

The Importance of Proper Insulation Coordination in Transmission Systems Through Practical Examples

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cigre

For power system expertise

Technical Brochure 913

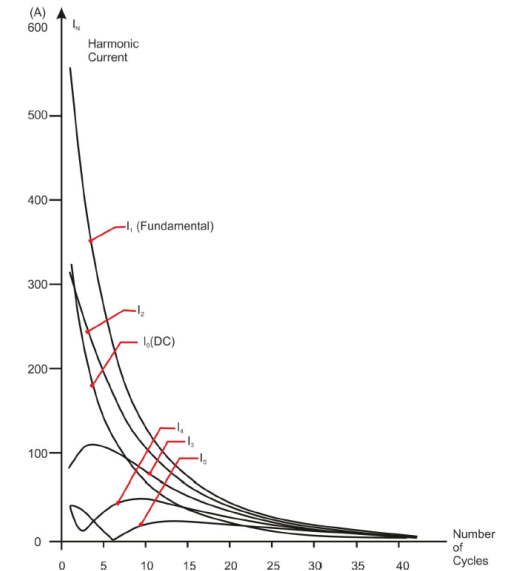
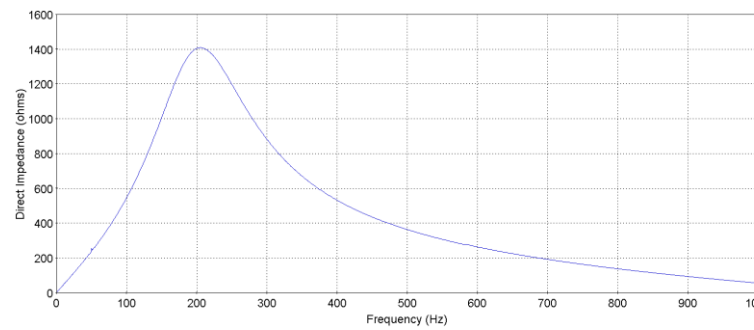
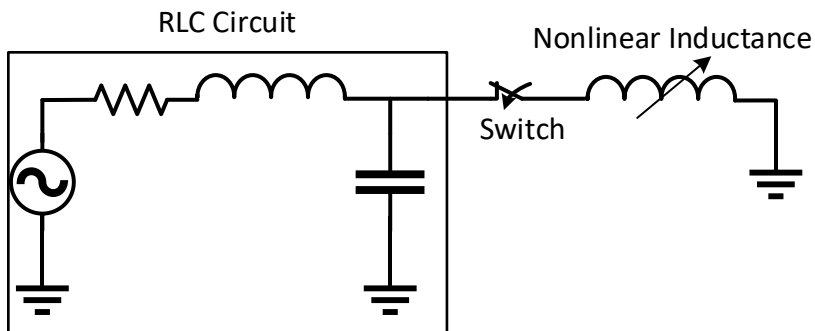
**Evaluation of Temporary Overvoltages in Power
Systems due to Low Order Harmonic Resonances**

Introduction and Motivation

- Temporary Overvoltage (TOV) is a typical phenomenon accounted for in insulation coordination studies
- Defined by IEC as a “*power frequency overvoltage of relatively long duration*”
- The standard testing waveform follows this definition by consisting in a “*short-duration power frequency test*”
- But, “*In some cases its frequency may be several times smaller or greater than power frequency*”, IEC (IEV ref 614-03-13)

