2024 Iris Rotating Machine Conference
Las Vegas, NV, June 17-20, 2024

ÉTS Le génie pour l'industrie

Hydro Québec

Review of DC testing for preformed windings of large rotating machine[1]

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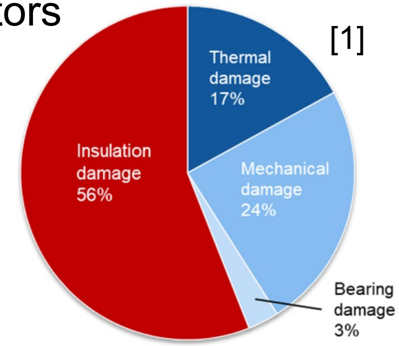
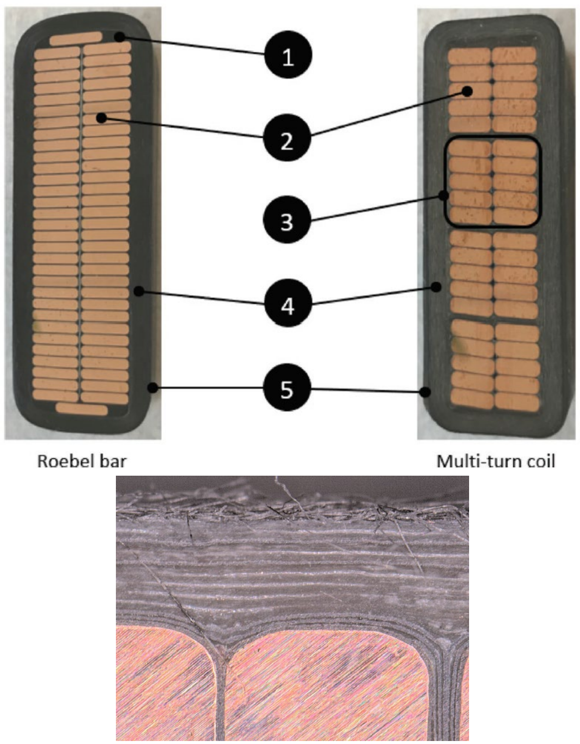
[1]Some of the Material for this presentation was extracted from the draft version of IEEE P97 *Trial-Use Guide for Diagnostic Test Methods for AC Electric Machinery using Direct Voltage*

DC testing

- Insulation damage accounts for a significant proportion of hydrogenerators failures
- The purpose of DC testing is to assess the reliability of the insulation
- It can be used for
  - Acceptance and/or maintenance testing and provides pass/fail + diagnostic capability
  - Insulation condition assessment and trending
  - Withstand test



[1]

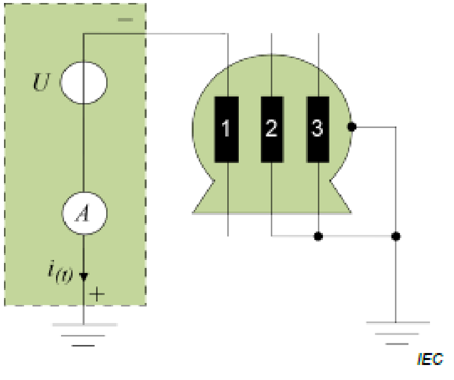


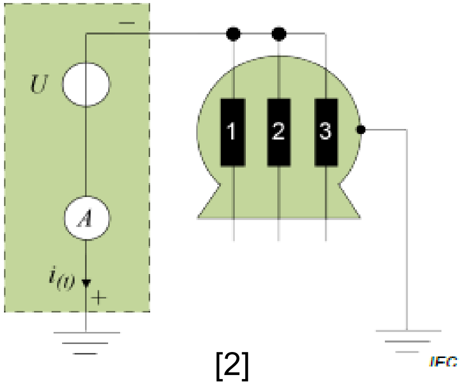
[2]

[1] CIGRE, "Hydrogenerator Failures – Results of the Survey," 2003.
[2] M. Lévesque et al, EIM, 2023.

DC testing

- It can be used on individual phases or complete windings as well as on individual coils/bars
- I can potentially detect the following conditions [1]
  - Delamination
  - Cracks/fissures
  - Internal/external contamination
  - Wet insulation
  - Localized insulation weakness
  - Partially cured epoxy (new/repairs)
  - Physical damage to the end windings
- Applicable IEEE standards
  - IEEE Std. 43 (latest version 2013)
  - IEEE Std. 95 (latest version 2002)
  - IEEE Std. 97 (not yet available)



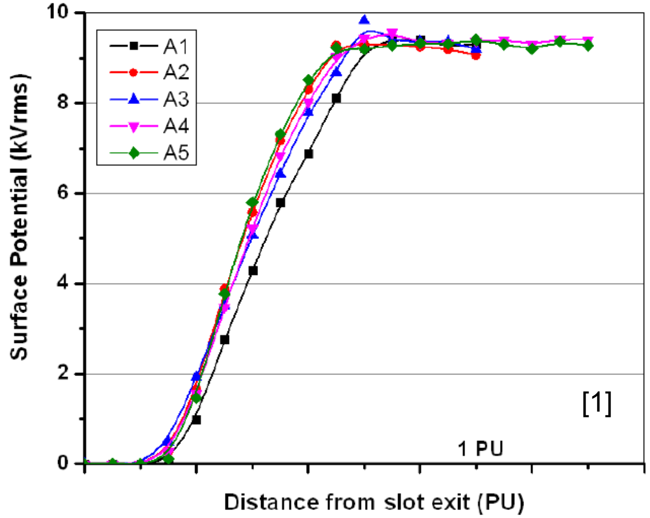


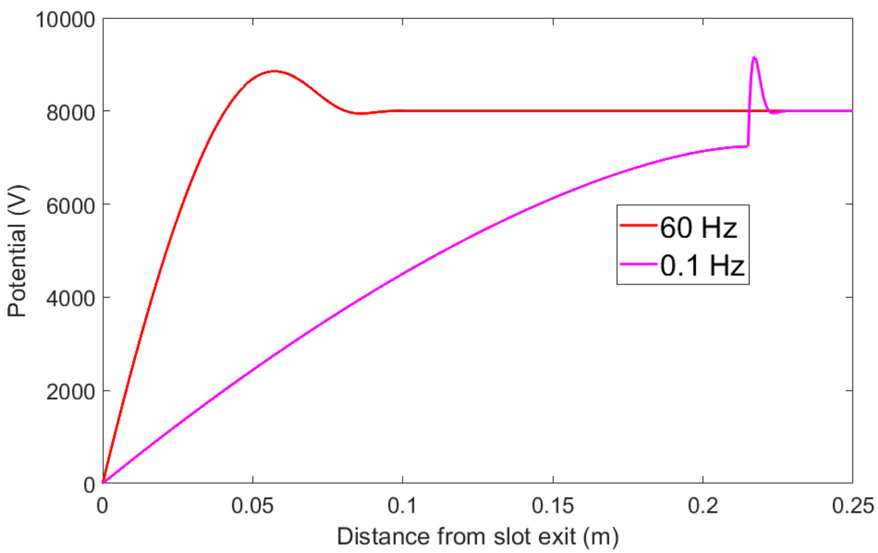
[2]

[1] FIST 3-1 (not yet available)
[2] IEC 60034-27-4

DC versus AC

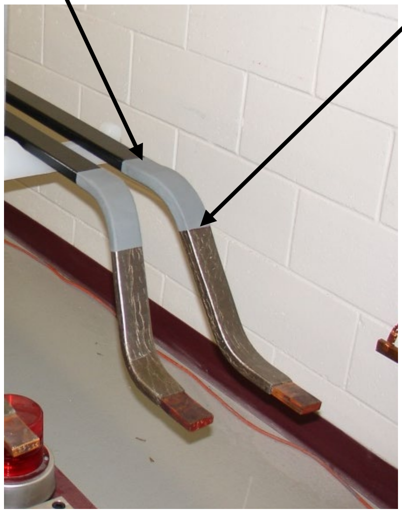
- No polarity alternance (sporadic PDs, if any)
- Light, portable and commercially available equipment
- Different distribution of gradient in end windings for machines with ECP systems

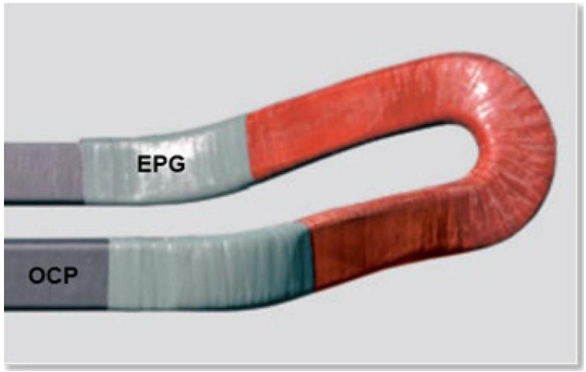




Full potentiel (AC)

Full potentiel (DC)





[2]

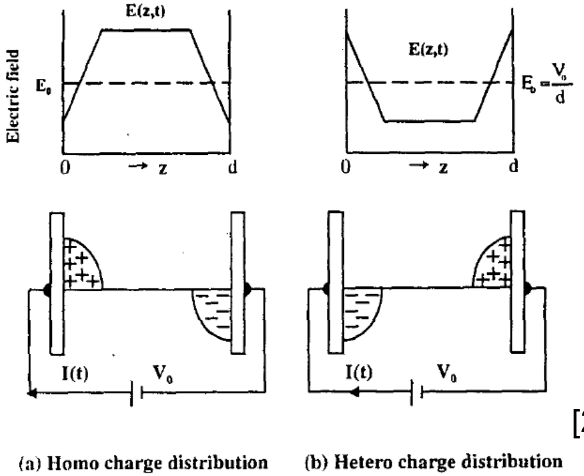
[1] S. Ul Haq, R. Omranipour, ISEI 2010
[2] M. Lachance, master's thesis, ETS, 2024

DC versus AC

- **Space charge: is this an issue? (VLF withstand test instead of DC)**

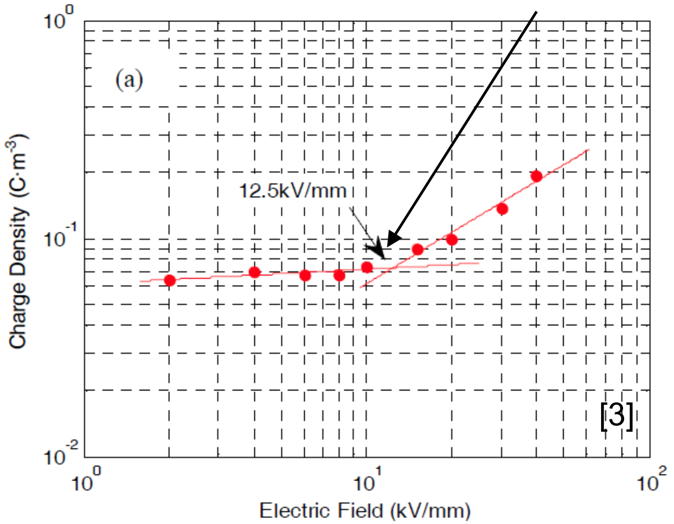
In a insulating material, space charge is formed due to [1]:

