> **Dry type, paperless insulation technology offers a safer and cost-effective alternative to traditional oil-filled current transformers**

ABSTRACT

The aim of this article is to make readers aware of a dry type, paperless insulation technology that offers a safer and cost-effective alternative to traditional oil-filled current transformers. The design concepts and advantages of this unique HV dry type current transformer technology have been delivering verifiable improvements to the power grid over the past 20 years from 35 kV to 600 kV. The example of the implementation of this technology in Canada is a good case in point. Multiple evolutions of the technology have been continuously expanding its application from HV to UHV operation. Furthermore, the addition of a built-in insulation condition monitoring system completes the safety and sturdiness of the platform.

KEYWORDS

Cascade construction, current transformer, dry type insulation, embedded monitoring, paperless

A dry type HV insulation system for extreme environments

The single dry paperless insulation platform that allows transition from analog to digital current transformers, from HV to UHV

1. Introduction

The HV DryShield® current transformer, which uses no oil or gas and no paper, offers an upgraded safety and reliability solution for utilities faced with the need to replace end of life and/or failing oil-filled current transformers. This article discusses the advantages of this unique current transformer technology and its implementation into the grid. The later introduction of a smart HV dry type current transformer with its built-in real-time monitoring of its primary insulation condition and secondary accuracy errors is also discussed.

This article then describes the design evolution of this technology into the cascade construction which offers significant cost savings and reliability benefits for EHV or UHV applications.

2. Development of this HV dry type insulation technology

A totally original dry insulation structure for current transformers using PTFE (PolyTetraFluoroEthylene) was developed in China throughout the 1980's, patented in the 1990's, and later trademarked as HV DryShield®. This technology has a proven service record with over 20,000 current transformers with ratings ranging from 35 kV - 600 kV in operation in all types of operating environments on T&D systems in many parts of the world [1].

This HV dry type current transformer uses a "U" shape primary and sealed, waterproof dry-type secondary windings, making it an immediately recognizable product in a substation, Figure 1.

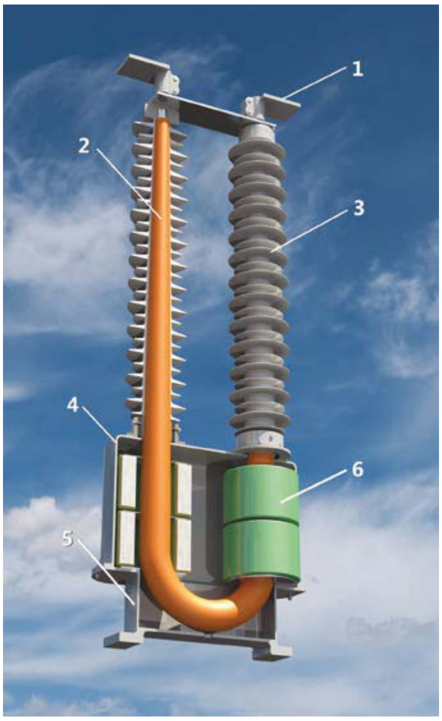
The primary consists of one or more turns of current-carrying conductor made of copper or aluminium, depending on the specified continuous primary current and short-time thermal current ratings, and a condenser graded insulation design that uses a high-grade polymer film for its main insulation material. The principal polymer used is PTFE (PolyTetraFluoroEthylene). PTFE is an excellent electrical insulation material with an extremely low dielectric dissipation factor and high physical, thermal, and chemical stability. The tape's characteristics were also developed specifically for the application by the inventors. Silicone gel is used along with the PTFE tape as a capillary interface to fill the micro gaps and expel air bubbles in the tape. Using these materials in the build of a condenser graded structure results in a current transformer with residual partial discharge, small tan δ and high withstand voltage. Finally, a high-grade heat shrink tubing is installed to seal and protect the primary condenser.

