

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.

Introduction

n 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.

Omar AHMED and Anne GOJ



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

Table 1: SCADA list of events

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



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.

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

TRANSFORMER PROTECTION

99 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:

$$\frac{C_2 H_2}{C_2 H_4} = R_2 \qquad \frac{C H_4}{H_2} = R_1 = 0.6089 \qquad \frac{C_2 H_4}{C_2 H_6} = R_3 \quad (1)$$

= 0.8326 = 5.241

	H2	CH4	C2H4	C2H6	C2H2	CO2	СО	02	N2	Total gas
Analysis date	Hydrogen	Methane	Ethene	Ethane	Ethyne	Carbon Dioxide	Carbonic Monoxide	Oxygen	Nitrogen	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	

Table 2: Dissolved gas analysis for transformer T2

Gas Concentration %

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

Table 3: Rogers' Ratio interpretation method

For interpretation of dissolved gases, Rogers Ratio method and Duval triangle were used.

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.

Short circuit energy

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

$$E = \int_0^T UIdt \tag{2}$$

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 4: Duval triangle for dissolved gas analysis

NUMBER Edited Fail Kall	COLUME Description Description <thdescriprint< th=""> <thdescription< th=""> <thd< th=""><th></th><th></th><th></th><th></th><th></th><th>1.0</th><th>1001 (1001)</th><th>44</th></thd<></thdescription<></thdescriprint<>						1.0	1001 (1001)	44
3.2 1.2 1.0 <th1.0< th=""> <th1.0< th=""> <th1.0< th=""></th1.0<></th1.0<></th1.0<>	1 1 1 10 <th>MUNUSAR DM 201 1999-MI Printy Pair Text</th> <th></th> <th></th> <th></th> <th></th> <th></th> <th></th> <th>12.140</th>	MUNUSAR DM 201 1999-MI Printy Pair Text							12.140
N.9 N.9 <th>N N<th></th><th></th><th>10111</th><th>740</th><th>hartest</th><th>Phase</th><th>NOV N</th><th>a Para</th></th>	N N <th></th> <th></th> <th>10111</th> <th>740</th> <th>hartest</th> <th>Phase</th> <th>NOV N</th> <th>a Para</th>			10111	740	hartest	Phase	NOV N	a Para
b.9 67.07 67.99 21.06 86.20 1.101 1.101 1.101 4.105 1.101 4.105 1.101 4.105 1.101 4.105 1.101 4.105 1.101 4.105 1.101 4.105 1.101 4.105 1.101 4.105 1.101 4.101 1.101 1.101 1.101 1.101 1.101	b,H 5,H 5				1048	15.85	21347 8	0.07 10.30	1 10.002
Num Num <td>M L</td> <td></td> <td></td> <td>6.91</td> <td>(51.03</td> <td>197.39</td> <td>22167 7</td> <td>1.518 717.8</td> <td>a 4563</td>	M L			6.91	(51.03	197.39	22167 7	1.518 717.8	a 4563
N.194 1.82 1.82 1.82 1.82 1.81 N.194 1.82 1.82 1.82 1.81 1.81 N.194 1.82 1.82 1.81 1.82 1.81 N.194 1.82 1.82 1.81 1.82 1.81 N.194 1.81 1.81 1.81 1.81 1.81 1.81 N.194 1.81 <td>1.000 1.00</td> <td></td> <td></td> <td>ALM .</td> <td>10.00</td> <td>10.40</td> <td>41527 1</td> <td>1011 10100</td> <td>C CROCAR</td>	1.000 1.00			ALM .	10.00	10.40	41527 1	1011 10100	C CROCAR
NO E7 107 2019 101 LO	NOM L47 L70 B710 L17 L170 L107 L10			INTON	1.202	142	4572 1	EN 320	1.70
b,0(1) 125 228 20,47 421 b,0(3) 128 328 328 328 3421 b,0(3) 128 328 328 328 3421 300 3421 b,0(3) 128 338 338 338 338	1.000 128 0.201 0	mannin		man aroi	1.407	1.277	STOR 1	m 194	1236
Number Numer Numer Numer <td>Line Line <thline< th=""> Line Line <thl< td=""><td></td><td>mannen</td><td>Man Market</td><td>125</td><td>-0.258</td><td>27.67</td><td>12: 1.17</td><td>128</td></thl<></thline<></td>	Line Line <thline< th=""> Line Line <thl< td=""><td></td><td>mannen</td><td>Man Market</td><td>125</td><td>-0.258</td><td>27.67</td><td>12: 1.17</td><td>128</td></thl<></thline<>		mannen	Man Market	125	-0.258	27.67	12: 1.17	128
Number Numer Numer Numer <td>Norm Times Usart <thu< td=""><td></td><td></td><td>14,6D</td><td>37268.187</td><td>34881.127</td><td>235 MH- 1</td><td>216.217 429</td><td>NCC - 107201.3</td></thu<></td>	Norm Times Usart Usart <thu< td=""><td></td><td></td><td>14,6D</td><td>37268.187</td><td>34881.127</td><td>235 MH- 1</td><td>216.217 429</td><td>NCC - 107201.3</td></thu<>			14,6D	37268.187	34881.127	235 MH- 1	216.217 429	NCC - 107201.3