- Injected charge carriers at the electrodes
- Charge already present in the bulk due to ionic impurities



[2]

~2.7V_{LL} (37.5 kV) for a 13.8 kV machine



[3]

- A **huge** amount of literature exists on the subject, mainly for thermoplastic insulation materials
- No evidence of damage to machine insulation due to charge injection has been reported of far

[1] G. Mazzanti, M. Marzinotto, Extruded Cable for HVDC Transmission, 2013
[2] T. Takada, CEIDP 1999
[3] P. Liu et al, TDEI, 2015

DC testing procedures

Survey (small) on the different variants of DC testing commonly used [1]

AFFILIATION	%
Manufacturer	23%
Repair Shop	18%
Utility	18%
Service Provider	14%
Laboratory	14%
Consultant	9%
Other	5%

Low voltage (all of them can be included in PDC test)

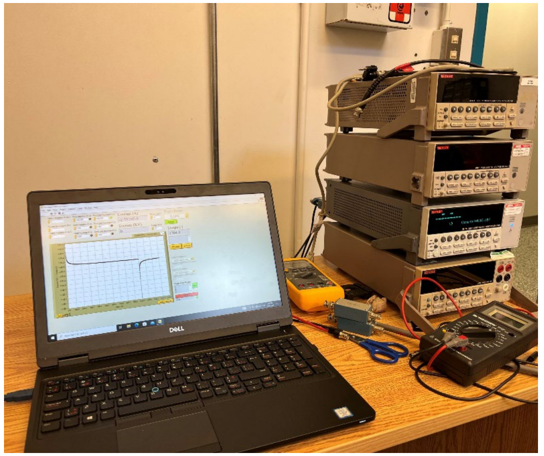
High voltage

DC Test	Test performed
Polarization index (PI)	100%
DC withstand test (Hipot)	92%
Insulation Resistance (IR)	92%
DC ramp test (DCR)	**77%**
Dielectric Absorption (DA)	54%
Insulation Resistance Profile (IRP)	54%
Dielectric Absorption Ratio (DAR)	31%
Polarisation and Depolarization (PDC)	**31%**

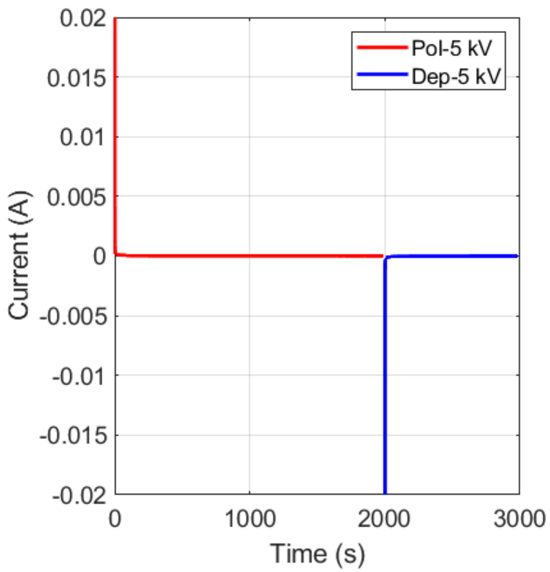
[1] Conducted for IEEE-97 WG

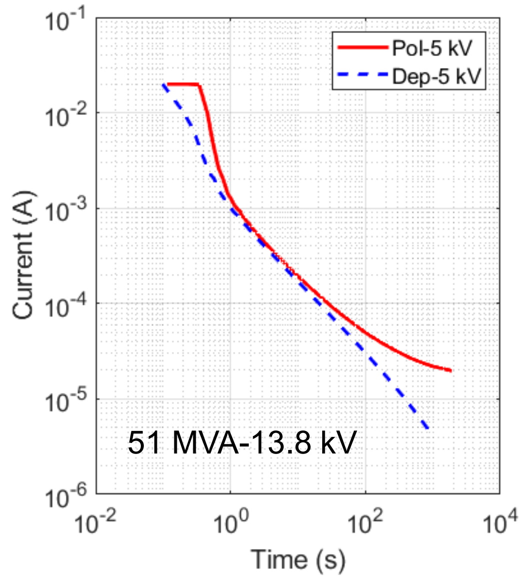
Low voltage DC testing

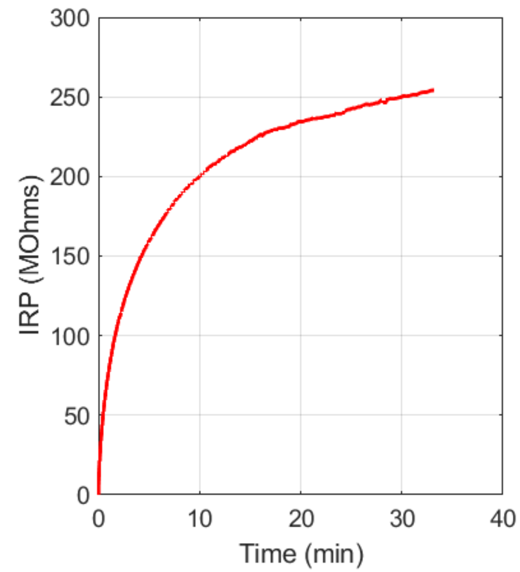
- LV DC Test: Single or multiple voltage step test with the continuous monitoring (or not) of charge or both charge and discharge currents: IEEE-43 (RP), IEC 60034-27-4 (S), IEEE-97 (G). Typical voltage is 5 kV for a 13.8 kV machine
- Commercialized or home-made equipment

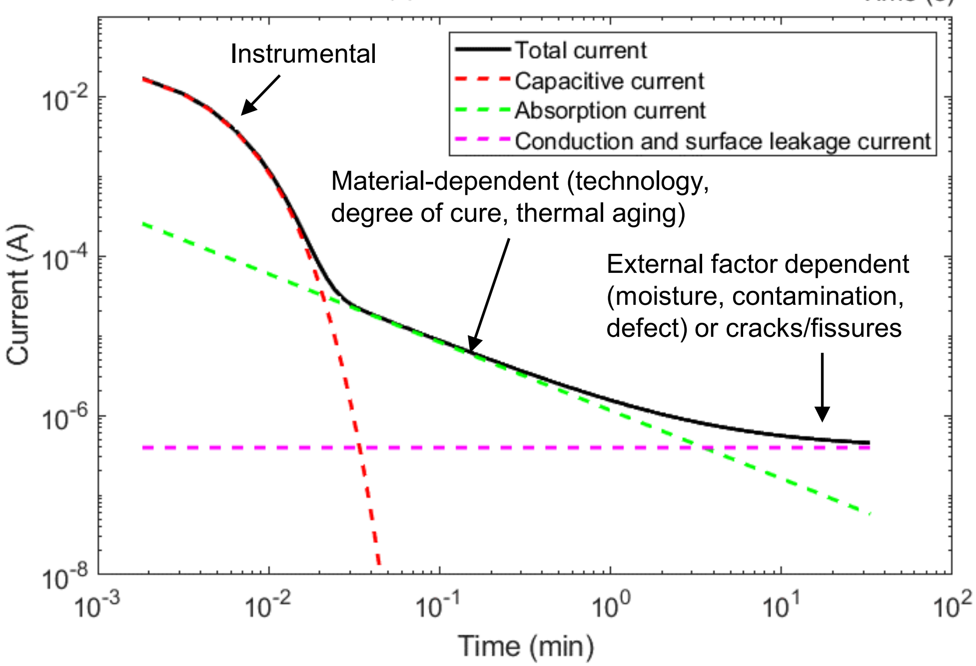


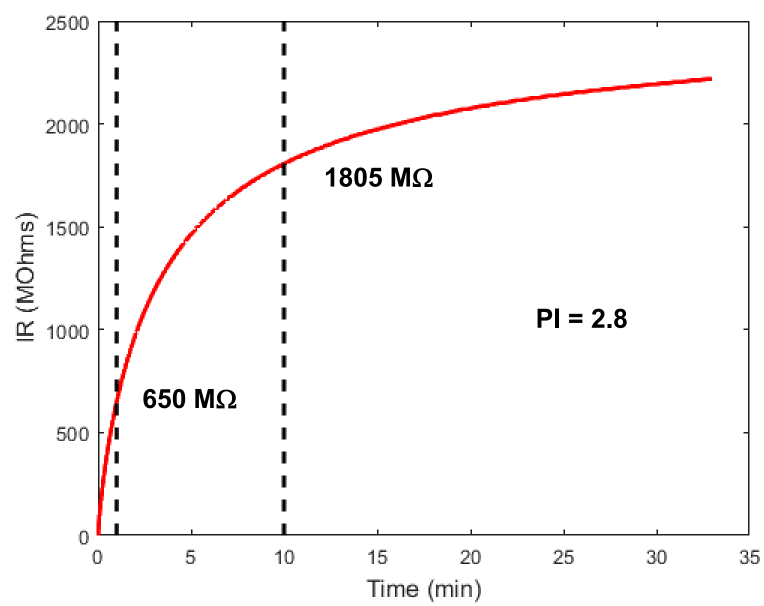
Single voltage step test (IR & PI test, IRP, PDC) – IEEE 43 & IEEE 97







