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A Station Service Voltage Transformer Designed and Tested to Withstand a Severe Internal Arc Fault

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SUMMARY

The risk of an internal arc fault of an oil-filled transformer is rare but could create an extreme hazard for both employee safety and the environment due to oil spilling and fire. As oil is an incompressible material, the pressure caused by the internal arc fault can be enormous. This pressure could potentially rupture the transformer tank wall, shatter the high voltage bushings, and eject shrapnel-like fragments of metal and porcelain. This sudden pressure rise would be greater in a small size transformer (e.g., an instrument transformer), as compared to a large power transformer of the same voltage class, due to the significantly smaller tank volume.

A numerical method was developed to design a power transformer tank to withstand an internal arc fault. The nonlinear internal pressure during an arc fault was calculated and simulated to analyze a transformer tank structure. This method was utilized to design a 138 kV, 100 kVA Station Service Voltage Transformer (SSVT). The tank structure was designed to withstand an arc fault with energy up to 4 MJ, as recommended for a power transformer tank at the same voltage class of 138 kV [1]. The calculation method was also adjusted to include the effect of the Pressure Relief Devices (PRD) on the transformer during an arc fault. Inputs for calculation were from the internal arc fault test setup specification per IEC standard 61869-1, version 2017 for instrument transformers (*Part 1 – General requirements*), at the most stringent level: Class II, Stage 2.

A full-size prototype of an oil-filled SSVT was built and tested per the internal arc fault test, at a fault current of 40 kA for a duration of 300 milliseconds (0.3 s). The SSVT withstood the pressure from the internal arc fault, with all parts remaining intact. This successful test demonstrated that the newly developed, highly accurate, numerical method could be applied for all sizes of transformer tanks, from large power transformers down to small station service voltage transformers.

Small transformers, such as instrument transformers and station service voltage transformers, are used as protection equipment for large power transformers. However, there is no protection equipment that can be applied to these smaller, typically lower-cost devices. Therefore, both IEEE and IEC standards for instrument transformers recommend internal arc fault testing for these products to improve the capabilities of withstanding an internal arc fault. This paper will also discuss the pros and cons of the internal arc fault withstand test requirements.

KEYWORDS

Station Service Voltage Transformer, Power Transformer, Internal Arc Fault, Tank Rupture, Rupture Prevention, Finite Element Method

1 INTRODUCTION

An internal arc fault of an oil-filled transformer is an extreme hazard for both employee safety and the environment due to oil spilling and fire. As oil is an incompressible material, the pressure caused by an internal arc fault can be enormous. This pressure could potentially rupture the transformer tank wall, shatter the high voltage bushings, and eject shrapnel-like fragments of metal and porcelain. This sudden pressure rise would be faster in an instrument transformer as compared to a large power transformer of the same voltage class, due to the significantly smaller tank volume.

One of the possible and effective risk mitigation approach is a tank designed to deform and, thereby, withstand a specified arc energy level; the design should include a fail-safe point if the energy goes beyond this limit [3] [4]. This solution was developed for power transformers and validated by a large series of destructive experiments and numerical simulations [5]. In 2017, the test of a full-scale, three-phase power transformer rated at 330 kV and 210 MVA, (designed per technical specifications from Hydro-Québec) proved this numerical method by withstanding arc energy equivalent to 20 MJ [6]. In this paper, the simulation technique was applied to a 100 kVA Station Service Voltage Transformer (SSVT) as validation before an internal arc fault test.

The internal arc fault test is a special short-circuit test. The test is the extreme occasion of a short-circuit event when the circuit is shorted directly from the high voltage to ground, inside a tested transformer. Therefore, the impedance of the transformer is bypassed. The fault current increases unlimitedly to near the fault capability of the system. The value of this fault current is many times higher than a normal short-circuit current from a secondary short-circuit test where the transformer's impedance is included in the circuit.

Both IEEE and IEC specify the internal arc fault test as optional for instrument transformers. The test acceptance is categorized as "Classes" for the tanks' mechanical strength, and as "Stages" for the fault duration.

2 SSVT DESIGN

2.1 General description

Station Service Voltage Transformers, or SSVT, are a special class of transformer. The main and original purpose of an SSVT is to provide a power source to operate the equipment in a power substation, such as lighting, firefighting pumping, and equipment in the control rooms. The electricity provided by an SSVT is transformed directly from the inbound high-voltage line, independent from any additional power sources (which might be not available).

