Commissioning & Maintenance Testing of HV & EHV Cable Systems

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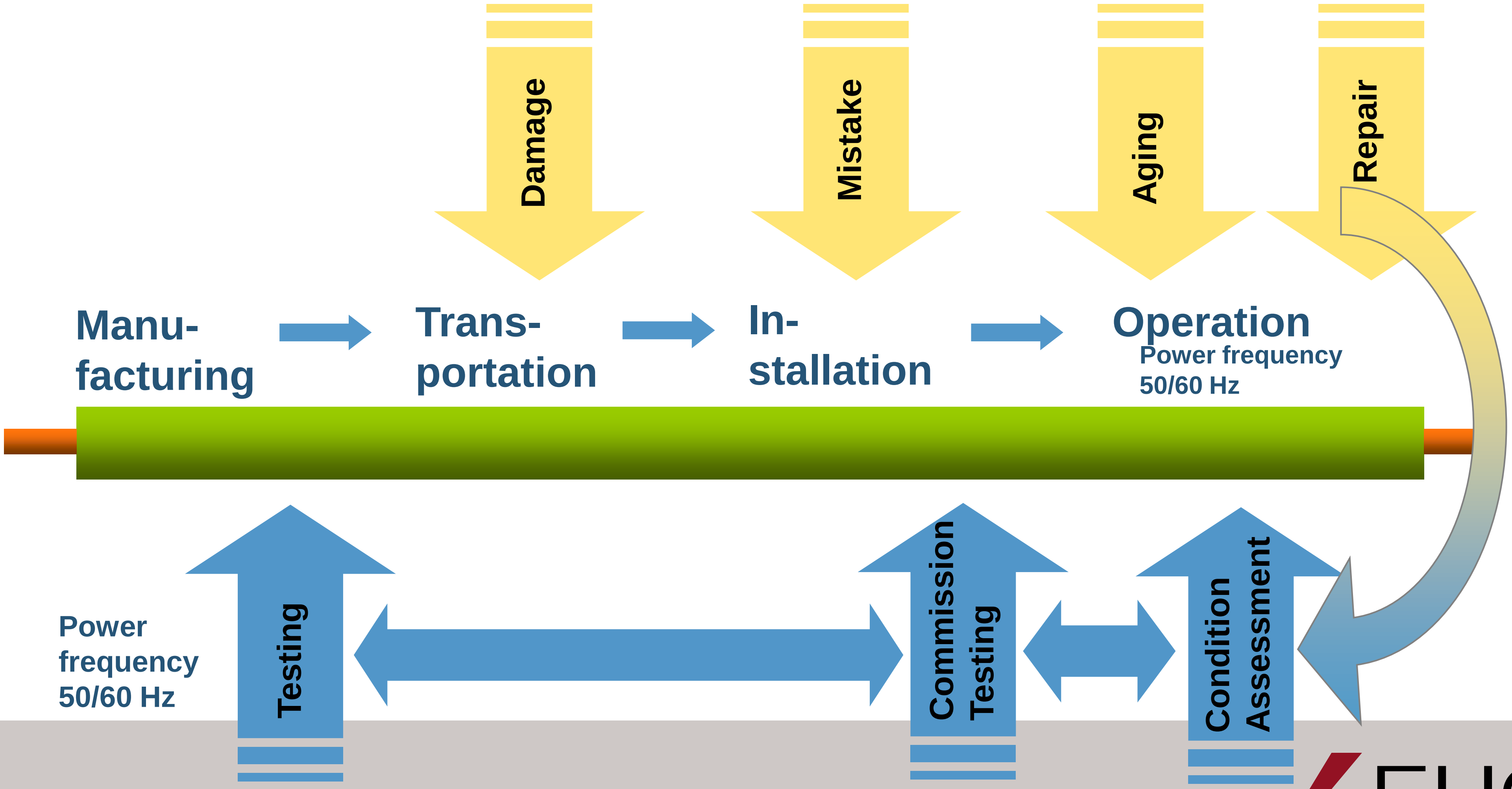
Cable Life Cycle



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A historical perspective..

Field Testing vs Lab testing

Initial Challenges…

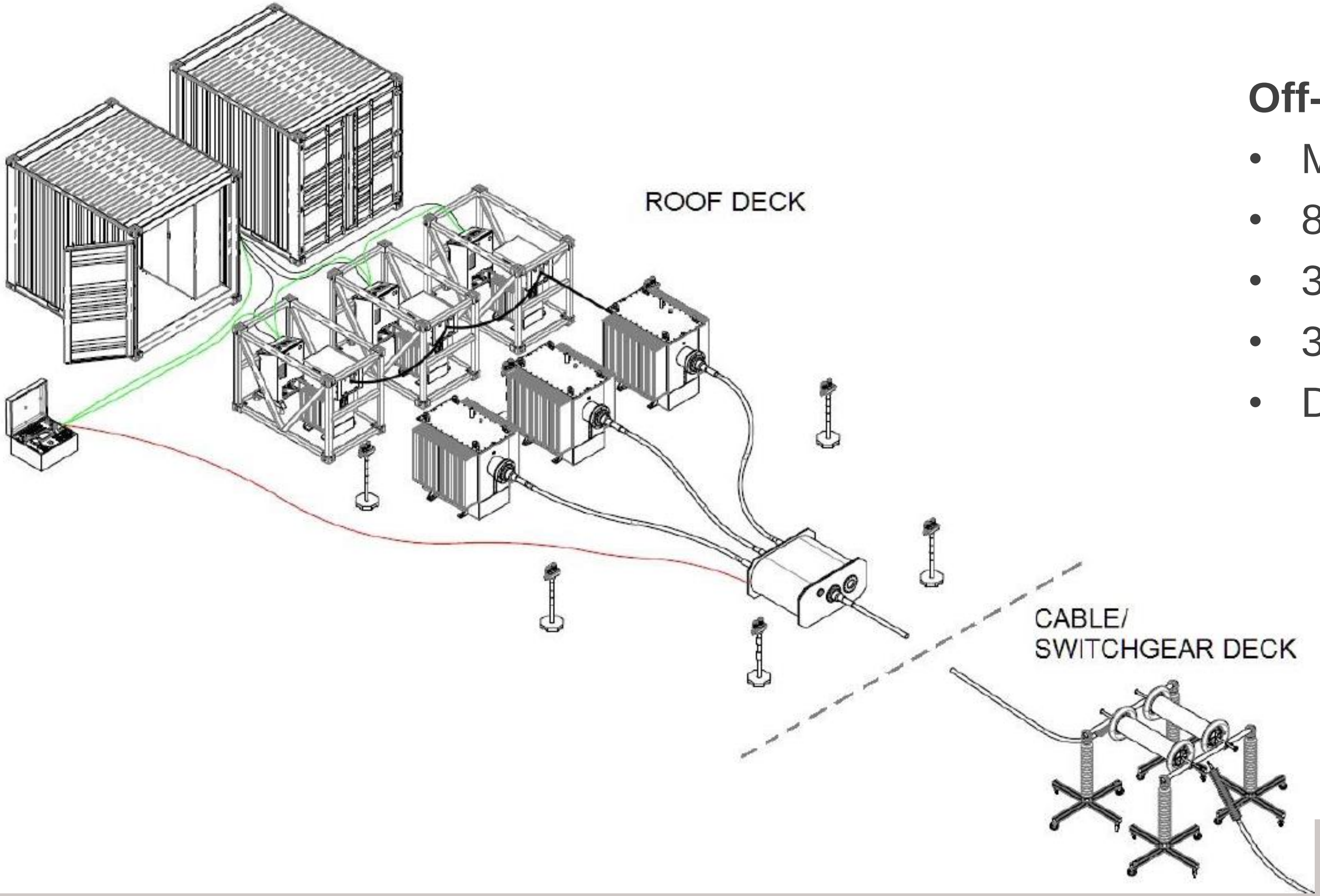
- Cable component and cable assemblies tested in factory and labs tested at Power Frequency
- Typically shorter lengths
  - Requiring less power for energization
  - Less issues with PD detectedion
- In the field, longer jointed cable systems
  - Require more power for energization
  - Issues with PD detection compared to methodology used in laboratory conditions
- First HV variable frequency test sets available in 1997
- First larger resonant test with PD in 1998

In the past 20 years.

- Resonant test systems have improved
  - Modular
  - Mobile
  - Various sizes
- Partial Discharge Measurement systems improved
  - Various types of sensors
  - Improved electronics in terms of dynamic range, acquisition repetition rate, sampling rate, data storing capacity and energy requirement (<18 Watts)
  - Battery operated
  - Daisy chained systems

⇒ Lengths of up to 200km of cable can be tested.

Off-Shore: Array Cable Systems



Off-Shore Array Testing System

- Modular RTS System
- 80kV/37.5Amp
- 3.1μF @ 72kV (~14km/reactor)
- 3.75 metric tonnes each
- DNV certified off-shore constrainers

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In the past 20 years…

COMMISSIONING

- Test Methodologies for Commissioning (Field Acceptance) incorporated in to domestic and international standards
    - AEIC CS-9, Senelec, HD:HD632
    - IEC 60840 Clause 16.3
    - IEC 62067 Clause 16.3
    - Cigre TB 841
    - Cigre TB 728
    - IEEE 400.3

MAINTENANCE

- In the past 10 years or so, experiences with maintenance testing of HV & EHV Cable systems using similar methodologies
    - Test levels lower
    - Durations lower
    - Primarily Diagnostic test or withstand component
- XLPE and EPR cable systems aged 38 years and up to 10 years years subjected to Maintenance or Condition Assessment tests

Test Levels, Durations & Acceptance Criteria - Commissioning

	Commissioning Tests				Maintennace Tests			
Voltage Class [kV]	Test Level [kV]	Duration	Freq. Range [Hz]	PD Test (pass/fail)	Test Level [kV]	Duration	Freq. Range [Hz]	PD Test (pass/fail)
66-72	2.0	60 min (or equivalanet number of cycles)	10 - 300	PDEV > 1.5U0	2.0	5min - 30min (or equivalanet number of cycles)	10 - 300	PDEV > 1.5U0
110/115								
132/138	1.7				1.7			
150/160								
220/230								
275/285								
345/400								
500	1.5				1.5			PDEV > 1.5U0

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PD Testing Methodology

CIGRE WG B1.28 Recommendations – TB 728

- Terminal PD Measurement: Termination to termination
- Double-Ended Terminal PD Measurement: Termination-Joint-Termination
- Distributed PD Measurement: 2 joints or more

ON-SITE PD ASSESSMENT

Type WG B1.28

Members'

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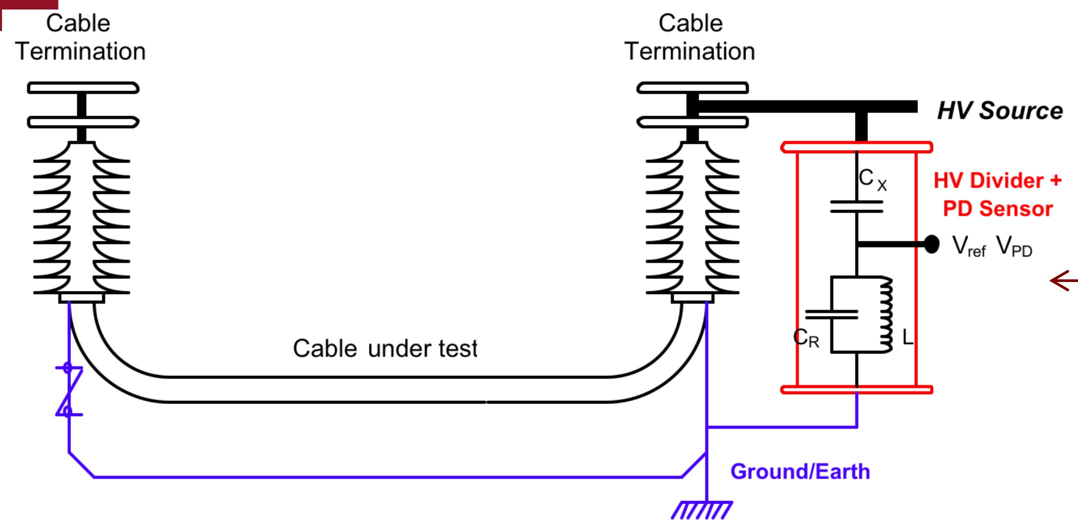
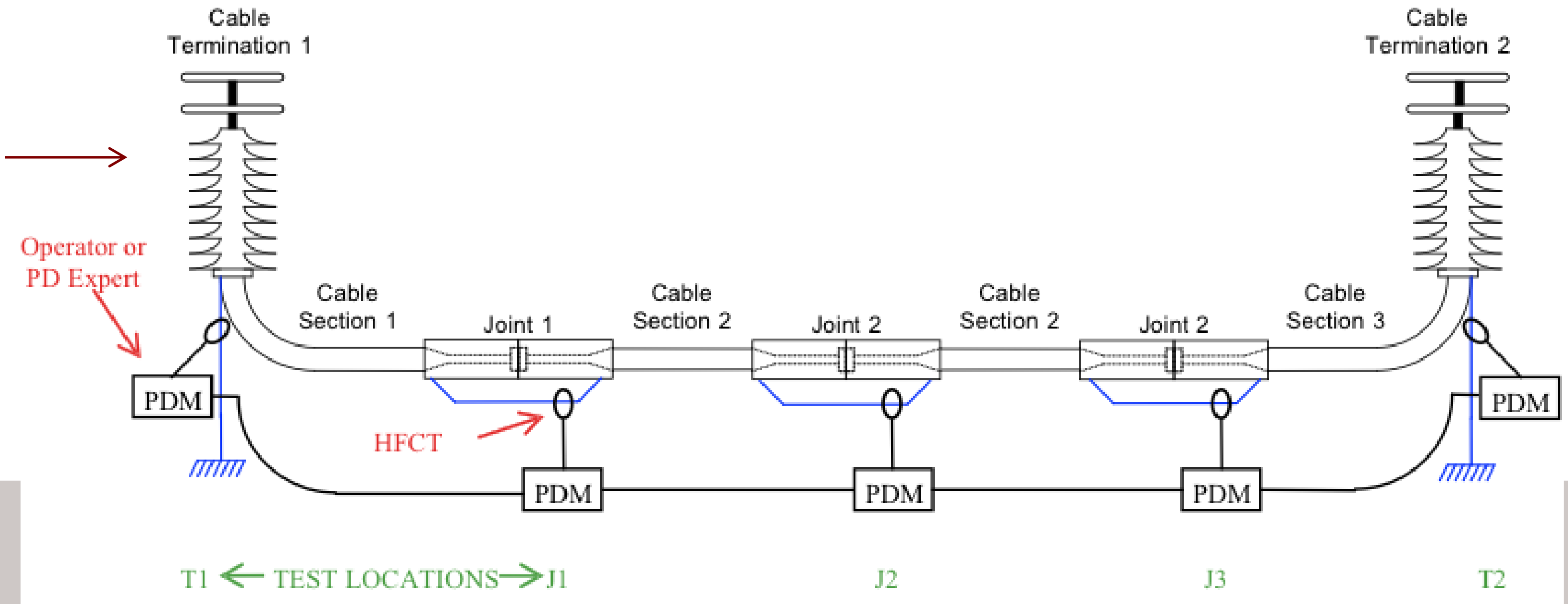
Terminal vs Distributed PD Measurement



