

HV and EHV Current Transformer dielectric condition assessment and root cause analysis

DIEGO M. ROBALINO
Megger
USA

ISMAIL GÜNER
Hydro-Québec
Canada

SUMMARY

Efficient operation of the existing electrical grid and effective transition into a newer and more complex smart grid requires proactive and accurate diagnostic methods capable to predict the condition of critical components within the electrical power system such as power, distribution and instrument transformers.

Current transformers (CT) serve a twofold purpose in the field. First, accuracy for metering and revenue applications and; second, robustness and reliability in complex protection and control schemes. Due to the criticality of these applications, instrument transformers' design has been improved and new materials have been developed to comply with even the most difficult environmental and operational conditions.

As any other HV electrical component, oil-impregnated paper (OIP) HV CTs suffer an inevitable aging process that affects solid and liquid insulation. If not detected on time, the non-monitored aging process may derive in possible early loss of life representing a hazardous operational condition, with high risk of injury to operations personnel and damage to other devices located in the near proximity.

A complete analysis of the electrical parameters and their compliance with nameplate information is the first step in qualifying the electrical condition of the CT. Besides electrical testing, non-intrusive and non-destructive dielectric testing evaluates the condition of the insulation system and supports proactive and/or preventive maintenance activities.

The preliminary research carried out on MV and HV CTs using advanced testing techniques including DGA (dissolved gas analysis) and DFR (dielectric frequency response) is the foundation of this work, to elaborate on the benefits, limitations and correlation of these testing techniques as applied to EHV CTs.

The work presented throughout this paper include field measurement results on different units, as well as a 765 kV rated oil impregnated CT removed from service to be fully dissected to analyze the correlation between DGA, DFR and actual findings inside the insulation system of the CT.

The information provided in this document may be used as a reference for asset managers, maintenance and operations staff regarding prioritization of maintenance activities and/or replacement of faulty units. Altogether, this paper presents a unique work to expand the knowledge on special applications of DGA, DFR and HV DFR for HV and EHC CT insulation condition assessment.

KEYWORDS

HV current transformer, dielectric frequency response, frequency domain spectroscopy, dissolved gas analysis, condition assessment

BACKGROUND

Hydro-Québec (HQ) is North America's largest producer of renewable energy and operator of an extensive high-voltage transmission system. In its complex electrical network, HQ has a significant number of EHV oil-immersed current transformers. Certain models of 800 kV oil-immersed current transformers has a paper-oil-sand (quartz filling) insulation system. The use of sand in the insulation system reduces the volume of oil, improves mechanical characteristics and allows the use of expansion systems with no moving parts.

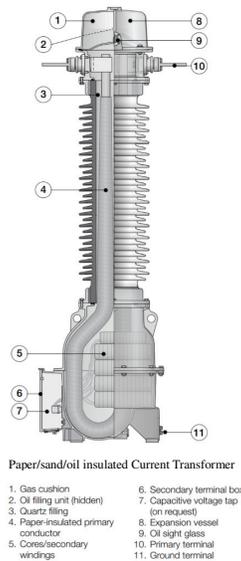


Figure 1 Generic design of EHV CT with sand-filling

Since 2003, certain number of 765 kV freestanding current transformers failed violently in service, causing major explosions and collateral damages in important substations. Flying debris from the porcelain insulator caused severe damage to the nearby switchgear equipment. Consequently, HQ set a 130-meter radius security perimeter around all the instrument transformers of the same model.

Additional preventive measurement were taken and HQ restricted access to these areas until the root cause of failure is declared with certainty. It became paramount for the HQ asset management team to identify a reliable testing methodology, besides routine practices, capable to determine potential risks of operation before catastrophic failure occurs.

The expected service lifetime for EHV quartz-sand filling type CTs is approximately 30 years according to the manufacturer. When the 30-year mark has passed, the unit should be scheduled for replacement. Nevertheless, in a complex network like HQ, certain equipment must be used even after the recommended service lifetime. Therefore, for EHV CTs, a procedure should be implemented to assess the condition of the insulation and to decide about monitoring, repair or replacement of existing units in the network. The data provided in [1] reflects the concern of utility operators and justifies any measure taken to minimize hazardous operation.

The application of DFR and DGA on MV and HV fluid-immersed CTs was investigated at Tennessee Technological University [2] and recently, IEEE published a guide for application of DFR on power and distribution transformers [3]. In this paper, the results of line-frequency PF/DF, capacitance (C), Dielectric Frequency Response (DFR) and Dissolved Gas Analysis (DGA) measurements are taken into account to correlate the advanced diagnostic techniques and define priorities and maintenance strategies to monitor, repair or replace HV and EHV CTs within HQ' power network.

