Dielectric Response of Machine Insulation Extracted from DC Ramp Test on Individual Stator Bars

E. David
ETS
Montréal, Canada
eric.david@etsmtl.ca

G.C. Stone, M. Sasic
Qualitrol-Iris Power
Toronto, On, Canada

***Abstract*— DC ramped voltage testing is used to assess the condition of the stator windings in high voltage generator stator windings. When used to only assess the ability of an insulation system to withstand a predetermined DC voltage level, the continuous (and usually slow, typically in the order of 1 kV/min) increase in applied voltage combined with the continuous monitoring of the current often allows a better control of the test to avoid unexpected failure and damaging the insulation. In addition, it can also be used as a diagnostic test and can provide quantitative information similar to the IR/PI test. This paper presents DC ramp test data from individual bars as well as the calculation techniques to calculate the insulation dielectric response compares it to results from polarization depolarization current (PDC) tests.**

Keywords—Machine insulation, dielectric response, DC ramped voltage tests

I. INTRODUCTION

The DC ramped voltage test where high direct-voltage is applied following a continuously increasing function has now been used since several decades to assess the condition of stator windings in high voltage rotating machine. The ramped high direct-voltage method of testing stator windings was first introduced in the sixties [1] and several electric utilities developed their own versions of the test equipment, but this technique became better known after the pioneering work by the Bureau of Reclamation [2] and by Manitoba-Hydro [3] in the nineties that led to the further development of the technique and its interpretation. It was introduced in the IEEE-95 standard for the first time in 2002 [4] (this standard has been re-affirmed since). More recently, additional contributions to the interpretation of the ramp voltage test results and to the development of instrumentation were also reported by Hydro-Quebec and co-workers [5, 6]. Review papers on the development of the ramp test are also available in the literature [7, 8]. All this development was basically motivated by the fact that they are some practical advantages to use ramped direct voltage for testing large machines. In addition to the relative compactness of the test equipment, the elimination of the manual adjustment of the voltage improves both the voltage control and the sensitivity of the test compared to conventional dc hipot tests. Indeed, in many cases the continuous monitoring of the charge current may also allow assessment of the condition of the insulation, instead of being a simple go/no go test. Many successful uses of this technique to detect insulation defects in machine stator windings are reported in the literature (see [9, 10] for example).

In addition to its application in the field, ramp tests can also be performed on individual bars or coils in the lab or in the factory for quality control assessment, provided that the instrumentation is equipped with a sufficiently sensitive current meter, since the current levels are in the nA rather than in the μA. The usual IR and PI parameters, as defined in the IEEE-43 standard [11], can then be calculated from the ramp test results with an appropriate modelling of the I-V curve. This paper presents DC ramp test data from individual bars as well as the calculation techniques to calculate the insulation dielectric response and the usual PDC parameters (IR and PI).

II. THEORITICAL BACKGROUNDS

The starting point of the calculation of the theoretical curve resulting from a DC ramp test is the general equation giving the current, I(t), measured by an external circuit when a linear insulating material is subjected to an arbitrarily time-varying potential difference, U(t):

$$I(t) = \frac{C_o \sigma U(t)}{\varepsilon_o} + C_o \frac{\partial}{\partial t}\left[\varepsilon_\infty U(t) + \int_0^\infty f_s(\tau) U(t-\tau) d\tau\right] \quad (1)$$

In this equation, C_o, ε_o, ε_∞, and σ are respectively the geometric capacitance, the vacuum permittivity, the insulating material dielectric constant and its conductivity. More details on this basic relation can be found in the general literature [12]. The term $f_s(t)$ is the material dielectric response function that can be easily calculated from the results of a polarization depolarization current (PDC) test. For machine winding insulation systems, the dielectric response function in the low frequency region can be assumed to behave approximately in accordance with a universal power-law given by

$$f_s(t) = At^{-n} = K\frac{C_\infty}{C_o}t^{-n} \quad (2)$$

where C_∞ is the measured winding capacitance and K and n are material-dependant parameters. This expression has been shown to be in good agreement with experimental data for different types of winding insulation systems at room temperature in the 1 to 1000 s range as shown in the Annex C of the latest version of the IEEE Std-43 by the discharge currents depicted in Fig. C.1. In the case of a ramp test conducted at a voltage rate α, with some approximations (1) and (2) lead to the following equation that can be divided into three components, the leakage, the capacitive and the absorption current [6]:

$$I(t) = I_L(t) + I_C(t) + I_{abs}(t) = \frac{\alpha}{R_L} t + \alpha C_\infty \left(1 - e^{-t/\tau}\right) + \frac{\alpha K C_\infty}{(1-n)} t^{1-n} \quad (3)$$

