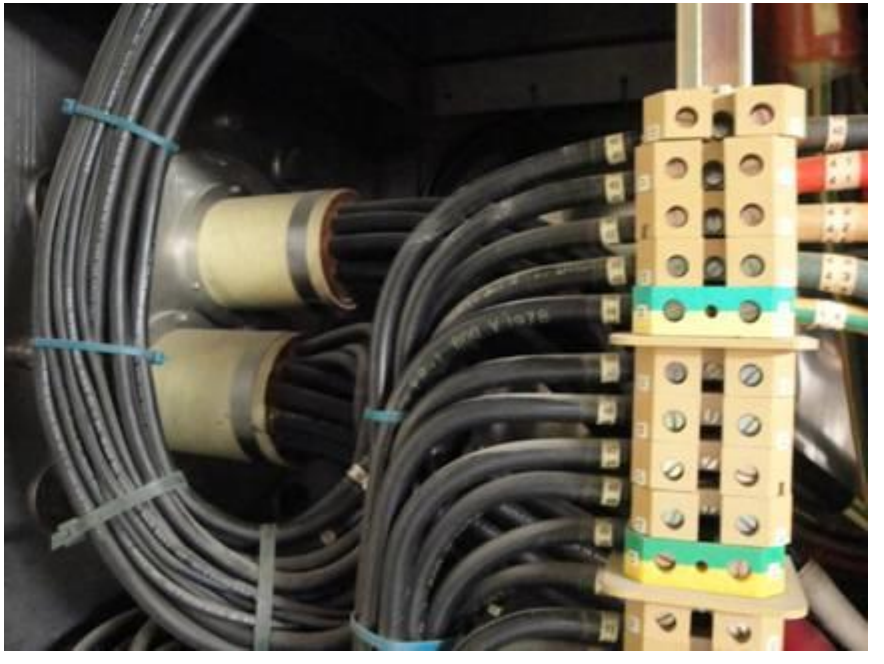
Advancements in Condition Monitoring of Electrical Cables in NPPs Using Line Resonance Analysis (LIRA)



Paolo F. Fantoni

Wirescan AS, Norway

39th Enlarged Halden Project Group Meeting

Fornebu, May 9th-12th, 2016

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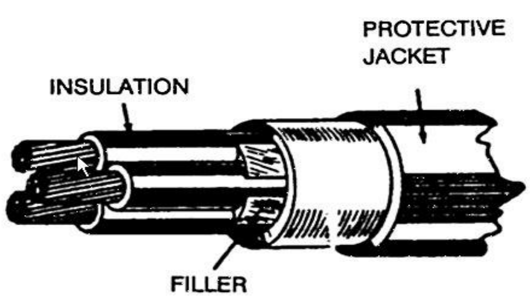
Ageing of electrical cables

As Cable age, Normal & Harsh Environments can impact the cable insulation

- Operational environment challenges cable insulations and jackets integrity. Ageing parameters include:
  - Temperature > 40°C)– dependent upon cable type
  - Gamma radiation
  - Humidity, steam
  - Mechanical
  - Chemical
  - Others
- Long term operation of cables in harsh environment can lead to insulation degradation and consequent loss of functionality
- Local Adverse Local Environments (ALEs)



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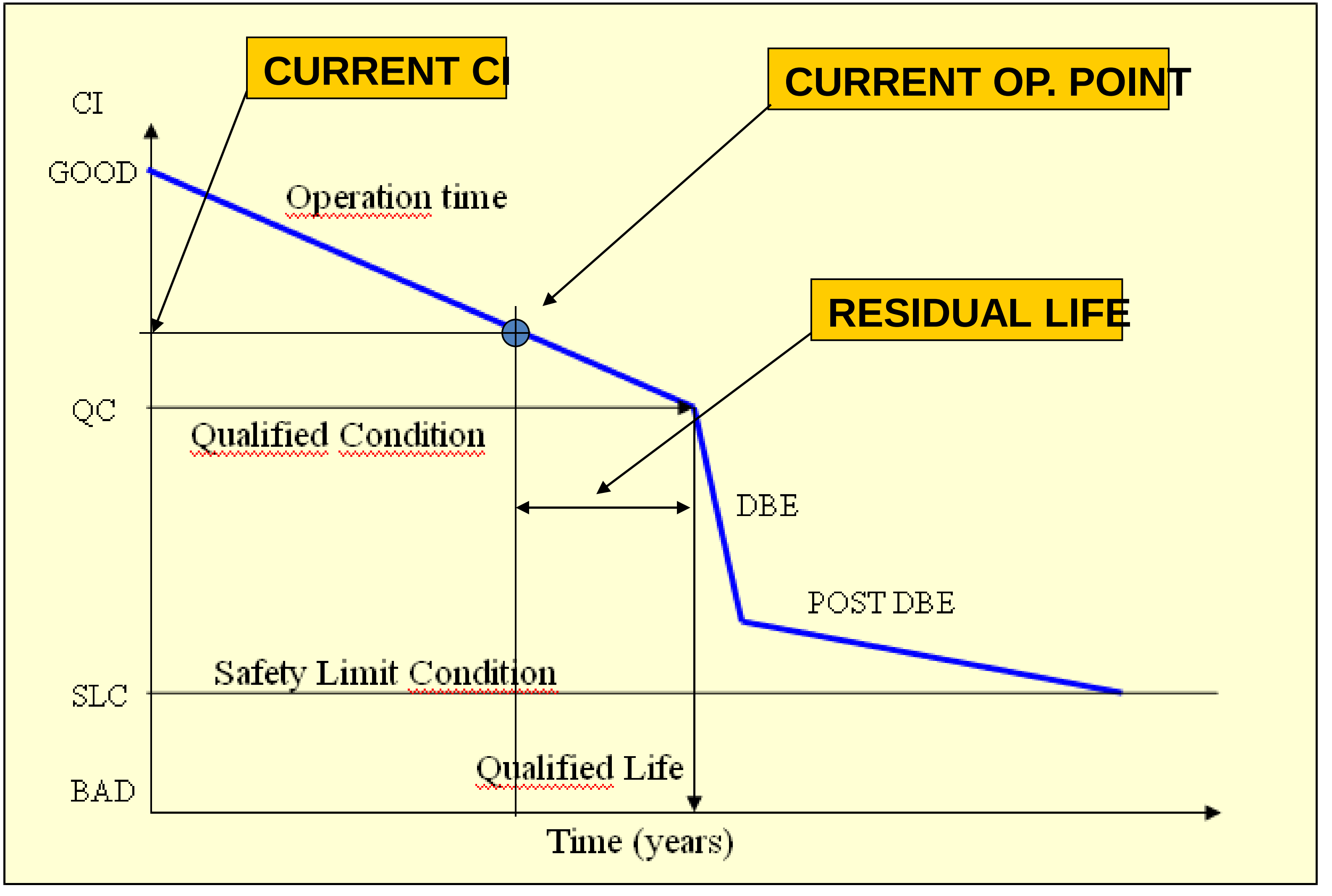
Cable Qualification
for Class 1E-LOCA Cables

EQ (Environment Qualified) safety cables must be operable at the end of their qualified life, during and after a LOCA accident, in order to support the actions required to bring the plant to a safe shutdown condition

The Qualification Process



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Adding Condition Monitoring to a Cable Ageing Program

- Identifying local weak points, as a consequence of local environment changes.
- There are uncertainties associated with the qualification process.
- On-going qualification strategy
- Qualified condition strategy vs. qualified time strategy.
- Not every cable needs to be EQ qualified,but still many cables are relevant to safety and need to be condition monitored.

Advantages of the Qualified Condition approach

- No dependence on uncertainties as activation energy, environment conditions, dose rate effects.
- When the cable is exposed to milder environment conditions, it can justify operation beyond qualified life.

However....