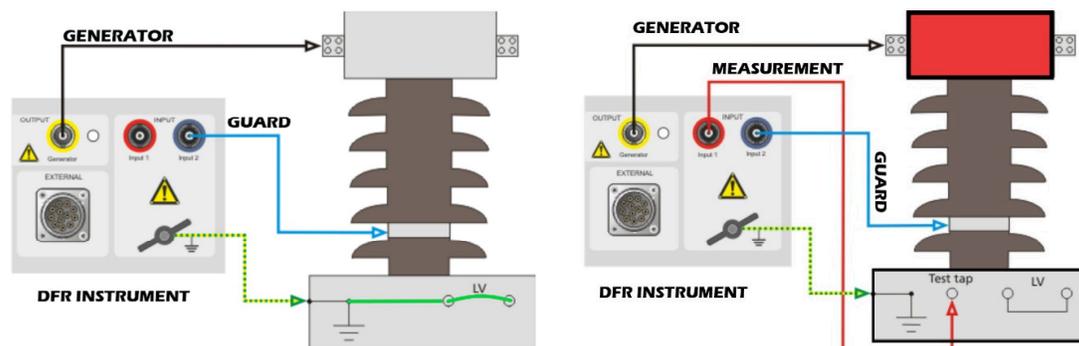
DFR application in EHV CTs is able to quantify the bulk moisture concentration in the solid insulation and the conductivity of the liquid insulation. In addition to moisture and conductivity, non-typical responses are indicative of potential contamination of the insulation system. Finally, the dielectric response in the frequency domain can be converted to the temperature domain to visualize the true behavior of PF/DF as a function of temperature for that specific specimen.

HV CURRENT TRANSFORMER FIELD TESTING

Field testing for condition assessment purposes can be divided into electrical testing and dielectric testing. A good description of the steps required and suggested for CT field electrical testing can be found in [4, 5, 6].

Dielectric testing is the focus of this work and the basis to elaborate practical conclusions about the insulation system of EHV CTs where oil sampling is not always an option and testing of the insulation system is critical. Therefore, advanced diagnostic techniques such as dielectric response testing in the frequency domain are used in the field. Line frequency PF/DF is typically performed to evaluate the average condition of the insulation system. The test provides a general idea of contamination and/or deterioration of the insulation system.

The DFR test involves a procedure similar to the PF/DF test method, but in this case, a wide band frequency sweep generates a unique dielectric response of the insulation (capacitance) under test. For most cases, DFR is carried out where the majority of solid insulation resides. Therefore, for CTs with test tap, DFR is performed on C1 and for CTs without test tap; an overall test is carried out shorting ground with the secondary winding as shown in Fig. 3.



a) Hook-up for dielectric test on HV CT without test tap

b) Hook-up for dielectric test on HV CT with test tap

Figure 2 Hook-up between DFR instrument and HV or EHV CT

DFR is carried out on HV CTs to:

- Estimate the percentage moisture content (%mc) in the solid insulation
- Determine the conductivity of the liquid insulation
- Obtain the true thermal behavior of dielectric parameters
- Identify non-typical responses due to contamination

FIELD EXPERIENCE

In the scope of root cause and failure analysis, HQ performed DFR measurements on 765kV current transformers. Correlations between dielectric frequency responses and dissolved gas analysis results were studied. In 2016, six 765 kV current transformers of the same model were tested after a CT of a same model and year of manufacture failed. This particular model has a capacitive test tap that simplifies the test and benchmarking as seen in figure 3.

