DRY-TYPE TRANSFORMER FOR POLE MOUNTED APPLICATION

Bandeep SINGH
ABB Inc. – USA
bandeep.singh@us.abb.com

Thomas HARTMANN
ABB Inc. – USA
thomas.hartmann@us.abb.com

Will E. PAULEY
ABB Inc. – USA
will.e.pauley@us.abb.com

Stephane SCHAAL
ABB Ltd. – Switzerland
stephane.schaal@ch.abb.com

Martin CARLEN
ABB Ltd. – Switzerland
martin.carlen@ch.abb.com

Andrej KRIVDA
ABB Ltd. – Switzerland
andrej.krivda@ch.abb.com

ABSTRACT

An outdoor 3-phase dry type 100 kVA, 15 kV, distribution transformer is developed for pole mounted application. This transformer follows IP00 protection degree, i.e. no enclosure is required. The transformer also provides low losses and compact dimensions within the IEC 60076-11 standard for dry-type transformers. The transformer design features include solid dielectric insulation, integrated cast LV and HV bushings with adaptability for Delta or Wye connection and overall outdoor compatibility with corrosion protection on the magnetic steel core. The optimizations of the internal and external design of the transformer were carried out using various finite and boundary element simulation tools. These simulations provided in-depth understanding of all aspects of the transformer. The optimizations included simulations of internal dielectric and surface stress calculations. A special cycloaliphatic epoxy suitable for extreme outdoor environments is used to cast this transformer. To further confirm and prove the long-term functioning, qualification is done in the very harsh outdoor environment of Koeberg Insulator Pollution Test Station in South Africa as well as under accelerated testing conditions in a salt fog chamber.

GENERAL CONCEPTS AND REQUIREMENTS FOR A POLE MOUNTED TRANSFORMERS

Pole mounted transformers, provide the required voltage transformation in the electric power distribution system, mainly, stepping down the voltage used in the overhead power lines to the level needed by the customer. Conventionally, these transformers are enclosed in steel cases which either contain oil (in case of oil type transformer) or air (in case of dry-type transformer) between primary and secondary windings as cooling and insulating medium.

Pole mounted transformers are used in close proximity to the end users of power, typically, installed on a utility pole next to a houses or commercial or industrial buildings, directly fed from overhead power lines. These transformers also find applications in auxiliary and sub-station service in pedestal mounted form. Pole mounted transformers containing oil pose some environmental risks, like oil spillage or sometimes even fire, especially in residential areas or near water springs, rivers or lakes, and public/national parks. In certain countries, issues of copper and/or oil theft and the related contamination of the ground are associated with oil insulated pole mounted transformers. On the other hand, using standard designs of air insulation between primary and secondary windings for dry-type transformers is also not suitable for outdoor transformers without enclosures due to the possibility of contamination and related transformer failures. Some of the other important criteria for pole mounted transformers are compact footprint, light weight, outdoor compatibility with integrated high and low voltage bushings and corrosion protection on all steel parts. Such an outdoor Dry type transformer should also be qualified for C2, F1 and wet test. To develop a dry type pole mounted transformer, main challenges were to develop an appropriate solid insulation system to encapsulate primary and secondary windings together to avoid any air gap and, outdoor design as a whole to fulfil the IP00 requirements [1-2].

MATERIALS AND DEVELOPMENT TECHNIQUES

Solid Insulation material

Solid insulation between the high and low voltage winding is the most critical area of the overall design. Eliminating the air gap between the coils removes the risk for contamination or ingress of animals between coils and is one of the most important factors for reliability of an outdoor transformer. Internal ABB simulation tools were used to define the electrical properties of this solid dielectric material. For this purpose, various insulation materials like Mylar, Nomex and epoxy were qualified. Based on simulations, various field grading materials with different dielectric constants and conductivities compared to the main high-low insulation material were also identified and incorporated in the design to achieve a successful solid dielectric pole mounted transformer.

