Nomex® aramid paper provides a 220 °C insulation class that limits the potential thermal degradation of windings due to insufficient ventilation in the vault or direct burial

ABSTRACT

The SIDT (solid insulation distribution transformer) was developed to provide an alternative solution to replace liquid-filled transformers that might leak oil to contaminate surrounding soil and underground water. Restoration costs could be higher than installing a new transformer. The SIDT has no insulation oil but uses solid materials as an insulating and cooling medium, so there is no risk of an environmental problem. Several special tests described in this paper proved a reliable performance of SIDT. This paper provides technical information on a submersible, solid insulation distribution transformer for building a safe and eco-friendly underground distribution system.

KEYWORDS:

development, distribution transformers, manufacturing, solid insulation, testing

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Solid insulation distribution transformer

Introduction

Underground transformer with insulating oil as the insulating and cooling medium has been used since the early 1960s. It uses mineral oil, as well as ester and silicone oil, and the enclosure is made of corrosion-resistant stainless steel. Underground, submersible and environmental conditions in which the transformer is installed are exposed to sewage, rain and surrounding

The main advantages of APG casting over conventional casting are lower shrinkage and lower mechanical stress, good material homogeneity and fast gelation due to controlled temperature throughout the mould

chemicals. If liquid-filled transformers leak due to corrosion or other damage to the tank, liquid can contaminate the surrounding soil and underground water. In addition, the potential risk of explosion and fire caused by the transformer failure is a fire spreading factor, which further increases the safety concerns. Therefore, there has been a demand for new technology to solve these problems. SIDT has many advantages such as eco-friendliness, safety and reliability. It can be installed not only for underground and submersible applications but also for areas impacted by natural disasters such as mountains, as well as wildfire, hurricane, typhoon and flood-prone areas.

1. Insulation system

The insulation system is made entirely of solid materials and does not use liquids or gases. The use of Nomex® aramid paper provides a 220 °C insulation class that limits the potential thermal degradation of windings due to insufficient ventilation in the vault or direct burial.

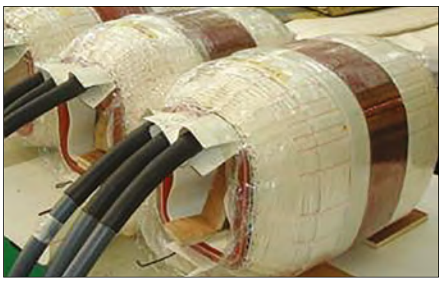

Figure 1. HV and LV coils

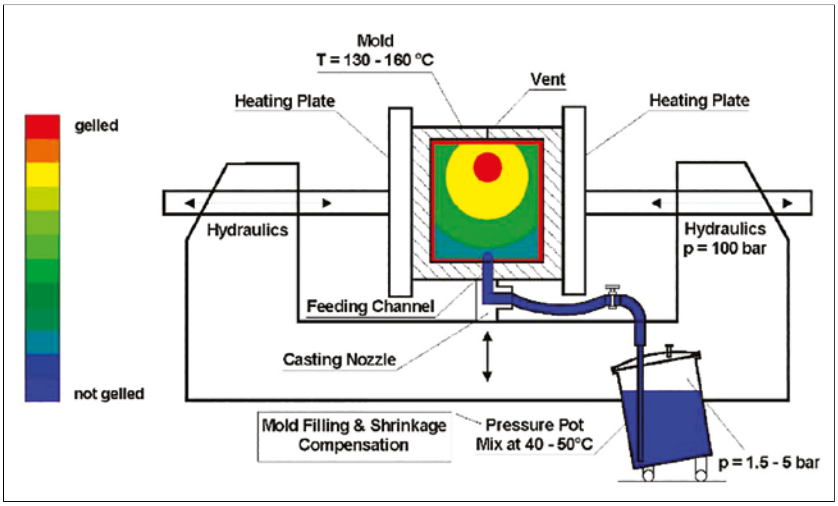

Figure 2. APG system

Epoxy resin improves the structural integrity of the transformer and creates a self-supporting structure for the core, coil and terminals.