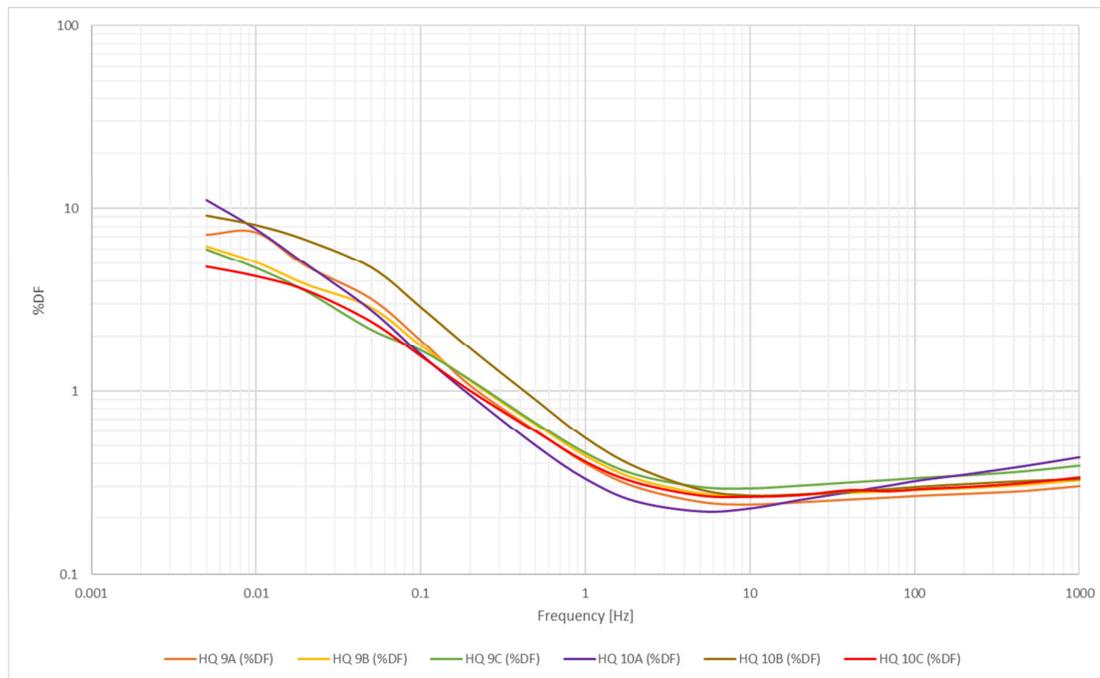


Figure 3 Characterization of EHV CTs with oil-paper & sand-filling insulation

Table 1 DFR & ITC on 6 EHV CTs with sand-filling (2016)

| CT | C | %MC | Cond | PF corrected to 20C by ITC | | | | |
|---------|------|-----|-------|----------------------------|-------|-------|-------|-------|
| | | | | 500Hz | 60Hz | 15Hz | 1Hz | 0.1Hz |
| 700-9A | 1154 | 1.3 | 0.073 | 0.303 | 0.269 | 0.254 | 0.3 | 1.07 |
| 700-9B | 1271 | 1.6 | 0.022 | 0.32 | 0.287 | 0.275 | 0.365 | 1.3 |
| 700-9C | 1363 | 1.5 | 0.021 | 0.37 | 0.327 | 0.305 | 0.419 | 1.5 |
| 700-10A | 1044 | 0.4 | 0.974 | 0.41 | 0.307 | 0.258 | 0.288 | 1.25 |
| 700-10B | 1120 | 2.1 | 0.052 | 0.325 | 0.292 | 0.274 | 0.459 | 2.3 |
| 700-10C | 1283 | 1.4 | 0.006 | 0.338 | 0.292 | 0.282 | 0.318 | 1.0 |

While DFR results showed a similar pattern in the range between 1 kHz down to 15Hz, 1Hz and 0,1 Hz provide the very first differences in the responses, DGA results did not demonstrate any abnormalities. In general terms, these measurements were taken as normal or healthy for the type of EHV CTs under investigation.

Other type of construction commonly encountered in HV systems without sand filling show a slightly different response as presented in figure 4.