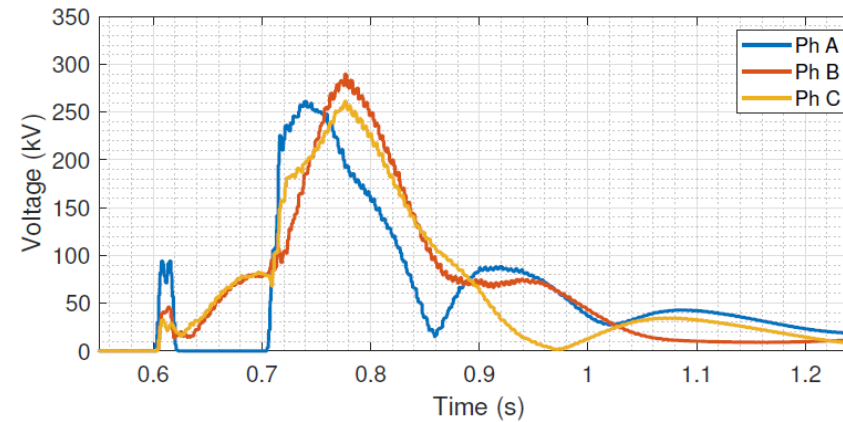
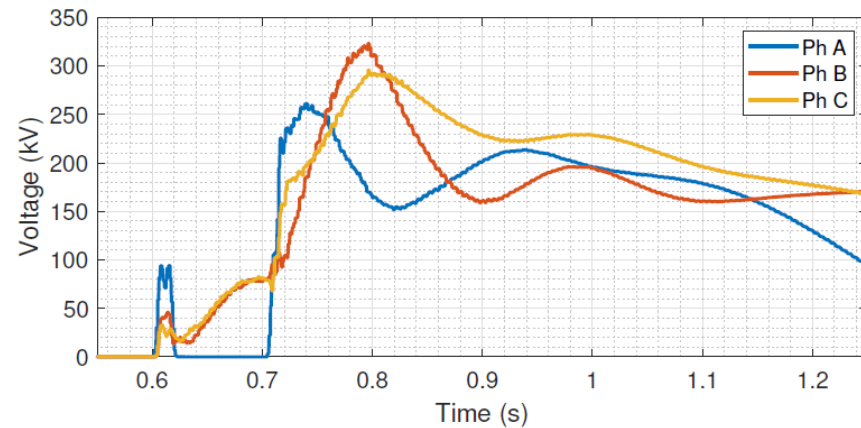
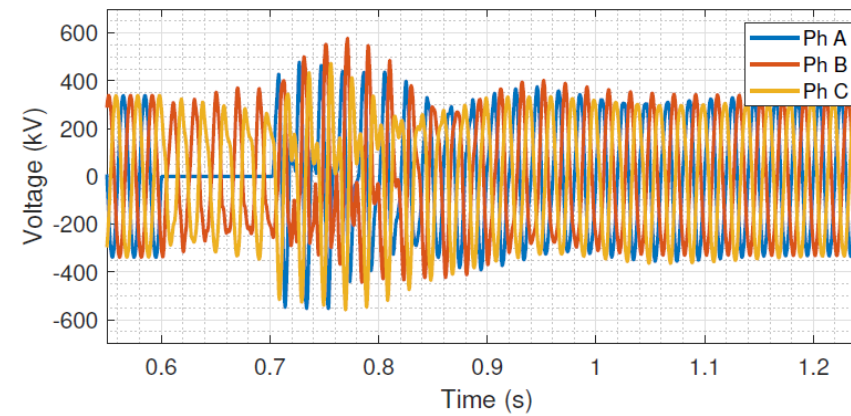
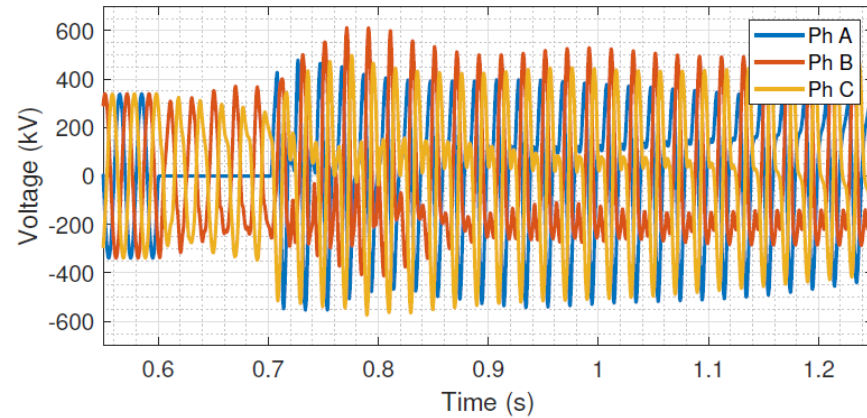
TOVs due to a harmonic resonance

- Typically, a TOV due to a harmonic resonance requires both:
 - ✓ A saturable core generating harmonic content-> e.g., inrush current of a transformer(s) during energisation
 - ✓ A resonance frequency at the frequency of one of the transient harmonics, or close to



Technical Brochure 568 (2014)
Transformer Energization in Power Systems:
A Study Guide, WG C4.307