Encapsulation material for an outdoor transformer

For an indoor cast dry transformer, primary and secondary windings are separately encapsulated with bisphenol based indoor epoxy and are assembled with an air gap between these two main cast windings. On the other hand, to encapsulate as a whole (avoiding any air gap between primary and secondary winding) an outdoor pole mounted transformer coil, proven technology of outdoor cycloaliphatic epoxy was used. This epoxy is superior in terms of UV, fire, and external tracking and erosion resistance with following characteristics.

Table 1. Properties of encapsulating resin

Chemistry	Cycloaliphatic
Flammability	V-0 for 12 mm specimen
Water absorption	< 0.1 wt%
Inclined plane tracking & erosion	>300 min. (t.t.t) @ 3.5KV
HV arc resistance	195-200 sec

Corrosion protection

Corrosion of core steel causes disintegration of the material into its constituent due to chemical reactions with its surroundings. An oxidant like oxygen in presence of moisture/water is responsible for this electrochemical reaction which leads to formation of oxides of iron and salt derivatives. Steel rusts when it comes in contact with water and an oxidant like oxygen in the atmosphere. Near the coast, rusting of steel becomes more predominant due to presence of salt which accelerates the electrochemical reaction responsible for rusting. Rusting or iron oxide layers form a coating on the surface of the iron (while rusting) and retards further oxidation reaction. Rusting begins with the transfer of electrons from iron to oxygen and forming a hydroxide ion as described by following reaction

$O_2 + 4\ e- + 2\ H_2O \rightarrow 4\ OH^-$
$Fe \rightarrow Fe^{2+} + 2\ e-$

The following reduction reaction occurs in presence of water forming rust

$4\ Fe^{2+} + O_2 \rightarrow 4\ Fe^{3+} + 2\ O^{2-}$

Galvanization or Zinc coating is one of the techniques used to prevent rusting of steel by forming a physical barrier, and act as sacrificial layer. A sacrificial layer acts as anode used in cathodic protection where it is more prone to oxidation than the active metal or steel to protect thus it must oxidize before the less active metal will corrode and act as a barrier against corrosion for the protected metal. Iron rusts as

$$4\ Fe + 3\ O_2 \rightarrow 2\ Fe_2O_3$$

instead, the Zinc oxidizes in the air;

$$2\ Zn + O_2 \rightarrow 2\ ZnO$$

Zinc reacts with oxygen and water to form zinc hydroxide. Finally zinc hydroxide reacts with carbon dioxide in the atmosphere to yield a thin layer of zinc carbonate ($ZnCO_3$) which adheres extremely well to the underlying zinc, thereby protecting it from corrosion.

On the basis of this principle, during materials development for core corrosion protection, 10 different coating systems with Zinc rich base coats and different variants of top coats were applied on samples of stacked core. The coated samples were then subjected to 1000 h of salt-fog testing.

Electrical testing

All the electrical testing was carried out according to IEC 60076-11.

Outdoor testing

To further confirm long-term outdoor performance of the pole mounted transformer in service, outdoor testing was performed in two different ways.

1. In an artificially created harsh environment i.e., in a salt fog chamber. Figure 1 details the 12 hrs. cyclic parameters used for testing an energized coil in salt fog chamber. This testing allows performing a controlled number of cycles in short time and under increased environmental stress. The UV irradiation used corresponds e.g. to about 20-50 times the maximum solar irradiance occurring in nature.