The sealed primary and secondary windings are then seated and fixed in a base box located at ground potential with the final position of the secondary windings being lower than the primary winding's last grading screen, Figure 1. Fixing flanges on the base box lid ensure a mechanically strong connection of the primary condenser to the base box. The secondary windings are terminated in a secondary terminal box located on the side of the base box. Also, located in the secondary terminal box, is the capacitive test tap providing a solid connection to the last grading screen of the primary condenser.

The external insulation housing is formed from individual high-quality silicone rubber sheds that have been designed and formed to overlap each other and exactly fit the profile of the finished primary condenser. The sheds are glued directly to the condenser structure, so no interstitial insulating filler is required.

An insulated connection board connects two arms of the "U" shape primary winding in order to stabilize and enhance the current transformer's mechanical strength. When a dual current primary is specified, the series/parallel connec-

Invented in the 1990's, this technology currently has an in-service population of over 20,000 units, many of which are operating reliably in severe environments



1 – Primary terminal
2 – Primary condenser insulator
3 – Silicone rubber sheds
4 – Base box upper casing
5 – Base box lower casing
6 – Secondary winding

Figure 1 – HV dry type current transformer basic structure

> **The design concepts and advantages of this HV dry type CT technology have been verified in power grids up to 600 kV over the past 20 years**

tion link board for changing the primary winding's ratio is also located here.

This HV dry type insulation system has a proven ability to sustain higher withstand voltages (up to 870 kV/1800 kV BIL). Lower dielectric dissipation factor and partial discharge values (< 0.1% and < 5pC respectfully) are also typical electrical performance characteristics of this HV dry type insulation system [2][3]. This type of performance provides larger safety margins for the HV insulation which should equate into a longer life expectancy for the equipment. In addition, the finely capacitance graded PTFE based insulation design allows both the core insulation and outer insulation to operate under a lower electrical stress. By adjusting the number and length of metal foil screens, as well as the layer thickness between the screens, the voltage drop and also electrical stress in the core and along its' surface can be controlled. This ensures a uniform electric field along the surface of the outer insulation increasing the flashover voltage withstand along the surface and helping to limit the deterioration rate of the silicone rubber. Another very interesting operating phenomenon exhibited by this HV dry type insulation system is the mechanism of PD self-attenuation when the equipment is in operation (i.e. PD levels eventually decreasing to undetectable levels). This is a phenomenon that has been repeatedly observed from field testing of our in-service units and is explained by the combined effect of PTFE film with interstitial silicone gel in a capacitive-graded insulation design [2][3].

3. Environmental testing of the HV dry type current transformer

The HV dry type current transformer design has been subjected to a wide range of type tests and special tests to prove its performance under severe environmental conditions, including: long duration thermal cycling tests, water spray test, internal arc fault test, and seismic test.

3.1. Long duration thermal cycling tests

This test was performed at a third-party test facility in China and was based on the specification requirements of a large eastern Canadian utility. The test unit was a 110 kV dry type current transformer. The test protocol required the test unit to be subjected to 25 thermal endurance cycles. A cycle involved lowering the temperature from ambient to -50°C (at a rate of 10 to 20°C/hour); maintaining the temperature at -50°C for 16 hours; applying 125% primary current during the last two hours at -50°C, meaning a high thermal shock; and then raising the room temperature back up to ambient. After every 5 cycles, a short-time power frequency withstand voltage was applied to the primary winding of the test unit followed by measurements of the partial discharge, capacitance, and dielectric dissipation factor. The CT didn't show any damage or any change of electric characteristics compared to routine test results after 25 cycles [4].