TOVs due to a harmonic resonance

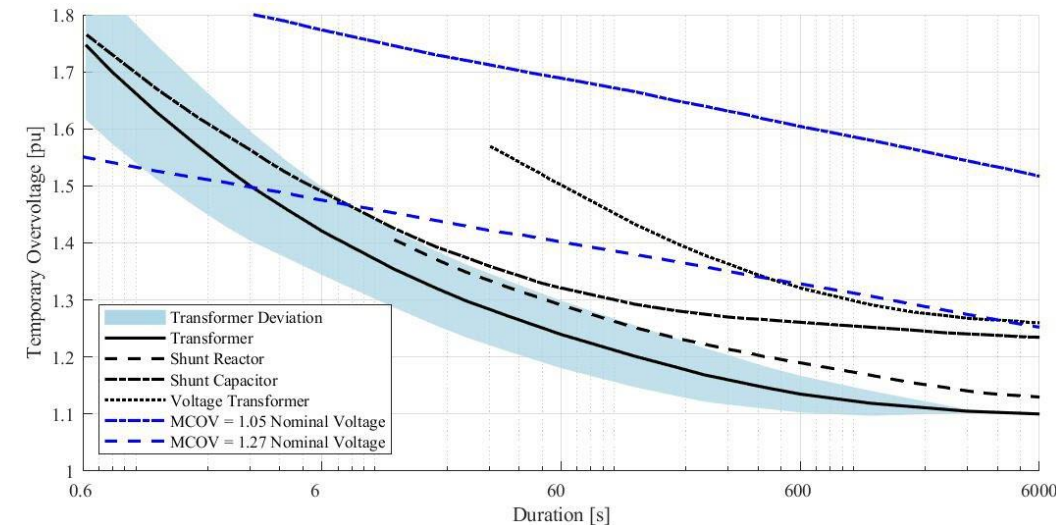


Why are these TOVs so special today?

- More likely to be a cause of concern today, because of:
 - ✓ **increasing undergrounding of transmission grids**
 - ✓ **large generation centers being connected using long radial links**
 - ✓ **reduction of network strength**
- These decrease the frequency of resonances that may end at or close to low harmonic frequencies, e.g., 2nd or 3rd
- In other words, today, the low order harmonic content “finds” resonances at a low frequency range, which may lead to a TOV

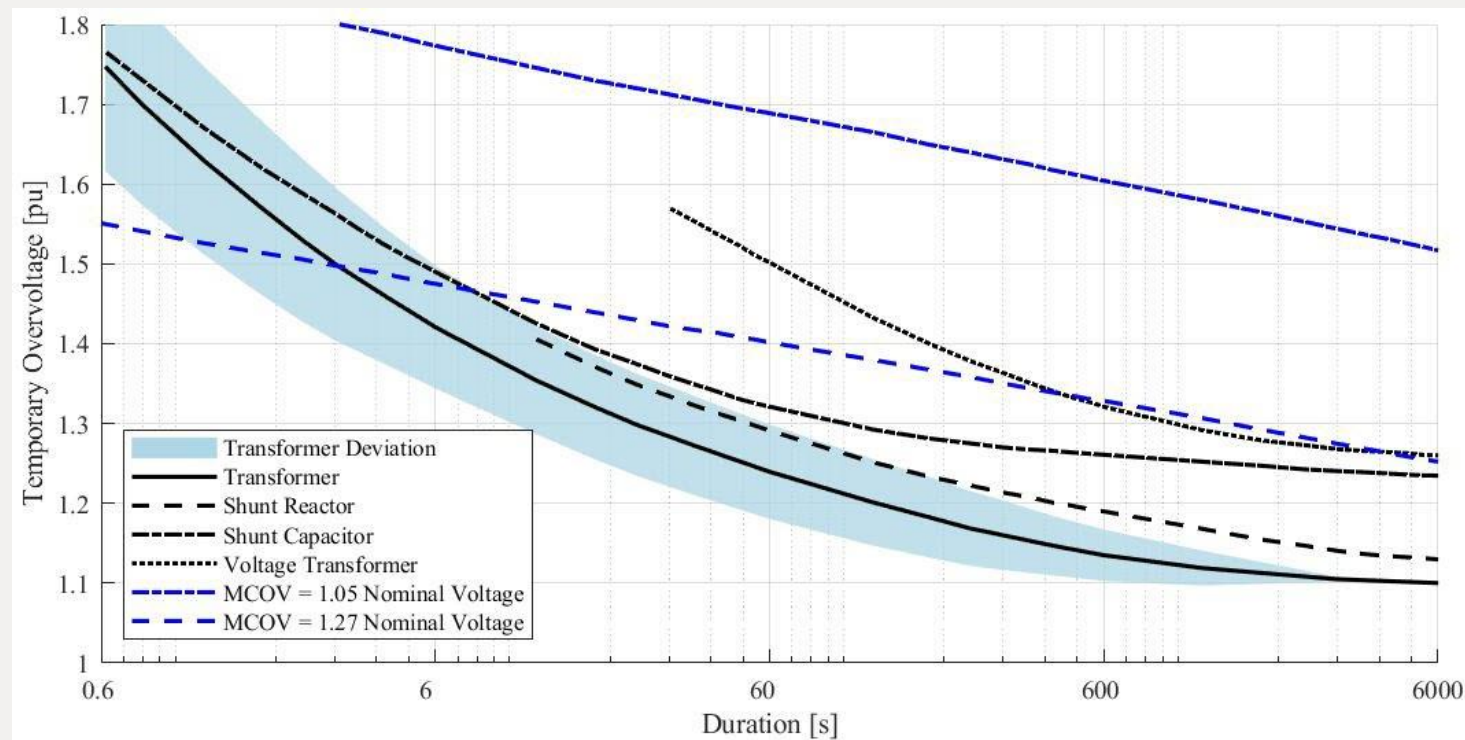
What is the problem exactly?