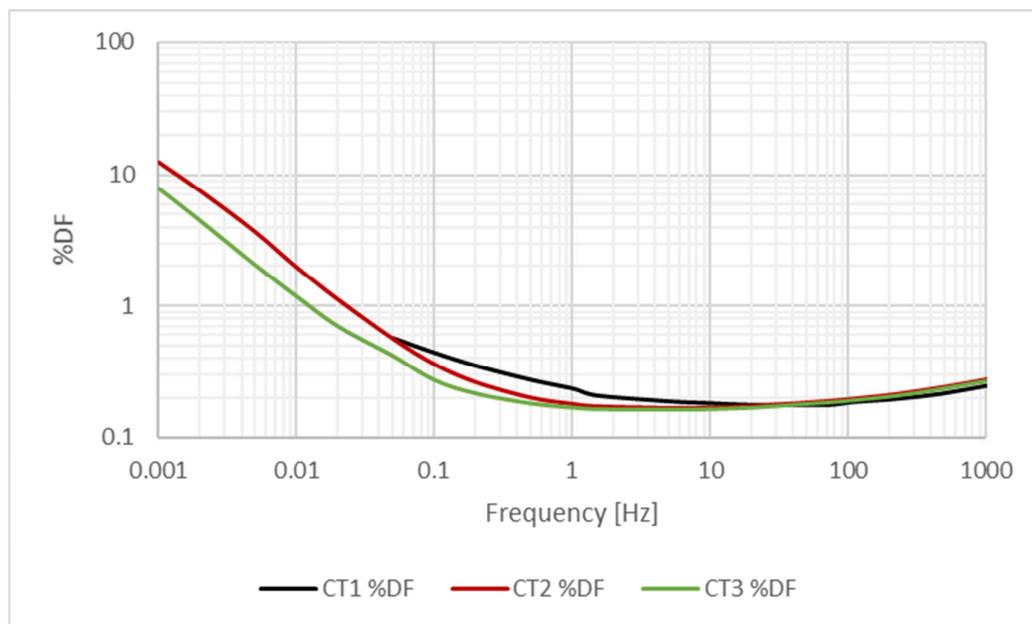


Figure 4 DFR characteristic of HV CTs oil-paper insulation only

Table II DFR and ITC characterization of EHV CTs without sand - filling

| CT | C | %MC | Cond | PF corrected to 20°C by ITC | | | | |
|------|-------|-----|-------|-----------------------------|-------|-------|-------|-------|
| | | | | 500Hz | 60Hz | 15Hz | 1Hz | 0.1Hz |
| CT 1 | 1662 | 0.8 | 0.012 | 0.225 | 0.176 | 0.176 | 0.225 | 0.41 |
| CT 2 | 831 | 0.4 | 0.045 | 0.26 | 0.187 | 0.173 | 0.175 | 0.32 |
| CT 3 | 846.3 | 0.3 | 0.019 | 0.26 | 0.188 | 0.172 | 0.165 | 0.23 |

Independent of the type and model of the CT under test, DFR provides a graphic visualization of the dielectric response that can characterize a specific type of apparatus. Capacitance, %DF/%PF, conductivity of the oil (σ) and % moisture are fundamental parameters obtained from DFR analysis. Individual Temperature Correction (ITC algorithm) provides one more advantage - the ability to normalize to 20°C the “entire” dielectric response. The dielectric response normalized to 20°C allows comparative and trending analyses of %DF values at frequencies different from line-frequency (50 or 60Hz).

For the experimental units there was no preliminary benchmark data acquired by HQ. In absence of a reference measurement during failure investigations, taking measurement on sister components of identical designs allows comparative analysis and the possibility to

elaborate a criterion for asset management. Important to mention that having a DFR reference from the CT manufacturer is of great value for future evaluation of service and aging conditions.

In 2018, HQ experienced failure of another EHV CT of similar model. At this point, HQ initiated an extensive condition assessment program on the entire HV and EHV CT fleet. DGA samples were taken and the analysis of gases suggested removal of one of the EHV CTs in the system. To better understand the gas evolution and its effect to the dielectric system of EHV CT, a DFR test was carried out to compare against healthy units.