The optimized ratio of mineral filler and epoxy resin reduces the mechanical stress caused by the thermal expansion and contraction of copper or aluminium conductors. The combination of high thermal conductivity of 0.7 W/mK of epoxy resin and a low load loss design eliminates the need for a separate external radiator for heat dissipation. In addition, the distance from low voltage to high voltage can be relatively small due to grounded high voltage and layer winding in the HV coil.

2. APG casting

After the LV coil and HV coil are completed, they are preheated to remove any moisture and then filled with epoxy resin using the APG (Automatic Pressure Gelation) casting method under vacuum. The main advantages of APG casting over conventional casting for a cast resin transformer are lower shrinkage and lower mechanical stress, good material homogeneity and fast gelation due to controlled temperature throughout the mould.

Solid insulation distribution transformers are designed to have a compact size by integrating HV and LV coil and meeting the high-efficiency requirements

3. Configuration

The primary terminals, 200 A bushing wells conforming to IEEE 386 [1], are cast directly into the coil with epoxy resin, eliminating the need for a separate part.

The secondary flexible cable is connected directly to the LV coil, eliminating the need for separate auxiliary bushing. The lifting and support brackets are assembled outside SIDT to prevent transformer corrosion.

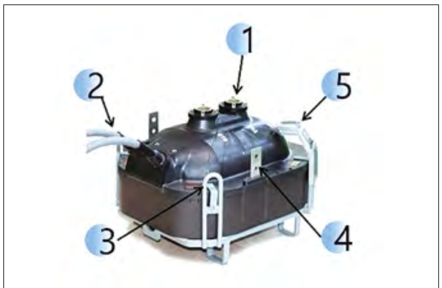

Figure 3. Basic Configuration
(Photo: Cheryong Electric)

❶ MV 200 A bushing well
❷ Flexible LV cables
❸ Support with lifting eyes
❹ Ground plate
❺ Parking stand

4. Compact size and high efficiency

SIDT is designed to have a compact size by integrating HV and LV coil and meeting the efficiency requirements of the United States' DOE 2016. The table below is taken from an actual test report from a power utility in California. The test result exceeds both requirements of liquid-type and dry-type transformers.

(Note: 167 kVA SIDT ranges from 99.32 % to 99.34 %.)

Long-term reliability is a must for a lower maintenance design, with a problem-free performance even in extreme environments such as immersion conditions

Table 1. Efficiency in 2016 DOE standards

kVA	Liquid-type	MV dry-type	Measured value of SIDTs
50	99.11	98.42	Min. 99.14
75	99.19	98.57	Min. 99.20
100	99.25	98.67	Min. 99.31
167	99.33	98.83	Min. 99.32

5. Development tests

Long-term reliability is a must for a lower maintenance design, with a problem-free performance even in extreme environments such as immersion conditions. Therefore, accelerated ageing tests, thermal shock tests, immersion tests, cold load pickup tests, fire behaviour and destructive short circuit tests were conducted to secure performance suitable for the harsh operating environment. The series of exams are listed below.

Product spec

- 1P, 75 KVA,
  12000 GrdY / 6930 V-240 / 120 V, 60 Hz
- Manufacturer: Cheryong Electric

Special tests

- cold load pickup test
- thermal shock test
- submersion and chemical resistance test
- destructive test
- fire behaviour test

5.1. Thermal shock test

A custom thermal shock test was performed to verify the environmental adaptability in cold weather. The test was performed down to -40 °C, which is lower than -25 °C for operation, but the same storage temperature of -40 °C at the C3 level is described in IEC 60076-11 [4]. The specific test includes the following:

- Put the transformer in the air conditioning chamber and lower the temperature inside the chamber so that the temperature inside the transformer reaches -40 °C.
- When the internal temperature of the transformer reaches -40 °C, apply 2 p.u. of the rated current at the rated voltage for 1 hour.
- While applying the above current, keep the internal temperature of the transformer below -40 °C.

Figure 4. SIDT in the thermal shock chamber

To ensure safety in case of a fire, the fire behaviour test of IEC 60076-11 was conducted by CESI, and the solid insulation distribution transformer passed F1 class

- After that, set the temperature inside the chamber to room temperature.

After the above process was completed, the transformer was taken out of the chamber and left to reach room temperature, and the following series of tests were conducted to confirm that there was no problem with the product.