3.2. Water spray test

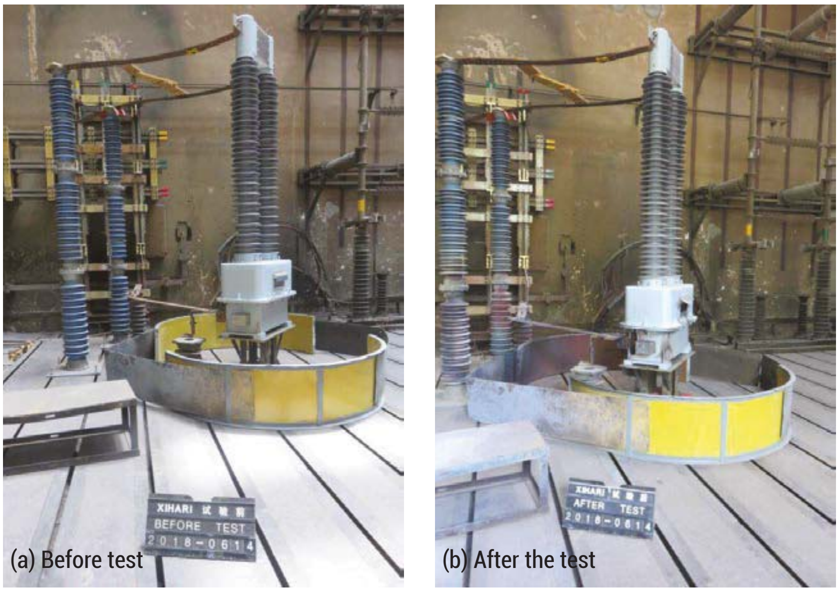
This was an in-house test conducted on three (3) 145 kV dry type current transformers. A 15-minute water spray test in accordance with IEC 60060-1 [5] was performed to verify the waterproof performance of the secondary terminal box. There was no effect on the test units.

3.3. Internal arc fault test

To further stress the HV dry type current transformer design, a 230 kV current transformer was subjected to an internal arc fault test in accordance with CAN/CSA C61869-1:14 [6]. A third-party test facility in China was contracted to perform this test. The fault current test level specified in the test plan was a short circuit current of 63 kA_{rms} with an asymmetrical peak current of 170 kA_{peak} for an arc duration of 0.3 seconds. A 2.5 mm diameter magnet copper wire was used for the fuse element which was installed in the PTFE insulation of the primary core during manufacture. To ensure a maximum impact test, the fuse element was installed in the U-shape bend area that is seated and fixed in the current transformer base box. Care was also taken to locate the fuse element in an area least favourable for the controlled pressure relief. Figure 2(a) & (b) show the test specimen before and after the test. This was a particularly severe test as internal arc fault tests are typically done at a lower short circuit current as the probability of a full short circuit fault is statistically very low. Nevertheless, the HV dry type current transformer design showed its ability to maintain its mechanical integrity after such a high energy blast [7].

3.4. Seismic testing

A 500 kV dry type current transformer was seismically tested in accordance with IEEE 693-2005 High Level [8] (see Figure 3). This testing was done at a recognized third party earthquake test facility in China. The shake table used had six degrees of freedom; three translational degrees and



(a) Before test

(b) After the test

Figure 2. The test specimen before and after the test

> **A condenser graded insulation design uses a high-grade polymer film, principally PTFE, for its main insulation material**

Figure 3 – 500 kV Dry type current transformer on shake table

three torsional degrees. Accelerometers and displacement meters were used to measure the acceleration and displacement responses respectfully. Three accelerometers were mounted on the shake table to measure the responses in the three directions. Other accelerometers were mounted separately on the tank, middle connection flange, and primary terminal of the test object. In addition, dual displacement meters were mounted at three locations on the test object (base, middle, and top primary terminal). The test protocol also called for routine electrical tests (power frequency voltage withstand, partial discharge, measurement of capacitance and dielectric dissipation factor, tests for accuracy) be performed before and after the earthquake test. Inspections and testing after the earthquake test showed that the current transformer suffered no structural damage and passed its electrical performance tests. [9].