An SSVT is a hybrid product which fills the gap between Power Transformers and Distribution Transformers. These fulfill a need for high or extra-high (up to 550 kV in United States) primary voltage distribution transformers, but at a low power rating (less than or equal to 500 kVA). The SSVT was developed based on Instrument Transformers technology which encompasses high-voltage but low-power characteristics.

The SSVT-IPC (SSVT for Internal Arc Protection Class) model is designed to meet the stringent requirements for Internal Arc Protection Class II, Stage 2. It utilizes a polymer insulator, significantly reducing the risk of fire and projectiles resulting from an internal arc, as compared to the traditional porcelain bushing which is the largest cause of transformer fires [2]. For additional protection, the transformer is equipped with two Pressure Relief Devices (PRD) which release the pressure and reseal afterward. Lastly, the tank withstands a resistance evaluation through the numerical process described below.

2.2 Geometry used for numerical simulation

The 3D geometry of the tank is first simplified for the numerical simulation by excluding small components: drain valves, nameplate, neutral bushing, PRD. The high voltage bushing itself is also neglected, but its flange remains for a joint-tightness evaluation and its stiffness effect on the cover. From preliminary simulation results, it is observed that inside parts of the tank have limited influence on the tank movement, and for this reason the magnetic core steel, coil assembly, and insulating materials are removed. However, the core influences the pressure distribution by making a barrier between the bottom and top section of the transformer; this is considered when applying the load.

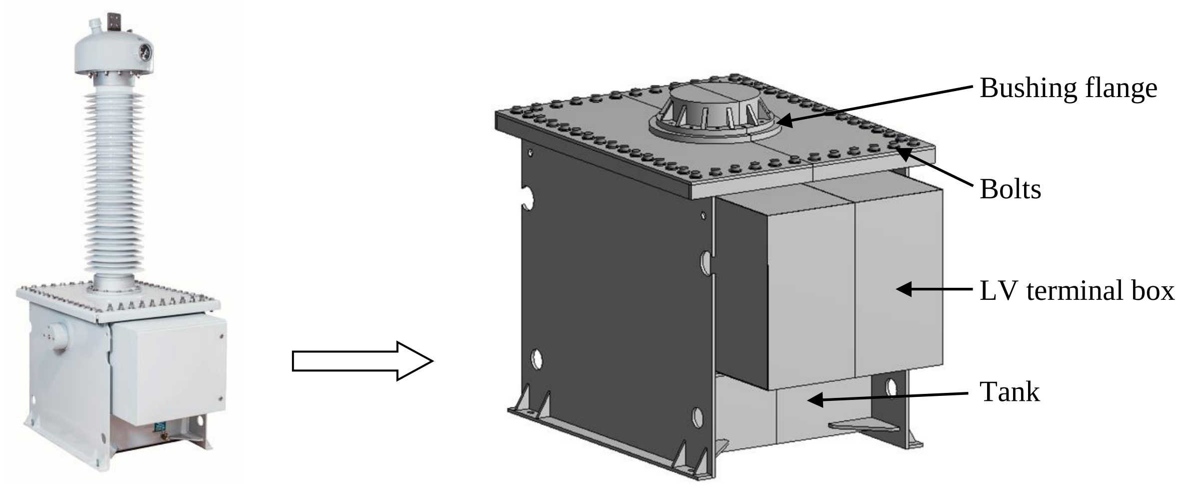

Figure 1: The SSVT (left) and the simplified model for simulation (right)

2.3 Material properties

The applied software takes into account the plastic deformation of the material during the simulation. The tank, bolts, and welds are assigned with their corresponding, true stress-strain curves to define the elastic and plastic domain in the same manner as was done in the full-scale, three-phase power transformer design with experiments [6]. Likewise, the strain-based rupture criterion is used to predict failure according to the ultimate strain of the material, and therefore ensure resistance of all parts.

2.4 Mesh

The tank is meshed with solid-shell elements to enhance the accuracy of the in-plane bending results, but high-order, 3D, solid elements are used for the bolts and bushing. The tank mesh size has been refined for the low voltage terminal box and small parts such as bolts or gaskets. A symmetry plane boundary condition was utilized to reduce the model size to a total of 132,000 nodes. Additionally, the high-strain regions were identified for further investigation. They were submitted to a sub-modeling analysis where the mesh was refined for proper use of the strain-based rupture criterion.