- Visual inspection
- Power frequency withstand voltage test
- Induced withstand voltage test (no PD test followed)

5.2. Fire behaviour test

To ensure safety in case of a fire, the fire behaviour test of IEC 60076-11 [4] was conducted by CESI, and it passed F1 class.

In the case of the fire behaviour test, a dry-type transformer is usually tested with one HV and LV coil on the test core, whereas SIDT is implemented as a real product.

The F1 class is fire-resistant, meaning means that only a minimal amount of toxic substances are released in case of a fire. It is stated in the standard that the use of F1 class transformer is recommended when there is a risk of fire.

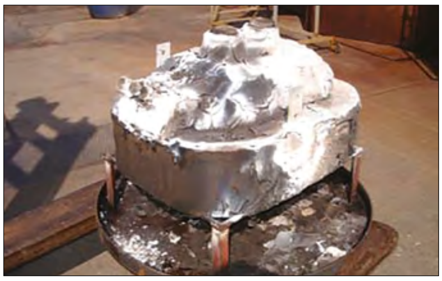

Figure 5. SIDT after fire behaviour test

5.3. Destructive short circuit test

A destructive short circuit test was conducted to confirm safety from fire and explosion. The purpose of a non-standard, destructive short circuit test is to prove safety even in case of transformer failure caused by a short circuit incident. To maximize the short circuit current, the secondary terminals (cables) were shortened. The pass and failure criteria were defined by the customer as no parts have blown due to the test. The test was performed at the rated primary voltage of the transformer, i.e., 6.93 kV, 60 Hz. The following is a summary of events recorded during the above test (time duration is approximate):

- Initial primary current was 452 A RMS.
- Short circuit current at secondary was approximately 13 kA RMS.

A destructive short circuit test at the nominal voltage was conducted to confirm safety from fire and explosion

- After 15 seconds, the secondary conductors started to smoke.
- After 22 seconds, the secondary conductors started to burn.
- After 26 seconds, venting started.
- After 37.7 seconds, a short circuit was established between primary terminals.

After a long-term destructive short circuit test of about 38 seconds, a visual inspection confirmed that there no transformer parts blew apart due to the test or fire. The following is a photo of SIDT after the destructive short circuit test.

Figure 6. SIDT after destructive short circuit test

5.4. Accelerated ageing test

An accelerated ageing test is performed to predict the life of the actual transformer within a short time. After conducting an ageing test equivalent to 40 years based on the customer's load profile, an induced withstand voltage test, a power frequency withstand voltage test, and a partial discharge test are performed to confirm that the SIDT has passed the test.

The sequence of the accelerated ageing test is as follows:

- Step I: performing the accelerated ageing test to predict the life of the actual transformer within a short time
- Step II: performing partial discharge measurement
- Step III: performing a cycle for a cold load pick-up

The test mainly repeats 5 cycles, each cycle consisting of 3 steps. Procedures in all steps, except in step I, are equally repeated through the whole test to confirm that the SIDT has passed the test.

The test was successfully conducted by KERI (Korea Electrotechnology Research Institute) to confirm high reliability with long lifetimes.

Table 2 shows SIDT ratings commercialized to cover the demands for distribution networks in North America. Single-phase units are currently available, and three-phase units are about to be launched for commercial sale.

After conducting an accelerated ageing test of equivalent to 40 years based on the customer's load profile, various tests are performed to confirm that the solid insulation distribution transformer is still working properly

Table 2. SIDT ratings

Capacity [kVA]	25, 50, 75, 100, 167
LV [V]	240/120, 480/240, 230, 277, 347, 480
HV [V]	4,160 GrdY / 2,400 ~ 24,940 GrdY/ 14 400
BIL [kV]	60 ~ 125
% Z [%]	1.0 ~ 3.5


Figure 7. SIDT installed at KEPCO in 2010

6. Field history

After the development test in May 2010, ten (10) single-phase 100 kVA, 22900 GrdY / 13200 V–230 V transformers were installed in a concrete structure at KEPCO (Korea Electric Power Company) and have been operating until now. KEPCO specification is for 3-phase, 4-wire, GrdY or a single-phase, and a full range current-limiting fuse with overload protection function is installed at the front end of the high voltage side for the system protection.

In the meantime, thousands of underground SIDTs have been installed in North America. Underground vault structures vary by power utilities. Some power utilities have adopted an open bottom-type structure to facilitate drainage of influent water, and some have adopted a hinge-type lid structure for the convenience of installation at the top.