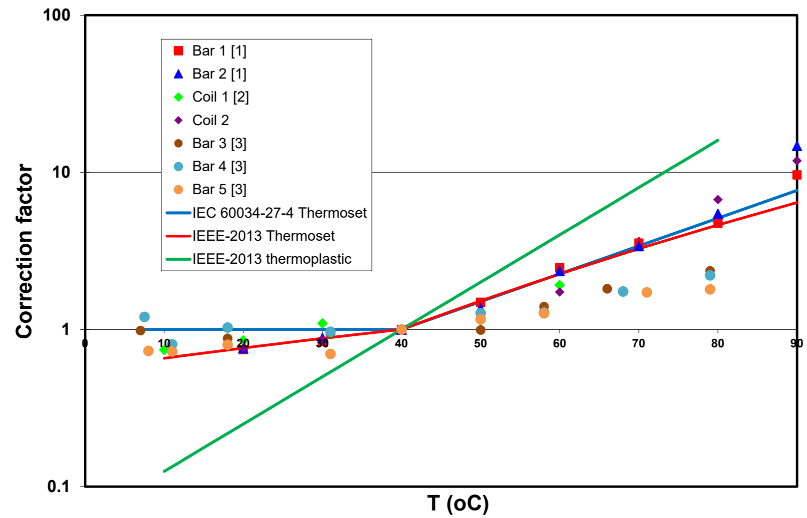


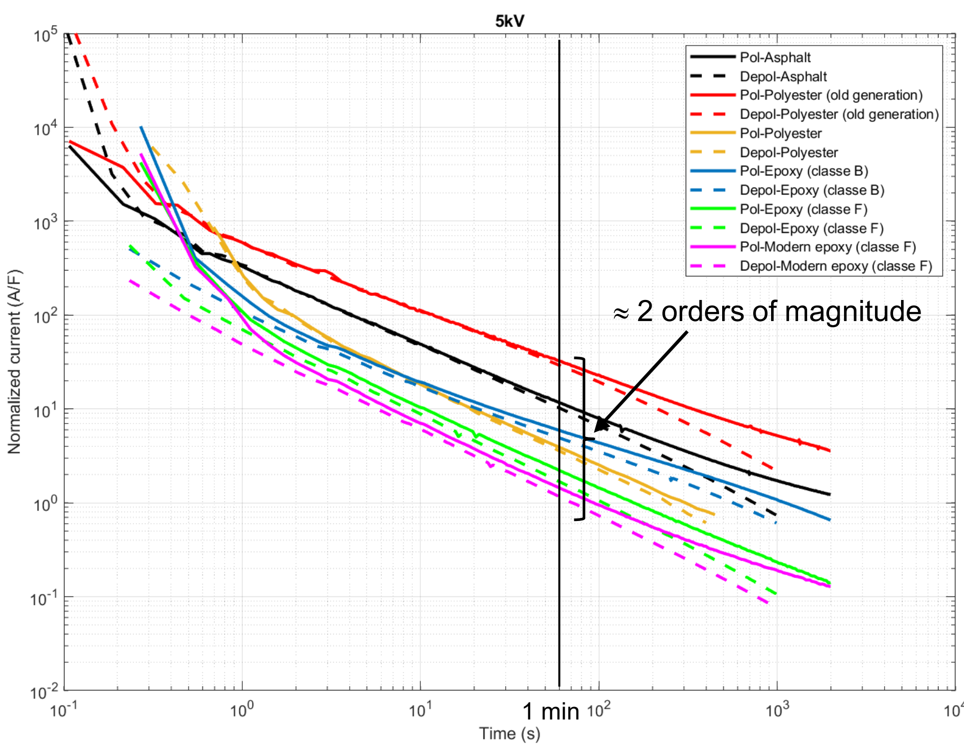


Single voltage step test (IR & PI test, IRP, PDC) – IEEE 43 & IEEE 97

Things to consider

- Dependency upon the chemical nature of the insulation system
- Dependency upon the size of the machine: useful to normalized by the capacitance for comparison purpose
- Moderate temperature dependency for modern epoxy-mica insulation system, higher for older systems



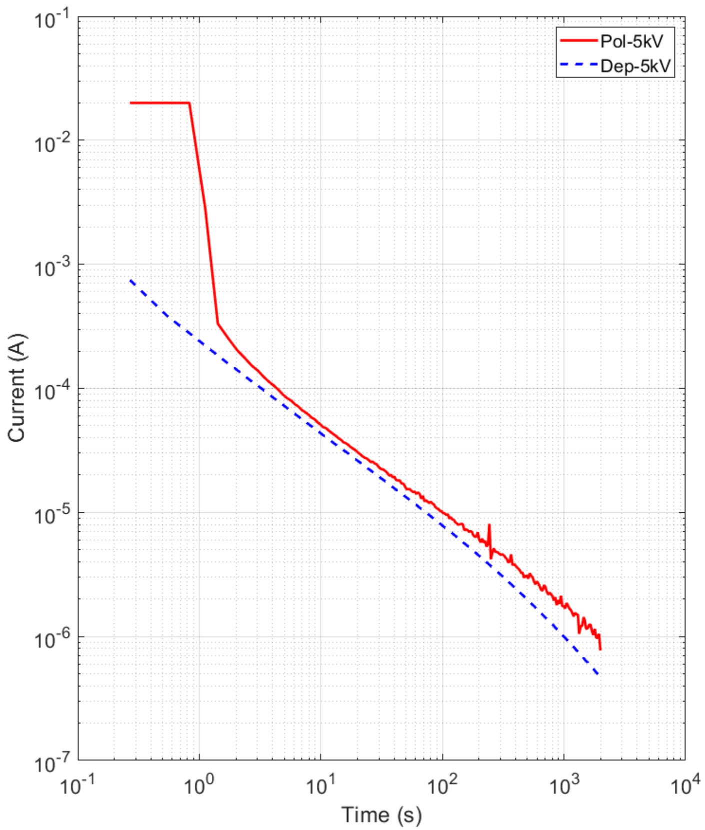


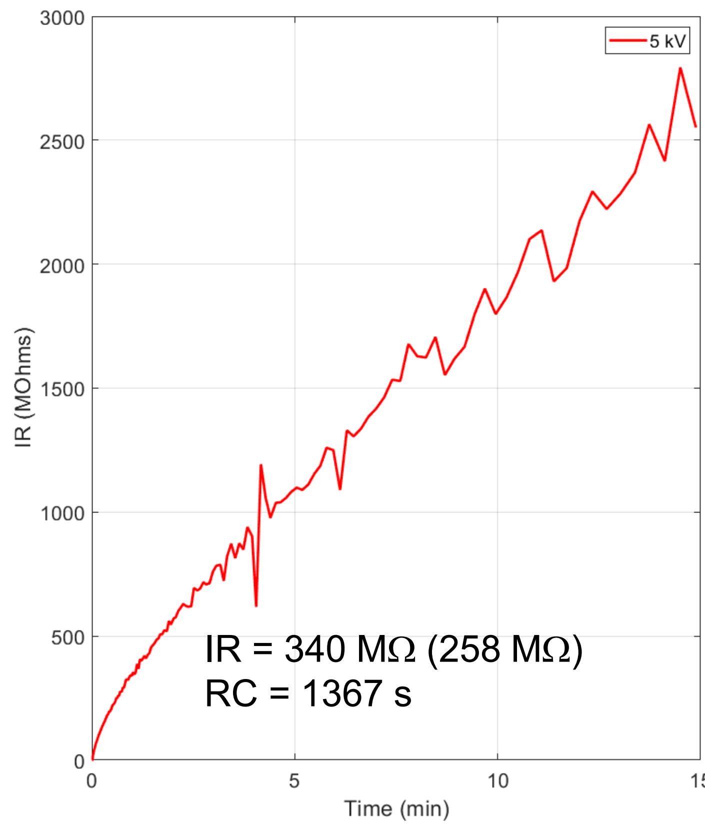
	IR (GΩ) [1]	1-µF Machine (MΩ)
Epoxy-1	1960	4970
Epoxy-2	787	2160
Polyester-1	341	1230
Polyester-2	29.9	149
Asphalt	175	462

[1] E. David et al, EIC 2007

Single voltage step test: large machine

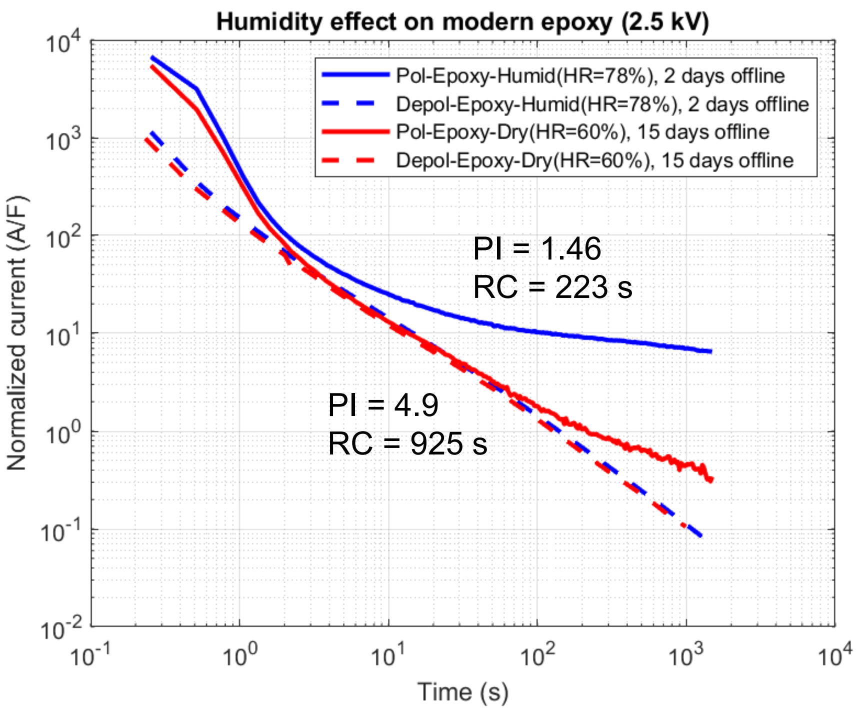
310 MVA – 21 years – 20°C - 3ϕ - 4.02 μF [1]