A Condition Monitoring technique is needed

Review of Current Cable Condition Monitoring Techniques

Process	Onsite?	LV/MV?	Powered?	Physical properties	Local/Full Length?
Visual inspection	Yes	Both	Yes	N/A	Both
Elongation at break	No	Both	No	mechanical	Local
Indenter	Yes	Both	No	mechanical	Local
Oxidation Induction Time (OIT)	No	Both	No	chemical	Local
Insulation resistance (IR)	Yes	MV(LV)	No	electrical	Full Length
Partial Discharge	Yes	MV	Possible	electrical	Full Length
Tan-Delta	Yes	MV	No	electrical	Full Length
Time Domain Reflectometry (TDR)	Yes	Both	No	electrical	Full Length
Infrared Spectroscopy	No	Both	No	optical	Local
Ultrasound	Yes	Both	No	acoustic	Full Length
LIRA	Yes	Both	Soon	electrical	Both

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LIne Resonance Analysis (LIRA)

- Project started at the Halden Reactor Project in the years 2004-2006

- Correlation between the insulation condition and the properties of the insulation dielectric material
  - Changes in dielectric constant, mainly capacitance, lead to changes in cable impedance (globally and locally). Local Adverse Local Environments (ALEs)
- Based on transmission line theory
  - Calculates and analyzes the complex line impedance as a function of the applied signal for a wide frequency band

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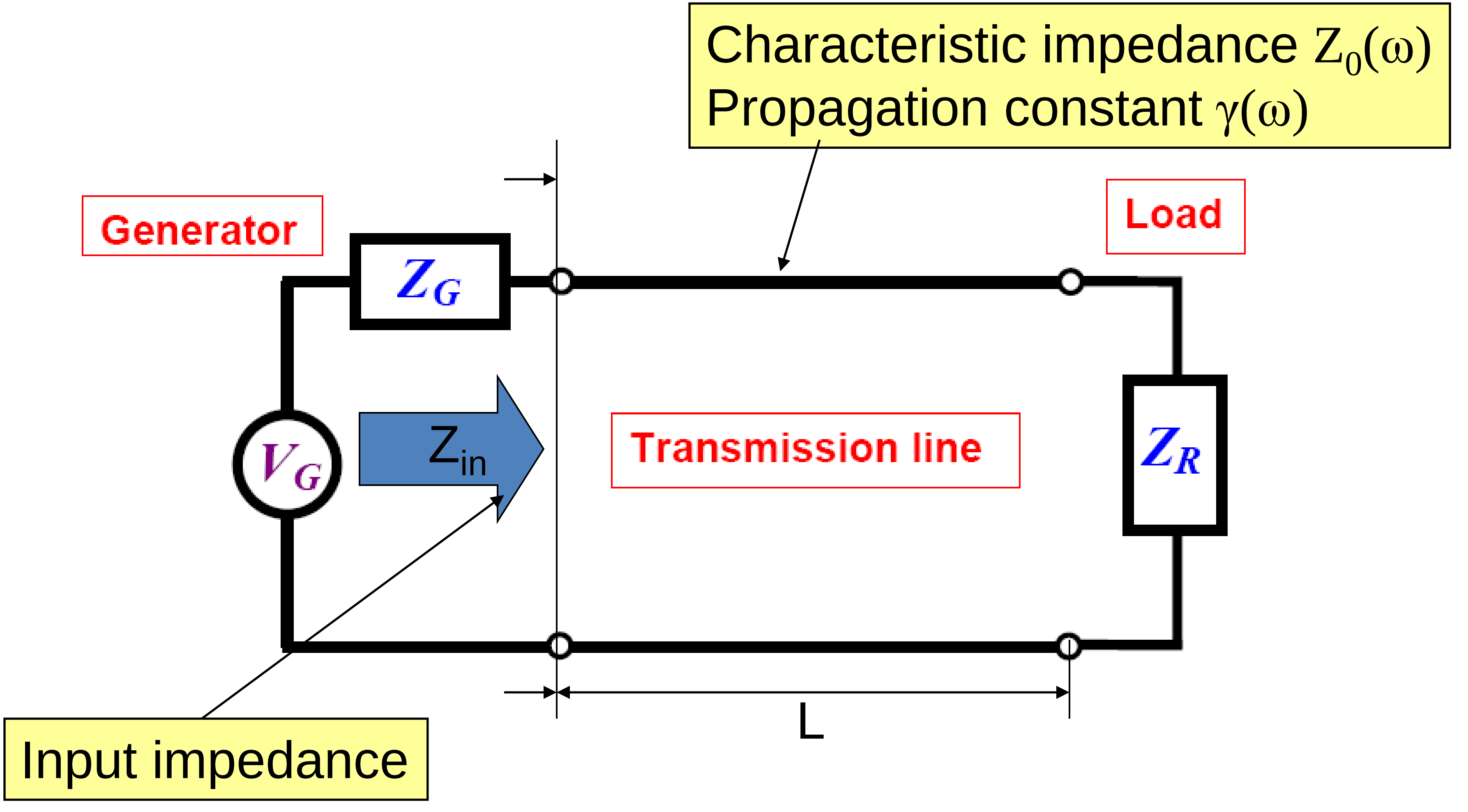
Transmission Line Theory



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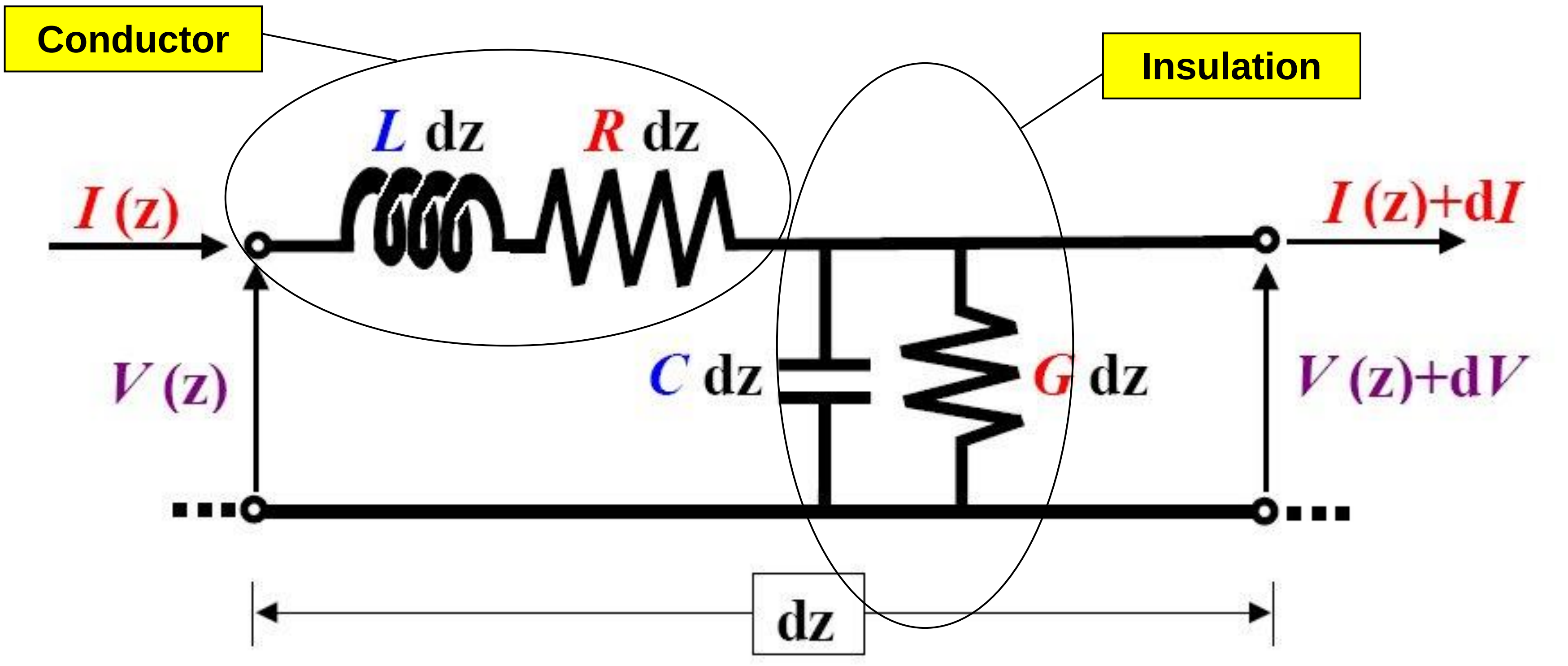
Electric parameters in a cable



R …series resistance
L … series inductance
G …parallel conductance
C …parallel capacitance

