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TRANSFORMER EXPLOSION AND FIRE PREVENTION

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1. Abstract

An essential step for SERGI is to show the TRANSFORMER PROTECTOR (TP) efficacy 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.
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 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.

When an electrical arc occurs, only one pressure peak is generated. The initial energy transfer is almost instantaneous, and so is the phase change. Because of the oil inertia, the gas is very quickly pressurised. As it is more difficult to vaporise a liquid than to crack oil-vapour into smaller molecules, the arc location would mainly remain in the gaseous phase after and less gas will be produced. As a result, when comparing tests for which pressure peaks are respectively equal to 8 bar (116 psi) and 8.8 bar (127 psi), the corresponding arc energies vary by an order 10 of magnitude (0.1 MJ and 1 MJ respectively).
The correlation of the results obtained between arc energy and dynamic pressure demonstrates that the arc energy is not the key parameter during transformer tank explosion, which is in opposition with the common electrical engineers belief.

2. Introduction

Transformer explosions are caused by low impedance faults that result in arcing once the oil loses its dielectric properties. Oil is then vaporised, and the generated gas is pressurised 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 [20]. Realising that the transformer explosion prevention is the sole effective solution to avoid such financial losses, SERGI designed and patented worldwide the TRANSFORMER PROTECTOR (TP) in 1999.

The TRANSFORMER PROTECTOR (TP) is a transformer explosion and fire prevention technology based on the direct mechanical response of a Depressurisation Set to the tank inner dynamic pressure increase due to a fault. Since transformers always rupture at their weakest point, the Depressurisation Set is designed to be this weakest point in term of inertia to break before the tank explodes. For that purpose, the Decompression Chamber is equipped with a Rupture Disk (RD). Indeed, after an electrical fault has occurred, the pressure rises, and the Depressurisation Set (DS) opens as soon as the pressure close to the TP has reached the calibrated pressure. Oil is then quickly expelled from the transformer tank, through the Decompression Chamber (DC), and into an Oil Gas Separation Tank (OGST), so that the TP depressurises the transformer tank within milliseconds, and prevents the transformer from exploding. Indeed, once the TP has activated, the mechanical energy is evacuated and the transformer is protected even if the electrical arc is still fed for one second [18].

3. Conclusion

An essential step for SERGI is to show the TRANSFORMER PROTECTOR efficacy 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.
The MTH model was upgraded in order to describe compressible two-phase flows, the pressure wave propagation inside liquids and gases, and to simulate the TP depressurisation process.
To verify calculations and simulations, CEPEL performed 34 experimental tests under low impedance faults. For each parameter, the following test results were found:

The Gas Generation

The gas volume generated during an electrical arc has been evaluated. The generated gas volume is a logarithmic function of the arc energy. This correlation is more reliable than linear extrapolations published up to day because it is based on experiments.
It is also shown that the gas production is huge at the creation of the electrical arc because of the intense heat exchange between the arc and the liquid. Then, the arc is partially or completely surrounded by gas. As a result, the arc energy is used to heat up the gas (thermal agitation), to crack the oil vapour into smaller molecules, and to change the gas into a plasma. Less and less energy is thus transferred to the dielectric oil for it to evaporate.
Consequently, for a 100 MJ electrical arc, the first Mega Joule transferred to the dielectric oil generates 2.3 m^3 (81.2 ft^3) of explosive gas, while the other 99 MJ contribute only to 2.0 m^3 (71.1 ft^3).

Pressure Peaks

Only one main pressure peak has been noticed for each test. Indeed, as the first vaporisation is a nonequilibrium phenomenon, it is more violent than the almost-at-equilibrium vaporisation occurring once the arc is ignited. 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 is very quickly pressurised, which generates the first very strong pressure waves.
As it is more difficult to vaporise a liquid than to crack oil vapour, the arc location would mainly remain in the gaseous

phase after its ignition. The vaporisation which happens after the gas bubble appearance is smoother and do not really generate physical conditions such as the ones in the very first arc instants. The secondary pressure variations are thus the result of the overlapping waves and structure influence combined with the smooth gas generation influence on pressure.

When comparing tests for which pressure peaks respectively equal +8 bar (+116 psi) and +8.8 bar (127 psi), the corresponding arc energies vary within on order 10 of magnitude (0.1 MJ and 1 MJ respectively).

Correlation between Arc Energy and Dynamic Pressure

The two above arguments demonstrate that the arc energy is not the key parameter to avoid transformer tank explosion as the gas production is huge only during the first Mega Joule, the pressure peaks amplitude does not increase significantly versus the arc energy.

The Pressure Wave Propagation

As predicted by the physical two-phase flow model, the pressure is not homogeneous in the transformer.

Moreover, the study of the experimental pressure curves shows that the tank structure has an influence. This influence is noted as well with the simulations.

· The displacement of the shock wave in the tank is exhibited, demonstrating that the pressure waves propagate at finite speed experimentally, in agreement with theory.

· The maximum distance between the arc location and the TP is thus the parameter that matters the most for the TP to activate.

Tank Resistance to Dynamic Pressure

The following unknown key parameters have been discovered during the CEPEL tests:

· The tank resistance to dynamic pressure amplitude, the walls and components elasticity such as bolts or welding has been tested for pressure peaks up to 10 times over the static pressure limit.

· The tank resistance to dynamic pressure peaks duration was tested for 4 times longer than for the biggest existing transformer.