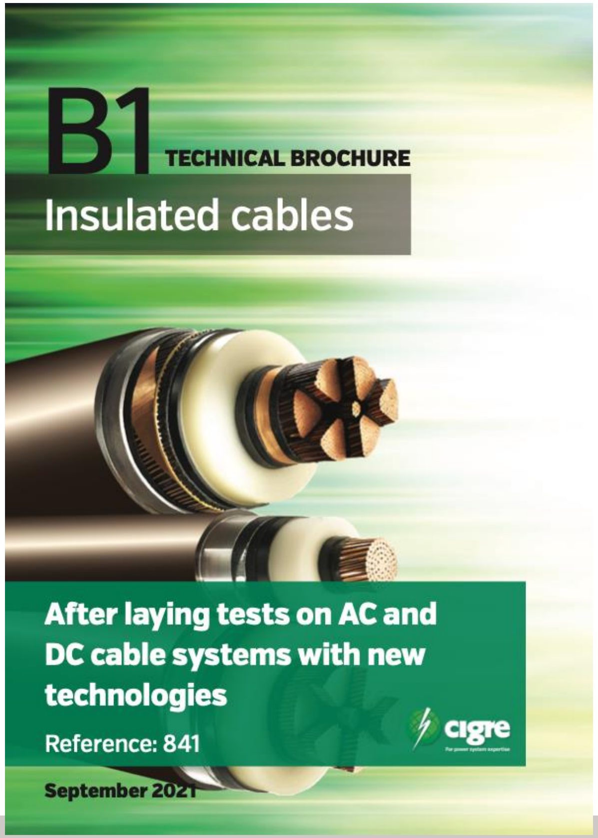
Terminal PD Measurement

Distributed PD Measurement



Testing Outcomes - Commissioning

Cigre TB 841 (WG B1.38)



	COMMISSIONING DATA – CONSOLIDATED					
	NPF		VLF		DAC	
	HV	EHV	HV	EHV	HV	EHV
# Years data collected	[1997 ; 2016]		[2010 ; 2016]		[2009 ; 2016]	
Conductor Length [km]	19,724	6,770	-	-	819	130
# Terminations	15,857	4,540	-	-	413	96
# Joints	10,976	7,960	-	-	660	174
Statistical Significance	Yes		No		Yes	No
Breakdown Under Test	109	35	n/a	n/a	n/a	1
% accessory	0.42	0.30	n/a	n/a	0.00	0.37
Non-Pass Rates						
% Terminations	2.17	2.89	n/a	n/a	0.00	0.00
% Joints	0.75	0.75	n/a	n/a	0.45	0.57
% cable sections	0.00	0.04	n/a	n/a	0.09	0.00
% Accessories Total	1.59	1.53	n/a	n/a	0.28	0.37

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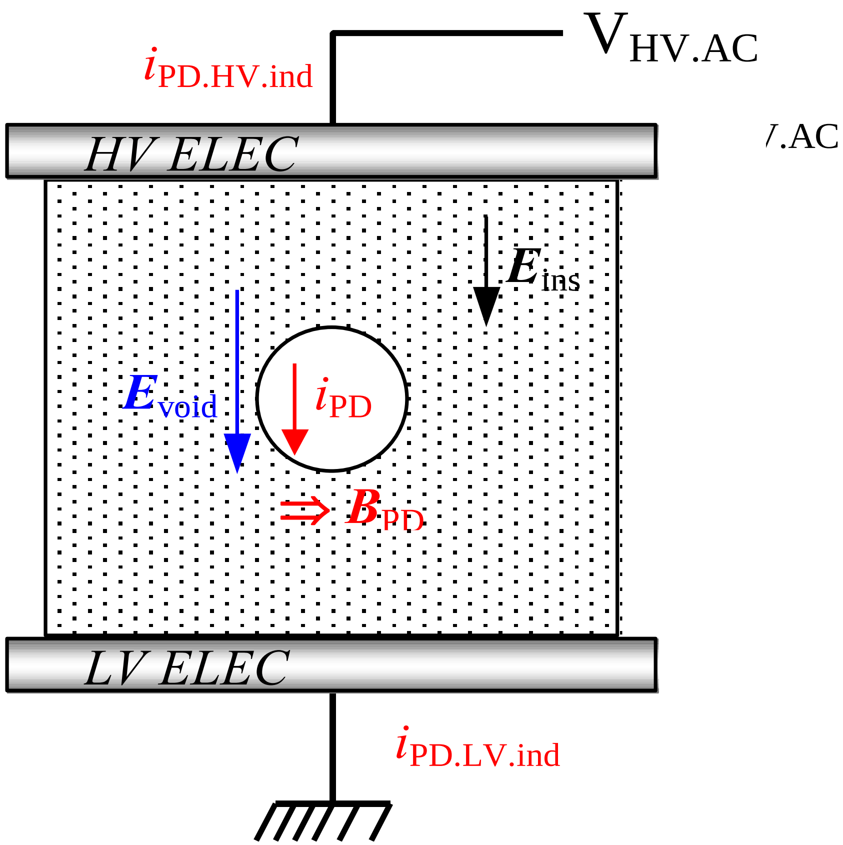
A few notes on Partial Discharge

Partial Discharge Theory



Conditions

- Void
- Free Electron
- $E_{void} > E_{breakdown}$

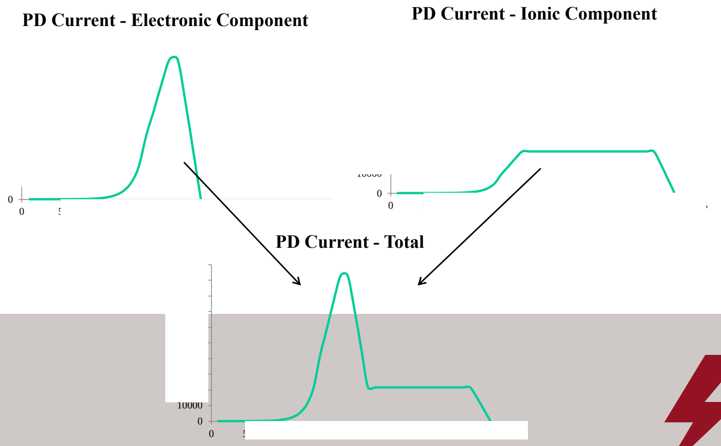
$\Rightarrow$ Current *induced* on LV and HV electrodes

$\Rightarrow$ Magnitude depends on void geometry and location

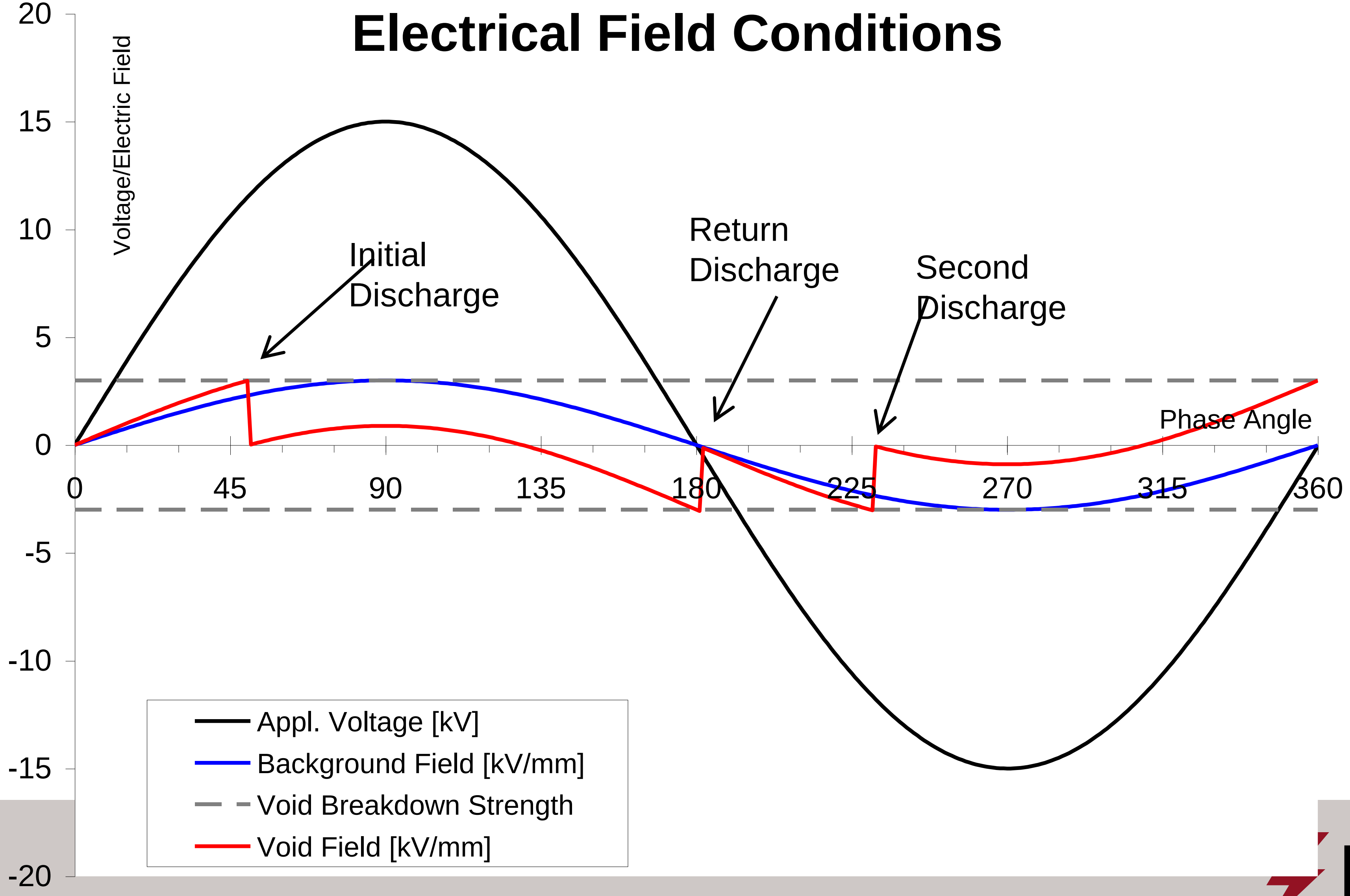
$\Rightarrow$ Rise-time depends on void size and shape

$$E(x) = \frac{V}{d}$$

$$E_{void} = \frac{3\varepsilon}{1+2\varepsilon} E(x) = \frac{3\varepsilon}{1+2\varepsilon} \frac{V}{d}$$