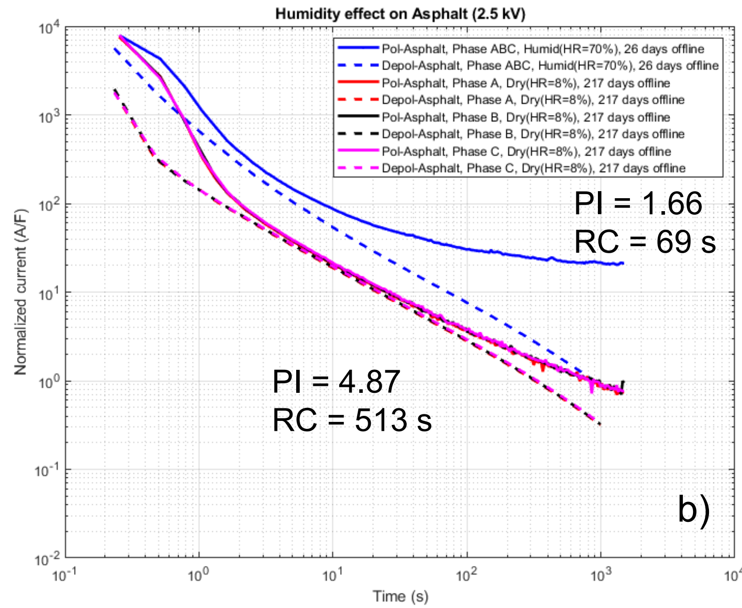


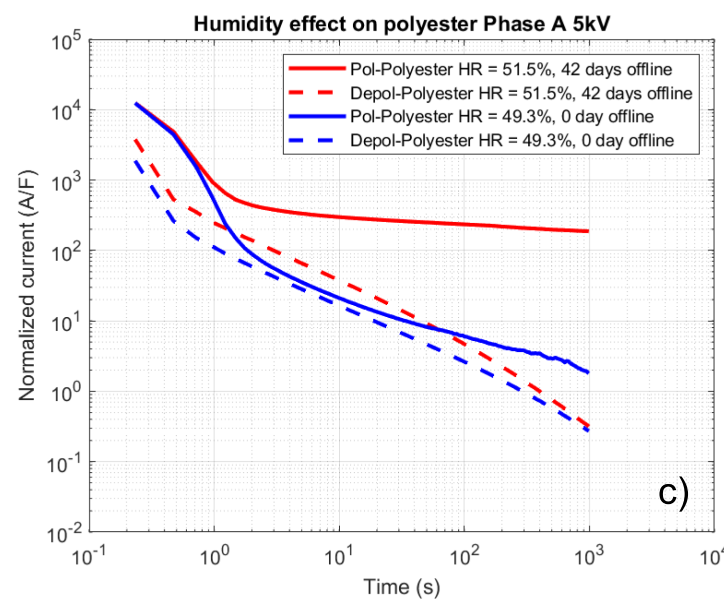


Single voltage step test: wet windings

Moisture will affect the polarization current (lowering IR and PI) and may or may not affect the depolarization current





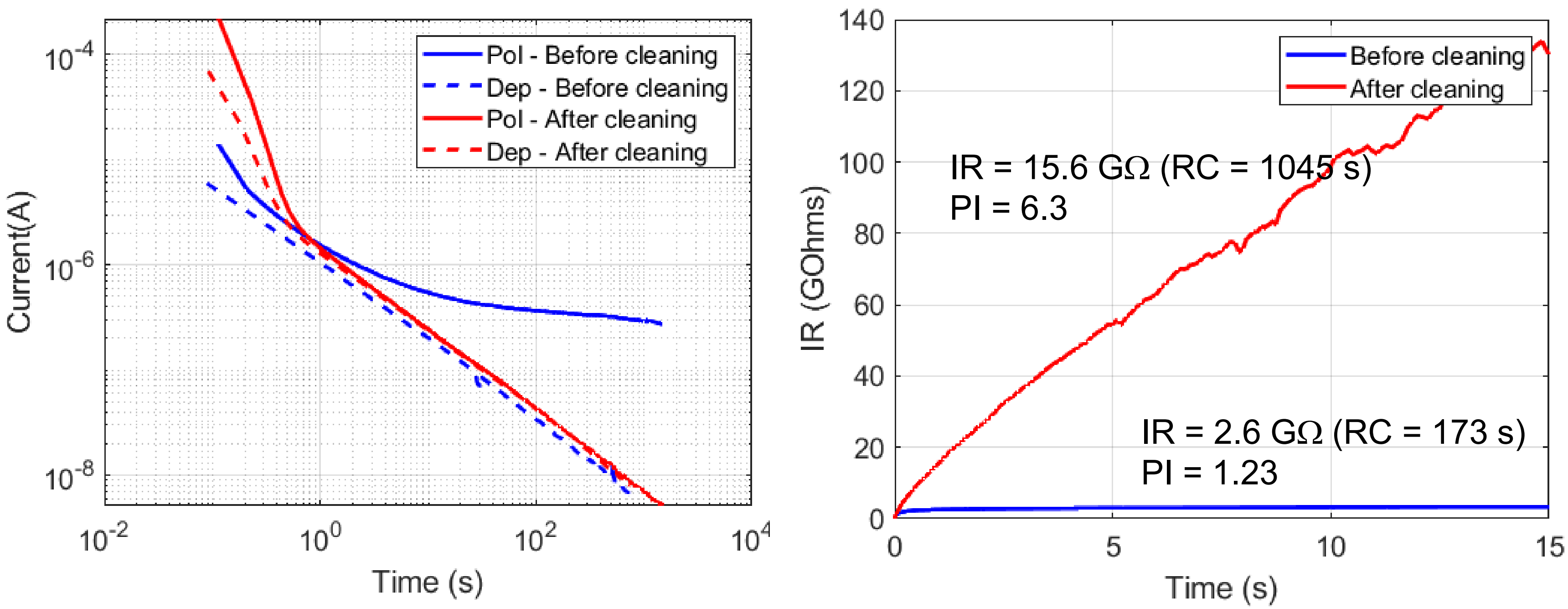


a) 3ϕ of a 36 MVA machine (C = 2.96 μF) in wet and dry conditions, **b)** 3ϕ of a 36 MVA machine (C = 1.369 μF) in humid condition and each phase measured separately after 6 years of aging in dry condition, **c)** ϕ_A of a 51 MVA machine (C = 0.585 μF) in humid and dry conditions.

Single voltage step test: surface contamination

Similarly, surface contamination will affect the polarization current (lowering IR and PI) and usually will not affect the depolarization current

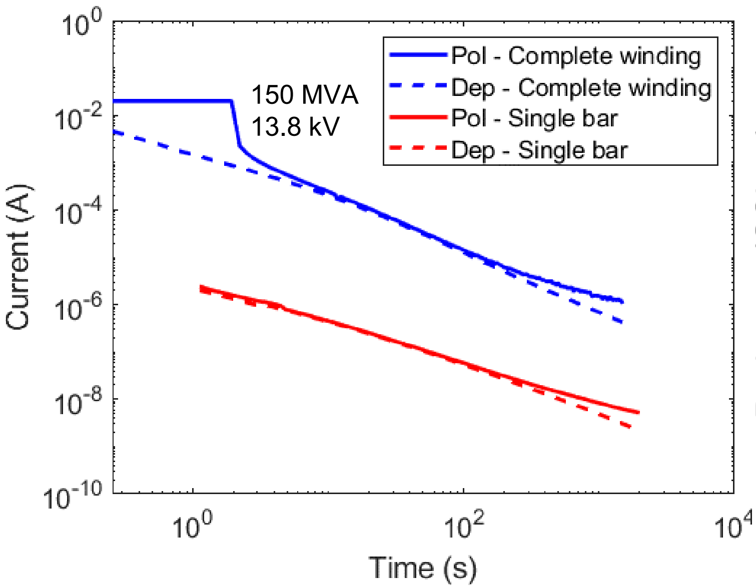
6.9 kV – 7000 HP motor - ϕ_A [1]

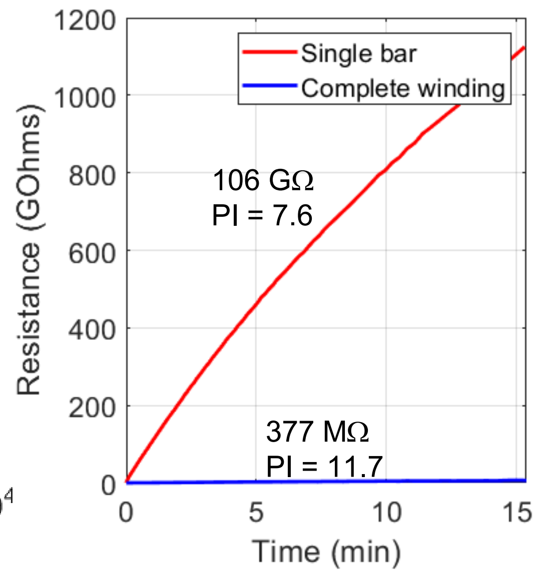


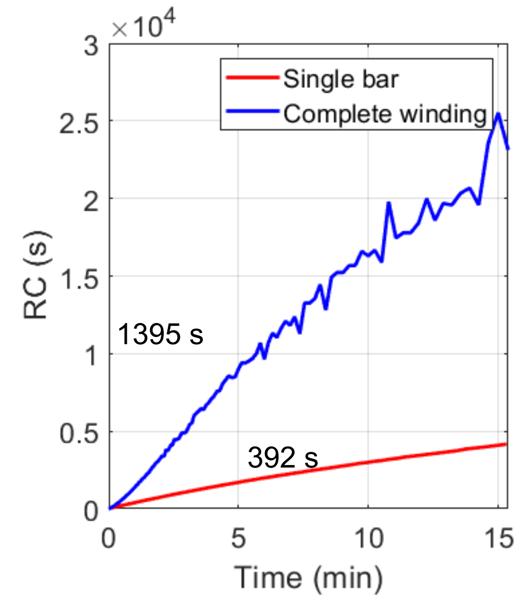
[1] C. Paynot et al, EIC 2005.

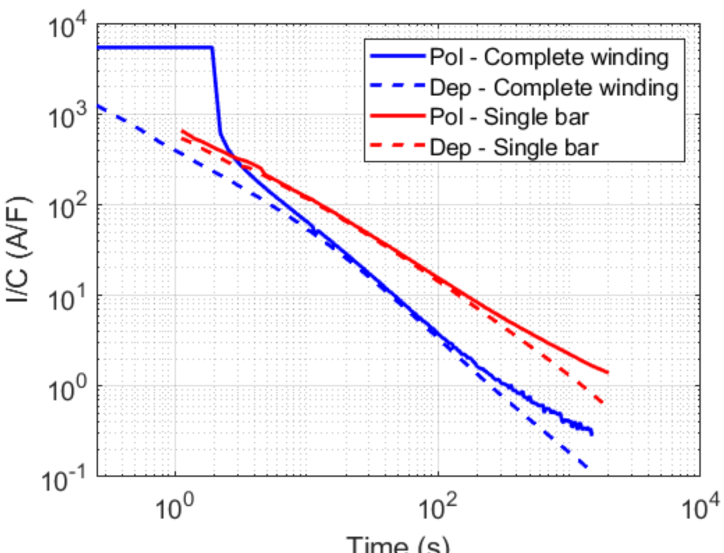
Single voltage step test: incomplete curing

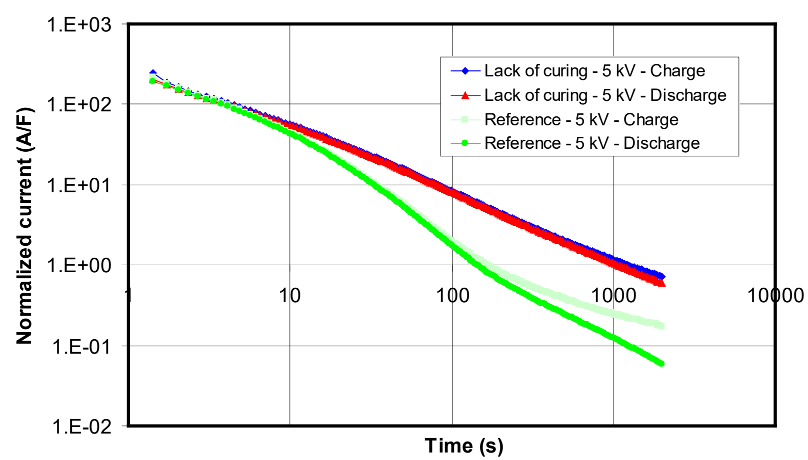
Incomplete curing will increase the dielectric losses (PF) and the absorption current in a DC test leading to an increase of both charge and discharge currents [1]