When the values of K, n and R_L are computed, the polarization index, PI, and the insulation resistance, IR (to not be confused with the leakage resistance, R_L) can be calculated using the following equations [6]:

$$IR = \frac{1}{K C_\infty 60^{-n} + 1/R_L} \quad (4)$$

$$PI = \frac{K C_\infty 60^{-n} + 1/R_L}{K C_\infty 600^{-n} + 1/R_L} \quad (5)$$

III. Experimental Results

A. Measuring systems

Two measuring systems were used. One of them was a commercially available equipment, the Qualitrol DCR-60 HVDC ramp test system that is mainly designed for field measurements and accordingly operates in grounded specimen test (GST) mode. A laboratory-made ramp system was assembled in order to compare the resulting I-V curve with the Qualitrol commercial system. The lab system included an analogic controllable switching power supply (Glassman High Voltage Inc., model ER60), a highly sensitive current meter (a Keithley 6517B electrometer) and adjustable external series resistor. This setup was controlled by a Labview application and both a DAQ and a GPIB card were used to interface with the dc voltage supply and the electrometer. It was designed to be used in ungrounded specimen test (UGT) mode only, so it is strictly for lab measurements. A schematic representation of the lab setup is shown in Fig. 1.

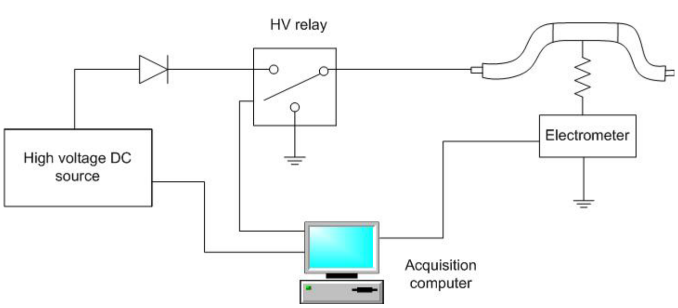

Fig. 1. Laboratory setup for ramp test in UGT mode (adapted from [6]).

B. Experimental results and modelling

Fig. 2 shows the I-V plot for a 2 kV/min voltage ramp, up to 20 kV on a 2.0 nF (bar#1) and a 4.3 nF (bar#2) hydro-generator epoxy-mica bar. The 2.0 nF bar was a spare bar and the 4.3 nF bar was a bar that was removed from a machine because of low values of IR. When tested in the lab, the IR of this bar was roughly three times lower than a similar spare bar [13].

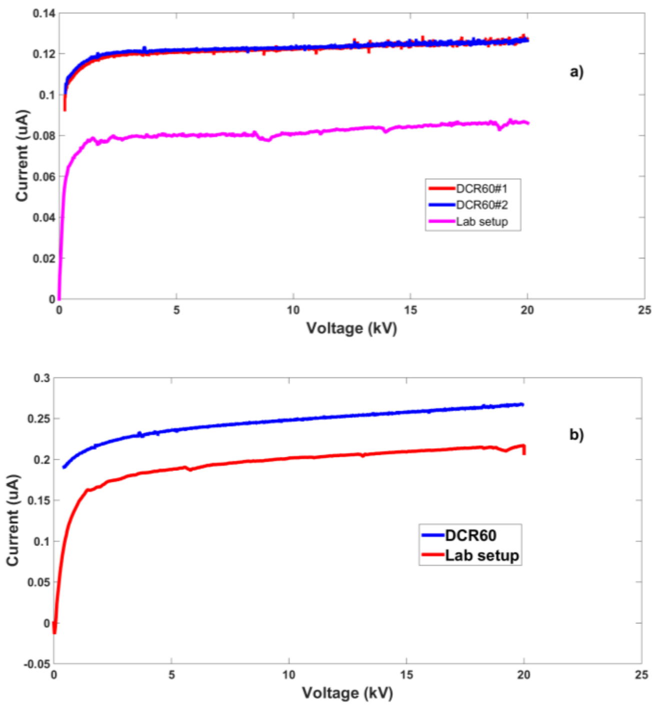

Fig. 2. I-V curves at a rate of 2 kV/min on a a) 2.0 nF a b) 4.3 hydro-generator bars obtained from the DCR-60 and from a lab-made equipment.