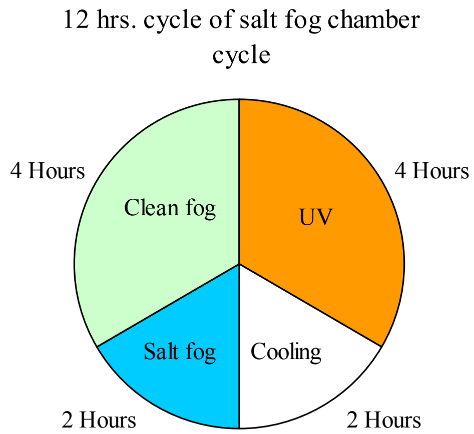

Figure 1. Salt fog multi-parameter ageing cycle, each section represents a parameter and the testing was performed in the following sequence: 4 hours UV, 2 hours cooling down period, 2 hours of salt fog with conductivity of 5000µS/cm, 4 hours of clean fog with conductivity of 1000µS/cm.

2. In a natural harsh outdoor environment of the ESKOM's, Koeberg Insulator Pollution Test Station (KIPTS) in South Africa [3-4]. KIPTS has such harsh environment due to its proximity to sea with lots of UV, Rain, wind & sand erosion, industrial pollution and salt containing moisture [5].

RESULTS AND DISCUSSION

Dielectric Design Simulations

ABB's internal simulation tool called 'Toolbox' was used to identify critical spots and carry out 3D dielectric simulations. These boundary element based simulations identified critical high E-field stress points responsible for partial discharges or internal failures. Geometrical methods and field grading and/or specialized materials were utilized to manage E-field in high stress areas. Special effort was taken to minimize field stress on the surface of the transformer. Figure 2 shows a section of the coil with high stress at the edge of the HV disc, identified with POLOPT solver of ABBs dielectric simulation Toolbox.

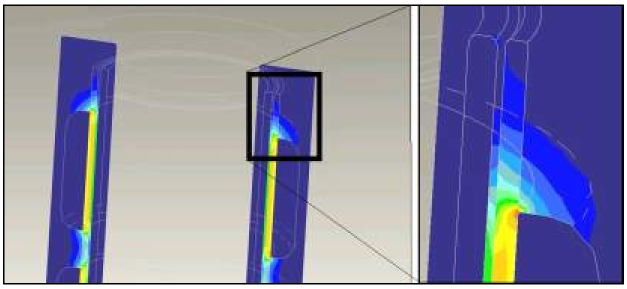

Figure 2. Simulation of high stress concentration point at the edges of the discs in solid dielectrics

Electrical Testing of the Transformer

The prototype pole mounted transformer successfully passed all electrical testing with low no-load & load losses. The results are summarized in Table 2.

Table 2. Electrical testing of 100 kVA, 15 kV, 3 phase transformer

	Result for 15 kV transformer
Load loss	1862 W
No-load loss	306 W
Sound power level	53 dB(A)
PD-level (@ 130% nominal voltage)	Passed (after pre-stressing to 200%)
HIPOT/Double induced	Passed
Heat Runs	Passed
Lightning impulse/ AC	Passed

Corrosion Testing

Figure 3 shows reference uncoated stacked core sample compared to one of the successful sample having corrosion protection after 1000 hrs. of salt fog testing. With this candidate protection system, sample showed no marks of rusting or corrosion on coated core steel laminates surface or edges, which are otherwise extremely prone to rusting. This sample consisted of a Zinc rich base coat with thermoset polymer as top coat. Various factors including resin chemistry of the coating system are vital for corrosion protection.

(a)

(b)

Figure 3. Stacked core samples after 1000hrs. of salt fog testing (a) reference, uncoated sample (b) successful, coated sample.

Other important factors include chemical reaction of the Zinc rich resin system with core steel, tightness or barrier characteristics of cured top coat against moisture, curing characteristics, thermal stability, coefficient of thermal expansions to avoid any cracking, hydrophobicity to have natural cleaning of the coated surface over time, durability of overall coating system against moisture attack, low or zero volatile organic component for minimal environmental impact, and longer shelf life of raw materials.

Qualification Testing

In Salt Fog Chamber

To carry to superior ageing, this 8.7 kV_{rms} phase to ground coil was exposed to multi-parameter aging as described in Table 3.