4. Introduction of the HV dry type current transformer to the Canadian market

There are over 20,000 HV dry type current transformers currently installed and operating world-wide. The HV dry type current transformer was first introduced to the Chinese power grid in 1998 and to date have operated reliably in all types of marine, highly polluted, seismically active, and extreme temperature environments.

Outside of China, Canada has become a very important user of HV dry type current transformers [10]. The first set of HV dry type current transformers installed and put into service in Canada was in 2007. To date, close to 550 units have been delivered or are in the process of being delivered for the Canadian market. In addition to their demanding performance specifications for temperature extremes (-50°C to 40°C), wind (160 km/hour) and seismic endurance, these utilities, like most North American utilities, have an aging transmission system. Of particular concern are their aging inventory of oil-filled current transformers which are now starting to add significant costs to their operating budgets due to higher maintenance (leaks), customer service interruptions, and unplanned outages for equipment replacement. In addition, many of these current transformers are starting to fail catastrophically, putting staff and the

Figure 4 – 115 kV dry type current transformer installation in Western Canada

Figure 5 – 230 kV dry type current transformer installation in Central Canada

> **The HV dry type CT design has been subjected to a wide range of type tests and special tests to prove its performance under severe environmental conditions**

general public at risk. Many Canadian utilities are now looking at significant instrument transformer replacement programs. In the case of the two western Canadian utilities, their due diligence identified the HV dry type technology as the appropriate solution for their aging oil-filled current transformers (Figure 4 and 5); subsequently committing to multi-year blanket agreements to supply their ongoing replacement requirements. Typical voltage ratings supplied to the Canadian market range from 72.5 kV to 600 kV with maximum current ratings from 1200 A to 4000 A. Protection classes specified are typically PX (2.5L800 and 10L800) and TPY (7.5 %). Metering accuracy is ANSI class 0.3B1.8 including Measurement Canada approved revenue-metering applications.

5. The cascade design for EHV dry type current transformers: addressing higher voltages while sustaining reliability and competitiveness

The idea of cascade construction for EHV current transformers was first introduced in the 1960's [11]. Although the economical advantages of the cascade construction were well recognized, it never became an industry accepted product as manufacturers were limited by the oil/paper insulation technology of the time which posed significant design challenges for the concept. Now, with the development of the HV dry type insulation technology, it is now possible to offer an economical cascade style current transformer for EHV applications [12].

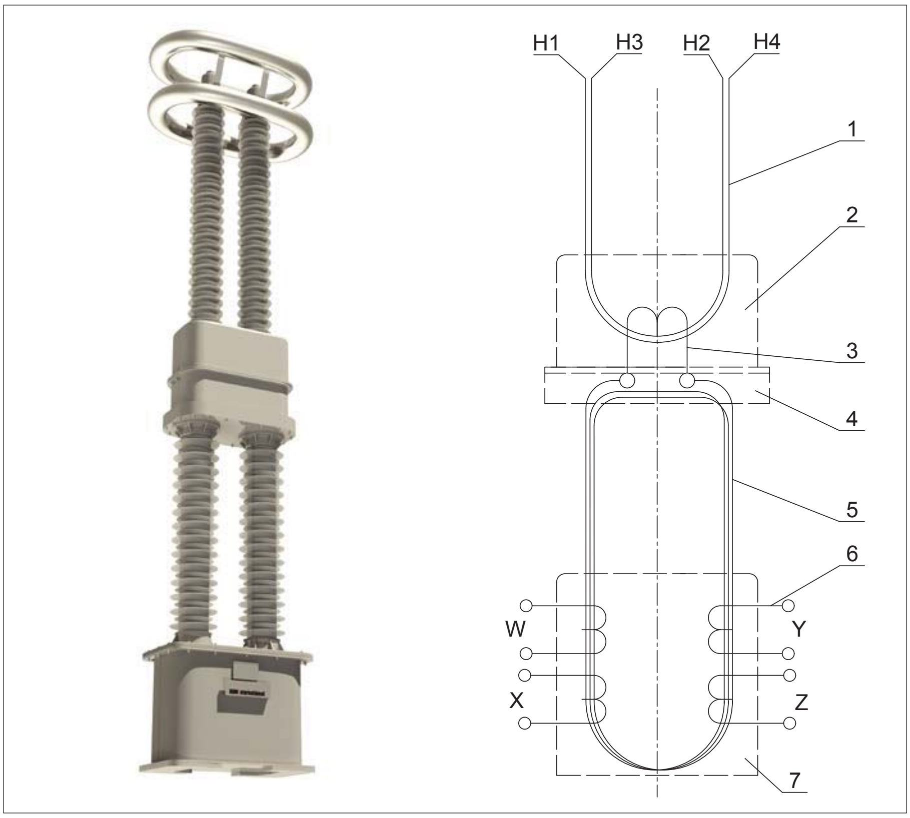
An EHV dry type cascade style current transformer is composed of no less than 2 current transformers, each with lower voltage levels. The basic construction of a 2-stage cascade current transformer is shown below, Figure 6.