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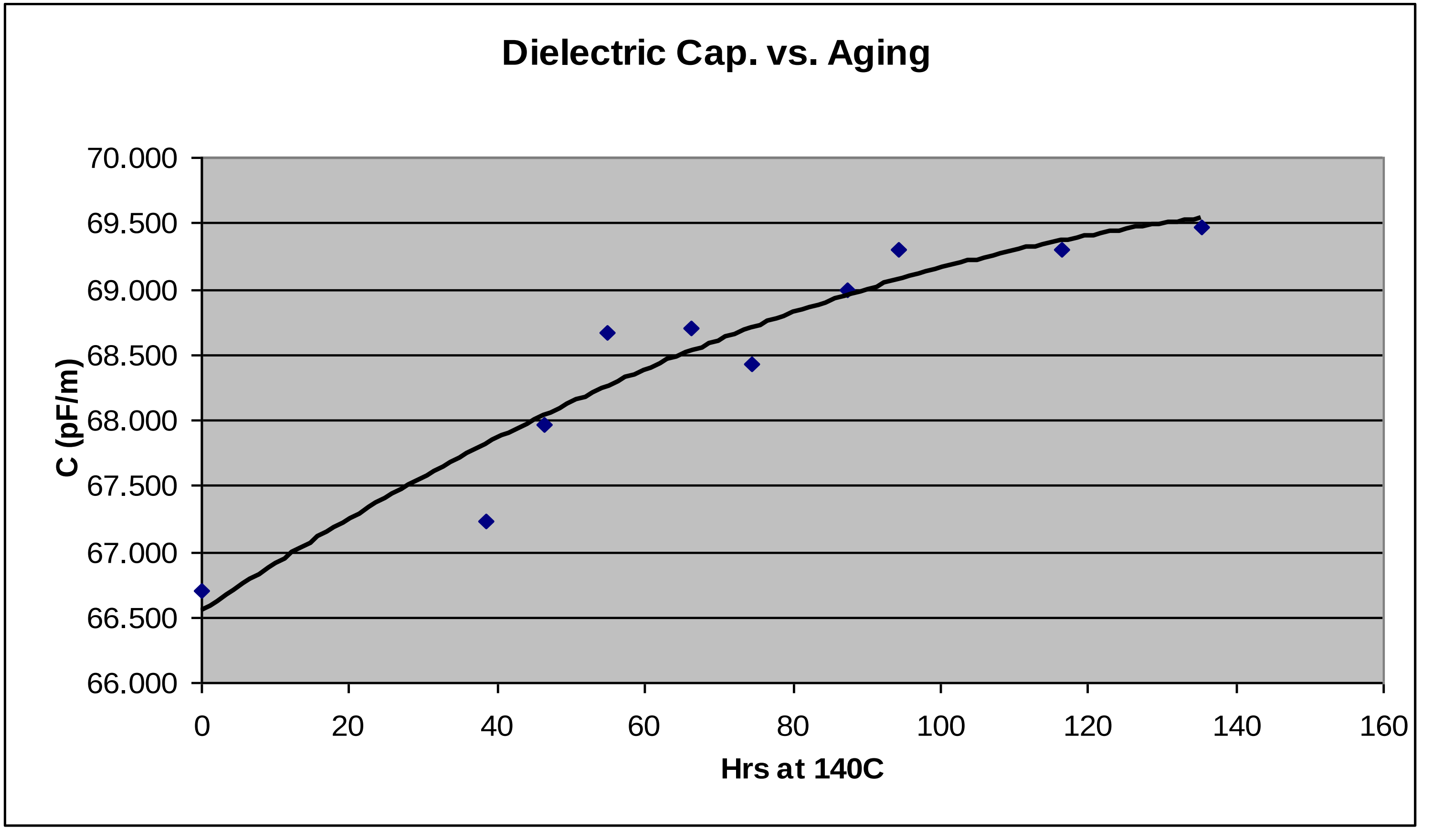
Dielectric Capacitance vs. Aging - EPDM



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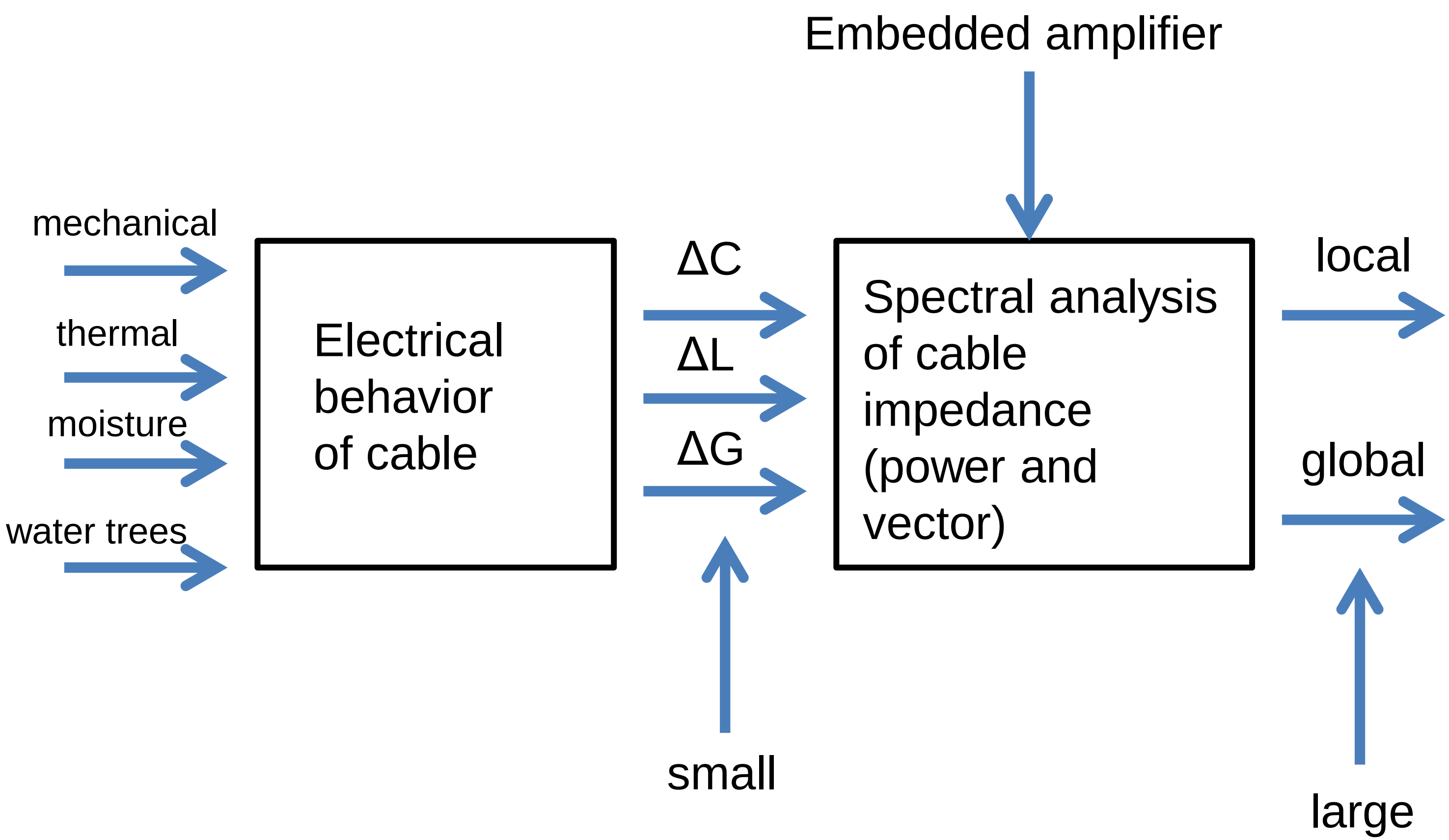
Broadband Frequency Domain Analysis of cable impedance



