Overpressure test of an arc resistant power transformer

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SUMMARY

Hydro-Québec has implemented arc resistance requirements in order to obtain equipment tanks that can withstand specified levels of arc energy, while failing safely beyond, by requiring that failure happen at the cover level. Accordingly, ABB has been improving its arc resistant withstand capability by developing a new design methodology.

This paper presents the testing of a full scale three-phase power transformer tank (330 kV, 210 MVA) to verify that it meets the required arc resistant criteria. This transformer was designed using nonlinear static finite-element analysis and a specific rupture criterion established based on experimental and numerical studies. The tank was designed to withstand a 20 MJ, three-cycle low-impedance fault in oil, and fail at its cover in a safe and controlled manner above that amount of energy. It was tested by injecting pressurized air at sonic velocity in a manner that had approximately the same effects as those generated by arcing in oil. The test parameters were determined using explicit dynamic simulations reproducing the effects of an arc in oil. The general test plan consisted of two tests:

1) Design test: to verify that the tank could withstand the effects of a 20 MJ fault in 50 ms.
2) Rupture test: to verify that the tank would fail safely in a controlled manner at the tank cover for a fault energy level beyond 20 MJ in 50 ms.

This study demonstrated that it is feasible to request and design any power transformer to withstand high-energy low-impedance faults of short duration, which fail safely at the cover at fault energies above the design fault energy. The governing design principle to achieve this is based on increasing the tank flexibility while providing sufficient strength. It is noteworthy that the tank performed with a relatively good agreement with the finite-element and explicit dynamic simulations results. It is to be underlined that very few arcing tests have been reported worldwide and that, to our knowledge, the equivalent level of arc energy here is the largest ever used. The tests reported also demonstrate the limitations of a conventional pressure relief valve to protect such equipment under low impedance faults of short durations.

KEYWORDS

Transformer – Arc – Tank – Pressure – Rupture – Prevention– Testing

1. INTRODUCTION

Due to their explosive nature, low-impedance arcing faults in power transformers and reactors are an important area of concern for utilities and equipment manufacturers. Possible consequences of such faults include oil spills and environmental pollution, projection of parts and flammable material, damage to adjacent equipment, fires and safety threats.

In a survey of transformer and reactor failures on its 120-kV to 735-kV system, from 1965 to 1986, Hydro-Québec observed that the rate of explosion resulting in fire was on average 0.14% per year, and that the rate of fire on its 735-kV system (0.22%) was about 10 times higher than on its 120-kV system (0.02%) [1]. In view of the preceding, Hydro-Québec has implemented arc resistance requirements in order to obtain equipment tanks that can withstand specified levels of arc energy according to their voltage classes, while failing safely beyond, by requiring that failure happen at the cover level in order to minimize oil spills, propagation of fires, damage to adjacent equipment, and risk to workers in the surroundings [1], [2]. Accordingly, ABB has been considerably improving its arc resistant tank design to meet these requirements.

This paper presents the testing of a full scale three-phase power transformer tank (330 kV, 210 MVA) to ensure that it meets Hydro-Québec arc resistance requirements. This transformer was designed for arc resistance using nonlinear static finite-element analysis and a specific rupture criterion. It was then tested using an experimental methodology based on injecting pressurized air. The test parameters were determined using explicit dynamic simulations, in order that the tests reproduced adequately the effects of an arc in oil.

2. TANK DESCRIPTION AND DESIGN

The tank under consideration is a 330-kV, three-phase power transformer rated at 210 MVA; its geometric model is illustrated in Figure 1. The tank inner dimensions are 4.9 m length x 2.4 m width x 4.2 m height. This tank was designed using static nonlinear finite element analysis. Several design principles were used to prevent failure at locations most likely to rupture, such as weld joints at wall corners, bottom, cover, and ends of stiffeners [3]; the main governing principle used was to increase the tank flexibility while providing sufficient strength as discussed in [4], [5]. The design, the rupture criteria used, and related calculations of the tank under consideration are detailed in [6]. The tank design pressure was evaluated by calculation at 556 kPa, and its rupture pressure at 946 kPa.