- Existing withstand limits are defined for power frequency
- Standards do not provide assessment guidelines if a high frequency component is present, and just motivate to avoid this type of conditions
- Question: What to do if the TOV has both a power frequency and a higher frequency component?
- Answer: That is what we hope to give in TB913



“Temporary Overvoltage Withstand Characteristics of Extra High Voltage Equipment”, Electra 179, August 1998, WG 33.10. (Figure redrawn by C4.46)

What is the problem exactly?



"Temporary Overvoltage Withstand Characteristics of Extra High Voltage Equipment", *Electra* 179, August 1998, WG 33.10. (Figure redrawn by C4.46)

Modelling Guidelines & Selection of Cases

$$f_{resonance} = f_n \cdot \sqrt{\frac{S_{sc}}{Q_{cap}}}$$

- Good enough approximation for radial networks, too simplified for meshed grids
- Resonance frequency depends on:
 - **System conditions**
 - **Total capacitance connected to the Pol**

Modelling Guidelines & Selected Cases

- Frequency scans form an initial screening process to identify and select relevant/onerous system conditions that require further investigation in the time domain
- Typically, a harmonic impedance analysis considers the following:
 - **System intact and contingency conditions**
 - **Operational scenarios and loading conditions**

 - **System strength → resonance frequency**
 - **System damping → impedance amplitude**