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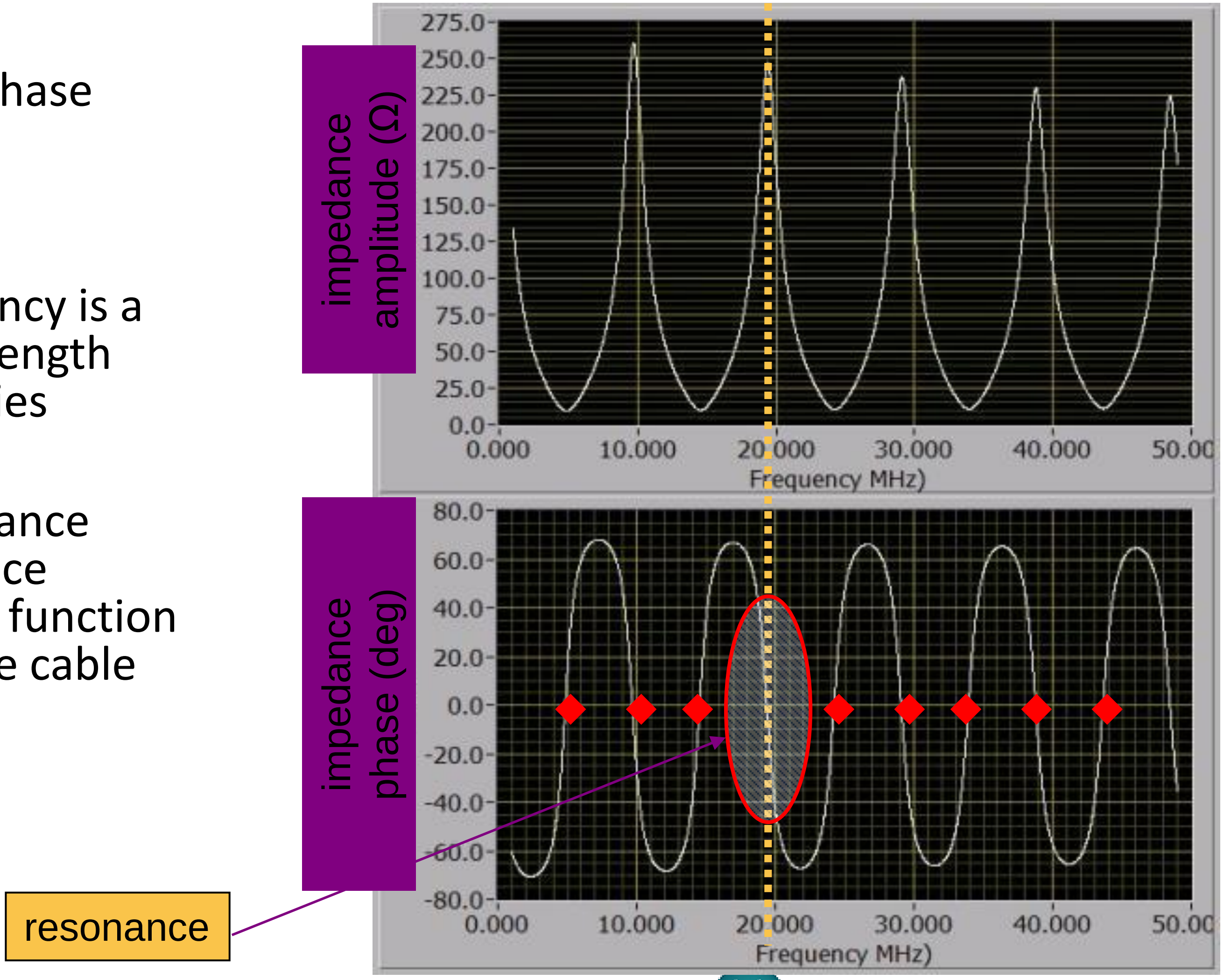
Resonance analysis of cables

- At all resonance frequencies, the phase shift of the cable impedance is zero
- Resonance frequency is a function of cable length and cable properties
- Cable peak impedance values (at resonance frequencies) are a function of the load and the cable attenuation



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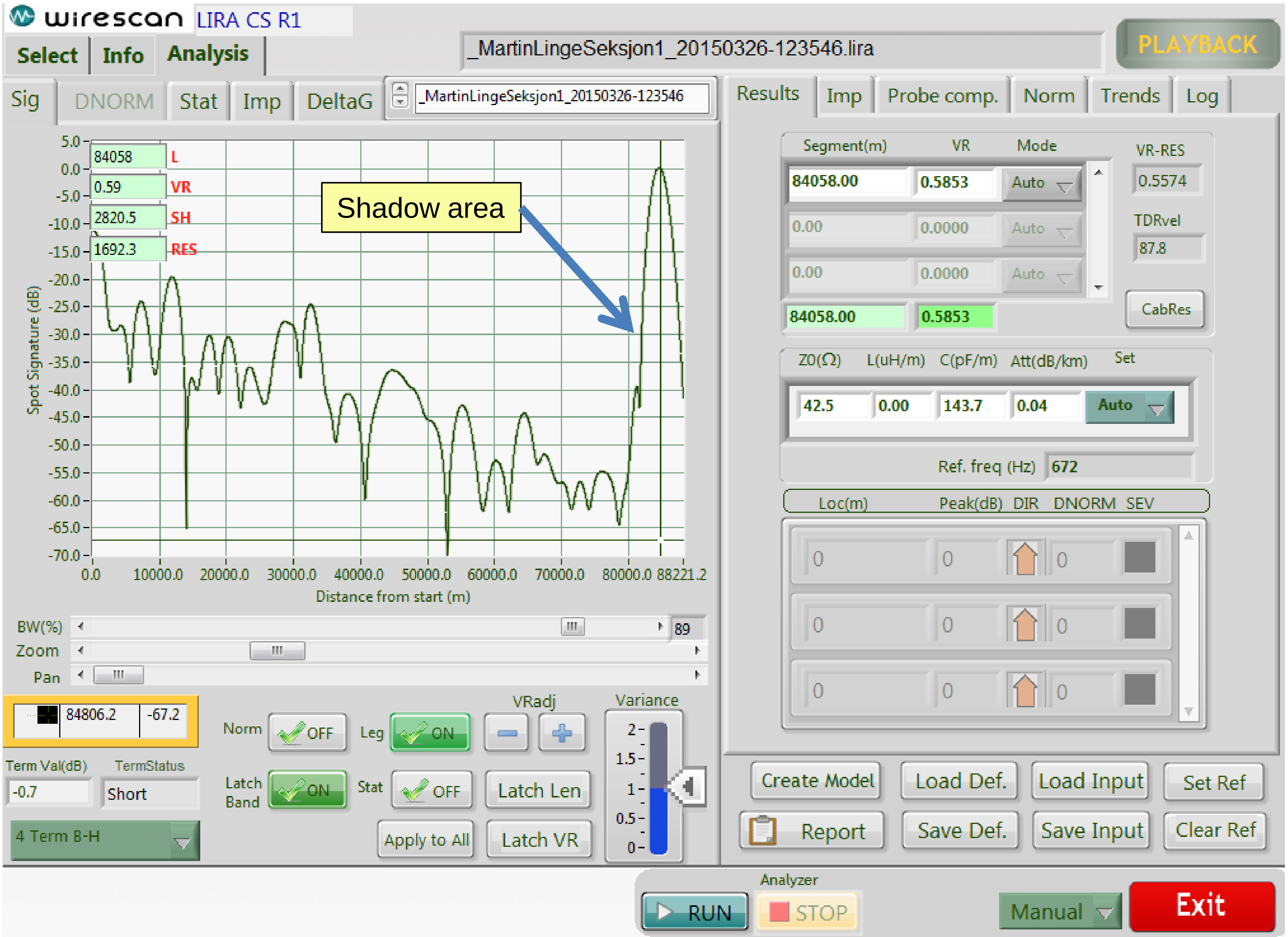
Local and Global Degradation

- Local Degradation
  - specific to certain section(s) of the cable
  - mechanical damages/stress
  - water treeing, heat-induced oxidation
- Global Degradation
  - applicable for the entire cable
  - general aging
  - oxidation in homogenous environments



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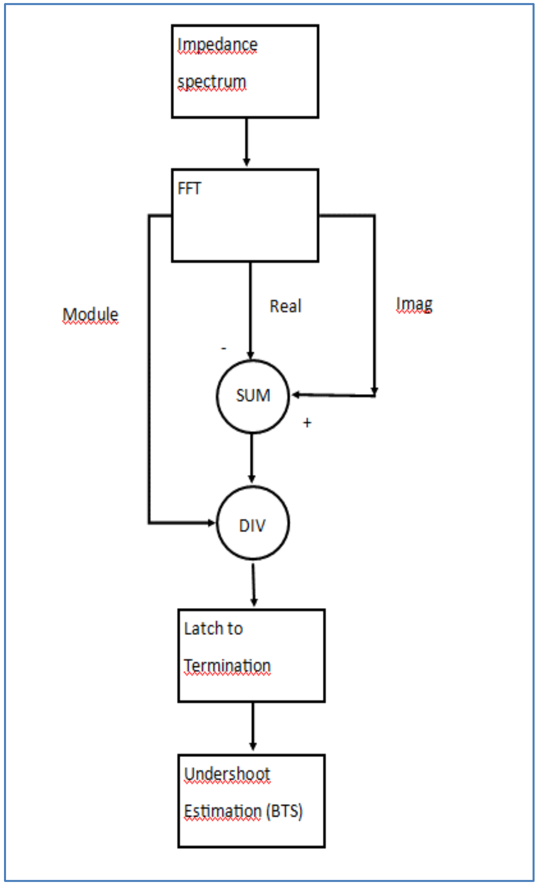
Balanced Termination Signature (BTS)