Partial Discharge Theory



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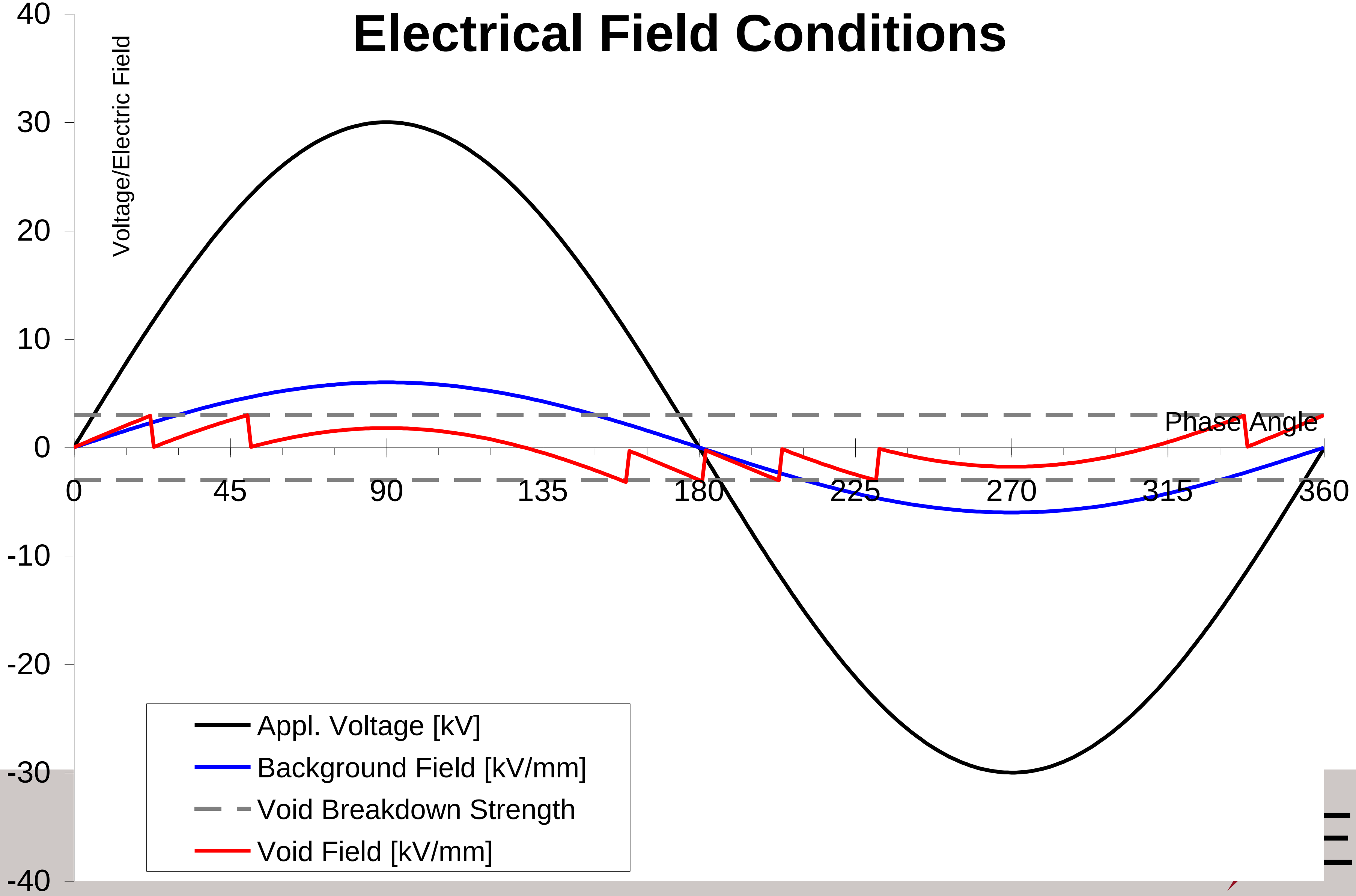
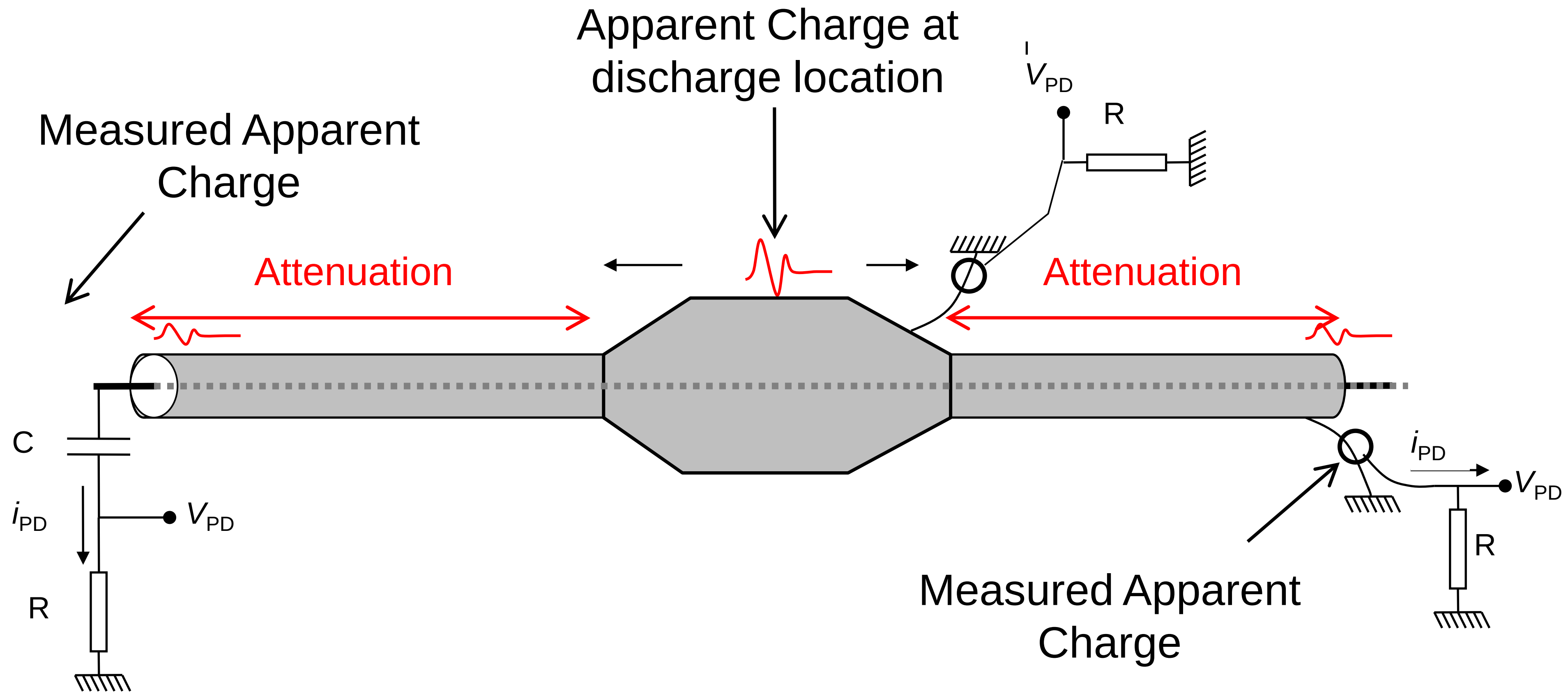
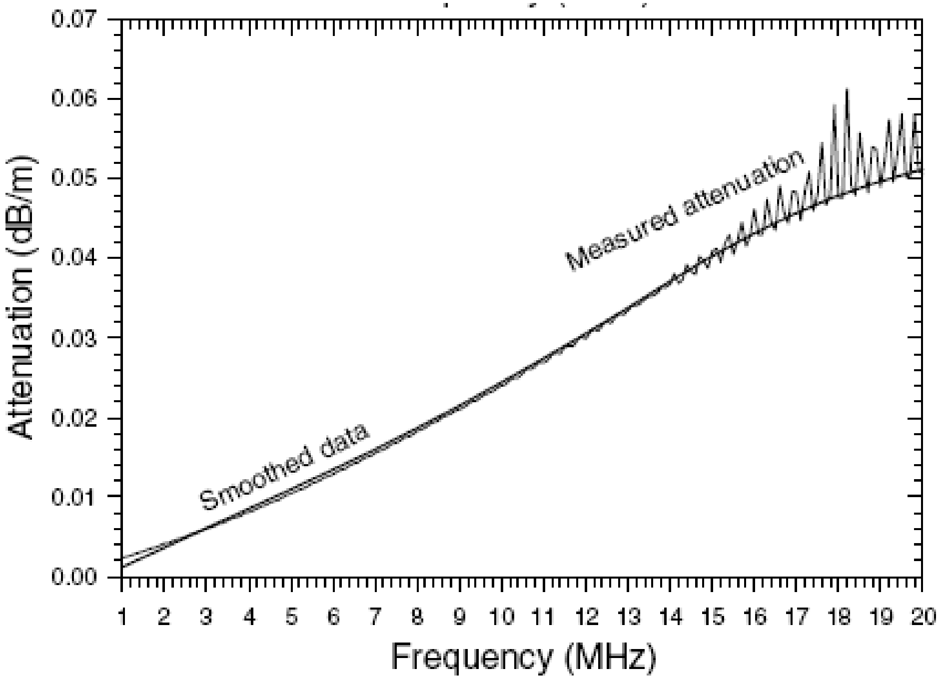
Partial Discharge Theory

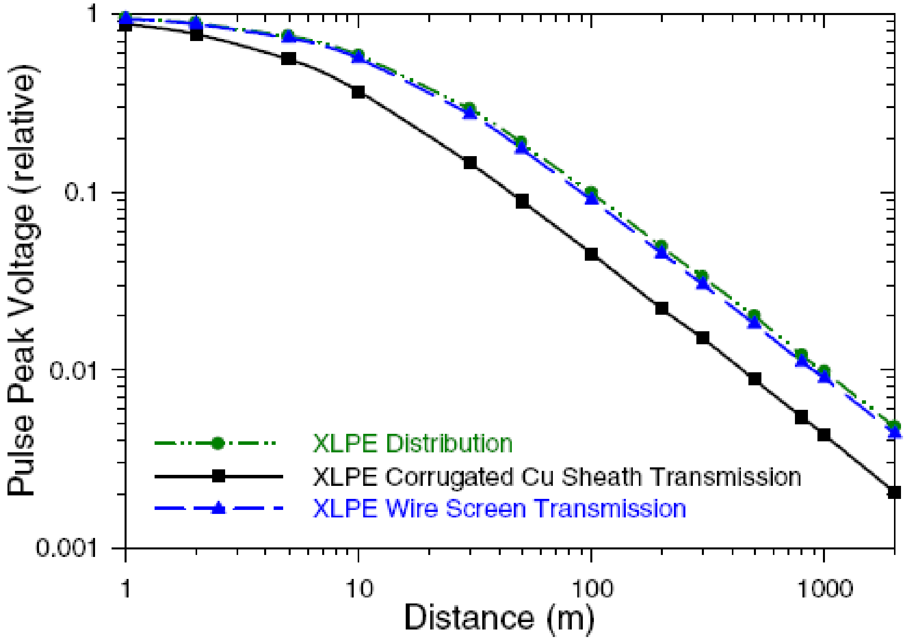


PD Theory: Apparent Charge



PD Theory: Signal Propagation





J.J Gou, L. Zhang, C. Xu & S. Boggs, "*High Frequency Attenuation in Transmission Class Cables Solid Dielectric Cable*" 2007 Fall ICC