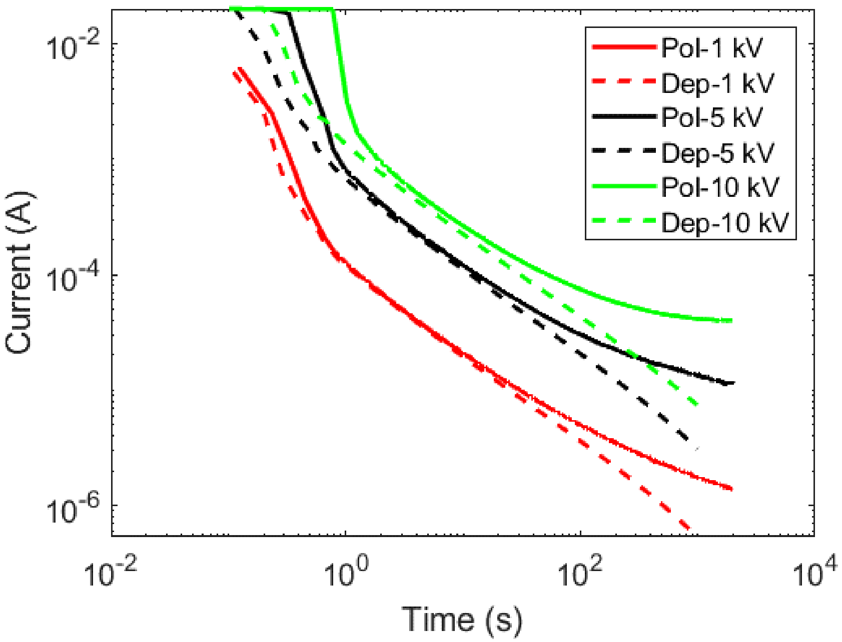


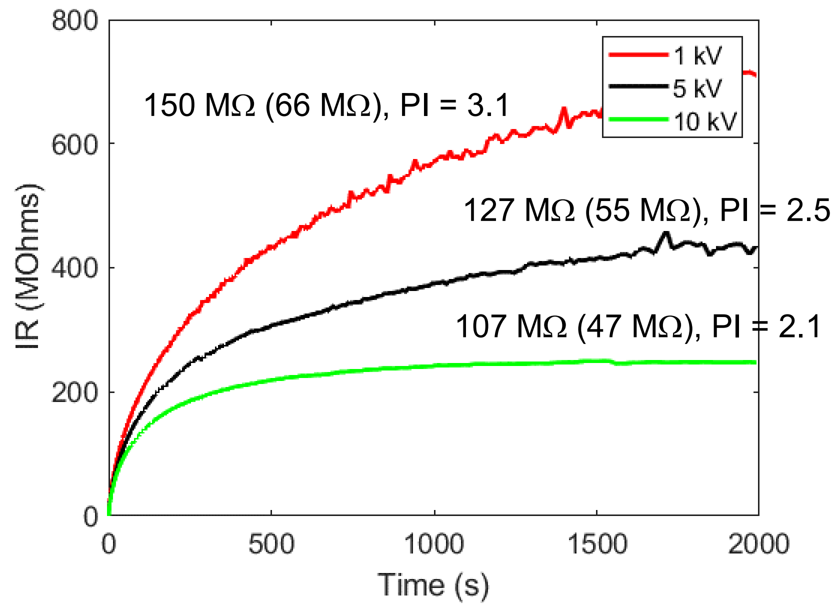


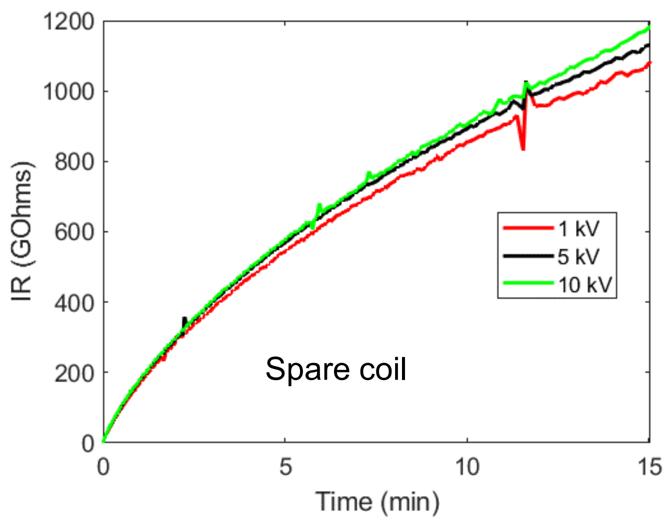
[1] E. David et al, EIC 2007

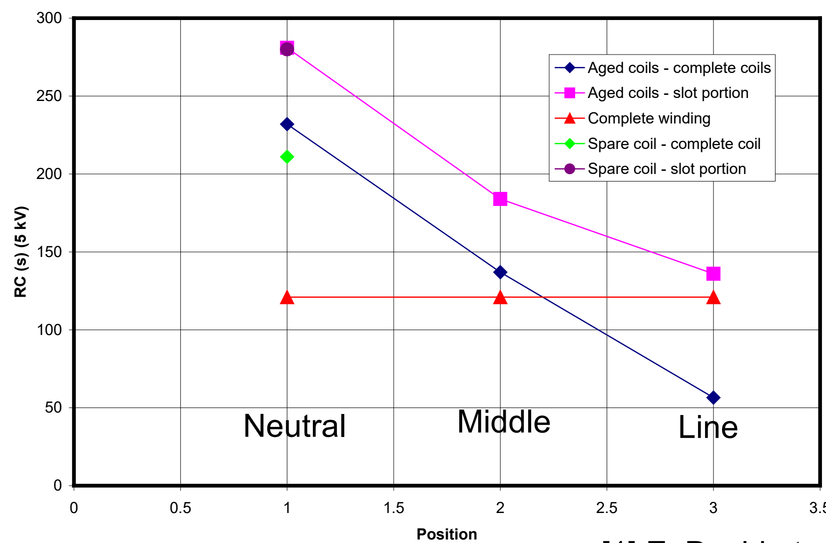
Single voltage step test: field aging

50 MVA – 13.8 kV machine – after 52 years in service [1]







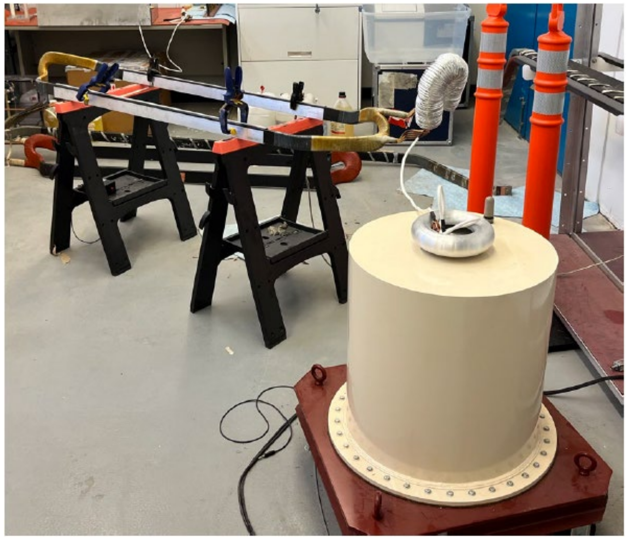


[1] E. David et al, ICSD 2004

Single voltage step test: lab aging [1]

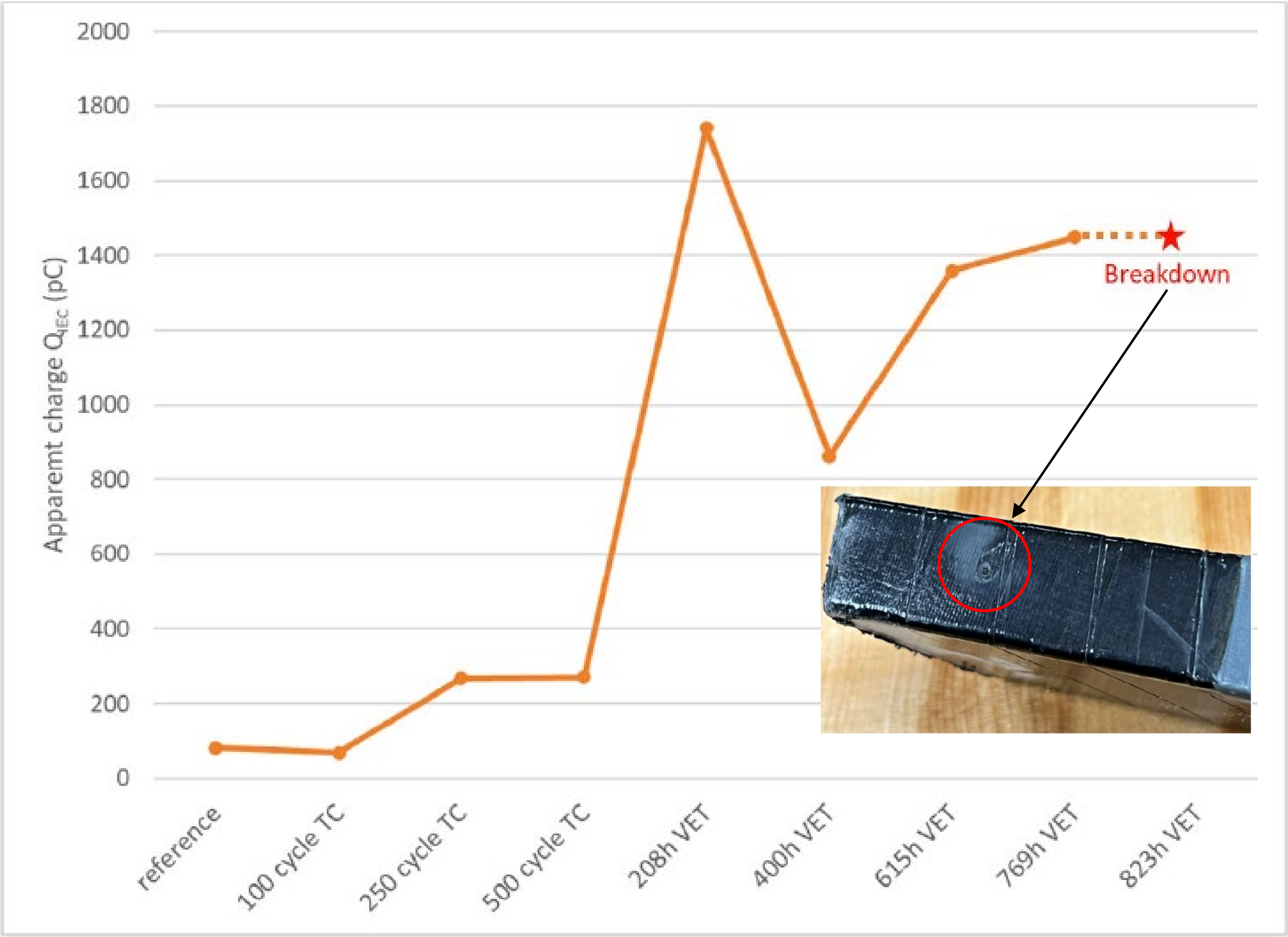
TC followed by 30/35 kV VET on three 13.8 kV coils up to failure