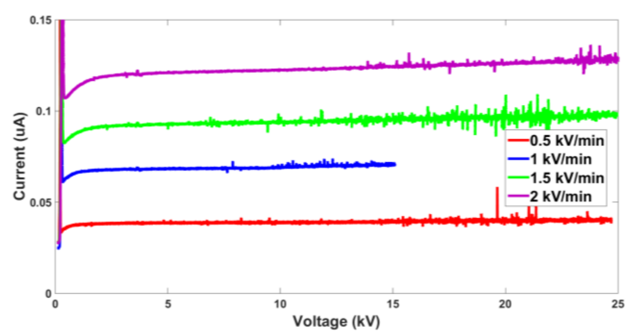

Fig. 3. I-V curves on a 2.0 nF hydro-generator bar measured by the DCR-60 at different voltage rates.

Ramp tests were repeated several times with the DCR-60 on the 2.0 nF bar and the results were very reproducible. Two typical curves are shown and essentially superimposed in Fig. 2a. Additional measurements were conducted on the same bar at different voltage rates, from 0.5 to 2 kV/min, as shown in Fig. 3. The current level decreases when the voltage rates decreases from 2 to 0.5 kV/min since the corresponding capacitive current decreases from 66 nA to 16 nA. It can be seen that the sensitivity of the current detector for the DCR-60 (the GST equipment) is good, probably lower than few nA. However, when the results from the DCR-60 were compared with the I-V curve on the same bar obtained with the lab-made equipment, both systems exhibited an offset of about 30 nA, as shown in Figs. 2a and 2b. This would have been negligible for field measurements but it was noticeable for measurements on individual bars. Equation (3) was used to model the experimental curves, as shown in Figs. 4 and 5. The capacitive current at 2 kV/min is 66 nA and 144 nA for the 2.0 and 4.3 nF bars respectively and is indicated by the dash-dot line.

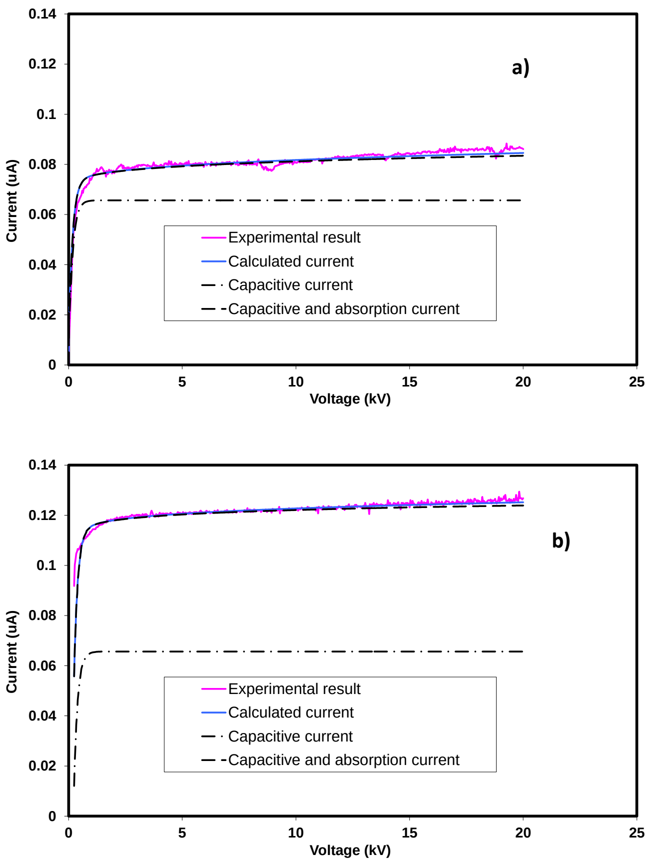

Fig. 4. Modelling (according to eq. 3) of the I-V curve at 2 kV/min on a 2.0 nF bar: a) DCR-60, b) lab setup.