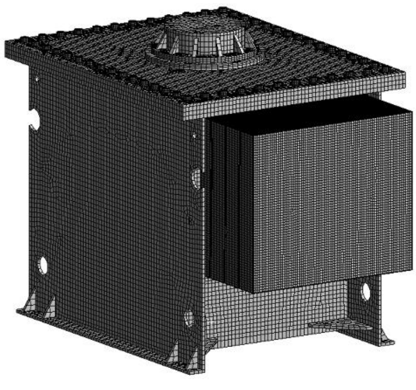

Figure 2: Transformer mesh

A welded cover is common for power transformers and is recommended per the IEEE transformer standard C57.12.10. A welded cover eliminates the worst case of bolt-head projectiles in the event of excessive arcing pressure. However, due to smaller sizes and different materials (i.e. cast aluminum in many popular designs), tank covers for instrument transformers in general, and specifically SSVTs, are normally sealed by bolting.

A pretension torque is applied to all bolts. This pretension torque is applied as a preload input for the simulation.

2.5 Arcing pressure load

The rupture-resistant tank design is based on the evaluation of the arc energy [2]. The arc energy is calculated using the following equation:

$$E = 0.9\ V.I.t \qquad \text{(MJ)} \tag{1}$$

V: Arc Voltage (kV)
I: Arc Current (kA)
t: Arc duration (second)

Per IEC standard 61869-1, the stringent test requirements for the substantial protection level of Stage 2 are 40 kA (r.m.s) fault current for a duration of 0.3 s. The arc voltage can be predicted based on the arcing distance [7]. From the SSVT model, the calculated arc voltage was approximately 0.4 kV. Therefore, the target withstand arc energy was determined to be approximately 4.3 MJ.

This arc energy is converted into a steady pressure with *Equation (2)* below. The pressure was used as a mechanical load in the static simulation [3]. *Equation (2)* has been proven to be conservative and safe for design applications when comparing the calculated results with the experimental results from a large power transformer [6].

$$P_d = F\left[100\sqrt{0.25+\frac{k.E}{100.C}}-50\right]+P_h \tag{2}$$

P_d: design pressure (kPa)
E: arc energy (kJ)
k: arc energy conversion factor (5.8 x 10^{-4} m^3/kJ)
C: tank expansion coefficient (m^3/kPa)
F: dynamic amplification factor
P_h: hydrostatic pressure (kPa)

2.6 Simulation and result analysis

The numerical simulation, comprising the bolt pretension load, the hydrostatic pressure, and the static uniform pressure (arc), is applied to the selected walls by taking into account the separation created by the core. The tank displacement results are retrieved to calculate the expansion coefficient C of Equation (2) as a function of the inner pressure. Then, the entire strain results are analyzed to ensure the tank can withstand the design pressure P_d.

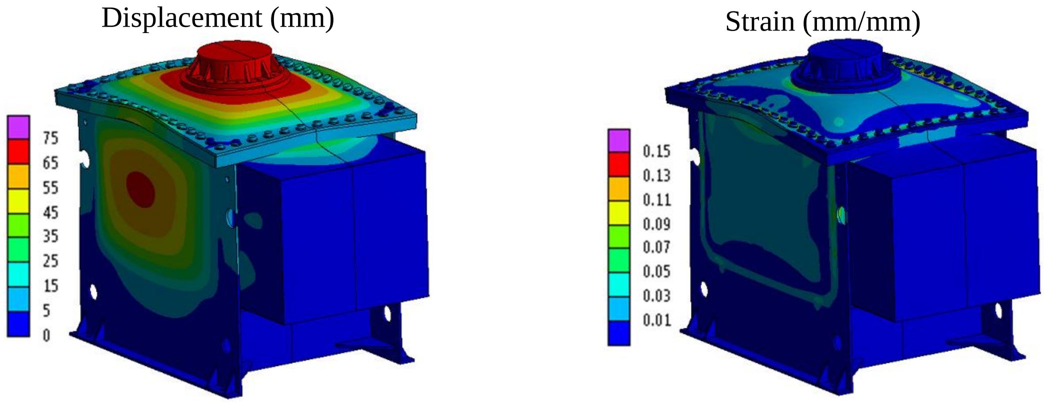

Figure 3: SSVT simulation results at the designed pressure

This design process requires several iterations of modifications to improve the initial tank design and ensure it could resist an arcing energy of 4.3 MJ. Results from the same nonlinear finite-element analysis applied to a large power transformer aligned with the prediction of the test pressure at rupture (deviation estimated around 6%) [6]. The comparison between the simulations and the experiment in a power transformer also confirms that the calculation approach has a high margin from the design point of view.