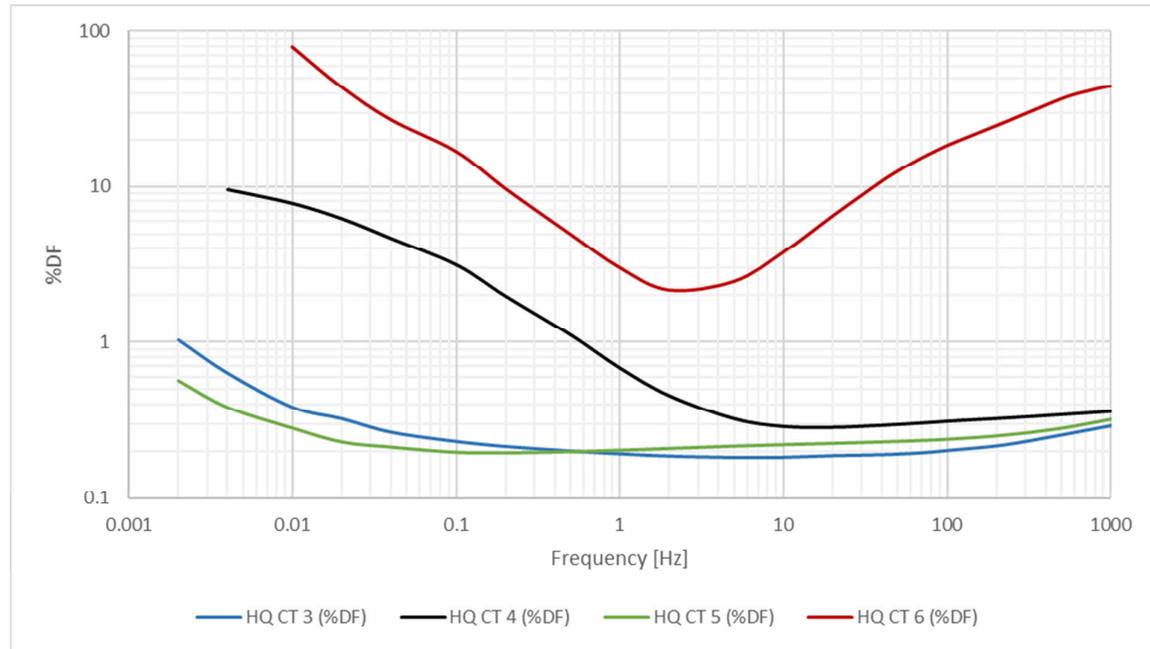


Figure 5 DFR from different EHV CTs as part of investigation by HQ

DFR showed a non-typical response of the insulation system of the specimen HQ CT 6 with high losses all along the frequency spectrum as compared to the reference measurements shown in Fig. 3 and other units in the system as shown in Fig. 5. DGA on HQ CT6 showed abnormal levels for certain hydrocarbons such as acetylene, which is a generally observed after an arcing event or significant partial discharge activity. Values as presented in Table III.

Table III DGA results of CT6

| DGA | H2 | CO | CO2 | CH4 | C2H2 | C2H4 | C2H6 |
|-------------------------|-----|-----|------|-----|------|------|------|
| Measured at bottom tank | 43 | 302 | 489 | 12 | 17 | 16 | 2 |
| Measured at top tank | 5 | 117 | 637 | 10 | 10 | 14 | 11 |
| Typical limit | 140 | 500 | 3000 | 35 | 2 | 15 | 35 |

HQ plans a thorough investigation on HQ CT6 unit with DFR measurements at different layers of the insulation system. At the time of the submission on this article, results from the internal inspection were not readily available.

EHV substations bring a new challenge to the typical LV DFR practice testing at 140V_{RMS}. In order to overcome the EMI of EHV and UHV substations, HQ implemented the use of a

voltage amplifier to improve signal-to-noise ratio. The test procedure developed at HQ considers a HV DFR test at $1400V_{RMS}$, with high quality measurements in the range of 1 kHz down to 10 mHz for 800 kV CTs.

CONDITION ASSESMENT

Most of the failures in instrument transformers result from progressive degradation of the insulation system, a process that must be monitored to avoid unexpected failure and to set an asset management plan prioritizing maintenance activities by proper condition assessment of the dielectric system.

The most common reasons for failure of oil-paper insulation are:

- Ingress of moisture,
- Oxidation and ageing of the oil,
- Partial Discharges ,
- Ageing of the paper, and;
- Thermal instability

Condition assessment methodology by means of DGA and DFR may lead to several of life cycle management decisions.

| Interpretation | Action |
|--------------------------------|---|
| Results are satisfactory | New sampling in 5 years |
| Result not clear or suspicious | New sampling within 6-12 month |
| Result indicates fault | Evaluate maintenance options Plan the replacement of the transformer |

Online monitoring of HV CTs is normally not an economically justified method. Off-line testing of DGA and DFR allow advanced prioritization metrics, leading to changes in the frequency of testing, maintenance or planned removal from the system.

A failure caused by degradation of the solid insulation can only be detected by the means of DGA if the degradation process leaves traces in the oil. Hence, a combined effort using DGA and DFR increases the possibility of effective detection of degradation of the complex oil-paper insulation.



CONCLUSIONS

Dielectric condition assessment of EHV CTs in the field under high EMI is possible using HV DFR ($1400V_{RMS}$). Dielectric analysis in the frequency domain provides a unique dielectric signature of the oil-impregnated paper (OIP) insulation in EHV CTs with and without sand-filling.

Latest development of DFR using the individual temperature correction (ITC) algorithm allow normalization of the entire dielectric response to $20^{\circ}C$. This feature opens now a real opportunity to rank the dielectric response at frequencies different from 60/50 Hz. The study determined that reliable %DF indicators were found at 1Hz and 0.1Hz when properly normalized by ITC; otherwise, the information is vague and potentially misleading.

The experimental work shows that DFR is able detect dielectric changes due to contamination or PD as well as moisture ingress.

Hydro-Québec asset management team will continue the investigation on faulty EHV CTs and together with industry experts will develop a DFR frame of suggested limits at different frequencies to ensure reliable operation and minimize the risk of operation in the field.

DFR and DGA provide advanced assessment of the dielectric condition of HV and EHV CTs. The information is of great importance for asset management and operations personnel.

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