Table 3. Applied test voltage and ageing time for the tested coil

Test Voltage [U/U_o, kV_{rms}]	Total Ageing Time [Hours]
1.03	160
1.5	378
1.8	303

Visually, no tracking and erosion was detected on cycloaliphatic epoxy encapsulated after completed salt-fog testing, confirming combinational performance of the materials and internal/external design. Leakage currents were found to be low ranging from 10mA under dry conditions to 100mA under salt fog at 1.8 U/U_o.

Outdoor testing at KIPTS

After 8 months exposure in KIPTS the transformer is still energized and the test proceeding. This confirms the robustness of the cycloaliphatic composition of encapsulated mix resin

Figure 4. Outdoor Testing of dry-type pole mounted transformer (from LV side). The installation is placed around 30 m from the Atlantic Ocean in Western Cape of South Africa

CONCLUSIONS

From the overall development, following conclusions can be drawn:

- Development of a 3 phase, dry type pole mounted transformer was successfully carried out according to IEC 60076-11.
- Various dielectric simulation techniques confirmed the internal and external design.
- Specially designed corrosion resistant coating system showed no signs of delamination or rusting of stacked core samples in 1000 h of extreme salt-fog conditions. This coating was selected to cover corrosion susceptible areas of the outdoor transformer.
- Both artificial and natural outdoor testing results have shown superior performance of the transformer under extreme outdoor environments.
- This Dry type pole mounted transformer product offers many benefits to the customers like enclosure-less design, compact dimensions and low losses. Not containing oil they minimise environmental risks and thefts associated with copper in the windings. Anticipated single pole installation of the transformer is drawn in Figure 5.

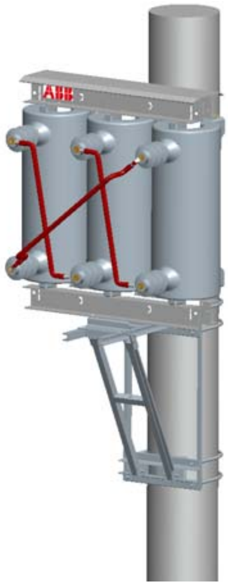

Figure 5. 3D-drawing of a pole mounted transformer installation (from HV side) on a standard $\phi = 360mm$ single pole.

Acknowledgments

The authors acknowledge valuable input from Eskom's KIPTS substation during outdoor testing this pole mounted transformer. We would also like to thank other ABB Inc. senior engineers like Charles W. Johnson for valuable discussions during course of development. We are grateful for the dedication and effort of the production team in Bland to make all the prototyping work happen.

REFERENCES

[1] I.J.S. Lopes, S.H. Jayaram, and E.A. Cherney, 2001, "A Study of Partial Discharge from Water Droplets on a Silicone Rubber Insulating Surfaces", IEEE Trans. Dielectr. Electr. Insul., vol. 8, 262-268.

[2] A.J. Phillips, D.J. Childs and H.M. Schneider, 1999, "Water Drop Corona Effects on Full-Scale 500kV Composite Insulators", IEEE Trans. Power. Deliv., vol. 14, 258-265.

[3] B. Singh, H. D. Le and P. Mahonen, May 31- June 3 2009, "Experimental evaluation of liquid 'glass-like' coatings to improve tracking and erosion resistance of insulators for outdoor applications", Proceedings IEEE Electrical Insulations Conference, Montreal, Quebec, Canada, 555-557.

[4] A. Krivda, L.E. Schmidt, X. Kornmann, H. Ghorbani, A. Ghorbandaeipour, M. Eriksson and H. Hillborg, 2009, "Inclined-Plane Tracking and Erosion Test According to the IEC 60587 Standard", IEEE Electrical Insulation Magazine, Vol.25, 14-22.

[5] M. Amin, M. Salman, 2006, Aging of polymeric insulators (An overview), Rev. Adv. Mater. Sci., vol. 13, 93-116.