As can be seen in Figure 6, the cascade current transformer is composed of 2 separate current transformers whose insulation levels are nearly the same. The primary winding of the upper current transformer is connected to the grid and is at high potential. The upper current transformer primary's last layer, secondary winding, casing, and duct board are connected with the primary of the lower current transformer which are at intermediate potential. The secondary winding and casing of the lower current transformer is at zero potential, i.e. earth potential. The secondary of the upper current transformer and the primary of the lower current transformer are in series connection and the secondary winding of the lower current transformer is connected to the external relaying or metering burden.

With the increase in voltage level, the amount of insulation materials consumed is related to the square of the multiple of the voltage increase, i.e. $(U_2/U_1)^2$ and the higher the voltage, the larger the insulation consumption. For example, the insulation material for a 220 kV current transformer is about 5 times that of a 110 kV current transformer while the insulation material for a 500 kV current transformer is about 8 times of that of a 220 kV current transformer. When a cascade approach is used for composite insulation dry type current transformers, the insulation material used is only what is required for the lower voltage design; e.g. a 220 kV cascade current transformer is composed of two 110 kV current transformers in series connection. Therefore, the cascade design can greatly reduce the insulation material consumption.

Since the insulation material used in the composite insulation dry type current transformer is an expensive PTFE film, the cascade current transformer design can greatly reduce insulation material costs. The lower-voltage current transformers use thinner insulation structures which are easier to manufacture. The simpler manufacturing process allows for larger insulation margins to be achieved, thereby increasing insulation reliability. Each stage of a cascade current transformer has secondary windings, meaning more cost for the secondary windings and the secondary winding casings. When designing the insulation for cascade current transformers, the designer has to take into account both the costs of the insulation materials and the secondary windings, and choose an appropriate number of stages to achieve the best performance at the lowest cost.

> **This technology enabled design evolution into the cascade construction which offers significant cost savings and reliability benefits for EHV or UHV applications**



1 – Upper CT; 2 – Upper primary winding; 3 – Upper secondary winding; 4 – Duct board; 5 – Lower CT; 6 – Lower primary winding; 7 – Lower secondary winding

Figure 6 – EHV cascade current transformer construction

The cascade current transformer is based on the following principles:

Current Ratio
If the current ratio of the upper current transformer is K_1, and the current ratio of the lower current transformer is K_2, the current ratio K of the entire cascade current transformer is: $K = K_1 \times K_2$. For example, the current ratio of the upper current transformer is 2000/20A, and the current ratio of the lower current transformer is 20/5A, then the current ratio of the entire cascade current transformer is 2000/5A.