- Cable termination assessment based on the relationship between real and imaginary components of the Fourier transform of the impedance phase spectrum



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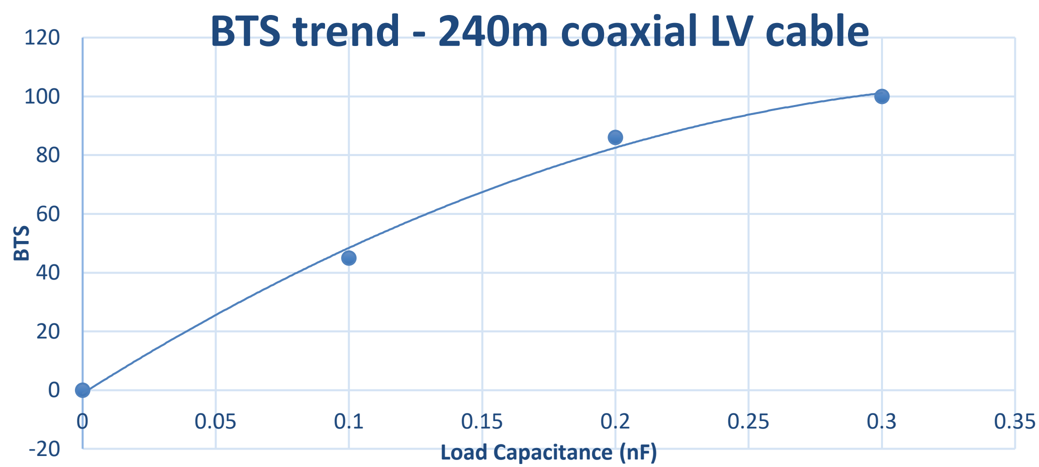
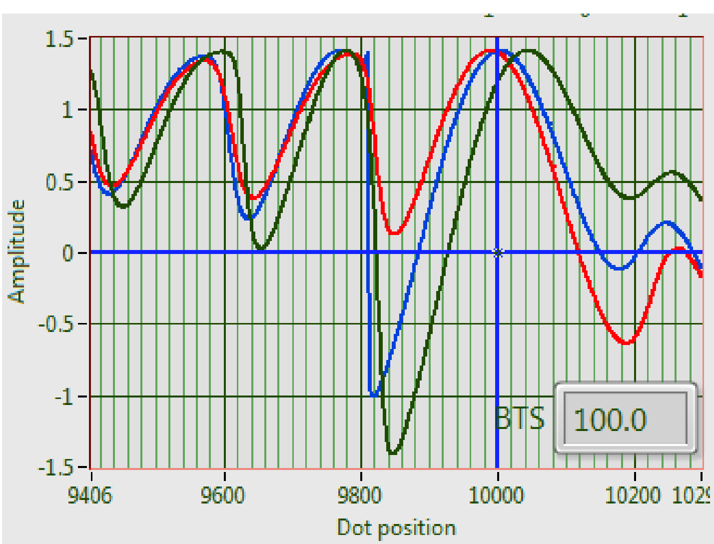
Balanced Termination Signature (BTS)



The BTS indicator (0 – 100) provides an estimate of the dielectric degradation at or near the cable termination



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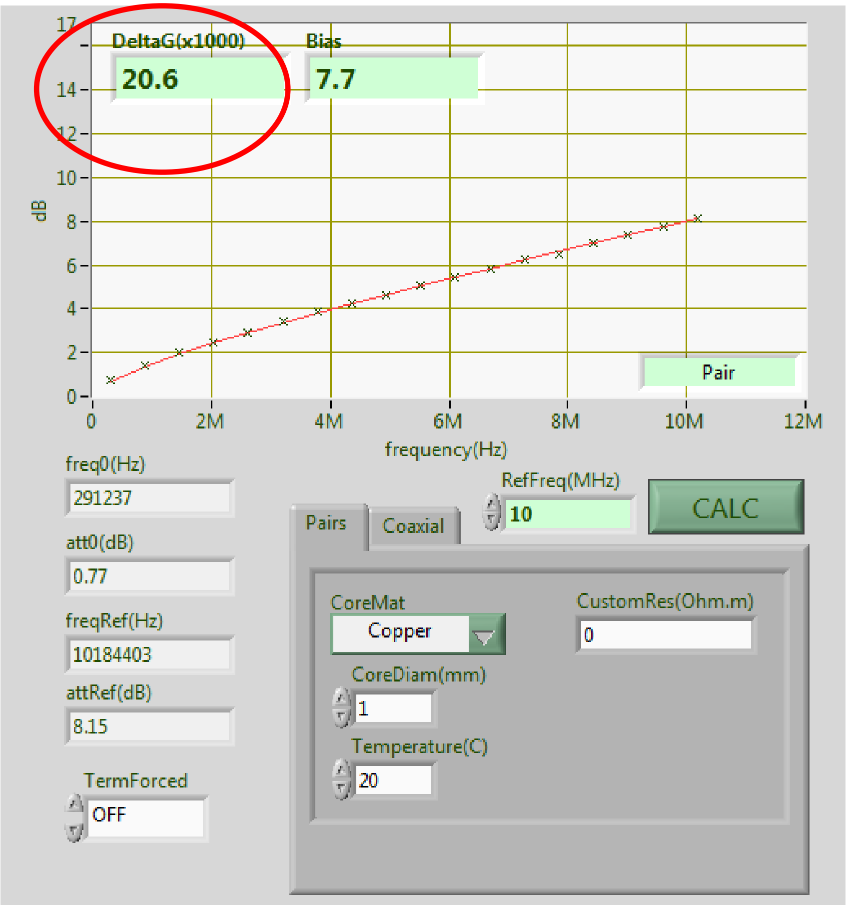
Global Degradation (LIRA DeltaG indicator) – Cont.

- DeltaG is an indicator of the dielectric losses, equivalent to TanDelta.
- It is calculated using the estimated attenuation through the all applied bandwidth.
- To calculate DeltaG, the following information about the cable are needed:
  - Core (and shield) material
  - Core (and shield) diameter
  - Temperature



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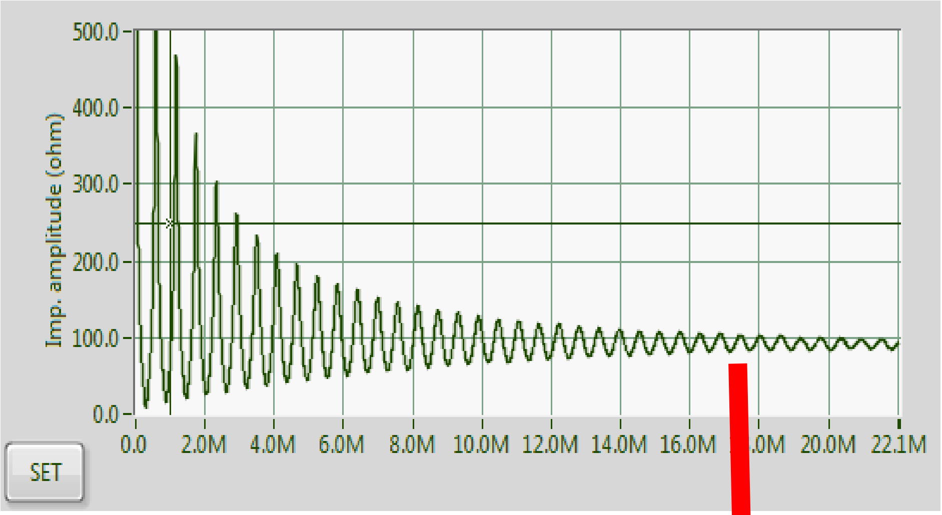
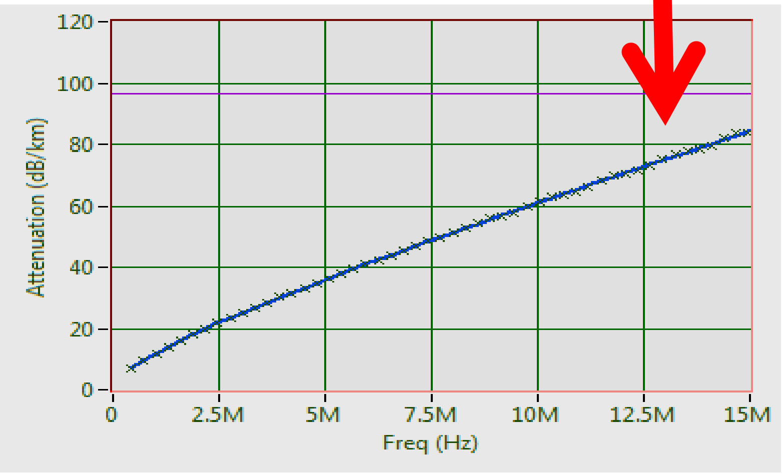
Global Degradation (LIRA DeltaG indicator)