2.7 Use of Pressure Relief Device (PRD)

A resealable, spring-loaded PRD is installed on liquid-immersed power transformers as per IEEE standard C57.12.10 requirement. This valve offers tank protection against a low rate of pressure rise. However, in the event of a high-energy fault, investigations concluded that PRDs cannot prevent tank rupture [3], [8]. This conclusion was confirmed during experiments on a full-scale power transformer [6].

The situation is different for SSVTs. Because of the small tank size, a fault would be close to the PRD, which would relieve the pressure more effectively. The arcing gas generation rate was determined to be 85 cm^3/kJ at Standard Temperature and Pressure (STP). This value has shown good correlation between numerical and experimental studies on distribution transformers [9]. Also, from this investigation, a constant gas temperature (2000 K) and chemical composition (70% H_2, 10% CH_4, 15% C_2H_2 and 5% C_2H_4), combined with the ideal gas equation of state, can be used to calculate the gas expansion properties. The tank pressure, assumed to be constant and uniform, is derived from *Equation (2)*, but with a constant expansion coefficient, C, for simplification.

The effects of PRD relief are added at an average activation time of 57 ms. The oil mass-flow rate is calculated using the Bernoulli equation, assuming the oil flow to be incompressible. The convergent tank pressure is calculated via an iterative process. The resealable, spring-loaded valve reflects an important pressure loss [8] on the system. This flow restriction is estimated (see

Figure) by comparison with a full-scale, three-phase power transformer experiment [6]. In addition, the pressure drop slope of this analytical approach has a good correlation with the explicit dynamic simulation of the test, during which the PRD valve is triggered to vent the tank cover. This numerical method has been detailed in [10].

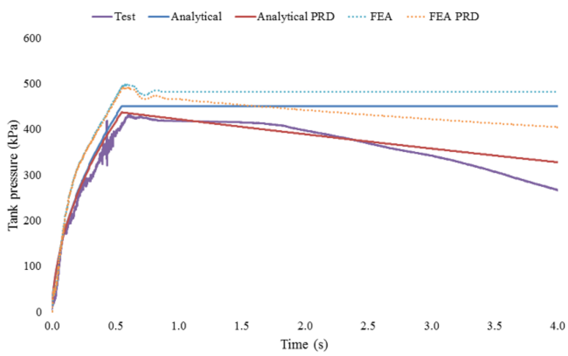

Figure 4: Comparison of the analytical calculation with an explicit dynamic simulation and experiment of a 330 kV power transformer experiment [6]

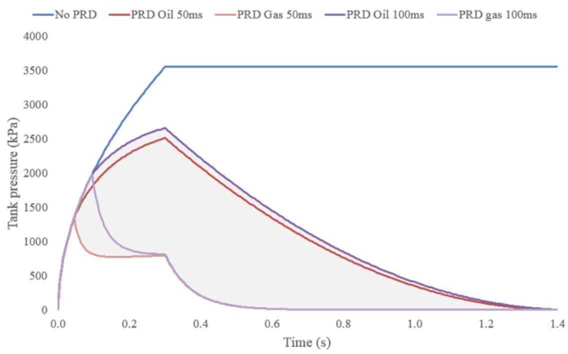

Figure 5: Comparison of the PRD relief and reaction time from analytical calculation for SSVT fault (40 kA for 0.3 s)

In the event of arcing gas discharge through the PRD, the flow rate of mass and energy is calculated with thermodynamic equations assuming an isothermal process. The high speed of gas through the PRD plane is limited to the velocity of sound. This mass flow is said to be choked.

Figure 5 compares the calculated tank pressure for the SSVT (arcing fault of 40 kA for 0.3 s) without a PRD versus with one PRD, activated at 50 and 100 ms, in both oil and gas insulation. It is observed that the PRD has a higher effect in gas than in oil. From this analytical valuation, it is concluded that PRDs have a beneficial relief effect for such arc energy levels on SSVTs. The use of PRDs would lower the tank pressure into the gray zone of the graph in Figure 5.