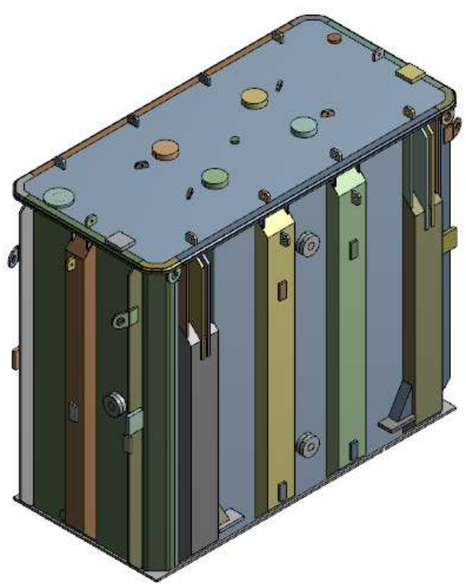

Figure 1: Geometric model of the transformer tank under consideration

3. EXPERIMENTS

3.1 Review of past work

Few experiments aimed at reproducing low-impedance fault conditions have been done on full-scale power transformers or reactors. To our knowledge, the first study ever done demonstrated the importance of tank flexibility and fault location in an oil-filled rectangular transformer, subjected to sudden discharges of nitrogen to reproduce the effects of an arc in oil [7]. Although not reported, the level of equivalent fault energy for these tests was obviously low, since the maximum recorded pressure was of the order of only 40 kPa.

Another investigation, using a special powder combustion vessel to replicate the effects of an arc in two 275-kV transformers (one shell form and one core form), demonstrated that such tanks, with appropriate reinforcements, could withstand an equivalent fault energy estimated at 11.2 MJ [5]. The pressure rises within these tests were compared to a simplified analytical model, and a good agreement was observed between the two.

The study reported in [8] describes several arcing tests in three different power transformers from 6 to 20 MVA that examined the spatial distribution of pressure within a tank, as well as the efficiency of a protective device against overpressures. The maximum arc energy in these tests was 2.4 MJ, with the majority being around 1 MJ or less.

From the preceding review, it can be inferred that the maximum energy yet used in a test has been about 11 MJ, while the majority of the tests reported have been at much lower levels of energy. It is also noteworthy that no tests have been reported describing the failure, under overpressure, of a full-scale power transformer.

3.2 Test plan

The general test plan consisted of two tests:

1) Design test: to demonstrate that a tank designed with the finite element method can withstand the effects of a 20 MJ fault in 50 ms.
2) Rupture test: to demonstrate that the tank would fail safely in a controlled manner by opening at the tank cover, as predicted by the finite element simulation, for a fault above 20 MJ of energy.

These tests were done on a single tank specimen. The rupture test was done following the design test, on the already deformed tank.

3.3 Methodology

The effects of an arc in oil were reproduced in our study by injecting pressurized air into the tank, in the same way that an arc generates a gas bubble by vaporizing the surrounding oil. The physics, assumptions and modeling of the mechanical effects of arcing in oil have been described in [9] and [10], among others, which are based on several studies that show the relationship between arc energy and the quantity of gas generated by oil decomposition [10]. In our study, the quantity of generated gas is assumed to be 85 cm^3 by kJ of arc energy at standard temperature and pressure, which value is in good agreement with several studies as reported in [10]. In the past, this value led to an excellent correlation between a numerical model based on it and experiments by different investigators on distribution transformers [10], [11]. With this value, it can be shown that 24% of the total electrical arc energy is actually transformed in the tank into mechanical energy, which generates the pressure rise. Therefore, the mechanical effects of an arc can be reproduced by introducing this fraction of energy as mechanical energy within a tank, which is done here by the injection of pressurized air. This method is based on the compressible flow of air from a pressurized pressure vessel and the determination of the tests parameters to obtain the equivalent effects of a 20MJ - 50 ms arc; determination of the tests parameters was done using explicit dynamic simulations as detailed in [6] and [12].