- The LIRA global ageing indicator DeltaG is based on an accurate estimation of the attenuation spectrum within the applied bandwidth.
- The attenuation is the result of 2 factors:
  - Conductor resistance (with skin effect): K1
  - Dielectric losses: K2

$$\propto = K1 \times \sqrt{f} + K2 \times f$$

- K1 and K2 can be accurately estimated using a non linear regression algorithm (Levemberg-Marquardt)
- K1 is not sensitive to ageing, while K2 increases with material degradation





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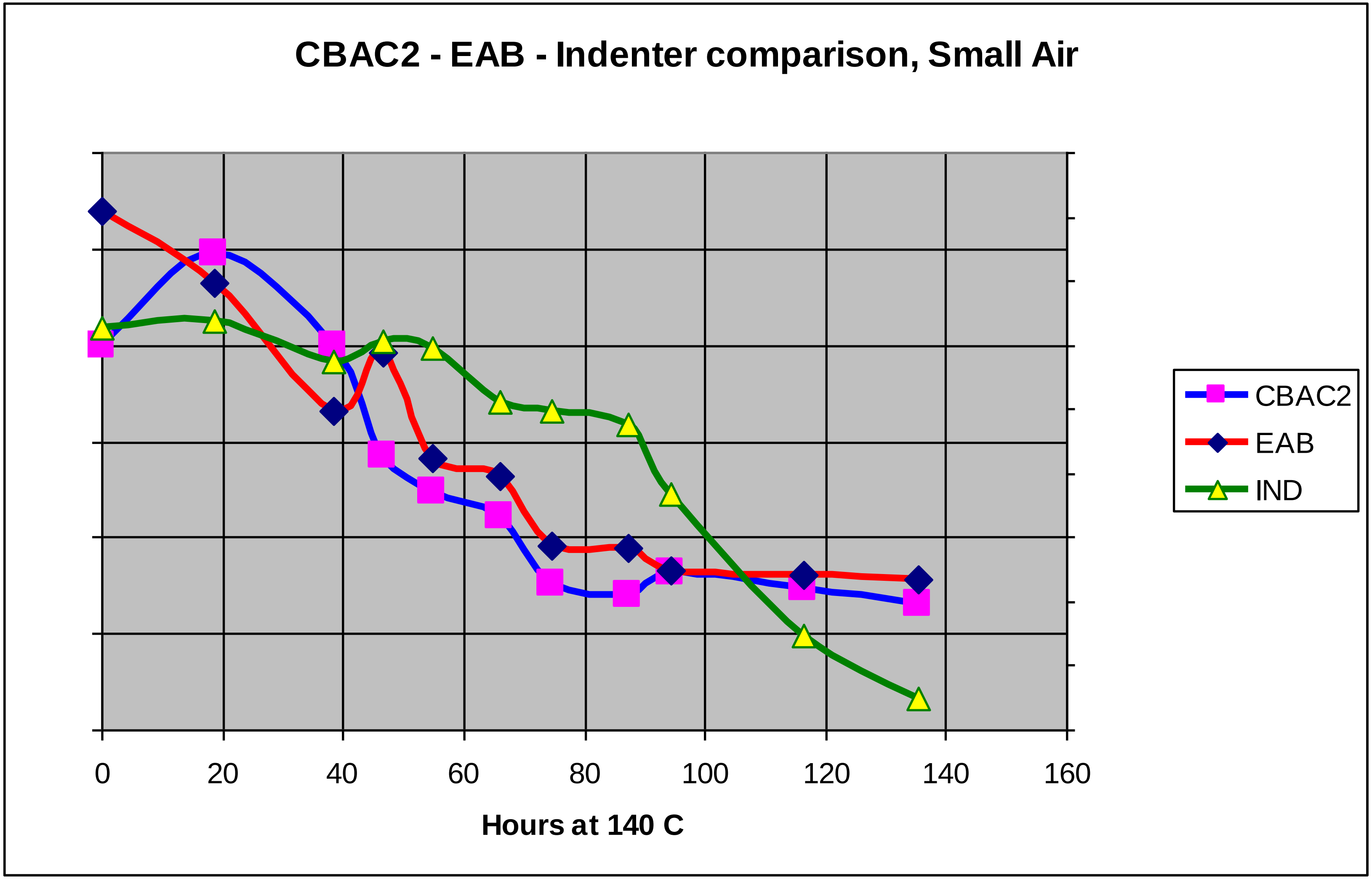
LIRA/EAB/Indenter – Small size, Air



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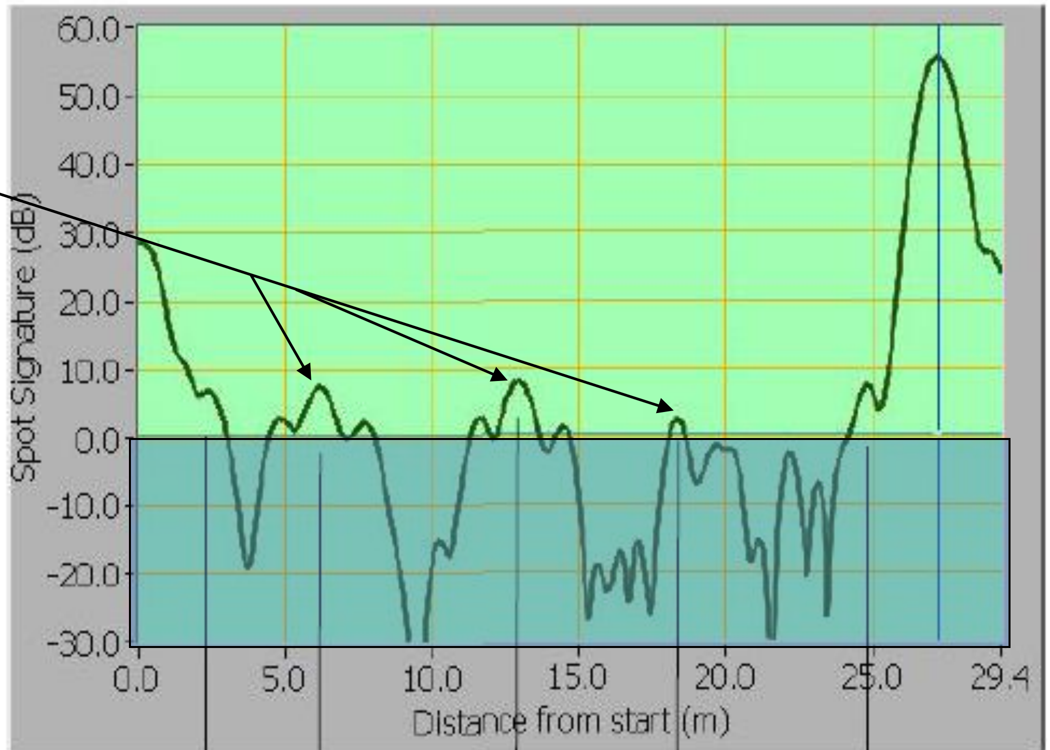
LIRA water tree detection on medium voltage XLPE cable (EPRI)



Water Trees

Beakdown Voltage Test

TanDelta Test

LIRA Spots m 2.4 m 6.5m 13.1 m 18 m 24.7
CTL m 0.25 2 m 5.2m 7.9 8.4 10.5 12.5 15.7 19.6 22.9 m

CTL ft 9 in 6ft 6 ft 24 25.5 ft 32 or 38 48 or 60 70 ft
BDxVo Fail 4.6 5.2 7.1 7.1 7.1 5.2
Tan δ(10^{-3}) - 200 74 50 29 29 37