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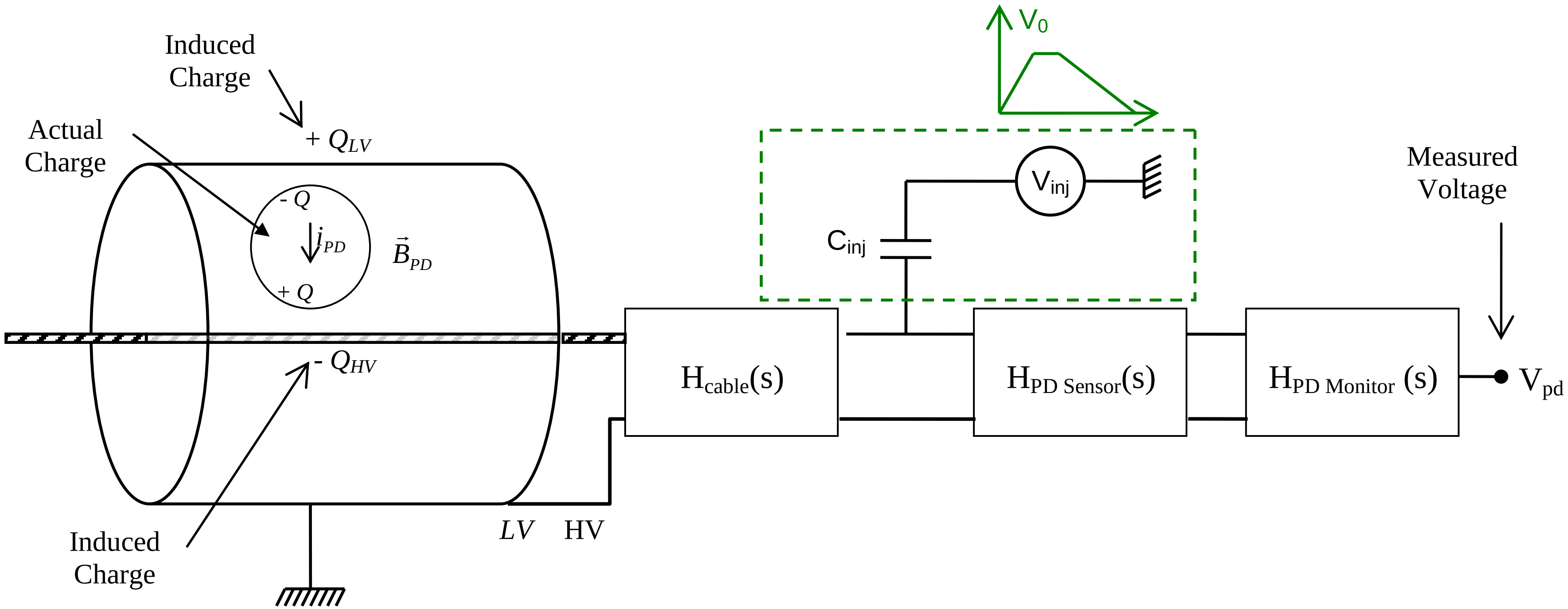
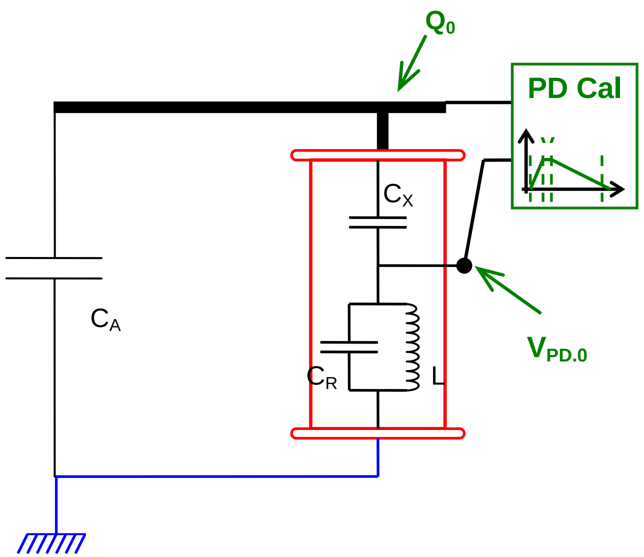
Sensitivity Assessment

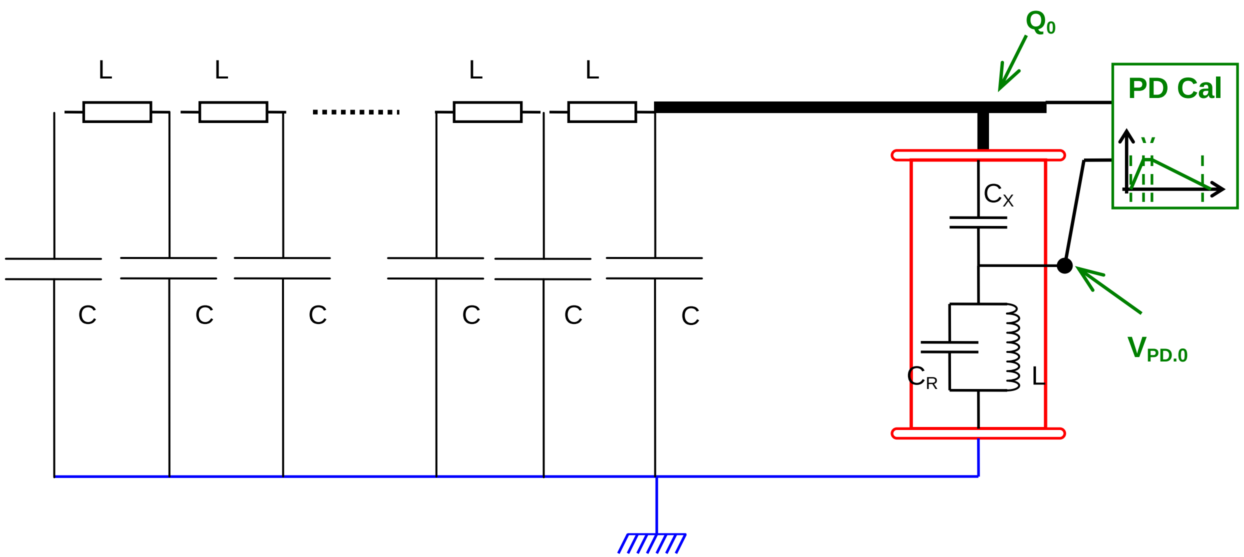


Laboratory vs Field Testing

Laboratory: Short circuit, largely lumped capacitance.

Longer jointed circuits: Distributed impedance





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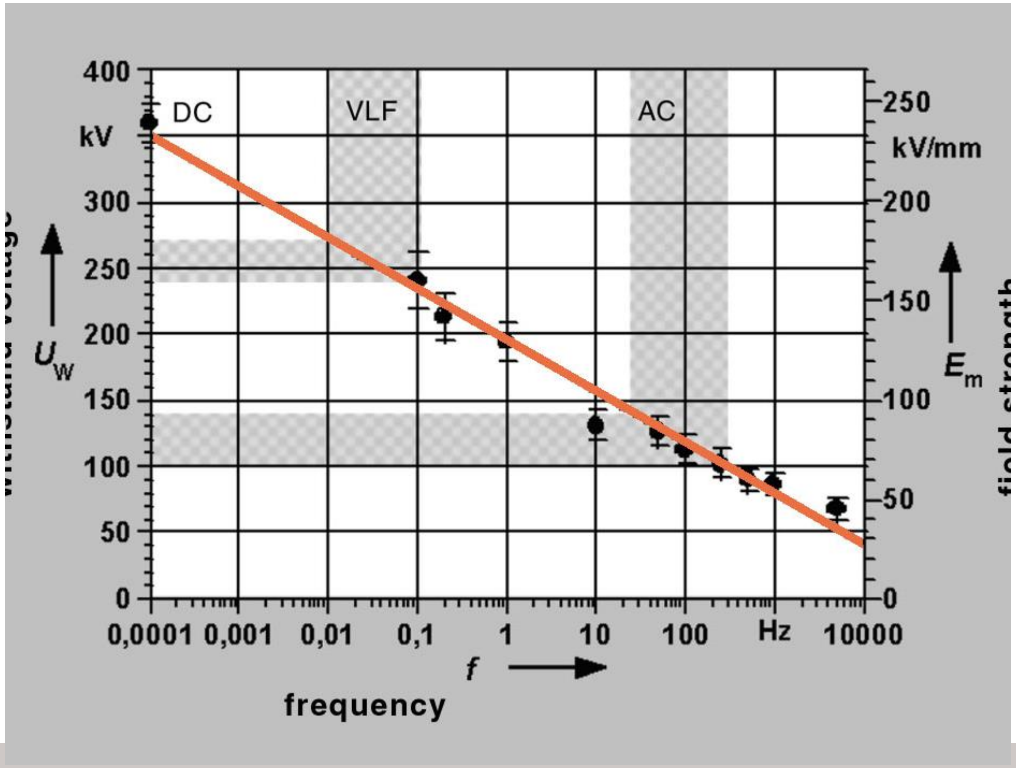
Just a few more notes…

The influence of frequency



- Model HV Cable system w joints
- Common defect. 5 break-down measurements per frequency
- Clear correlation between test frequency and withstand voltage.
- The lower the test frequency, the higher the test voltage.
- Near Power Frequency defined as ± 10% deviation in withstand voltage relative to 50 Hz. ⇒ 20 Hz to 300 Hz

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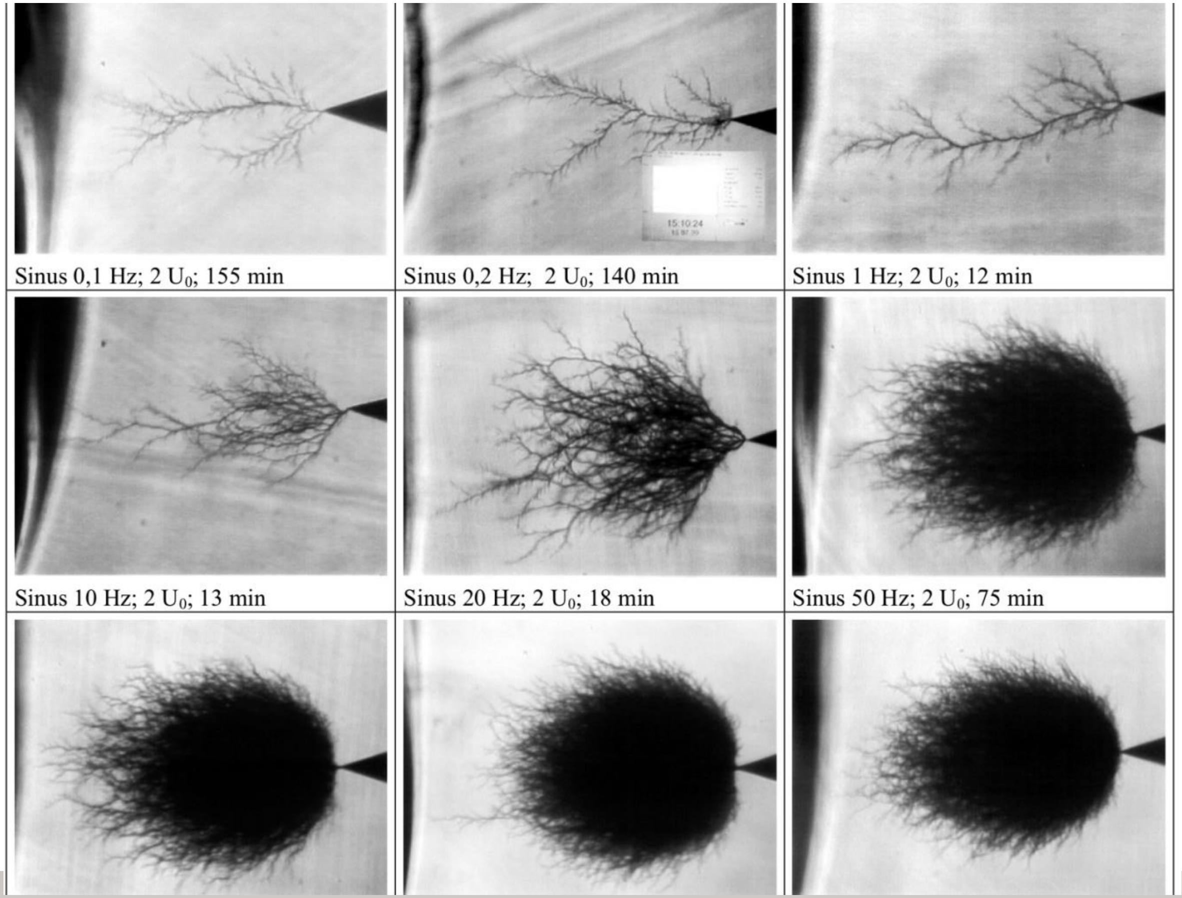
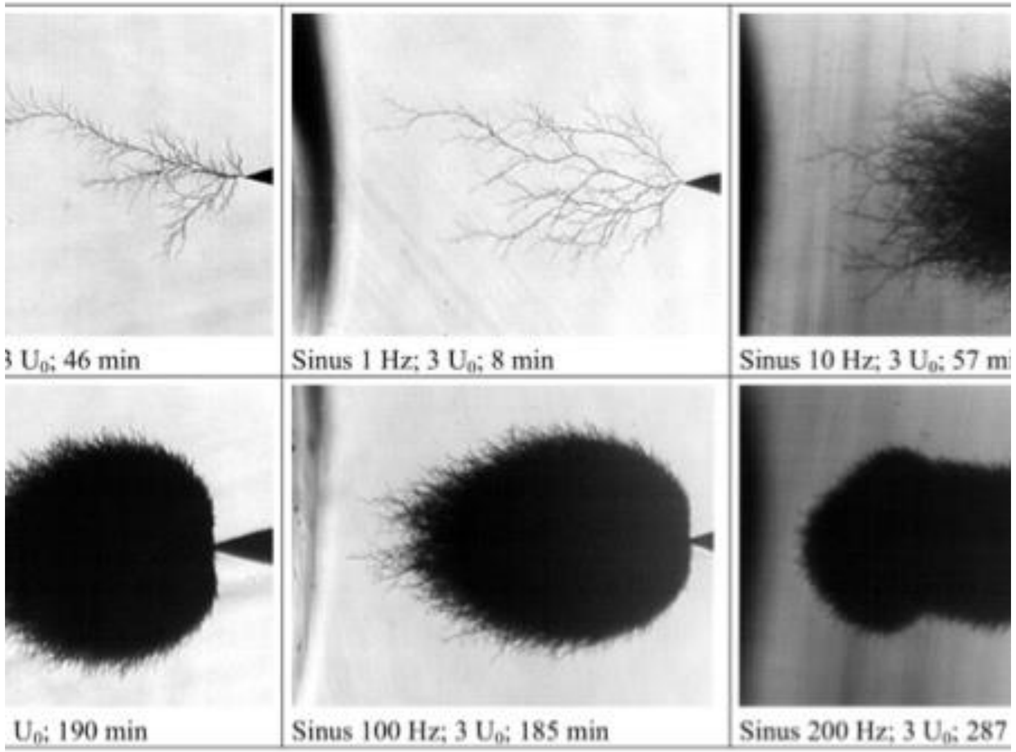
Breakdown after initiation of first PD