3 SSVT TEST

An SSVT prototype was built based on the modifications suggested from a mechanical strength analysis using the method described above.

3.1 Standard requirements

The SSVT test was mainly based on the IEC standard 61869-1, *Instrument transformers - Part1: General requirements*, as the IEC standard is more stringent and has more test details than IEEE standard C57.13.5 (*IEEE Standard for Performance and Test Requirements for Instrument Transformers of a Nominal System Voltage of 115 kV and Above*) At the time of this paper, a standard for SSVTs was being developed (IEEE C57.13.8), and details of the internal arc fault test were still in discussion.

3.2 Test acceptances

Both standards, IEEE C57.13.5 and IEC 61869-1, have the same classification for passing an internal arc test. Class I allows the tested transformer to shatter during the test, but the projected fragments must remain within a determined containment diameter around the tested unit. Class II qualification requires the transformer remain intact during the test, although any protection equipped devices, such as a PRD, can be activated. Therefore, oil spilling and fire are also allowable. IEC 61869-1 also specifies Stages for the arc durations. Stage 2, for a long duration, is a minimum of 300 ms (0.3 s) for a test current of 40 kA and above, or 500 ms (0.5 s) for a test current less than 40 kA. IEEE C57.13.5 does not specify stages; it only requires the test duration minimum of 200 ms (0.2 s).

3.3 Test setup description

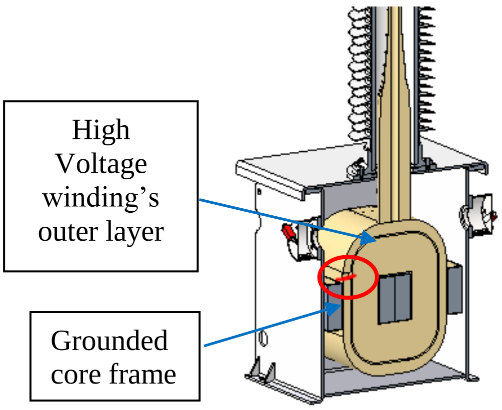

Figure 6: Location of the wire fuse for the internal arc fault test for SSVT

The SSVT was connected to the generator (power source) using large copper bars with 1000 mm^2 cross section [11]. The high voltage lead from the test circuit was connected to the primary terminal on top of the SSVT's dome. The neutral lead was connected to the ground pad on the SSVT tank's side wall.

The arcing location was set using a wire fuse between the high voltage winding's outer layer and the grounded core frame. The fuse was a copper wire, size AWG-16 with a cross-sectional diameter of 1.3 mm (see Figure 6).

The tested SSVT was mounted on a stand (height not less than 500 mm), to mimic standard working conditions. The test would be considered a failure if any fragments were ejected outside the containment diameter. This containment diameter was determined by the following equation:

Diameter = 2 x transformer height + transformer diameter (or largest horizontal dimension) (3)

3.4 Test results

The test was successfully conducted at an independent laboratory [11]. The test voltage was 0.8 kV at the source. The voltage-drop during the arcing, or arc voltage, was estimated in the range of about 0.3 to 0.5 kV. The test current was 40.3 kA (r.m.s.), with its peak at 68.3 kA, for a duration of 320 ms or 0.32 second (see Figure 8).

The PRD switches were activated quickly. The PRD closest to the arcing site was activated at 11 ms, less than one cycle, while the PRD farther away from the arcing location activated after 32 ms, or less than 2 cycles (see Figure 9). The PRDs completely resealed after approximately five to six seconds. A very limited amount of oil was evacuated through the PRDs. The SSVT tank remained intact; no visual damage was found from outside the tank. The very short activation time of the PRDs proved that using PRDs is very affective for small size transformers such as SSVTs.

Figure 7: Pictures 1a (left), 1b (top right), and 1c (bottom right): The SSVT was intact after the internal arc fault test (1a). A minimum oil volume was evacuated, most of the oil volume was maintained inside the tank (1b), and the PRD switches were activated rapidly (1c).