Modelling Guidelines & Selected Cases

Example case

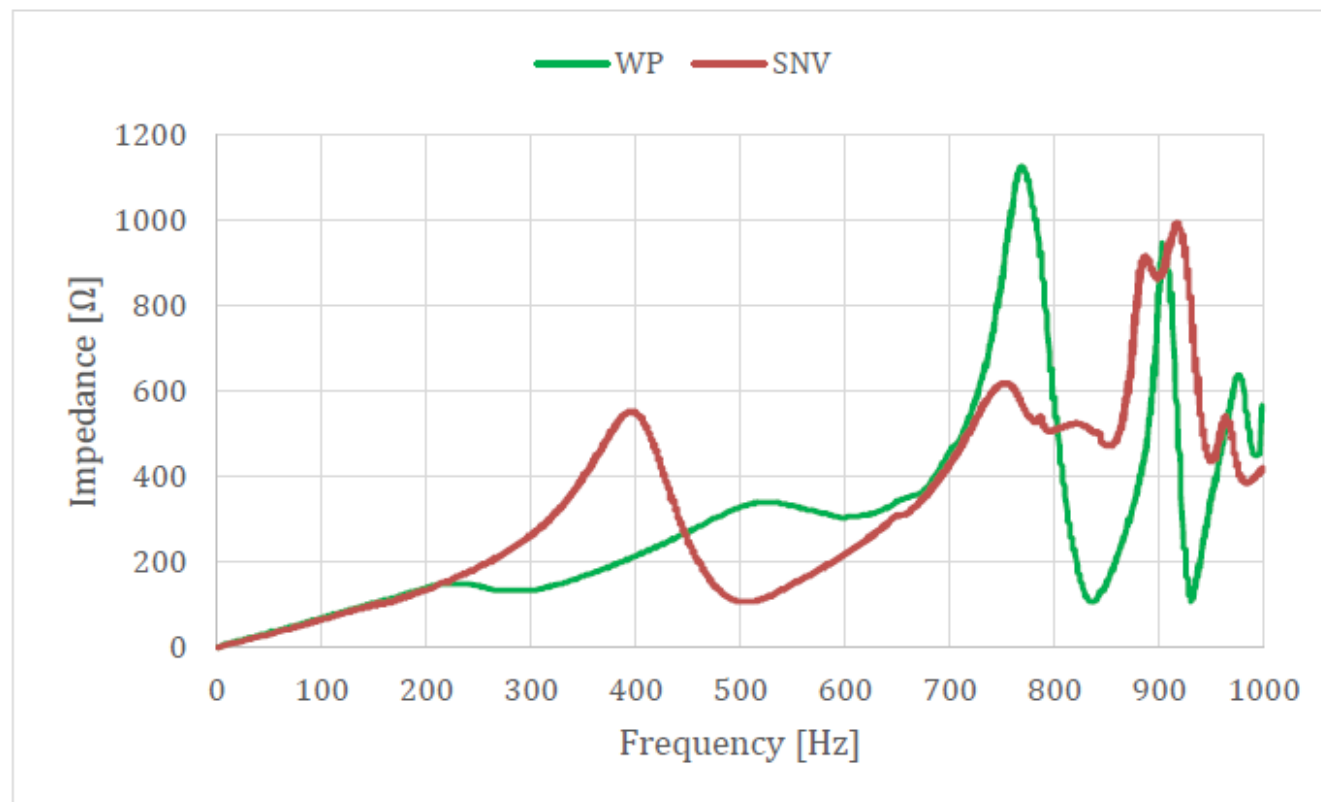


Figure 3-1 Harmonic impedance comparison for minimum (brown) and maximum (green) fault level

Modelling Guidelines & Selected Cases

- In general, harmonic impedance & EMT calculations are sensitive to system and component parameters
- Modelling aspects & assumptions are of great importance
 - Model extent
 - Load representation
 - Inverter-based generator representation
 - Available input data
 - ...

Modelling Guidelines & Selected Cases

- Several CIGRE modelling-related guidelines:
 - Harmonic analysis
 - Cables
 - Power transformer
 - Power electronics

Modelling Guidelines & Selected Cases

In a nutshell:

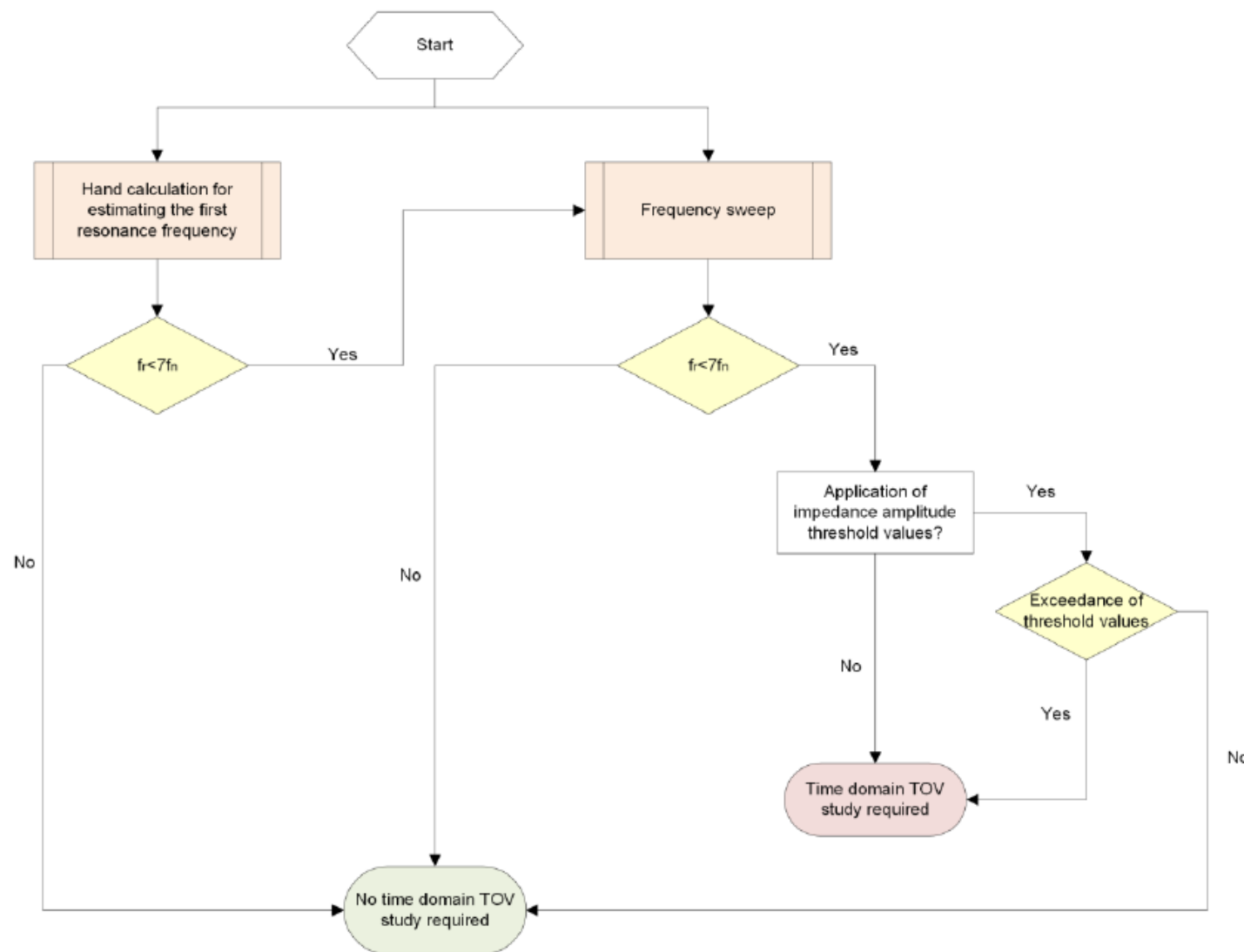


Figure 3-10 Methodology applied for harmonic resonance studies and TOVs

Assessment methods

The methods presented:

- Assessment of TOV at power frequency
- Moving window method – RMS
- Moving window method – peak
- Frequency-Based Assessment for Transformers
- “Gauge method”