The main advantages of such a methodology are that it does not involve a high-power source, and that the amount of energy injected is controlled and repetitive, contrary to an actual arc, which has varying resistance from test to test [13].

3.4 Test set-up

The general test set-up is shown in Figure 2 and Figure 3. The active part of the transformer has been replaced by three gravel-filled hollow steel cylinders of similar dimensions. To avoid projection of parts, most of the external accessories are removed except for the pressure relief device (PRD), rated for opening at 70 kPa, and chains are installed to prevent large motions of the transformer during the tests. The tank is filled with water instead of oil to avoid soil contamination in case of a large spill, and since it is easier to handle.

A 312-litre pressure vessel, with high-working pressure, was used to inject the air, and the duration of injection was controlled by two electro-pneumatic valves in parallel, each mounted on 2-inch inner diameter pipe from the pressure vessel, converging together into a series of 3-inch pipes connected to the tank at the injection location. The fault location where the gas is injected was chosen strategically near the bottom of the transformer, centered on the longest wall, to demonstrate that, even for a fault farthest from the cover, the failure point would remain at the cover level as required. It has also been demonstrated through explicit dynamic simulations that a fault located at the center of the longest wall yields the most severe stresses on the tank [6].

The test instrumentation consisted of nine pressure sensors distributed on the walls and cover of the transformer, and one pressure sensor within the pressure vessel injecting the gas. 3D scans were performed before and after the tests in order to measure the tank deformation.

Figure 2: Test set-up

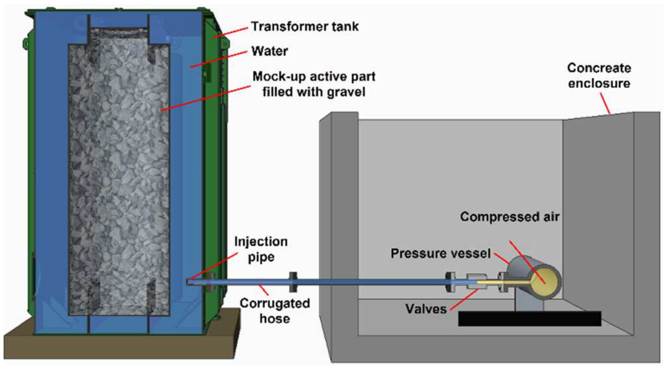

Figure 3: Schematic of gas injection system with respect to the tank

4. TEST RESULTS

3.1 Design test

The tank withstood the test without any rupture, projection of parts, or leak, despite significant (permanent) plastic deformations. Figure 4 shows the tank before and after the test.

Figure 4: Tank deformation before and after the design energy test

Figure 5 shows the pressure variation within the tank for the nine sensors, as well as their average; all signals shown were filtered using a 20-point moving average. Also shown is the average pressure within the tank from the explicit dynamic simulation performed to determine the test parameters as detailed in [6]. A good qualitative agreement is obtained between the dynamic simulation and the experimental results. The maximum average pressure from the test is 430 kPa, while the maximum average pressure from the simulation is 488 kPa; a difference of 13%. Also, the design pressure at 556 kPa determined from nonlinear finite-element analysis (see [6]) is confirmed as a safe design approach, since it is higher than the pressure obtained experimentally. Considering the phenomena involved, such as large plastic deformations over a short duration, as well as the idealizations inherent in the modeling, the agreement between the test and dynamic simulation is very satisfactory.