- 500 cycles of TC according to IEEE-1310 (155^{o}C – 40^{o}C)
- VET according to IEEE-1043 - Schedule A (30 kV - 90^{o}C) for 400h
- VET at RT at 30 kV until failure



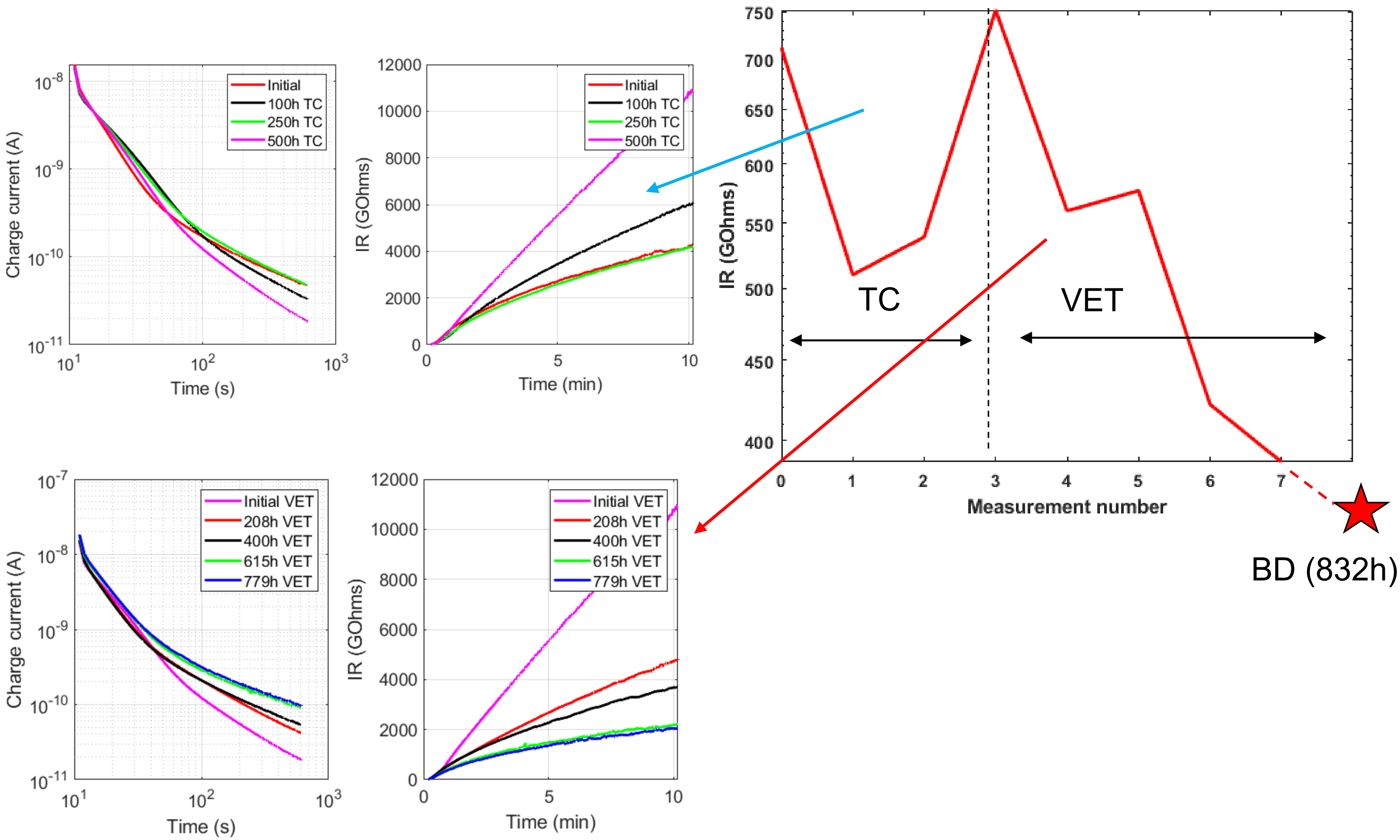
[1] M. Lachance, Master's thesis, ETS

Single voltage step test: lab aging [1]



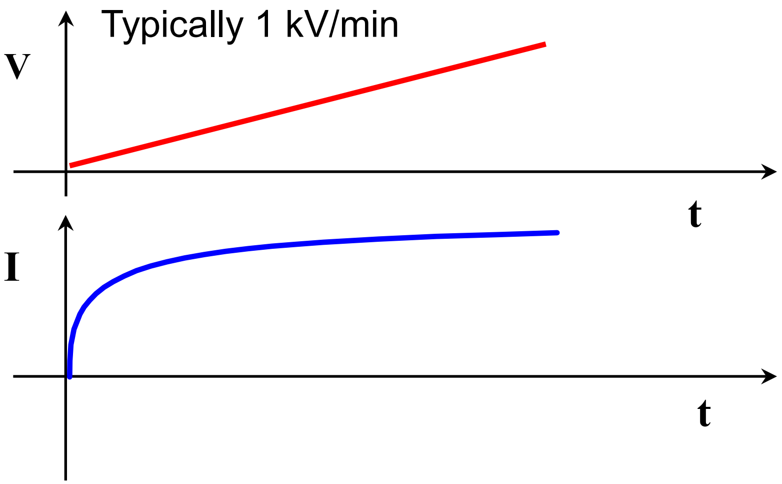
[1] M. Lachance, Master's thesis, ETS

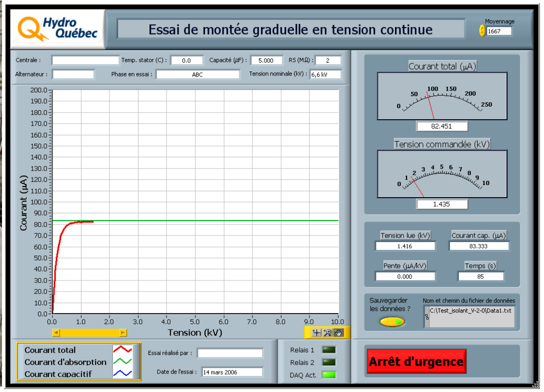
Single voltage step test: lab aging [1]



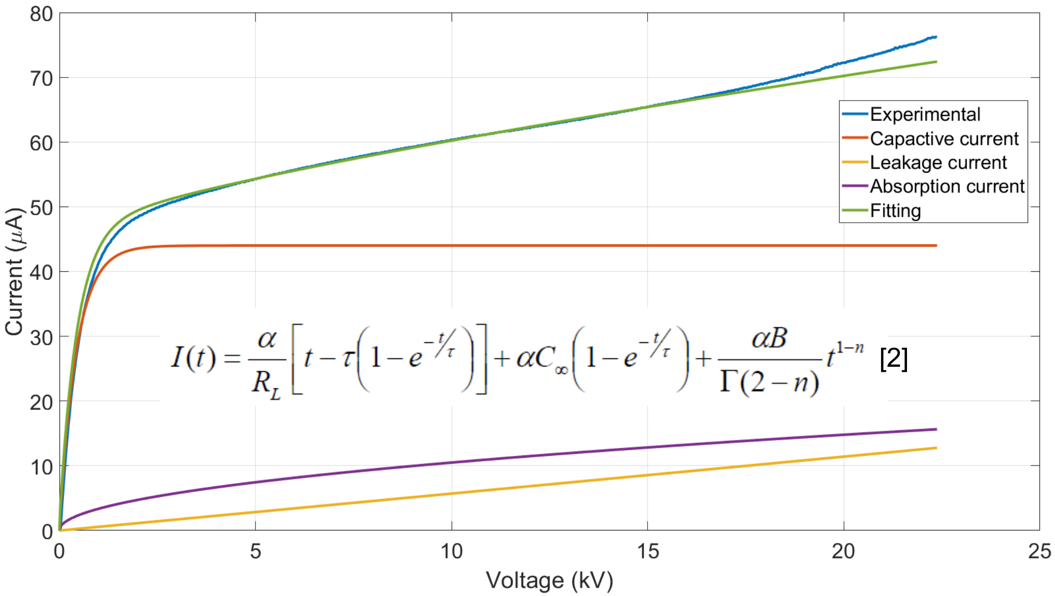
[1] M. Lachance, private communication

Direct Current Ramp (DCR) test: IEEE 95, IEEE 97, FIST 3-1





[1]



$$I(t) = \frac{\alpha}{R_L}\left[t - \tau\left(1 - e^{-t/\tau}\right)\right] + \alpha C_\infty\left(1 - e^{-t/\tau}\right) + \frac{\alpha B}{\Gamma(2-n)} t^{1-n}$$ [2]

DCR Test of the 3 phases of a 46.6 MVA-13.8 kV polyester-mica hydrogenerator

[1] E. David et al, Hydrovision 2006
[2] E. David et al, TDEI, 2007

DCR EOT voltage selection

Typical EOT voltages (according to a recent survey)

Respondent	Commissioning	Maintenance	Repair
Hi-pot IEEE95 (1 minute)	(2E+1) x 1.7	125 to 150 %E x 1.7 65 à 75 % (2E + 1) x 1.7	
1	1.65 x 1.7 E	1.25 x 1.7 E	
2	2.17 E or 30 kV for 13.8 kV	0-10 years : 2.17 E or 30 kV for 13.8 kV 10-20 years : 1.81 E or 25 kV for 13.8 kV	
3	1.5 E x 1.7 x 0.85	1.25 E x 1.7 x 0.85	1.25 E x 1.7 x 0.85
4		(2E+1) x 1.7 x 0.66	
5	1.25 E to 1.5E	1.5 E if done by OEM 1.25 E if done by us	
6		E* 1,7	E* 1,7
7	30kV (for 13.8 kV)		21kV (for 13.8 kV)
8		if E≤13,8 kV, E* 0,9* 1,7 if E>13,8 kV, 21kV	