Fig. 9 shows the first three-phase SIDT manufactured and delivered in 2020 to a power utility in North America. The difference from a single-phase one is that the shell material is made of stainless steel to prevent corrosion and is finished with a corrosion-resistant coating. RIV (Radio Influence Voltage) test is a special test that has been conducted based on IEEE C57.12.90 [6] instead of a PD (partial discharge) test at the customer's request.

Conclusion

The SIDT offers a unique set of performance characteristics that cannot be found with any other solution. The ability of a dry-type transformer to be used in both a vault or direct burial installation allows for added flexibility. The SIDT has proven reliable in the networks of utilities across the world and provides more pleasing aesthetics than a pad-mounted solution. The performance has been proven through the various required special tests, including the PD test. The resiliency of the SIDT to both immersion during floods and inherent flammability resistance in a potential wildfire allows for applications in the most extreme environments. Additionally, the total installed cost can be lower than a Class K insulated liquid-filled transformer since there is no need for containment nor remediation in the case of a leak.

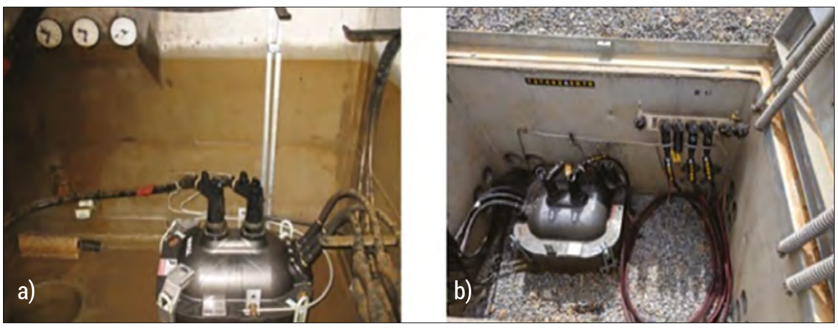

Figure 8. SIDTs installed in North America: (a) concrete structure (b) open-bottom structure

Figure 9. SIDT: 3P, 300 kVA

The solid insulation distribution transformers offer a unique set of performance characteristics that cannot be found with any other solution

Bibliography

[1] IEEE Std. 386 IEEE Standard for separable insulated connector systems for power distribution systems rated 2.5 kV through 35 kV, 2016

[2] IEEE Std. C57.12.01 IEEE Standard for general requirements for dry-type distribution and power transformers, 2020

[3] IEEE Std C57.12.23 IEEE Standard for underground type, self-cooled, single-phase, distribution transformers with separable insulated high-voltage connectors; high voltage 25,000 V and below; low voltage 600 V and below; 167 kVA and smaller, 2009

[4] IEC 60076-11 Power transformers -Part 11: Dry-type transformers, 2018

[5] CSA Standard C9-02 Dry-type transformers, 2016

[6] IEEE Std. C57.12.90 IEEE Standard test code for liquid-immersed distribution, power, and regulating transformers, 2015

[7] IEEE Std. C57.12.00 IEEE Standard for general requirements for liquid-immersed distribution, power, and regulating transformers, 2010

Authors

Kacey Lee majored Electrical Engineering at university and had designed VPI and cast resin transformers at transformer manufacturer in Korea before joined DuPont in 1998. He has worked to develop insulation technology for dry type and liquid filled transformers as a global AD leader for DuPont Nomex® business in AP region. He is a member of IEEE Power Engineering Society.

Byungchul Mun had dedicated to developing and designing various transformers for power utilities and industrial customers at LS Electric (ex. name is LGIS) and Hyosung Heavy Industries in Korea and was employed at Cheryong Electric Company in 2017. As a transformer design and development leader, he has developed new dry-type transformers based on long transformer design experience.

Casey Ballard received his BSEE with a focus in power systems from Virginia Polytechnic Institute of State University in 2003 and is the Global Technology Manager for electrical applications at DuPont. His previous work experience in the transformer industry includes roles of a design engineer as well as research and development, where he led testing on the evaluation of insulation systems. He is a senior member of the IEEE Transformers Committee and IEC TC14 and TC112 delegate for the US Technical Advisory Group with active participation in various working groups.