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MV Pink EPR, 10kV, 30 years

3-phase 10kV underground shielded cable, 345m long to the Auxiliary Feedwater Pump.
In operation since 1983

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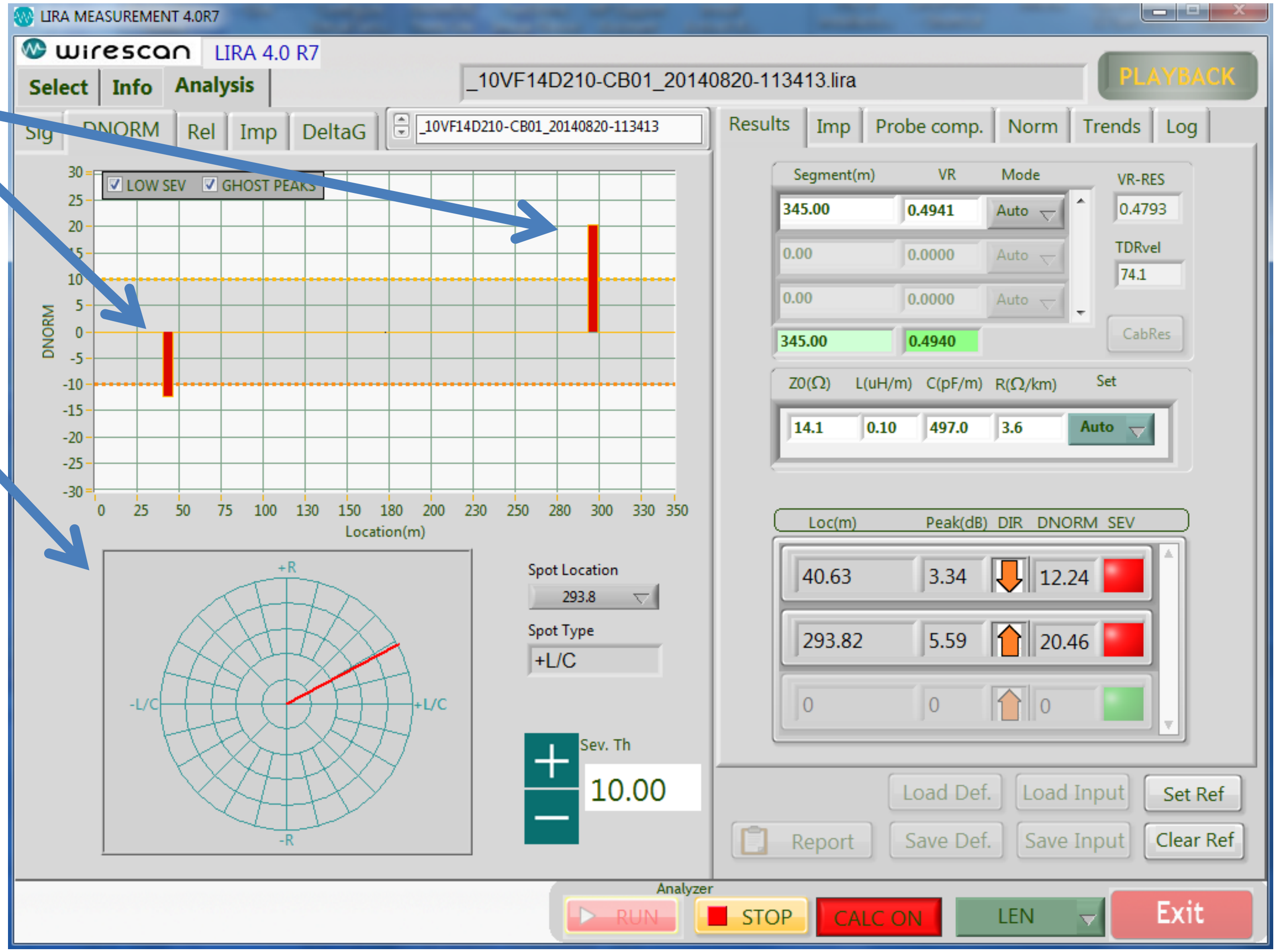
MV Pink EPR, 10kV, 30 years

Local spots

Impedance spot analysis



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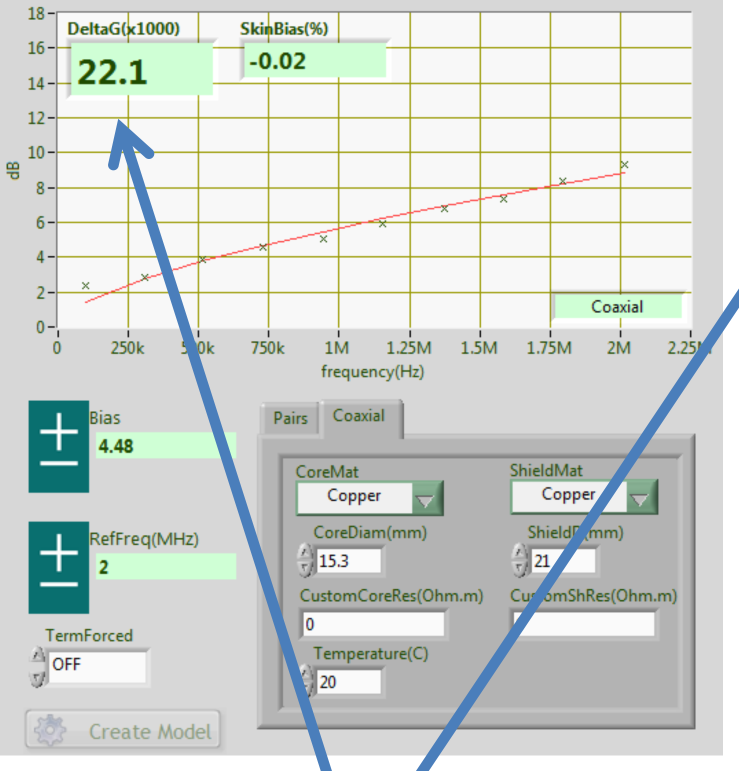
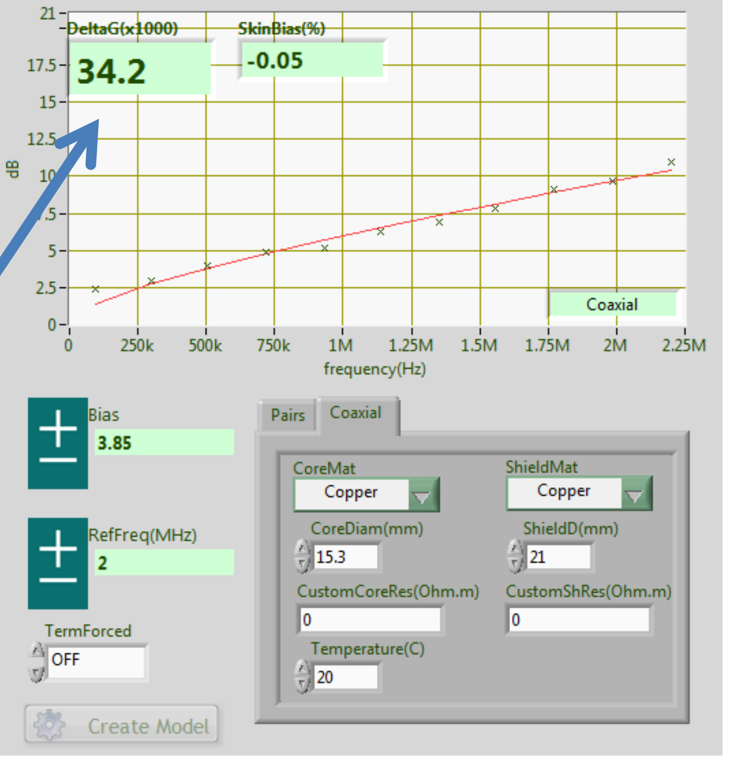
MV Pink EPR, 10kV, 30 years

Red phase



Blue phase



Dissipation factor (DeltaG)

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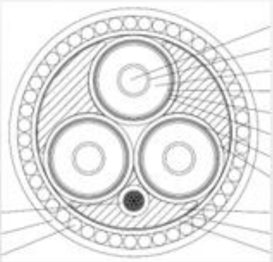
LIRA® Fact Sheet

Customer: Offshore Wind Farm Operator

Market segment:
Offshore Wind

- Customer request: **Fault location**
- Location: Offshore Netherlands
- Cable: Export cable – 15,6km – 34kV XLPE