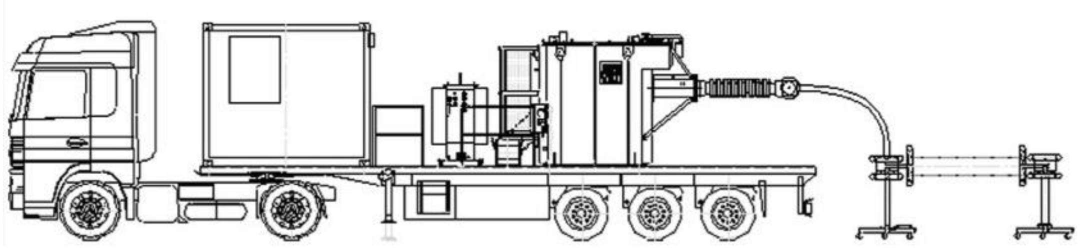




Testing of Solid Dielectric & Fluid Filed Cables Systems

OFF-LINE PD – Near Frequency Testing

Near Power Frequency AC Testing



Trailer with control container (including frequency converter, exciter transformer, HV reactor 260 kV/ 83 A and HV filter and right a combination of two reactors

Complete ACRF test system 50 kV / 25 A in a van

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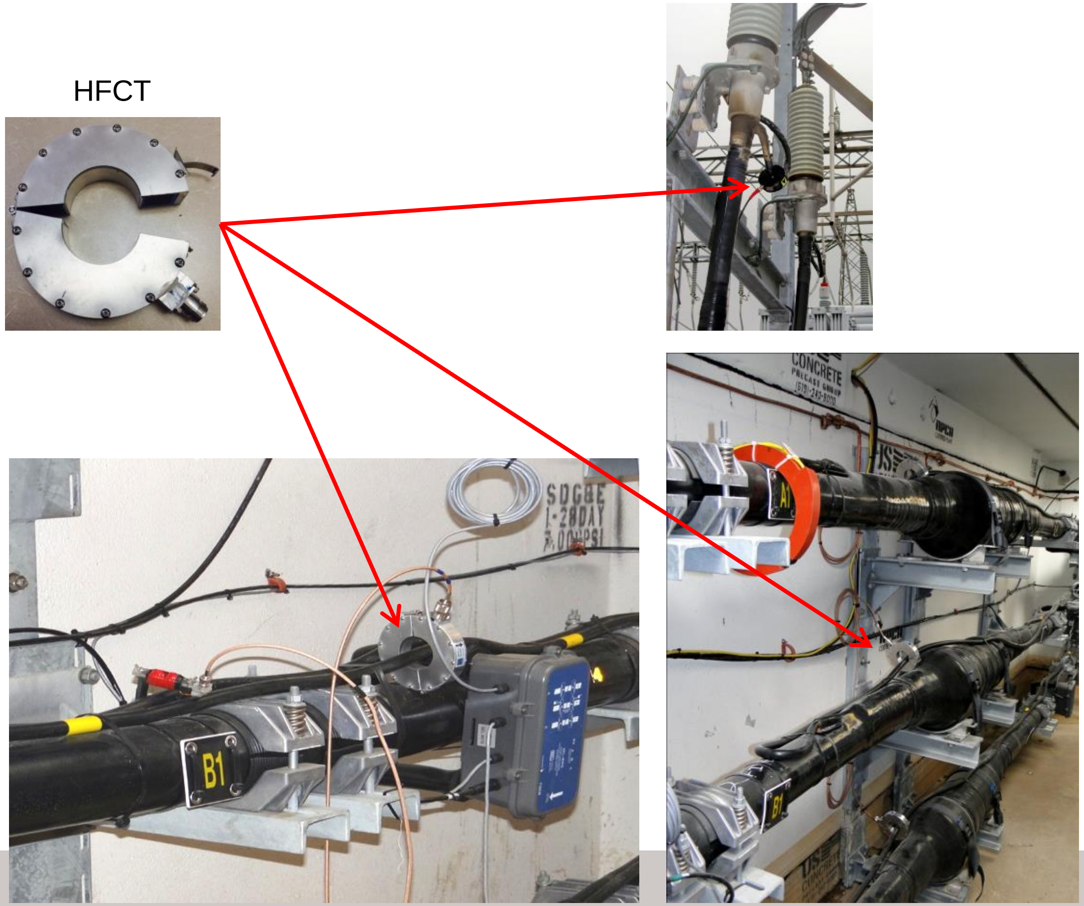
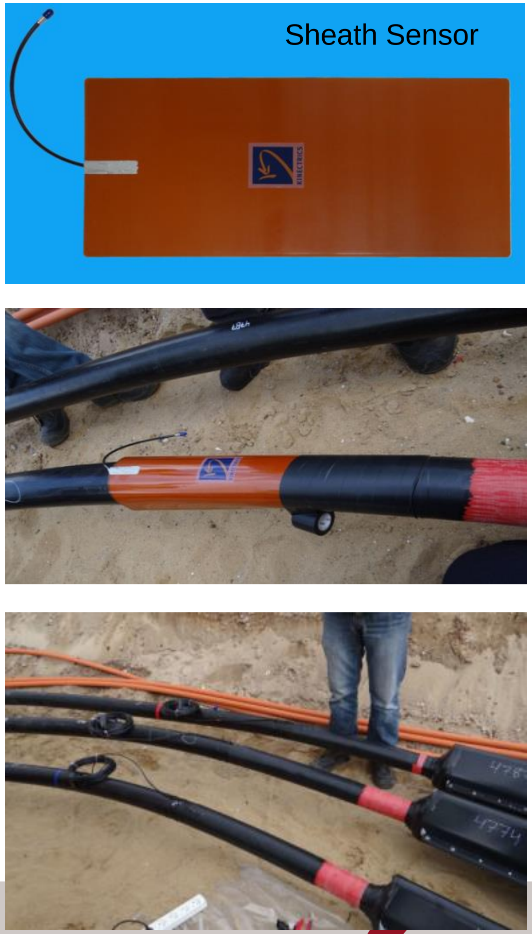
PD Sensor used on HV / EHV cable systems:

HFCT (High Frequency Current Transformer & Sheath Sensors are designed and built at Kinectrics.

HFCT





Preparation of Circuit

System Preperation

- Arrestors Removed
- SVL's removed or shorted out
- Straight through sheath for jointed systems
- Corona Free HV Connection cable capable of carrying a minimum 83 Amps of current
- Corona Mitigation
- PD Sensors

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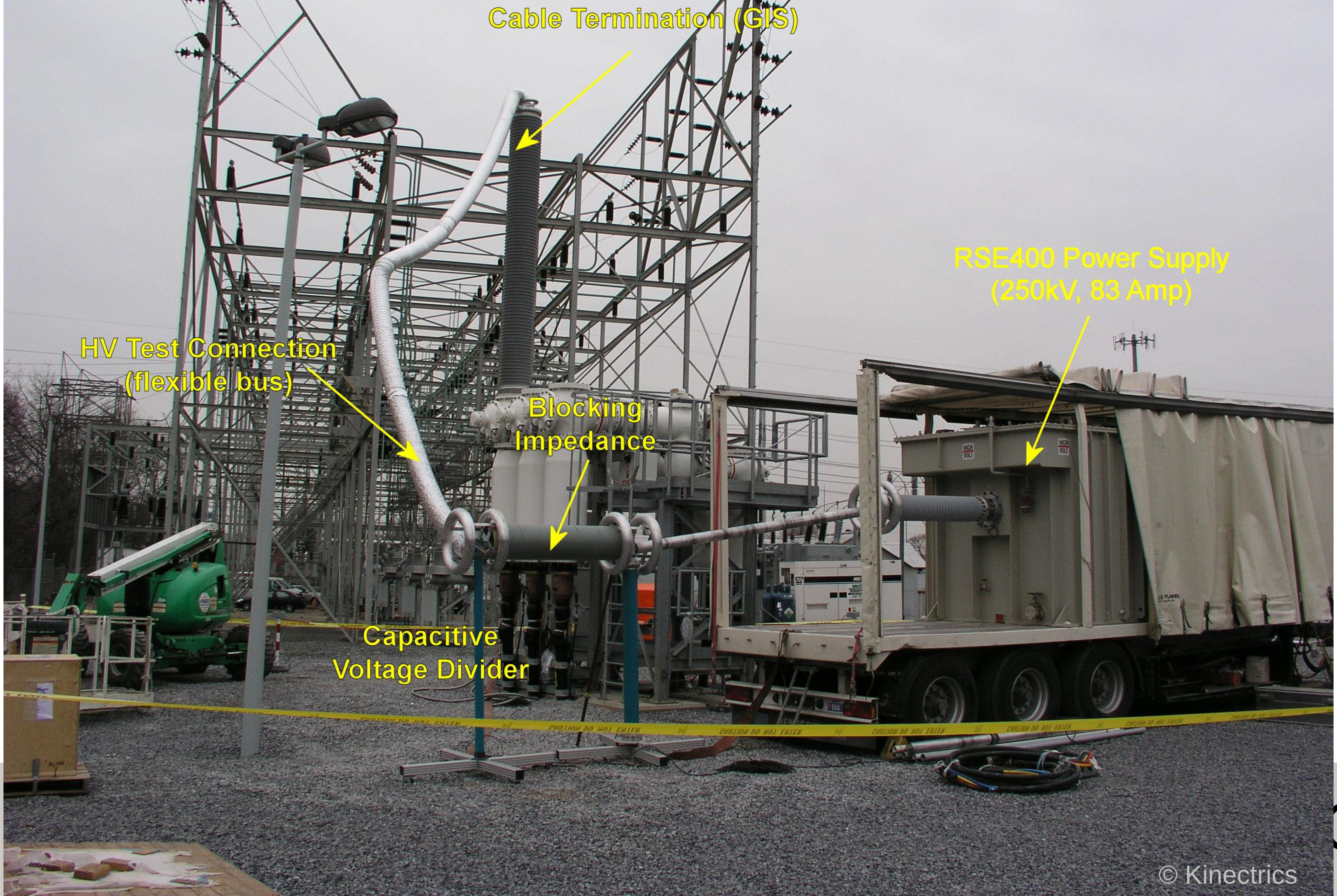
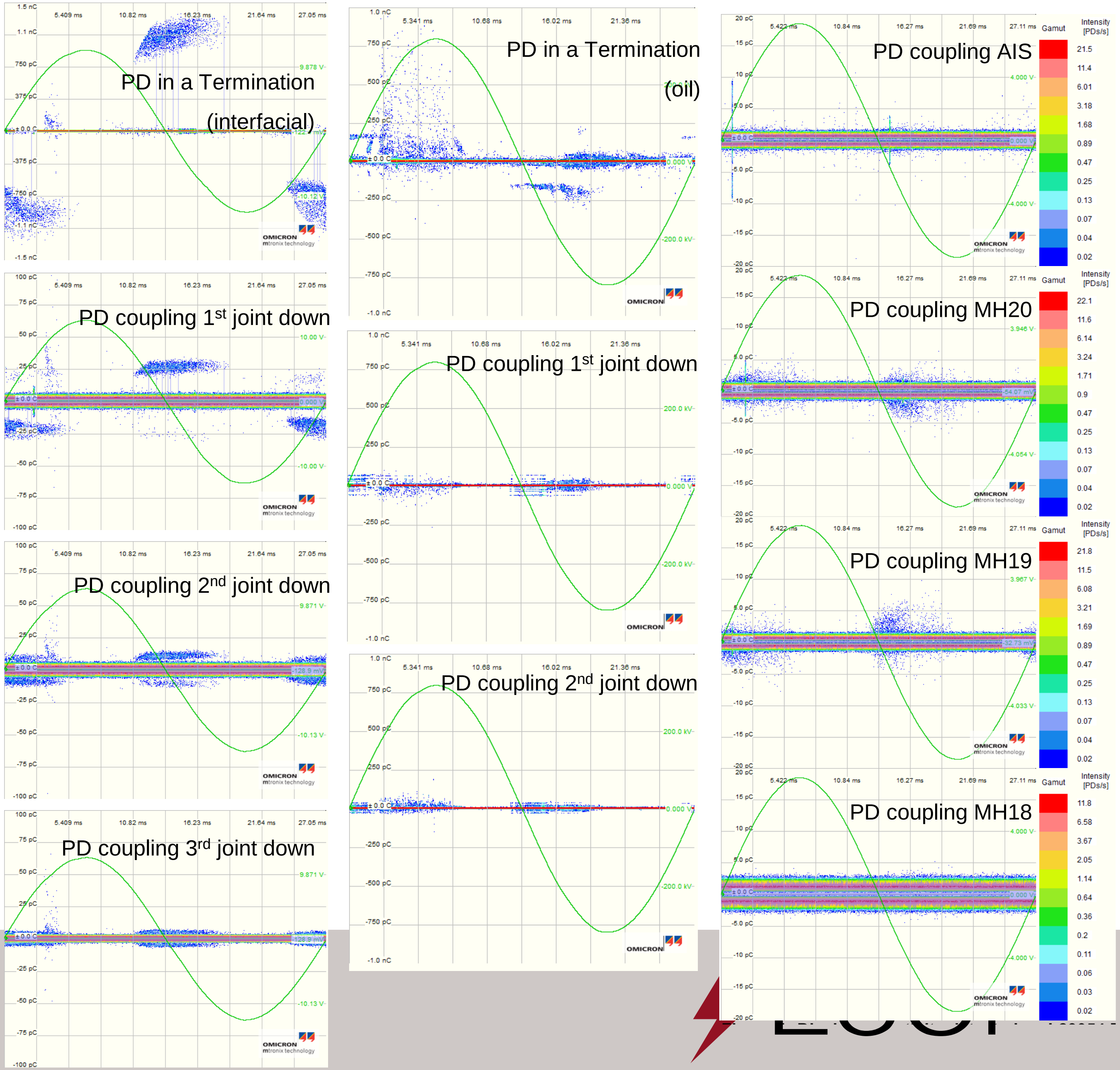
Example of Test Setup