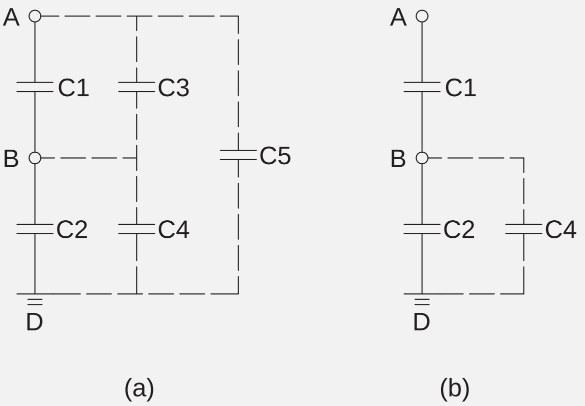
If the current error of the upper current transformer is f_1, the phase error is δ_1, the composite error is $\dot{\varepsilon}_1$; and the current error of the lower current transformer is f_2, the phase error is δ_2, the composite error is $\dot{\varepsilon}_2$, then the current error, phase error, and composite error for the entire cascade current transformer will be defined by the following equations:

$$f = f_1 + f_2 \qquad \delta = \delta_1 + \delta_2 \qquad \dot{\varepsilon} = \dot{\varepsilon}_1 + \dot{\varepsilon}_2$$

Voltage Distribution
Both the upper and lower current transformers of the cascade current transformer use capacitance-graded insulation whose equivalent capacitance distribution is shown below, Figure 7.

Where:
C1 - Upper capacitance
C2 - Lower capacitance
C3 - Stray capacitance between the upper HV side and the intermediate potential
C4 - Stray capacitance between the intermediate potential and earth
C5 - Stray capacitance between the upper HV side and earth

In Figure 7(a), C5 is unrelated to the voltage distribution of the upper and lower current transformers while it is known from actual measurement that C3 is so small that it is negligible. Therefore, the capacitance distribution can be simplified as shown in Figure 7(b). The voltage division ratio of the upper and lower current transformer approximates (C2+C4):C1. In the capacitance-graded insulation designs, we must take C4 into consideration while trying to make C1 equal as close as possible (C2+ C4) so that the insulation levels of the upper and lower current transformers are approximately the same.



(a) (b)

Figure 7 - Cascade Current Transformer capacitance distribution

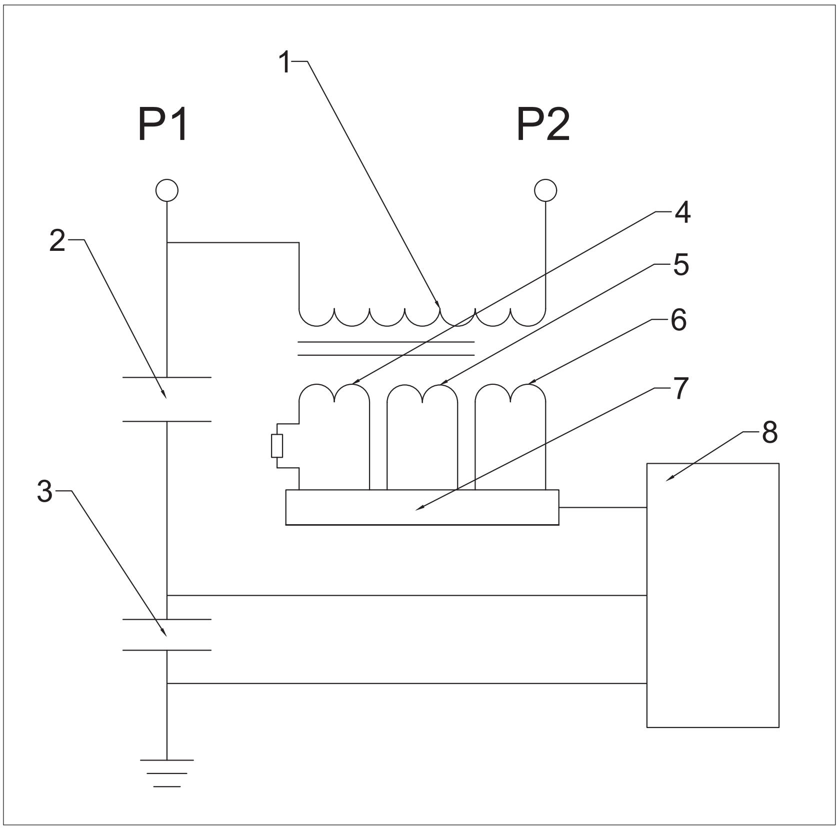
6. The smart HV dry type current transformer - embedded monitoring