KdR 201.80 406.22 41.82 10.80 L S S S S S S L S S S S S S S L S S S S S S S S L S	K-60 III.30 6602 III.30 1II.30 III.30 IIII.30 IIII.30			a,im	1944 (61)	14.00119	stonr a	44.00 100.	83 32(14.)
B_11 ULUE ULUE <th< td=""><td>N_10 Value ORA C240 NL70 E230 <th< td=""><td>~~~~</td><td></td><td>6, 601</td><td>3379.300</td><td>1061.521</td><td>96.78° S</td><td>10171 11213</td><td>MI (MIA 11</td></th<></td></th<>	N_10 Value ORA C240 NL70 E230 NL70 E230 <th< td=""><td>~~~~</td><td></td><td>6, 601</td><td>3379.300</td><td>1061.521</td><td>96.78° S</td><td>10171 11213</td><td>MI (MIA 11</td></th<>	~~~~		6, 601	3379.300	1061.521	96.78° S	10171 11213	MI (MIA 11
1.10 1.20 <td< td=""><td>N.10 L2 L</td><td></td><td></td><td>AUI .</td><td>141.02</td><td>458.80</td><td>22.88</td><td>61.292 #123</td><td>RI (457.0</td></td<>	N.10 L2 L			AUI .	141.02	458.80	22.88	61.292 #123	RI (457.0
Number Number<	1 502.07 101.08 248.07 610.08 648.07 648.07 1 101.07 101.08 248.07 610.07 648.07 648.07 1 101.07 101.08 248.07 610.07 648.07 648.07 1 101.07 101.08 248.07 610.07 648.07 648.07 1 101.07 101.08 248.07 610.07 648.07 648.07 1 101.07 100.07 100.07 100.07 648.07 648.07 1 101.07 100.07 100.07 100.07 100.07 648.07 1 101.07 100.07 100.07 100.07 100.07 100.07 1 101.07 100.07 100.07 100.07 100.07 100.07 1 101.07 100.07 100.07 100.07 100.07 100.07 1 101.07 100.07 100.07 100.07 100.07 100.07 1 101.07 100.07 100.07 100.07 100.07 100.07 1 101.07 100.07 100.07 100.07 100.07 100.07 1 101.07 100.07 100.07 100.				142	1,228	NTMT C	296 -6285	1118
VIII WIIII VIIIII VIIIIII VIIIIII VIIIIII VIIIIIII VIIIIIII VIIIIIII VIIIIIIII VIIIIIIIII VIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII	1 92135 92137 921			101	836.117	FT1 04	CAMP 4	CE 81 - 614	er neur
Image: Second	Line Billing B	~~~~		1. m. m.	36,1122	100017	10/107 8	H573 1855	NI IZUUI
North Bit North Bi	Interface Interface <t< td=""><td>~~~~</td><td>~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~</td><td>B(.**</td><td>800.562</td><td>TITIK SA</td><td>riter 1</td><td>18 CS 301</td><td>P1 1-042 (</td></t<>	~~~~	~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	B(.**	800.562	TITIK SA	riter 1	18 CS 301	P1 1-042 (
Image: Second	Unit MK 770 Status Status <td></td> <td></td> <td>14(16)</td> <td>127728</td> <td>3855</td> <td>117957 9</td> <td>155 015</td> <td>a testa</td>			14(16)	127728	3855	117957 9	155 015	a testa
Image: State	NF 63.1 2010 11 91.1 MI 2013 11 91.0 MI 2014 11 91.0 MI 91.0 MI <t< td=""><td></td><td></td><td>P.M.</td><td>H9604 750</td><td>3641.022</td><td>10,734 8</td><td>14.31 570</td><td>HL THE</td></t<>			P.M.	H9604 750	3641.022	10,734 8	14.31 570	HL THE
HP 643 400,00 700,00 701,00<	NB 96 L CR3, 60 L			rives)	200311	191.545	22.6N 3	16.00 NP3	
IPE 000 CONTR <	NU BL 456.0 200.00 <td></td> <td></td> <td>RIFOLI</td> <td>4254.400</td> <td>3900.000</td> <td>21977 N</td> <td>8307 HCK</td> <td>a</td>			RIFOLI	4254.400	3900.000	21977 N	8307 HCK	a
Image:	NEW NEW <td></td> <td></td> <td>torbu</td> <td>456.400</td> <td>100.902</td> <td>22973 A</td> <td>193 (419</td> <td></td>			torbu	456.400	100.902	22973 A	193 (419	
Image: Second	HIP Schule Light III Light IIII Light IIIII Light IIIII Light IIIII Light IIIIII Light IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII			TTA BOL	147.30	10105	NUMP 2	HIN NO	2011
1 1	NUMBER NUMBER<			PTW EX TUDE	104210	10140	steatr. b	14.002 19.002	
17 DAME 100 100 100 100 100	119 54200 05425 10410 0542 10410 1042 119 54200 1040 1040 1040 1040 1040 119 54200 1040 1040 1040 1040 1040 1040 119 5640 1040 10405 10448 20175 10448 20175 10448 20175 10448								
	641 Car 11.271 11.382 11.582 11.587 11.381 11.582 11.587 11.581 1			THE REAL PROPERTY	Marga .	100.01		0.19 2.94	ince a
ALL PART IN THE SAME AN AVE.	11 Ma. 2014 2017 1948 2017 1948 2017 1948 2017 1948							the the	-
				and the second se			111	antic Ala	1.20
				s fint s for	0 22	1110	3 1990	104029 (03	
				A LEW CONTRACTOR	3.8	120	8 1113		
					1.1	1111111	5 1115	125 83	
				2 Her Juckt	1.4	191094034	5 1910 A	1940.9 0.4	
				1 10 10 10 10 10 10 10 10 10 10 10 10 10	5.5	干部器	8 1116	262 65	