PD in a Termination (interfacial)
PD coupling 1st joint down
PD coupling 2nd joint down
PD coupling 3rd joint down
PD in a Termination (oil)
PD coupling 1st joint down
PD coupling 2nd joint down
PD coupling AIS
PD coupling MH20
PD coupling MH19
PD coupling MH18

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Commissioning Testing: 220kV Export Cable

- Testing at $1.7U_0$ (226kV)
- Testing time normalized to 60 minutes at 50 Hz
- Testing of subsea cable only with temporary test terminations at transition joint location
- PD measurements at accessories
- (End to end test performed later)

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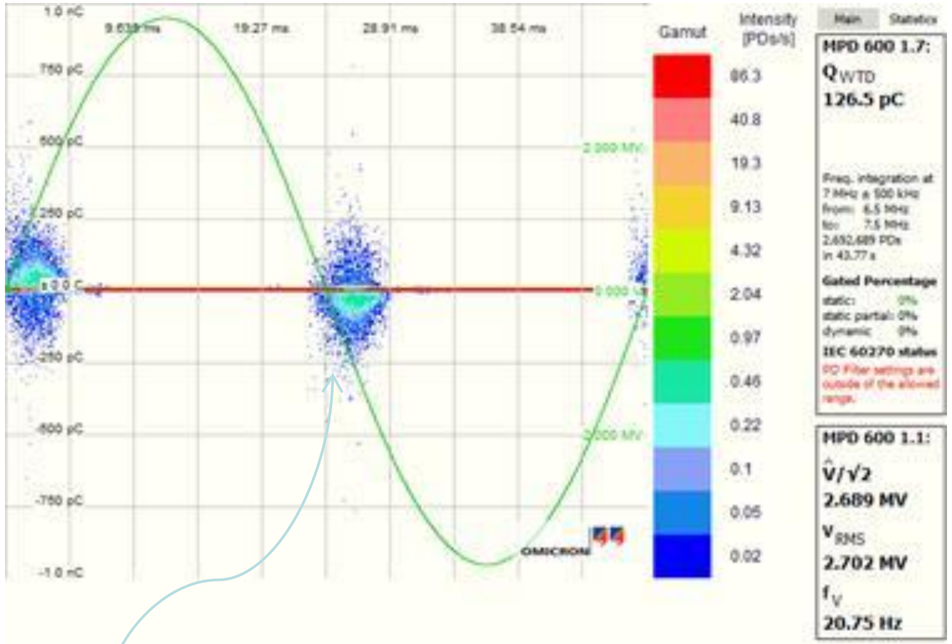
400kV Cable System + Distributed PD

345kV tested at 1.7Uo = 339kV

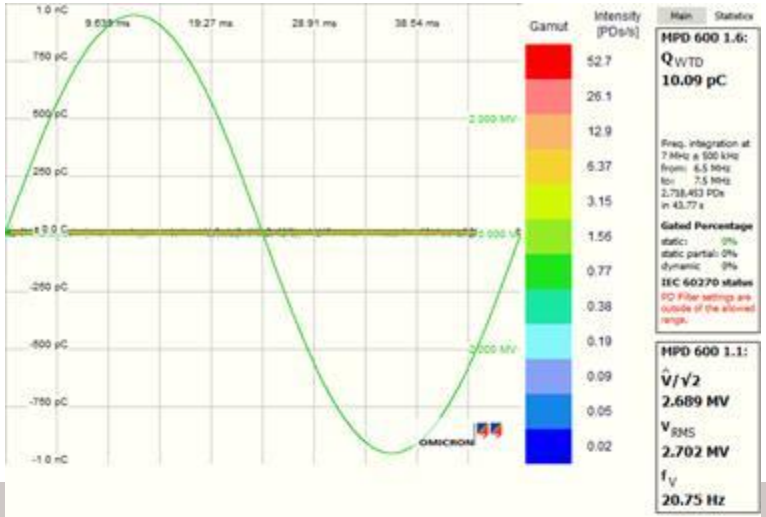
- 2 RTS systems is Cascade configuration
- Test Voltage 339kV for 1 hour per IEC
- Daisy Chain PD system (17 joints)
- 6 Cables (AIS / GIS)

- Results:
- 1 Failed Termination (PD)
- 1 Failed Joints (PD then Dielectric)
- 1 Failed Joint (PD)
- 1 Failed Joint after initial repairs (PD)

345kV tested at 1.7Uo = 339kV



Joint was replaced & retested, no PD present



PD was detected at 339KV at Joint 6 via PD sensor

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Maintenance Testing – Solid Dielectric Cables

Background

- A larger population of HV cable systems installed in the 1970ties and 1980 have approached and passing end-of-mean life
- In-service failure statistics show that most failures are related to accessory failures

⇒ Can life extension be performed by identifying accessories at risk and replacing?

	OPERATING ELECTRICAL STRESS (RMS) AC Systems	
	Inner Conductor	Outer Conductor
MV	< 2 kV/mm	≤ 1 kV/mm
HV	< 8 kV/mm	< 4 kV/mm
EHV	< 15 kV/mm	< 8 kV/mm

- Significant experience with off-line condition assessment for MV solid dielectric cables
  - Partial Discharge, Tanδ, Dielectric Spectroscopy, DFR/LIRA,
- Larger body of experience with on-line PD testing of HV/EHV cable systems
- Little experience with off-line PD testing of HV solid dielectric cables
- Recently, proposed guidance in CIGRE TB 728, CIGRE TB 841 & IEEE 400.3
- In the last years, some utilities in North America have experimented with off-line testing as a maintenance tool.

Condition Assessment Approach: Off-Line

- Off-Line Overvoltage PD Tests at Near Power Frequency. (20 Hz – 300 Hz)
- Broad-Band PD sensors and PD Monitors
- PD Measurements in accordance with CIGRE TB728.
  - Terminal PD Measurements on short lengths of cable
  - Distributed PD Measurements on longer lengths of cable
- Calibration/Sensitivity Assessments
- Additional Electrical Tests
  - Over-sheath maintenance tests
  - Sheath Voltage limiter tests
  - Contact Resistance Measurements
  - (TDR)
- Manhole inspections

Condition Assessment Approach: Off-Line

TESTING PRE-REQUISITES

- Outage required (planning)
- Up front discussions on next-steps in terms of positive-test results
  - Documentation from original install
  - Accessory spares, link-box & SVL spares, re-work capacity
- Removal of HV arrestors
- Know joint locations (!)
- Access to joint locations
- Typically test campaign well planned in advance for back-to-back testing on multiple circuits

PRACTICAL DIFFERENCES TO COMMISSIONING TESTING:

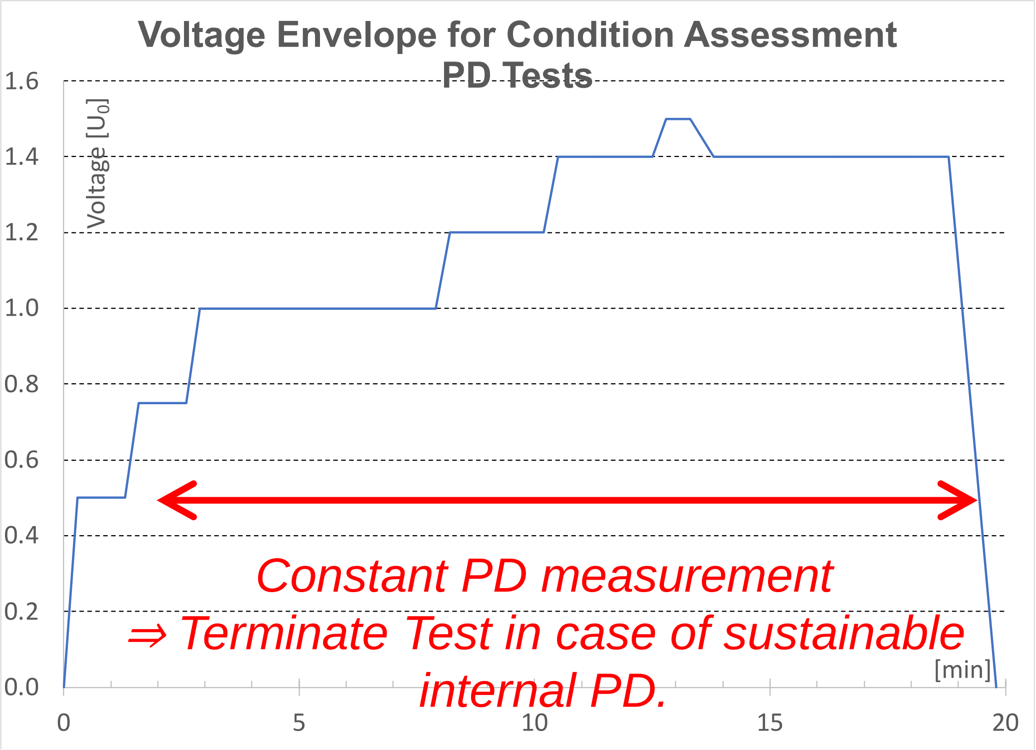
- SVL's shorted out but not always straight-through sheath
- Shorter time duration for test
- Pass/Fail criterion not "black and white"
  - If No PD, recommendations for additional testing testing in the future
  - If PD, criticality depends on PDIV, PDEV and magnitude.
- Skilled Mobile PD crews for "joint hopping"

Condition Assessment Approach: Off-Line

- Over Sheath (JIT) maintenance tests should be performed prior to off-line testing.
- PD monitored continuously at $0.5U_0$ and upwards

⇒ allows for terminating test avoiding failure

- Voltage levels in accordance with CIGRE TB-841 however durations have varied
  - Added 30 seconds of press-stress at $1.5U_0$
- Typically 5 minutes of over voltage at $1.4U_0$.
- Additional Electrical Tests
  - Over-sheath maintenance tests
  - Sheath Voltage limiter tests
  - Contact Resistance Measurements
  - (TDR)