The smart HV dry type current transformer comes equipped with a built-in monitoring device that provides real-time monitoring of the current transformer's primary insulation condition, and the ratio and angle errors for each of the current transformer's secondary coils.

Primary insulation condition monitoring is achieved by building in a large LV signalling capacitance Cs that is connected in series with the last capacitive screen of the high voltage C1 capacitance (Cs>>C1) to form an integrated system where Cs and C1 are sealed together within the primary core. Because the materials and processes used in C1 and Cs are the same, there will be no large errors due to changes in temperature, frequency, and other factors. The principle behind this design is to think of the current transformer's condenser graded main insulation as a series of capacitors separating the conductor and the ground. The process of insulation breakdown that would be initiated by a defect is sequential; the insulation of one of the capacitive screens is damaged leading to the failure of other screens and possibly the breakdown of the entire insulation. As screens fail, the reduction of series connected capacitors causes a gradual increase in capacitance and capacitive current. This variation in capacitance and capacitive current can be measured to provide an indication of the degree of damage. The fabrication of the LV signalling capacitor Cs and the selection of its capacitance value are key to ensuring accurate monitoring and stable operation of the monitoring device. The capacitance value of Cs is much larger than C1, so the external online monitoring device will not affect the main insulation. At the same time, the selection of the Cs capacitance value must also consider the impedance value of the monitor to ensure that almost all of the capacitive current flowing through C1 to the ground will pass through the monitor. When the monitor detects an increased capacitance current to ground, a fault signal is transmitted in an appropriate manner.

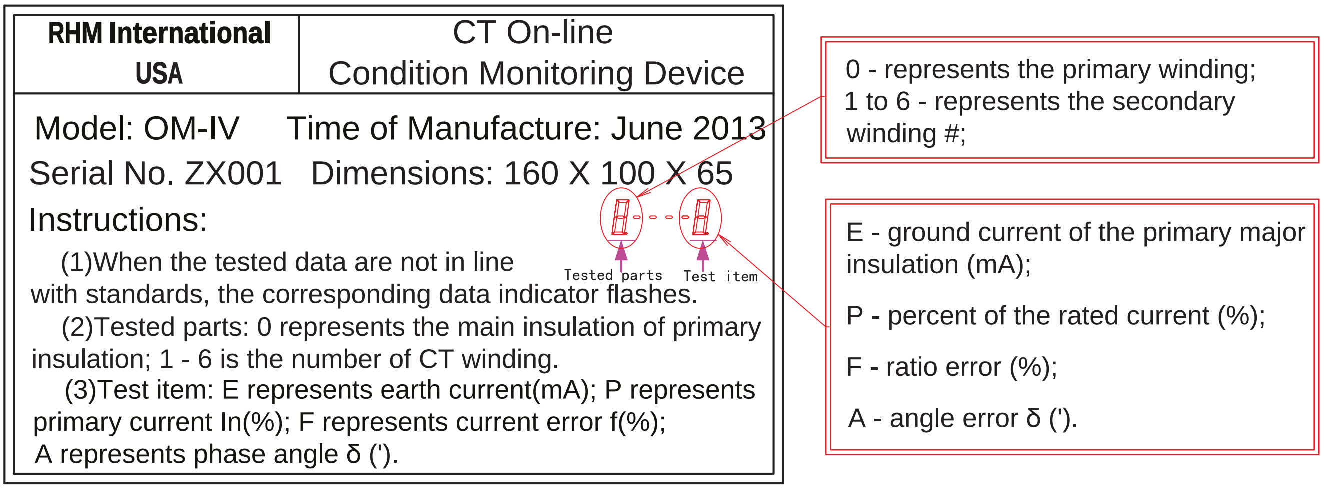
The error monitoring is done with a standard reference coil and a Rogowski Coil installed in parallel with the secondary