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

TRANSFORMER PROTECTION



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



Figure 7: Relation between arc voltage and arc length

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.

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

$$E_{\rm low} = 4.578 \,\,{\rm MJ}$$
 (4)

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

$$E_{\rm high} = 6.586 \,\,\mathrm{MJ} \tag{5}$$

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 H₂, C₂H₂, CH₄, and C₂H₄, given a gas temperature *T* [3]. The simplified model is shown in equations 6-8

$$H + H \to H_2 \tag{6}$$

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

$$CH_3 + H \to C + 2H_2 \quad if \ T \ge 1500K \tag{8}$$

99 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:

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

Specifically, a 6.586 MJ arc produces a gas volume of 3.11 m³ 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.

www.transformers-magazine.com

TRANSFORMER PROTECTION

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

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

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

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

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

$$\frac{\partial E}{\partial t} + div((E+P)\vec{u}) = \Phi_g^E + \Phi_\mu^E + \Phi_T^E + \dot{E}$$
(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 Transformer Explosion **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

	p _∞ (Pa)	C _p (J kg ⁻¹ K ⁻¹)	C _v (J kg ⁻¹ K ⁻¹)	γ	q (J kg⁻¹)	q' (J kg⁻¹K⁻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

Table 4: Fluid parameters for usage in simulations

99 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 with-stand 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].

99 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

References

[1] Transformers Committee of the IEEE Power Engineering Society, IEEE PC57.104 *Guide for the Interpretation of Gases in Oil Immersed Transformers:* IEEE Standards Activities Department, 2004.

[2] Kawamura, T. et al., *Prevention of Tank Rupture due to Internal Fault of Oil Filled Transformers*, CIGRE, Volume 12-02, 1988

[3] Duval, M., A Review of Faults Detectable by Gas-in-Oil Analysis in Transformers, DEIS, 2002

[4] Guillard, H. & Murrone, A., *A five equation reduced Model for compressible two phase flow problems*, INRIA, Volume 4778, 2003

[5] Brady, R. et al., *Prevention of Transformer Tank Explosion, Part 2: Development and Application of a Numerical Simulation Tool*, ASME PVP, Chicago, IL, 2008

[6] Brady, R. et al., *Prevention of Transformer Tank Explosion, Part 3: Design of Efficient Protections using Numerical Simulations*, ASME PVP, Prague, Czech Republic, 2009

[7] RusHydro, *Successful Activation Certificate*, ArkbT-P130503RUS59A5824br, 2013

Authors



Omar Ahmed completed his undergraduate degrees in Mathematics and Physics at the University of Texas, Austin, and completed his Masters in Geophysical Fluid Dynamics at Rice University. He is currently working at Transformer Protector Corporation as a Research Engineer,

where he is modeling the physics associated with transformer explosion and depressurisation strategies. He specialises in optimising the computational fluid dynamics algorithms to model energy transfer from the arcing event to the transformer oil, and the subsequent pressure wave propagation.



Anne Goj studied theoretical and computational physical chemistry at Cornell University before relocating to TX in 2007 and then joining TPC in 2013. She spends so much time calculating quantities with physics that she occasionally wonders how her degrees all have 'che-

mistry' written on them.