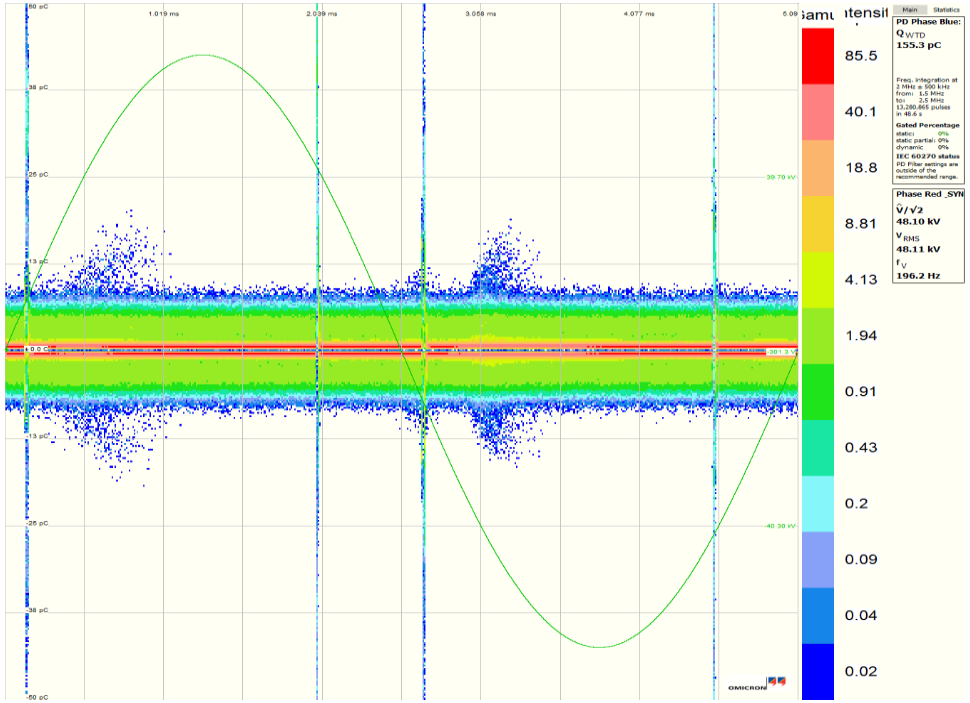


Test Outcomes

Rated	Cable Population				Year of Install	Test Voltage		Duration	% PD	
Voltage [kV]	# Circuits	#Term	#Joints	# Cables		[kV]	U_0	[min]	Term	Joint
69	17	102	15	66	[1975 ;1986]	56	1.4	5-15	12.7%	6.7%
138	2	12	24	30	[1997 ;1998]	112	1.4	5-15	8.3%	0.0%
230	1	8	24	27	2007	184	1.4	30	0.0%	0.0%

- 69kV circuits > 40 years old at the time of testing, 138kV circuits > 23 years old
- No failures occurred during testing

Test Outcomes – Example 1, Off-Line

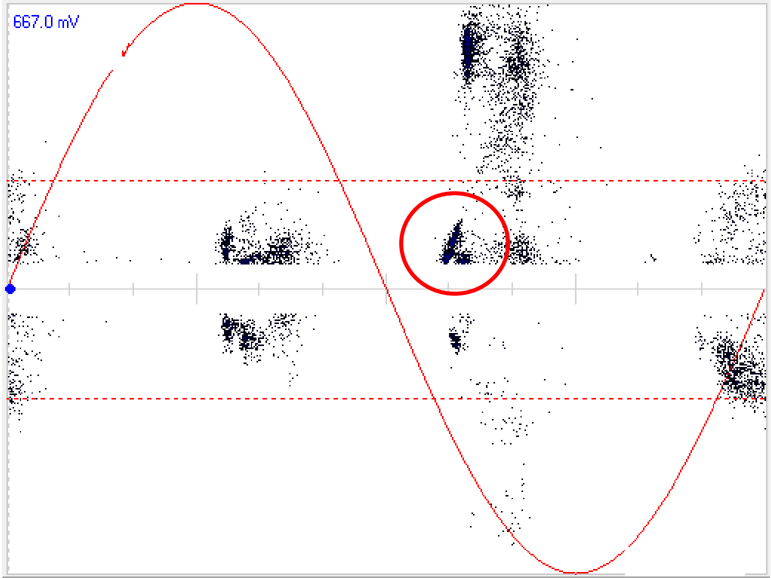


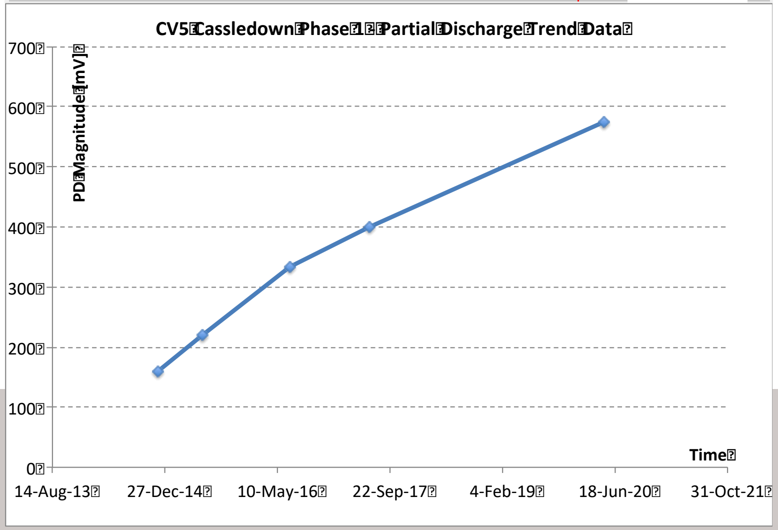
- Example of PD Pattern from Termination
- PDIV = 49.7kV (1.24U_0)
- PDEV = 47kV (1.17U_0).
- Follow-up On-Line PD measurements periodically

Test Outcomes – Example 2, Off-Line

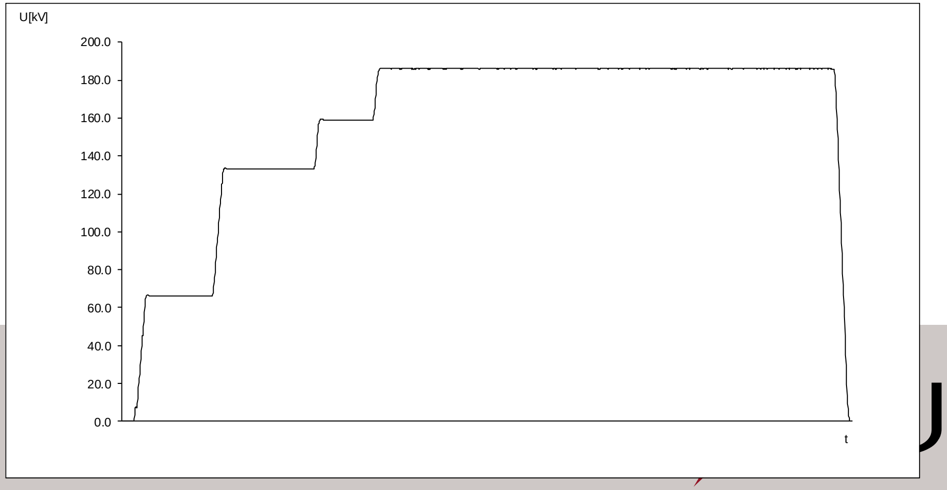
- Example of PD Pattern from a joint
- PDIV = 60kV (1.50U_0)
- PDEV > 56kV (1.4U_0).
- Voltage duration increased from 5 – 10 minutes. No PD detected at 1.4U_0 from the joint in the extended over-voltage test
- Repeat off-line measurements in 3-4 years

Test Outcomes, Example 3, On-Line + Off Line





- Long 230kV circuit monitored periodically with on-line PD (terminations only)
- PD source detected on one termination. Trended over the course of 5 years.
- Progressive increase in PD activity detected.
- Allowed for predictive maintenance performed replacing 3 terminations at one substation end.
- Following by off-line PD testing on the entire circuit including joints at 186kV (1.4U_0) for 60 minutes.



Test Outcomes, Example 3, On-Line + Off Line

Additional Electrical Tests

- Sheath Voltage Limiter Tests
- Contact Resistance Measurements in all link-boxes

⇒ Identified one severely corroded link-box

⇒ Temporary cleaned and then replaced.

Discussion

- Database relatively small as of yet however for the 69kV class cables sufficiently large in terms of the number of terminations and cable systems tested to be statistically significant.
- All 69kV circuits older than 40 years at the time of test
- No failure have occurred during testing ⇒ test interrupted in case of sustainable internal PD
- For the off-line tests, sustainable PD was detected in both terminations and in joints
- The measurement of PDIV and PDEV is, like on all other insulation system tests, essential for asset condition assessment.
- Additional issues such as link-box corrosion was detected in more than one case.
- For some 69kV circuits deemed critical the test time at $1.4U_0$, following pre-stress at $1.5U_0$, was extended from 5 minutes to 15 minutes
- Additional tools like ultra-sonic probes and corona-cameras helpful in eliminating external discharge which, from a PD pattern point of view, were similar to internal surface discharge of oil filled terminations.
- Experienced showed on-line PD measurements can be effective for oil-filled terminations as an asset condition assessment tool.
- For most circuits maintenance over-sheath maintenance tests (jacket integrity tests) were performed.
- Manhole inspections found corroded link-boxes and also in once case a severely compromised mechanical support system
- In the cases where non-PD diagnostics were performed (DFR, LIRA) the circuits tested free of internal PD so no correlation has presently been performed.
- No in-service failure have occurred after testing.

Further Work & Conclusions

FURTHER WORK

- Additional work is needed in terms of validating the test methodology in-particular for cable systems rated 132/138kV and higher.
- Growing the database for all cable classes
- Split database down on age categories.
- Correlate non-PD diagnostics such as Tanδ and DFR/LIRA with test outcomes

CONCLUSIONS

- The methodology applied has yielded positive results in terms of early detection of PD sources and allowed for planning for predictive maintenance.
- No dielectric failures have occurred thus far using the test protocol outlined.
- Additional tests such as SVL and Contact Resistance Measurements have identified issues allowed for preventive maintenance.

Testing of Fluid Filled Cables Systems

Diagnostic Approaches

Chemical Tests

- Dissolved Gas Analysis
- Degree of Polymerization
- Leak Detection

Other

- X-Ray

Electrical Tests

- Dissipation Factor/Capacitance Measurements
- Withstand Testing
  - DC/VLF/AC
  - Go/No Go
- Partial Discharge Tests
  - On-Line/Off-Line
- TDR

Manifestation of PD in fluid filled systems

So, if PD is present in a fluid filled cable system…

High Frequency electrical currents travelling along the cable conductor and the cable shield → Electrical PD measurements

If discharging into oil, then gives rise to chemical reactions causing hydrogen, ethylene and acetylene → Dissolved Gas Analysis (DGA)

If between paper tapes gives rise to aging of the paper tapes → Degree of Polymerization

This can then be detected via..

Electrical PD measurements

Dissolved Gas Analysis (DGA)

Degree of Polymerization

Dissolved Gas Analysis

Challenges:

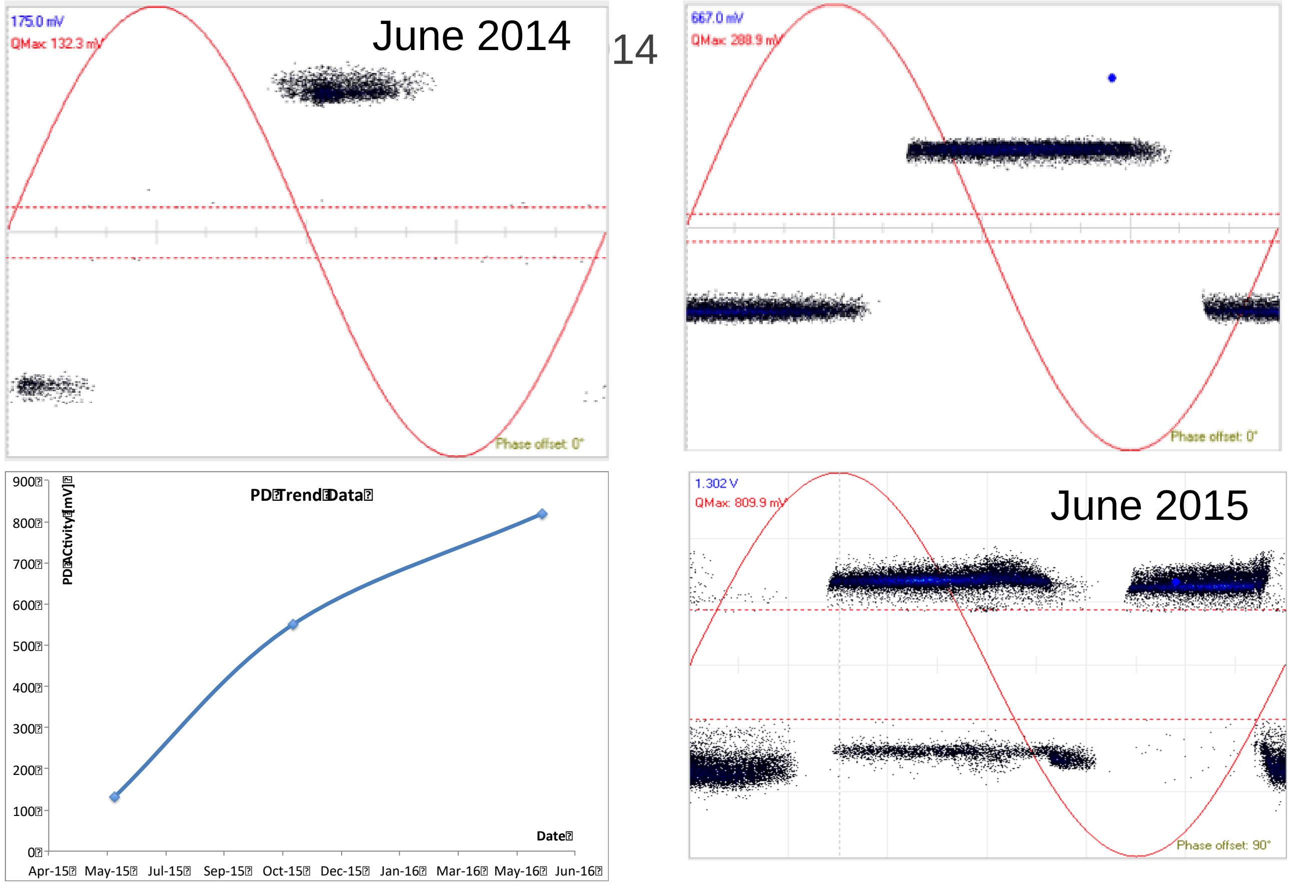
- Extraction of oil samples from joints and terminations
- For systems with circulating system, positive DGA results may be obtained on multiple locations but does it represent multiple problems?
- Obtaining representative samples from static systems