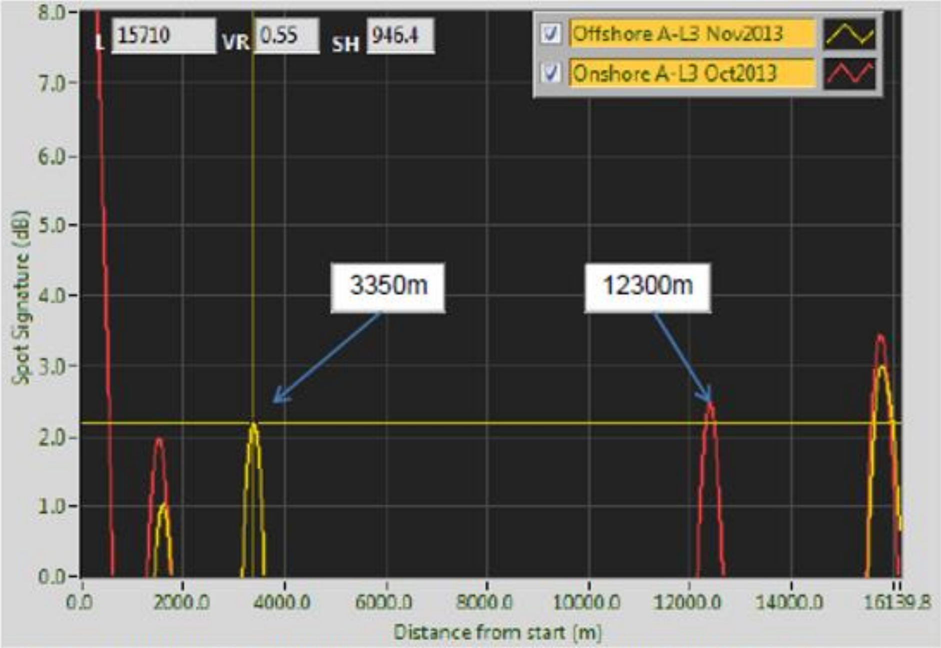


Figure 1 L3 signatures from both sides. The mark at 3350m (from offshore) corresponds well to the mark seen from onshore in October 2013

- **A cable fault was indicated at the same location on measurements both from onshore and offshore substation. Further visual inspection showed failure at this point with less than 0.3% accuracy.**

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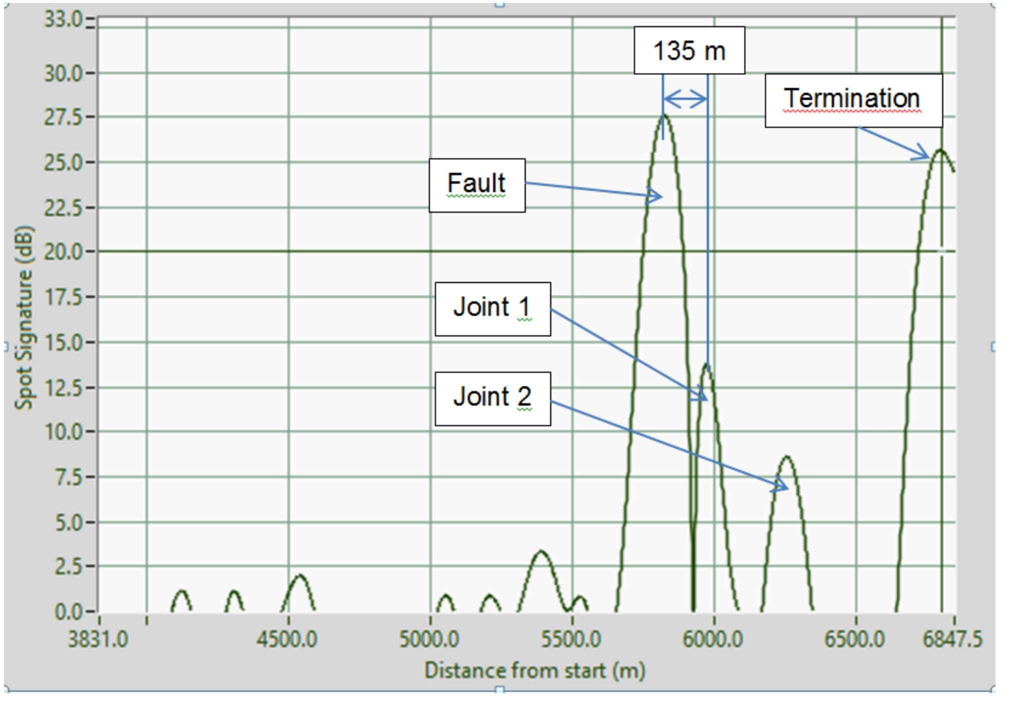
LIRA® Fact Sheet

Customer: Offshore Wind Farm Operator

5 kV XLPE 3 phase cable
6800 m length

Fault on phase 1
135 m before first joint



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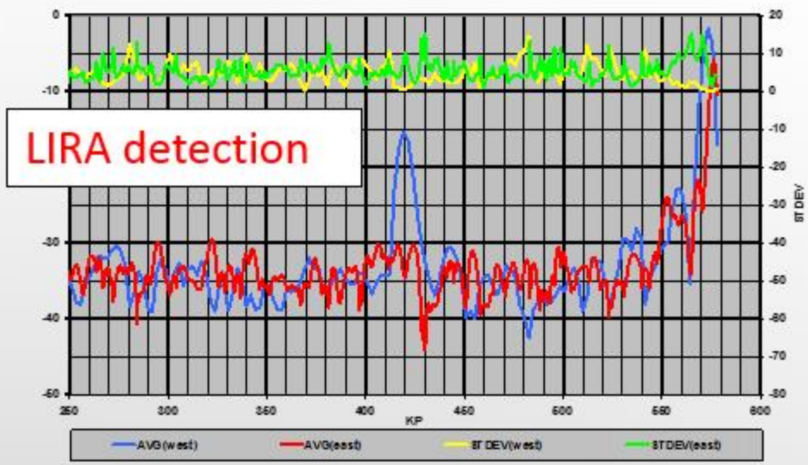
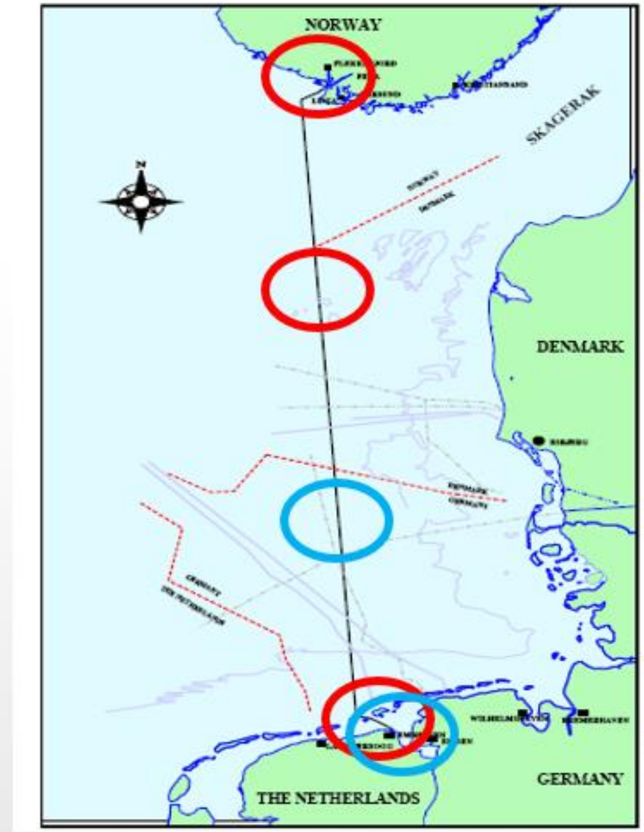
LIRA® Fact Sheet

Customer: National Utility

Market segment:
Power Transmission

- Customer request: **Cable fault location**
- Location: Netherlands/Norway
- Cable: 580 km HVDC, paper insulated





- Two TDR measurements could NOT give accurate location of failures.

- **LIRA measurements located the failures better than 0.3% of total cable length**

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Conclusions

- Plant life extension and component aging results in a clear need for monitoring cable conditions and residual life.
- A number of unresolved issues must be addressed by international research initiatives.
- **Threshold evaluation of different CM techniques must be studied, in order to use them for residual life assessment (EURATOM project ADVANCE).**

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LIRA References

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