For V_{LL} = 13.8 kV

Respondent	Commissioning	Maintenance	Repair
Hi-pot IEEE95 (1 minute)	49 kV	29 kV to 35 kV 32 kV to 36 kV	
1	39 kV	29 kV	
2	30 kV	0-10 years : 30 kV 10-20 years : 25 kV	
3	30 kV	25 kV	25 kV
4		32 kV	
5	17 kV to 21 kV	21 kV if done by OEM 17 kV if done by us	
6		23 kV	23 kV
7	30 kV		21 kV
8		21 kV	

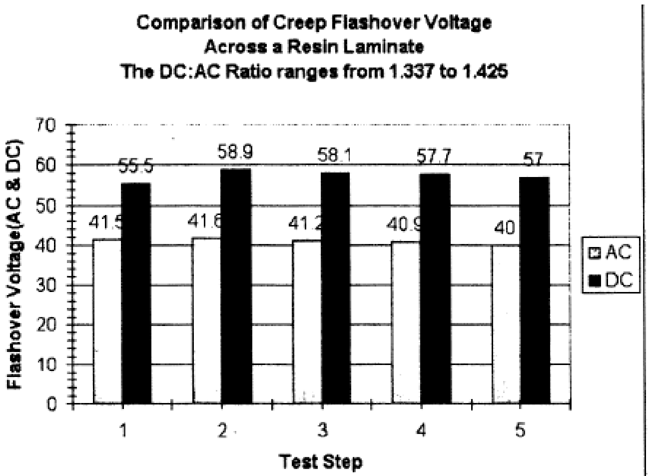
$$V_{EOT} = 1.5 \times V_{LL} \times 1.7 \times 0.85$$ New (0-5 y) machine

$$V_{EOT} = 1.25 \times V_{LL} \times 1.7 \times 0.85$$ Field-aged (5+ y) machine

[1]

The 1.7 ratio [2]

Lower values [3]:



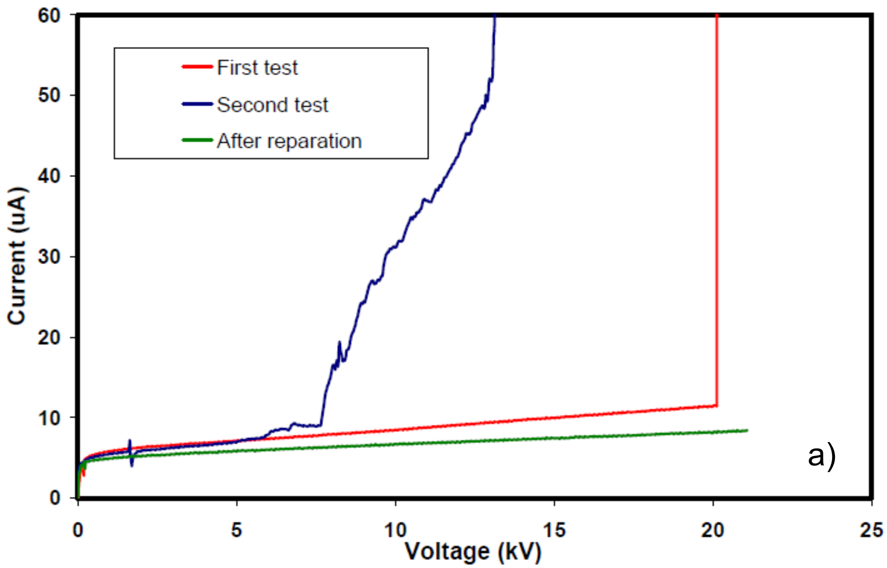
Higher values [4]:

- VET 35 kVac – 110°C: all bars failed between 25 and 150h
- VET 59.5 kVdc – 110°C: no failure after 2000h

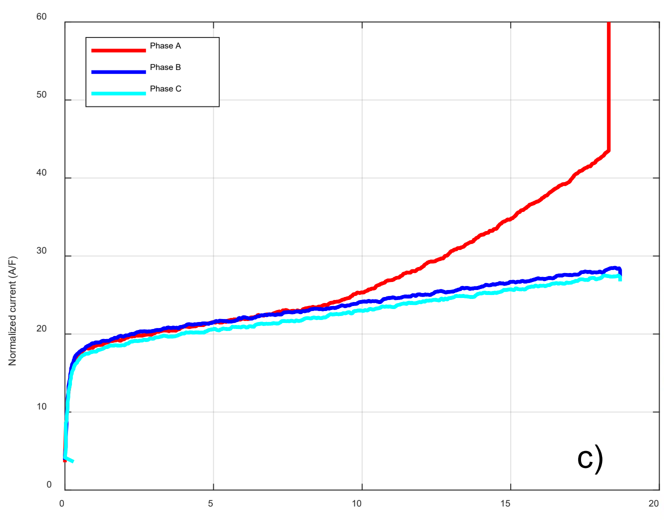
[1] FIST 3-1
[2] IEEE-95 Annex A
[3] T. Emery, EIC 2005
[4] C. Millet, EIC 2011

DCR test: could it fail the insulation?

"The test doesn't fail the insulation, it's the insulation that fails the test"



b)

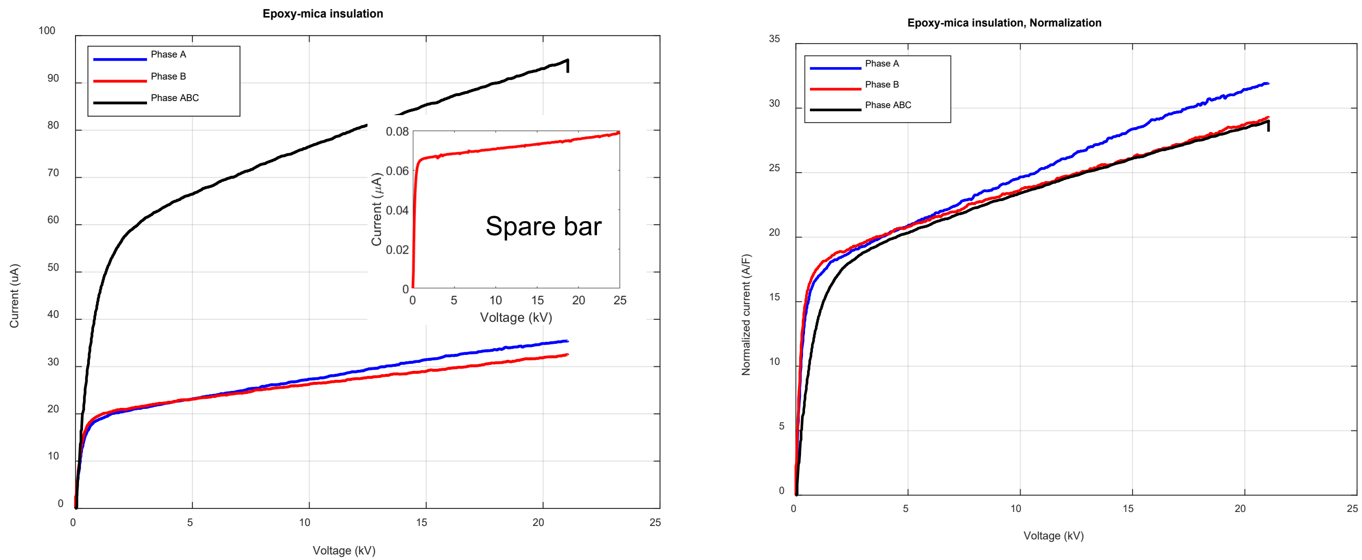


a) DCR on a winding with a defective coil [1]
b) Removal of the defective coil [1]
c) DCR on a 51 MVA, 11 kV 27-year-old polyester-mica insulated generator, returned in service and failed five years after the test (leg 68T) [2]

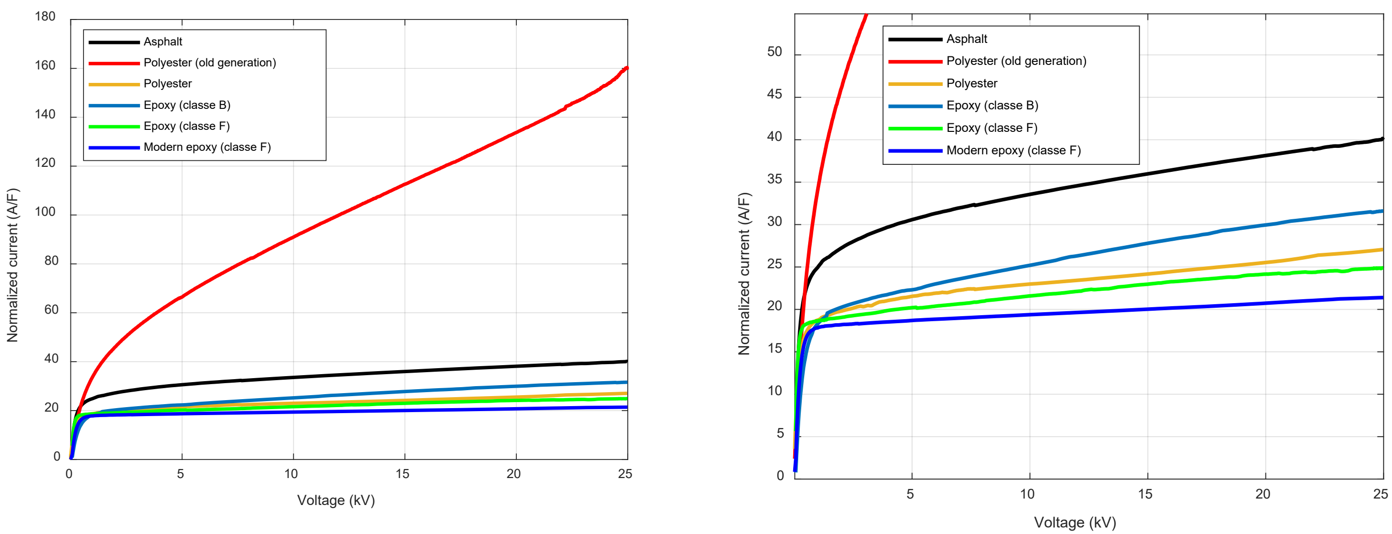
[1] E. David, Hydrovision 2006
[2] A. Raymond, EIC 2021

DCR test: size and material dependency

As for PDC test, it is useful for purpose of diagnostic, to normalize to the capacitance and to take into account the material dependency of the typical curves