A best fit of (3) was calculated for each experimental result and is indicated by the curve labelled "calculated current" in Figs. 4 and 5. The difference between this curve and the dash curve labelled "Capacitive and absorption current" corresponds to the contribution of the leakage current. The dielectric parameters K and n were extracted from this calculation and reported in Table 1 for each of the four curves of Figs. 4 and 5. The polarization index (PI) and the insulation resistance (IR) were calculated from (5) and (4) respectively using the values K and R_L calculated from (3). These values were also reported in Table I as well as the normalized resistance in charge (RC) and in discharge (RC') as described in the annex C of [11]. The later values were measured at room temperature and would need to be multiplied by roughly 0.8 in order to report them at 40°C according to the procedure recommended in [11] for thermosetting resins. The RC' for the 2.0 nF bar was typical from a modern state-of-the-art epoxy-mica insulation [14] while it was noticeably lower for the 4.3 nF bar. Furthermore, in the case of the 4.3 nF bar, an non negligible leakage current was observed from the modelling of both I-V curves from the lab setup and the commercial equipment. This observation was in good agreement with the lower values of PI observed for bar#2 as listed in Table I and also with previous PDC measurements done on the same bar that has shown low IR values [13].

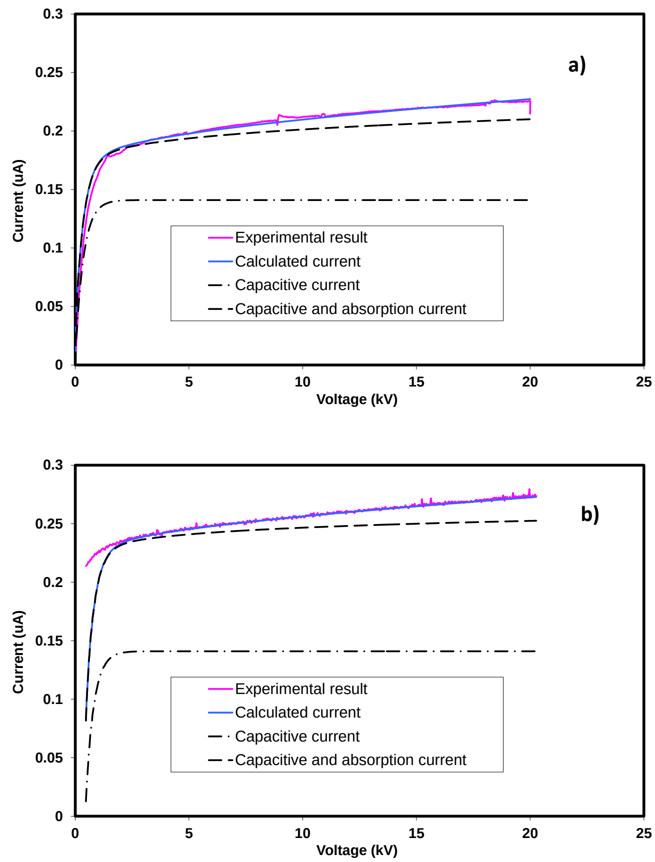

Fig. 5. Modelling (according to eq. 3) of the I-V curve at 2 kV/min on a 4.32 nF bar: a) DCR-60, b) lab setup.

TABLE I: DIELECTRIC PARAMETERS EXTRACTED FROM THE I-V CURVES SHOWN IN FIGS. 4 AND 5.

	K $s^{(n-1)}$	n	PI	RC (s)	RC' (s)
Bar#1-Lab	0.015	0.81	5.07	1700	1780
Bar#1-DCR60	0.030	0.95	6.38	1580	1670
Bar#2-Lab	0.027	0.81	3.34	817	984
Bar#2-DCR60	0.037	0.93	3.13	928	1200

IV. CONCLUSION

DC ramp tests were conducted on individual epoxy-mica insulated hydro-generator bars with two different systems operating in GST and UST modes respectively. The I-V curves were modeled assuming a power-law behavior of the dielectric response function. Although an offset of few dozens of nA was observed between the two systems, the basic dielectric parameters (K, n, R_L) and diagnostic parameters (IR, PI) extracted from the I-V were in good agreement for both systems.

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