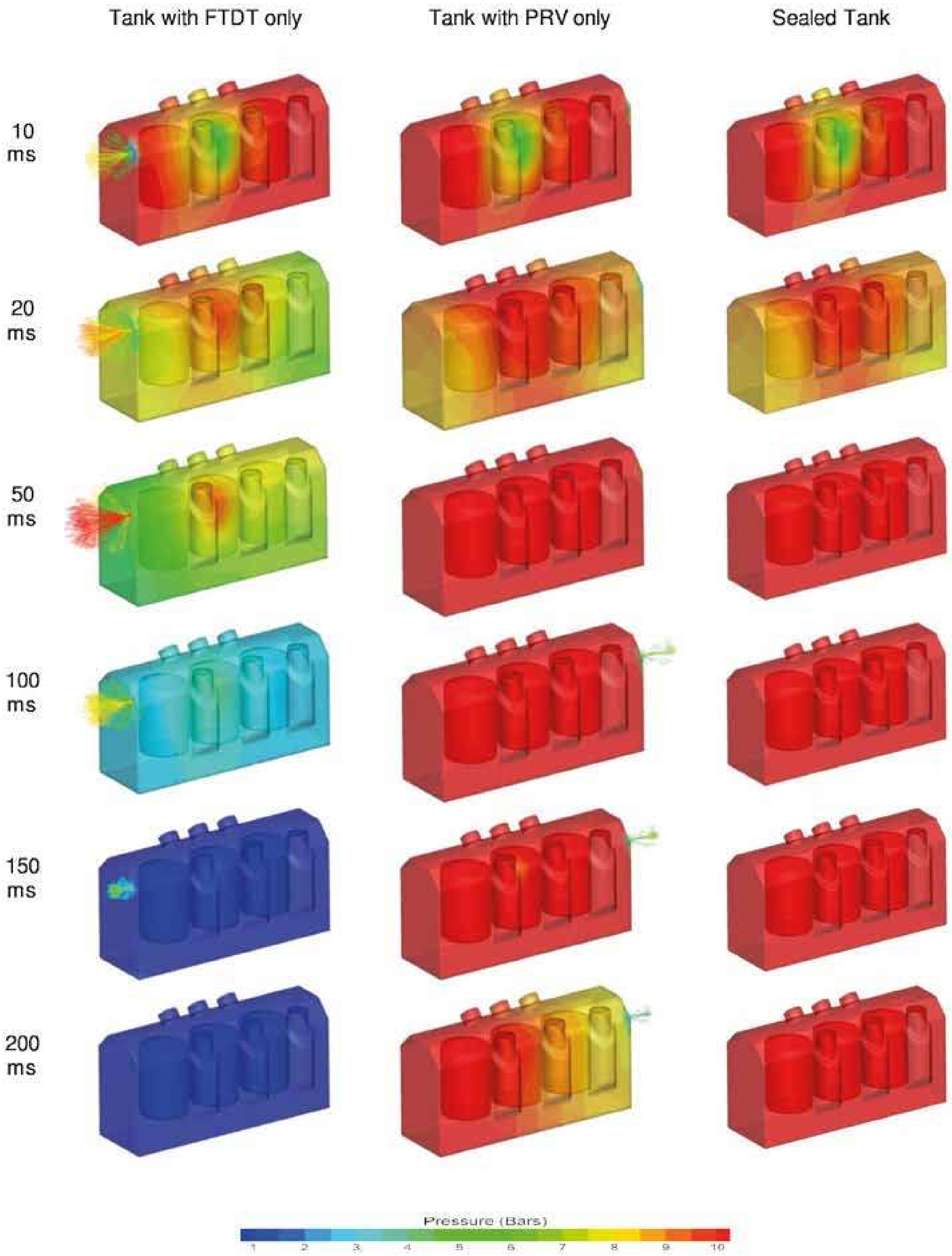


Figure 11: Pressure evolution in three most distinct cases

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