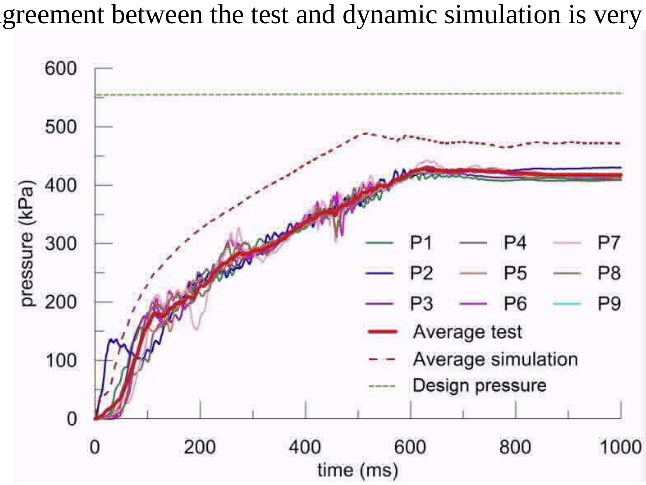

Figure 5: Design energy level test pressure measurements

Once the pressure in the transformer was relieved by the PRD operation, a scan of the transformer was performed. The tank's permanent displacements were obtained and compared with the pre-test scan, as shown in Figure 6. It is observed that the maximum displacement at the center of the wider wall is 108 mm. Figure 6 also shows the permanent displacements from the dynamic simulation results; the maximum observed is 112 mm. Comparisons of both figures and their maximum displacements demonstrate a relatively good agreement between the test and simulation.

Based on the comparison of pressure and displacements between test and simulation results, it can be concluded that the simulation methodology provided conservative, yet representative results.

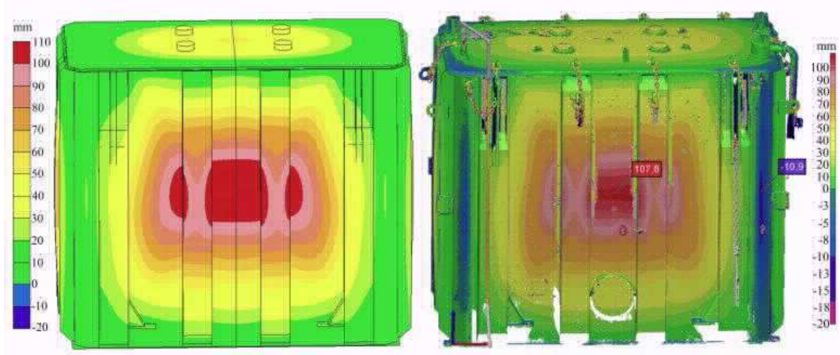

Figure 6: Permanent displacements after the design energy level test (left: simulation; right: scan measurement)

During the test, the PRD opening command was triggered at 57 ms, corresponding to an average pressure of about 50 kPa within the tank at this time. Video recordings showed that from that point on, water was forcefully ejected onto the ground through the vertical pipe attached to the end of the valve. After 1 s, the average pressure within the tank was 417 kPa, while it was 220 kPa after 5 s.

To investigate the effect of the PRD, the explicit dynamic simulation model, used to obtain the variation of pressure and the permanent displacements shown above, was modified by adding a 0.01 m^2 opening at the PRD location after 60 ms of air injection, as shown in Figure 7. This opening in the tank cover represents the PRD guiding pipe area of 0.008 m^2 and it assumes that the valve is fully open without any flow restriction.

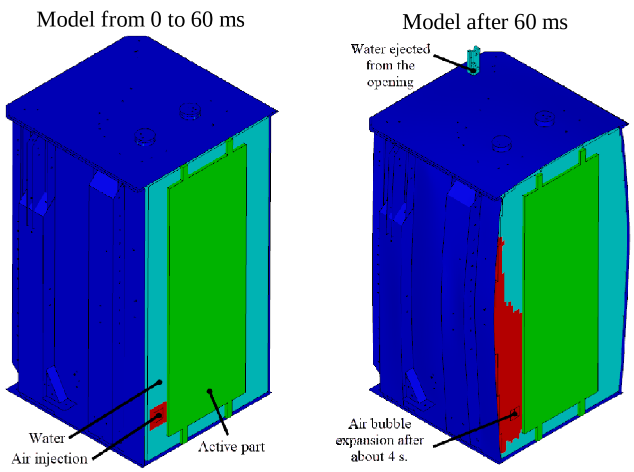

Figure 7: Tank cross section model for explicit dynamic simulation

The results of this simulation is illustrated in Figure 8 and shows that the it takes about 1 second before a noticeable a pressure drop happens due to the PRD effect ; however the experimental result shows that the actual pressure drop from the activation of the PRD appears noticeable after about 1.8 s. During the test, the PRD opening command was triggered at 57 ms ; its pressure relief effect is therefore rather slow in comparison to a 3-cycle fault duration (50 ms). Hence, for the transformer tank under consideration in our study, both the simulation and experimental results show that the PRD does not have a noticeable effect on the maximum tank pressure rise ; this observation is in good agreement with another numerical study on venting aperture in function of the arcing location [2]. It is therefore inferred that such devices cannot be used effectively as a protection for low-impedance faults of short durations.