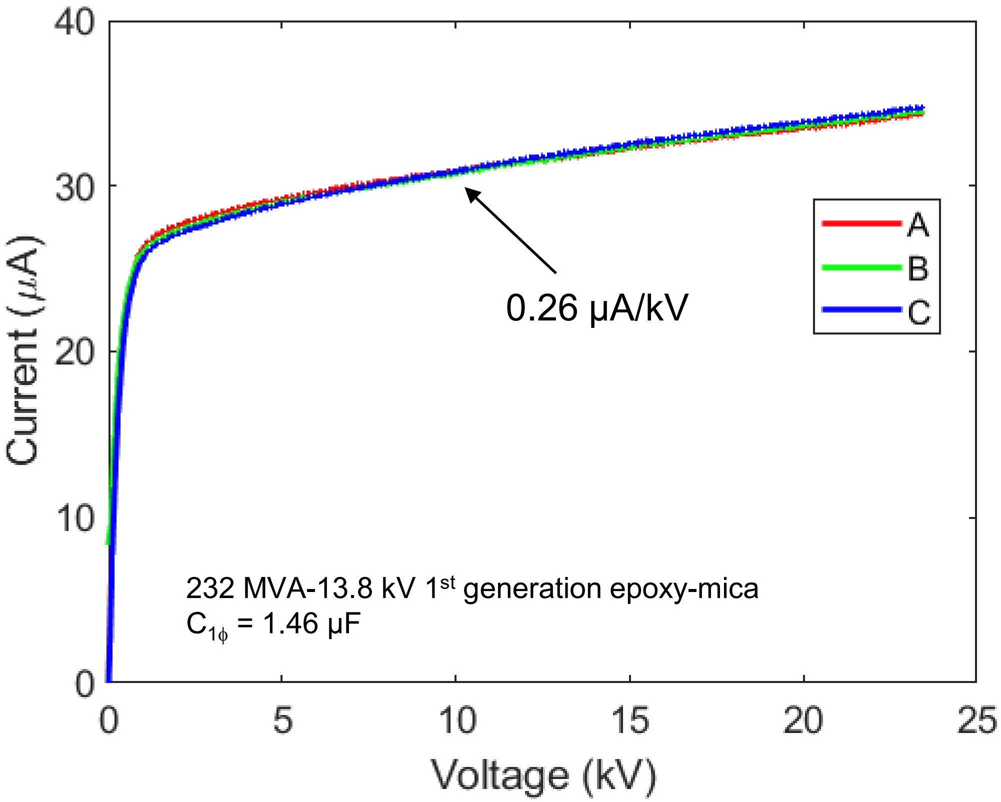


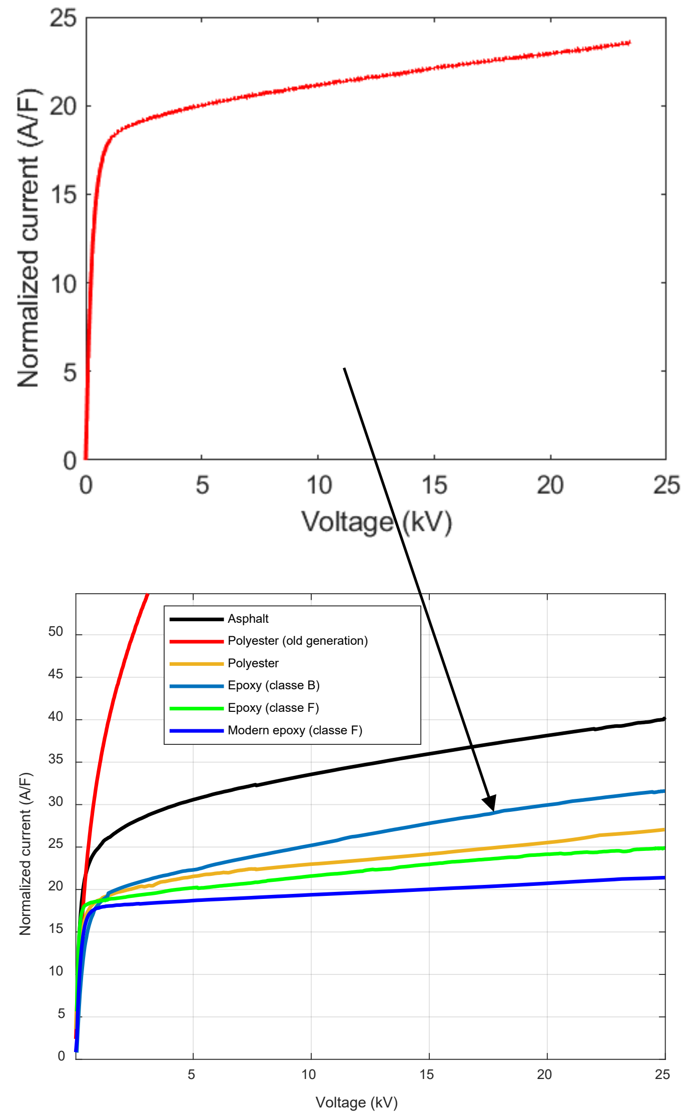
DCR test on a epoxy-mica insulated stator winding of a 386 MVA-18.0 kV, 5-year-old hydrogenerator



Typical normalized curves shape from DRC tests performed on spare bars and coils with different type of resin

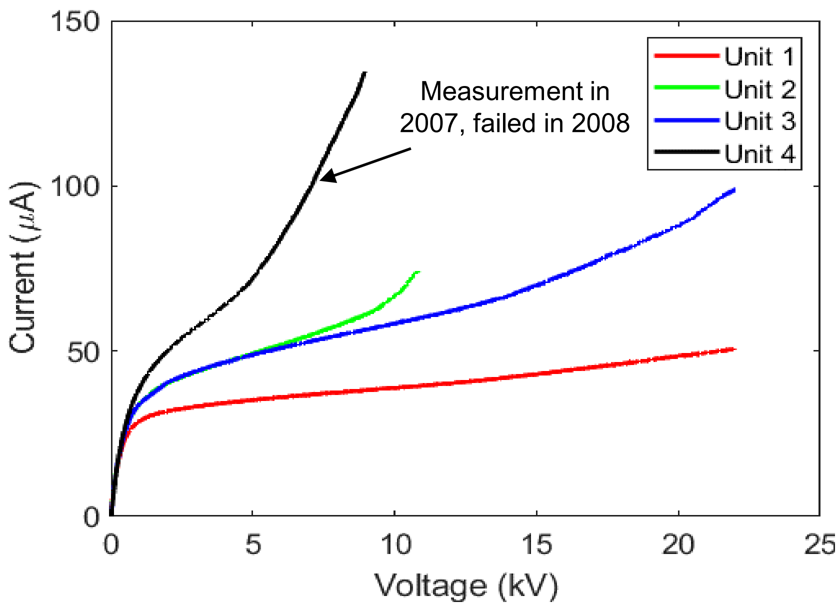
DCR test: Typical result





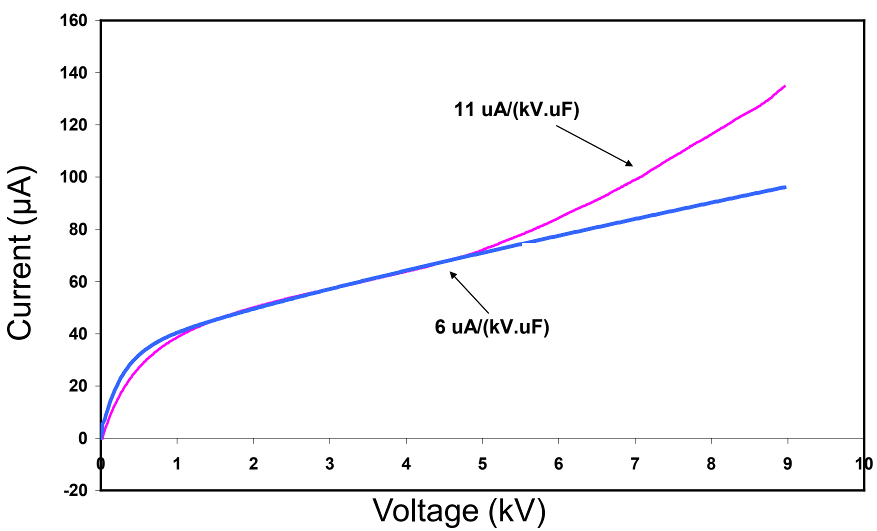
Normal I-V curve for winding in good condition (benchmark)

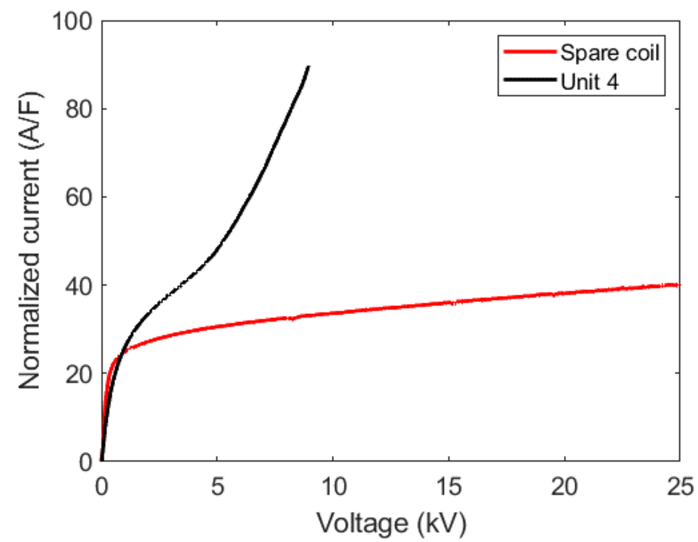
DCR test: diagnostic capability



DCR test on 4 different 50 MVA-13.8 kV units

Insulation systems	Typical acceptable slope (μA/kV) for a 1μF machine
Thermoset	0.7
1st generation polyester	8
Thermoplastic	1





Conclusions

- DC testing provides pass/fail criteria
- The continuous monitoring of the both charge and discharge currents provides additional information and enable the detection of several conditions such as incomplete curing
- Higher voltage test such as DCR can also be used a diagnostic test in addition to a withstand test and can be more efficient to detect crack/fissure and delamination [1, 2]
- Efficient to detect wet and/or contaminated windings
- It can be used on complete windings or to assess the condition to spare bars/coils prior to installation
- Measurement on spare bars/coils when normalized can be used as benchmark of a unaged insulation in good condition
- Allows the recording of specific indicators for condition assessment and trending

[1] S. Bernier et al, ISEI 2010
[2] H.G Sedding et al, ISEI 2004