Pro's

DGA provides historic "view" of discharge activity from cable system into oil

Trendable results

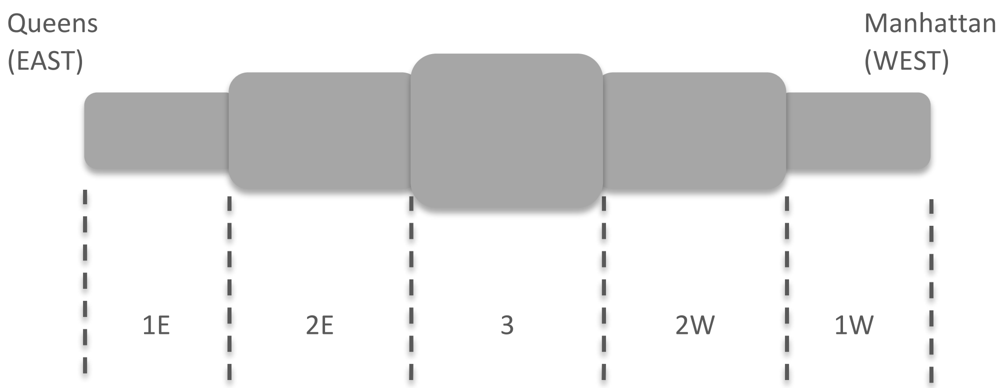
On-Line PD: 72kV SCFF Terminations



- For fluid filled terminations, on-line PD is a trendable tool
- Rule of thumb: An increase by a factor of 2 in 6 months is indicative of progression of aging
- Need to monitor for at least a few hours per termination initially as PD many not be consistently present.

Tanδ: A few notes

- Performed using conventional technology for off-line energization
- Testing at 20 Hz to 300 Hz which gives realistic electrical stresses and realistic PD behaviour
- Perform a distributed PD measurement, where possible, simultaneuously to the Tanδ measurement.
- Scanning joints
- In addition, perform Low Frequency (0.01 – 0.1Hz) Tanδ if suspection of ingress of moisture



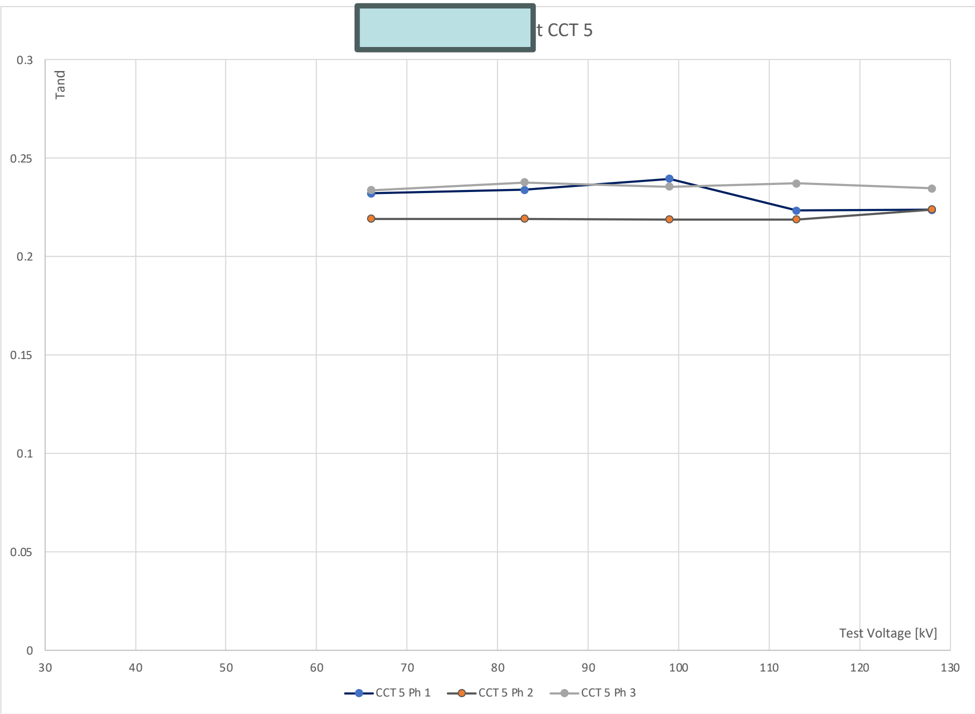
Tanδ: Test Setup

Courtesy of National Grid

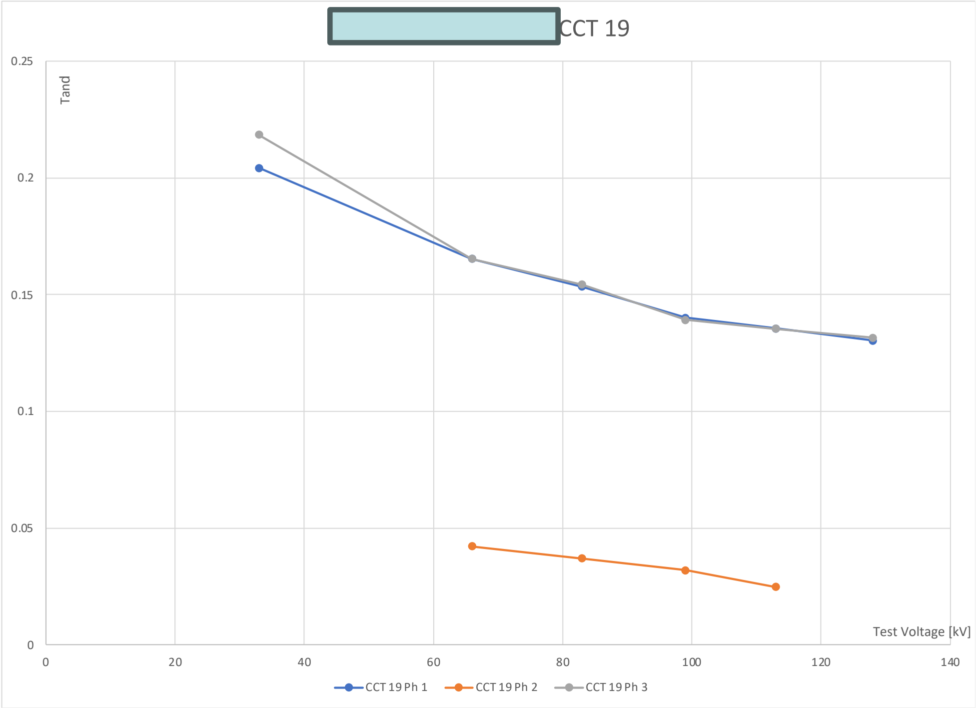
EUCI

Tanδ: Outcomes

Healthy

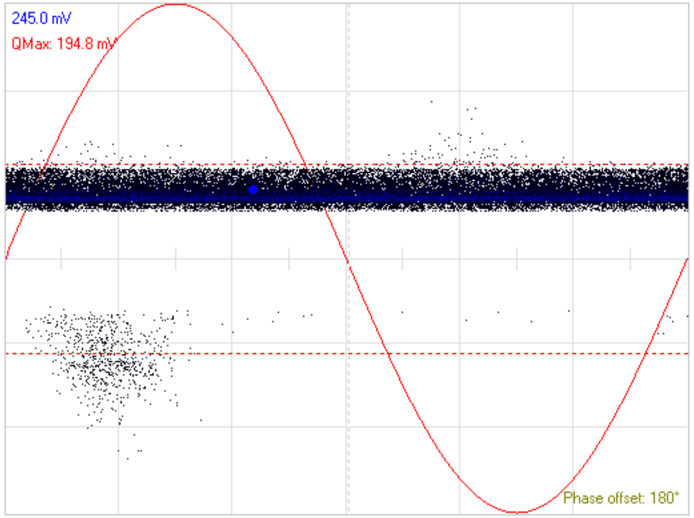


Thermally Aged



Distributed PD Measurements

- PD Measurements performed on terminations during testing at each voltage step
- PD Measurements performed on joints, if accessible, at each voltage step
- Joints scanned with differential sensor
- Example of dissection of joint due to PD detected



Example of PD in a 115kV SCFF AIS Termination


Example of PD in a 138kV HPFF joint (circulated oil)

Recap: Reporting

		Trinity – River Side CCT: #19			Trinity – Riverside Cct: #18		
	Phase	1	2	3	1	2	3
	Date [October 2021]	14th	14th	14th	18th	18th	18th
AC Hi-Pot Data	Voltage [kV]	128	113	128	128	128	128
	Current [A]	32.35	36.68	36.60	32.97	32.72	33.11
	Frequency [Hz]	34.33	34.28	34.37	38.11	38.43	37.98
	Derived Capacitance [nF]	1,327	1,330	1,324	1,075	1,058	1,084
	AC Hi-Pot	PASS	PASS	PASS	PASS	PASS	PASS
PD Data	Trinity Substation [mV]	0	0	0	0	0	0
	Manhole 5573 [mV]	0	0	0	0	0	0
	Manhole 5572 [mV]	0	0	0	0	0	0
	Manhole 5571 [mV]	0	0	0	0	0	0
	Riverside Substation [mV]	0	0	0	0	0	0
	PD Test	PASS	PASS	PASS	PASS	PASS	PASS
Tanδ	Voltage [kV]	66	66	66	66	66	66
	Tanδ	0.16536	0.04215*	0.16528	0.26337	0.21890	0.20083

Salient Points (Technical & Commercial)

- This is a trend test to be repeated every 3 - 7 years depending on results and criticality. So repeat business.
- Positive and zero sum impedance measurements to be sold also
- Engineer must be on site for testing. Techs will likely not be able to do this stand alone.
- Partner up with USi for repairs as needed
  - Not only accessory problems can be repaired. Cable problems in practice means replacement.
  - The combination of Tanδ and PD at accessories helps identify positive if accessory or cable problem
  - Can help utilities plan for replacement.

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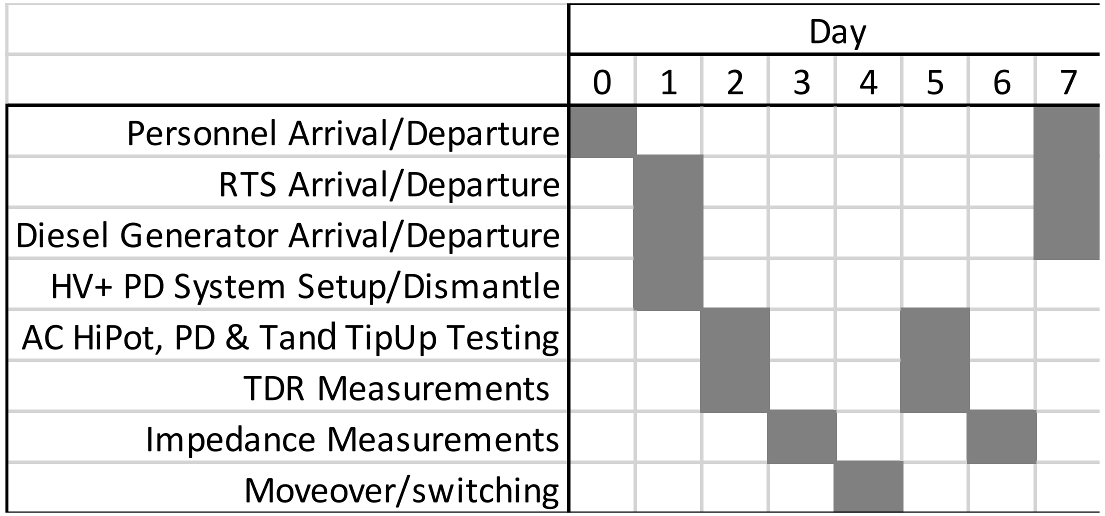
Execution: Typical Schedule



<u>Execution Considerations:</u>

- Test calculations *must* be done at proposal stage.
- Coordination with end client needed
  - Outage Planning
  - Pumping of manholes, traffic control
  - Disconnection of cable circuit
- 3 man crew for jointed circuits
- Expert test: Each test *must* have an trained engineer on site!
- Can test two circuits in 1 week including impedance measurements
- Reporting 2-3 days (data intensive) depending on number of joints