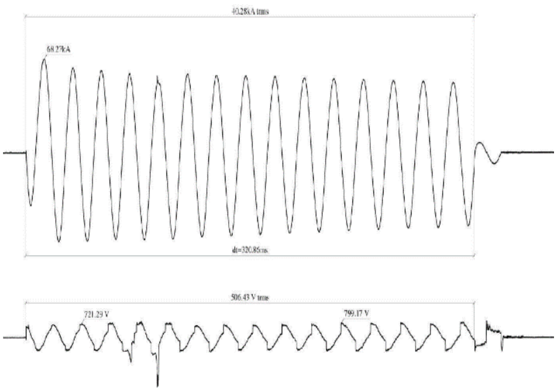

Figure 8: Test Current and Voltage oscilogram

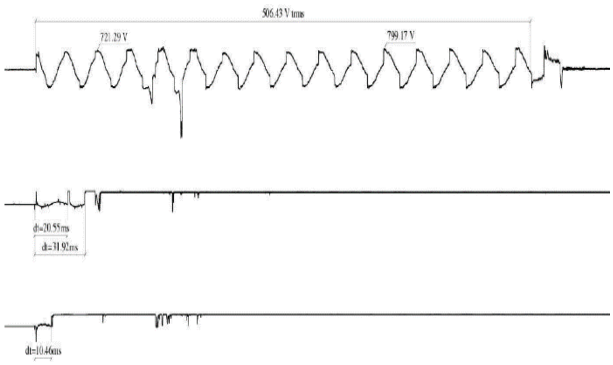

Figure 9: PRD activation times (two signals below)

3.5 Pros and cons of actual tests

The SSVT is a unique product which is still in its developing phase. The size and structure of SSVTs are different from one manufacturer to another. Previous experience from dozens of instrument transformer internal arc fault tests was not directly applicable for this situation. The power ratings for SSVTs are much higher than those of regular instrument transformers, which have burdens as high as a few kVA maximum. As a result, internal arc faults in SSVTs are comparatively much more violent. This requires a strict adherence to safety during test setup with regard to personnel and equipment and may create extra work cleaning up after the test.

Ideal test conditions would be inside a test cell well-equipped with fire extinguishing and oil collecting systems. However, a normal test cell might be not large enough for such a test where the results, especially at stage I, may require an allowable diameter for expelled fragments which might be larger than the test cell dimensions. On the other hand, testing outside in a large, open area allows for easy observation of any repelling fragments, but lacks the fire-extinguishing and oil-collecting systems. That might violate one or more local safety and environment codes. The fundamental requirements of the test have globally limited the number of available independent laboratories which might be able to perform the tests. This results in one of the single, most expensive transformer tests.

Furthermore, the arcing fuse setup inside the transformer is also important for the test success. If the parts that the fuse bridges over are not strong enough, the gap between the parts would open widely and quickly, causing a surge in the arc voltage. This surge, in turn, would activate the test circuit protection to shut down regardless of whether or not the arcing duration has met the requirement yet. On the other hand, the arc may cause localized, rapidly-increasing pressure, which might back-fire on the arc, and cause it to self-extinguish before meeting the required duration. Because of these issues, the internal arc test has a low first pass yield of success. This may cause the test to be even more expensive if repetition is required.

Due to the dense internal structure, or shorter possible arcing distances in SSVTs, the arc voltage is likely lower in SSVTs, compared to power transformers of the same voltage class. Therefore, the energy levels of the suggested arc fault withstand capability might be proportionately reduced for the smaller sized instrument transformers (e.g., SSVTs). The tested SSVT design withstands 4 MJ of arc fault energy as suggested for 115 to 138 kV rated voltage power transformers [1]. This design could effectively serve the whole SSVT family from 69 kV to 161 kV rated voltage.

4 CONCLUSION

Oil-filled transformer tanks designed to protect against internal fault can be achieved from nonlinear numerical simulations. The method developed for power transformers has been successfully adjusted to a Station Service Voltage Transformer (SSVT) tank. Also, the analytical calculations show that a Pressure Relief Device (PRD) might not faultlessly reduce a tank pressure to withstand a high-energy fault within a power transformer but could be highly effective in a small SSVT.

An actual SSVT prototype was built with several design improvements based on the simulations. The prototype successfully passed the internal arc test at the highest Class II, for the longest duration Stage 2, which translates to a 40 kA fault current for a 300 ms duration.

The simulations helped the SSVT design pass the internal arc test at its first attempt.

5 ACKNOWLEDGMENT

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