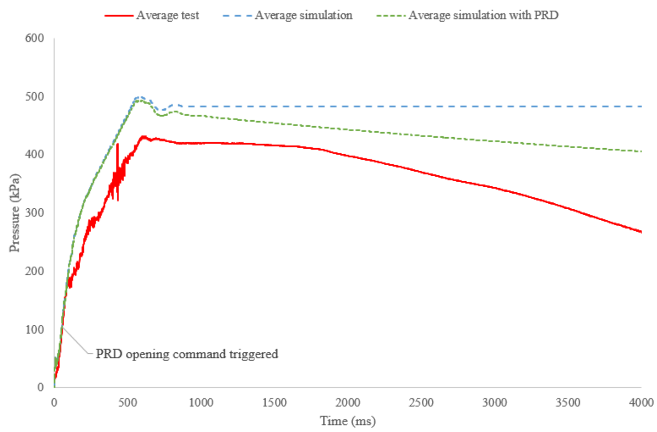

Figure 8: Tank pressure comparison with PRD

3.1 Rupture test

For this test, water was added to the already deformed tank, until it was completely refilled, replacing the volume change obtained from the design test. In order to generate rupture conditions within the tank and verify that it would fail at the tank cover as designed, the same test procedure was repeated but without reclosing the valves once opened, from the same initial pressure within the pressure vessel. This corresponded to a potential release of energy amounting to a 66 MJ fault for the complete emptying of the pressure vessel.

It was observed that the tank failed at the cover level (Figure 9), approximately 450 ms after the start of the injection process, at an average pressure of 486 kPa based on the peaks from the filtered signals at the nine measurement locations. The unfiltered signals revealed short time duration pressure peaks over 1,000 kPa at some locations but it is difficult to assess if these are real or simply related to the dynamic response of the sensors.

Figure 9: Rupture at the tank cover

Since the test started with an initially deformed tank which was refilled, and assuming that only a small amount of energy is needed to recover the elastic deformations in the tank to continue the permanent deformation process, it was determined that this tank could withstand a fault of about 30 MJ in 50 ms before rupturing [6]. Additional dynamic simulations following the same steps as the two experiments here (first experiment, tank refilled, second experiment) supported this hypothesis. A dynamic simulation of 30 MJ in 50 ms yielded a peak pressure of about 1,000 kPa in the area close to the cover, in good agreement with the 946 kPa rupture pressure obtained from the tank design static calculations.

From the difference of approximately 10 MJ between the energy level at rupture (30 MJ) and the design energy level (20 MJ), it can be concluded that this particular design possesses a good safety margin before rupture at the cover level.

CONCLUSIONS

This study demonstrates that it is feasible to request and design any power transformer to withstand high-energy low-impedance faults of short duration, which fail safely at the cover level at fault energies above the design fault energy. The governing design principle to achieve this was based on increasing the tank flexibility while providing sufficient strength. The tank was designed using nonlinear finite-element analysis, using a rupture criterion that is safe from a design point of view, as supported by the experiments reported here. The tests were designed using explicit dynamic simulations in order to reproduce the effects of an arc in oil by injecting pressurized air. It is noteworthy that the tank performed with a relatively good agreement with the finite-element and explicit dynamic simulations results. This study also showed that pressure relief device (PRD) cannot be used effectively for power transformers as a protection for low-impedance faults, due to their slow response relatively to the fault duration, as the quantity of gas they can evacuate in a short amount of time is small in relationship to the important volume of power transformers. The energy levels used in the tests reported are, to our knowledge, the largest ever reported.

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