References

[1]. R. ABGRALL, "How to prevent pressure oscillations in multi-component flow calculations: A quasi conservative approach", Journal of Computational Physics, vol. 125, pp. 150-160, 1996.

[2]. G. ALLAIRE, S. CLERC & S. KOKH, "A Five Equation Model for the Simulation of Interfaces between Compressible Fluids, Journal of Computational Physics, vol. 181, 2, pp. 577-616, 2002.

[3]. M.R. BAER & J.W. NUNZIATO, "A Two-phase Mixture Theory for the Deflagration to Detonation Transition in Reactive Granular Materials", International Journal of Multiphase Flow, vol. 12, 6, pp. 861-889, 1986.

[4]. N.P. CUK, "Oil Tank Explosion Resistance", CEA No. 149D491, Powertech Labs Inc., Surrey, B.C., June 1990.

[5]. F. DUBOIS, "Boundary conditions and the Osher scheme for the Euler equations of gas dynamics", internal report CMAP 170, Ecole Polytechnique, Palaiseau, France, 1987.

[6]. E. GODLEWSKI & PA. RAVIART, "Numerical Approximation of Hyperbolic Systems of Conservation Laws", Press, Applied Mathematical Sciences, vol. 118, ed. Springer Verlag, Berlin, 1996.

[7]. S.K. GODUNOV, "A Finite Difference Method for Numerical Computation of Discontinuous Solutions of the Equations of Fluid Dynamics", Math Sb., vol. 47, pp. 357-393, 1959.

[8]. O.R. HANSEN, "SEBK Project: Results from Phase 2 Laboratory Scale Experiments", Gexcon, May 2001.

[9]. A.K. KAPILA, R. MENIKOFF & D.S. STEWART, "Two-phase Modelling of Deflagration to Detonation Transition in Granular Materials: Reduced Equations", Physics of Fluids, vol. 113, 10, pp. 3002-3024, 2001.

[10]. O. LE METAYER, "Modélisation et résolution de la propagation de fronts perméables - Application aux fronts d'évaporation et de detonation", Ph. D. Thesis, Université de Provence, Mechanics & Energy, Marseille, France, 2003.

[11]. J. MASSONI, R. SAUREL, B. NKONGA & R. ABGRALL, "Proposition de méthodes et de modèles eulériens pour les problèmes à interfaces entre fluides compressibles en présence de transfert de chaleur"/ "Eulerian model and method proposal for flows with interfaces in presence of heat transfers", International Journal Of Heat and Mass Transfers, vol. 45, 6, pp. 1287-1302, 2002.

[12]. A. MURRONE & H. GUILLARD, "*"A Five Equation Reduced Model for Compressible Two-phase Flow Problems"", Journal of Computational Physics, vol. 202, Issue 2, 2005.*

[13]. R. SAUREL & R. ABGRALL, ""A multi-phase Godunov Method for Compressible Multi-fluid and Multiphase flows"", Journal Of Computational Physics, vol. 150, pp. 425-467, 1999

[14]. R. SAUREL & R. ABGRALL, "A Simple Method for Compressible Multi-fluid Flows", SIAM J. of Scien. Comput., vol. 21, 3, pp. 1115-1145, 1999.

[15]. R. SAUREL & O. LEMETAYER, "A Multi-phase Model for Compressible Flows with Interfaces, shocks, detonation waves and cavitation", Journal Of Fluid Mechanics, vol. 431, pp. 239-271, 2000

[16]. SERGI, "Development of a Magneto-Thermo Hydrodynamic Model and Design of a Transformer, On load Tap Changer and Bushing Oil Cable Box, Explosion and Fire Prevention", IEEE Publication, ref. rpiip01a, 1999.

[17]. SERGI, "Comparison of the SERGI developed Magneto-Thermo Hydrodynamic Model results with measurements made on a 160KVA Transformer", IEEE Publication, ref. rpijp01a, 2000.

[18]. SERGI, "Study and Design of Power Plant Transformers Explosion and Fire Prevention", Australia, TechCon 2001, ref. rpitp05a, 2001.

[19]. SERGI, "Transformer Relief Valves efficiency calculations by comparison to the SERGI TRANSFORMER PROTECTOR during short-circuits", ref. rpisp01a. [20]. SERGI, "Transformer Explosion and Fire, Guideline for Damage Cost Evaluation, TRANSFORMER PROTECTOR Financial Benefit", ref. fTPoa03a, 2004.

[21]. SERGI, "Study of the Pressure Wave Propagation and Depressurisation Process for an Electrical Transformer Subjected to Internal Arcing, Design of a Decision-Making Management Tool for Transformer Explosion Prevention", ref. Arpiyp02a, 2006

[22]. SERGI, "Pressure Wave Propagation in a Transformer Tank: Numerical Simulations, Experiments, and Extrapolations", ref. Fre30rr09a, 2005.

[23]. N. THEVAND, "Contribution à l'Etude Numérique des Ecoulements Instationnaires et Visqueux de Mélanges Gaz-Particules Dilués", Ph. D. Thesis, Université de Provence, Méchanics & Energy, Marseille, France, 1999.

[24]. E. TORO, "Riemann Solvers and Numerical Methods for Fluid Dynamics", Press, ed. Springer Verlag, Berlin, 1997.

[25]. G. WALLIS, "One Dimensional Two-Phase Flow", Press, ed. Graw Gill Company, New York, 1969.