Figure 8. Smart HV dry type CT



1 - CT primary winding; 2 - Major insulation capacitance C1; 3 - LV signalling capacitance Cs; 4 - Monitored secondary coil; 5 - Standard reference coil; 6 - Benchmark Rogowski Coil; 7 - Data Aquisition Unit; 8 - Real-time display window

Figure 9. Block diagram of the smart HV dry type current transformer: real-time insulation and error monitor



RHM International USA

CT On-line Condition Monitoring Device

Model: OM-IV Time of Manufacture: June 2013

Serial No. ZX001 Dimensions: 160 X 100 X 65

Instructions:

(1)When the tested data are not in line with standards, the corresponding data indicator flashes.

(2)Tested parts: 0 represents the main insulation of primary insulation; 1 - 6 is the number of CT winding.

(3)Test item: E represents earth current(mA); P represents primary current In(%); F represents current error f(%); A represents phase angle δ (').

0 - represents the primary winding;
1 to 6 - represents the secondary winding #;

E - ground current of the primary major insulation (mA);

P - percent of the rated current (%);

F - ratio error (%);

A - angle error δ (').

When ratio error or angle error exceeds the standard value the display will flash

Figure 10. Smart HV dry type current transformer monitoring device nameplate

> **The addition of a built-in insulation condition monitoring system completes the safety and sturdiness of the platform**

winding coil, Figure 9. Since the standard reference coil is also an iron core coil, the hysteresis loss after long-term operation causes the performance of the core to change and becomes an insufficient 'standard'. Therefore, it is necessary to install a Rogowski Coil in parallel with the standard reference coil for real-time online verification of the unloaded standard reference coil, thereby solving the problem of requiring the power to be off to check the standard reference coil. Because the Rogowski Coil has no iron core loss, the problem of core saturation does not occur which can be used to verify the standard coil, ensuring the accuracy and reliability of the measurement results. This built-in monitoring device needs no external power as its power source comes from the current transformer itself and is isolated from the HV primary so as not to affect the current transformer's performance. Finally, standardized data interfaces according to IEC 61850 [13] communication protocol are provided.

A smart HV dry type current transformer will help to prevent outages due to failing

Winding # 1
Operating at 100.124% of the rated current

(a)

Winding # 1
Angle error is -2.1799'

(b)

Winding # 1
Ratio error is 0.10561%

(c)

Figure 11. Smart HV dry type current transformer monitoring device displays

> **This HV dry type current transformer uses a "U" shape primary and sealed, waterproof dry-type secondary windings, making it an immediately recognizable product in a substation**

insulation and discover accuracy errors in real-time caused by secondary remanence and inter-turn short circuits. It is well known that revenue-metering current transformers once installed usually do not get checked for accuracy "drift" over their service life. This can result in a significant loss of revenue for the utility. Using a smart HV dry type current transformer allows the utility to regularly check the accuracies without having to do expensive off-line testing.

7. Conclusion

Transmission class dry type equipment and components are starting to become a significant option for the electric power industry. The high voltage dry type, paperless insulation technology described in this article provides users with an alternative insulation technology for their HV and EHV current transformers; a technology that is free of the problems associated with oil and gas and promises a maintenance-free product with a higher level of safety and reliability.

This technology also offers built-in monitoring of the core insulation condition status and continuous tracking of metering accuracy that does not require any plug-ins and external connections to the unit.

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