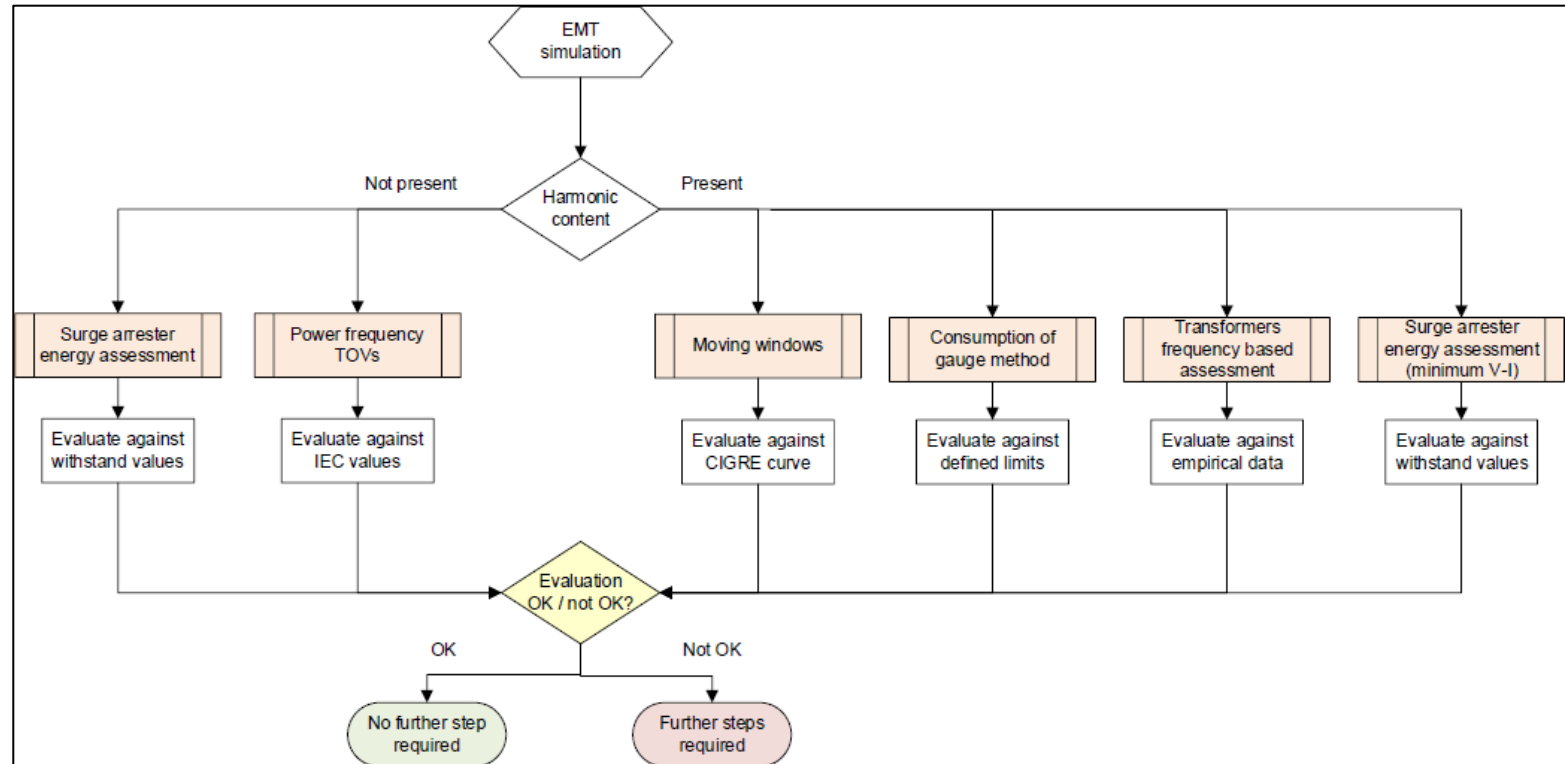
Assessment methods

Existing TOV withstand characteristics are defined for

- constant amplitude
- constant frequency

TB913 presents methods for assessing TOVs with

- varying amplitude
- harmonic content



Mitigation strategies

- The following strategies/methods are discussed in the TB:
 - ✓ **Operational constraints**
 - ✓ **Temporary detuning using disconnection of cables**
 - ✓ **Synchronized/Controlled/Point-on-wave switching**
 - ✓ **Pre-insertion resistors**
 - ✓ **C-type harmonic filters**
 - ✓ **Disconnection of transformers**
 - ✓ **(Sacrificial arresters)**
- A distinction should be made between methods applicable to transformer energization and fault clearing, respectively

Mitigating strategies - summary

Method	Applicability	Pros	Cons	Maturity
Operational constraints	Energization	Cost-effective	Adds complexity, risk for human error	Mature
Detuning by cable switching	Energization Fault clearing	No impact to system in normal operation, cost-effective	Limited to certain conditions (requires cables or other components that can be disconnected to shift the resonance), adds complexity (operational aspects)	Recently proposed, no operational experience
Controlled switching	Energization	Effective in mitigating inrush currents, proven technology, also reduces voltage dips, etc.	Expensive, adds complexity, requires suitable breakers (single-pole operation)	Mature
Pre-insertion resistor	Energization	Effective in mitigating inrush currents, proven technology, also reduces voltage dips, etc.	Requires a lot of maintenance, must consider environmental surroundings, requires special breakers (including resistor) or additional components – adds complexity and cost	Mature
Filter	Energization Fault clearing	Effective in mitigating resonance conditions	Costly, adds complexity, needs extensive design studies (lack of common practice), increase in system losses	Limited operational experience
Undervoltage protection/disconnection of transformer	Energization Fault clearing	Easy to implement	N/A to fault clearing depending on what is connected to the secondary side	Limited operational experience
(Sacrificial arresters)	Energization Fault clearing		Risk of repeated fault clearing	Mature (in other applications)

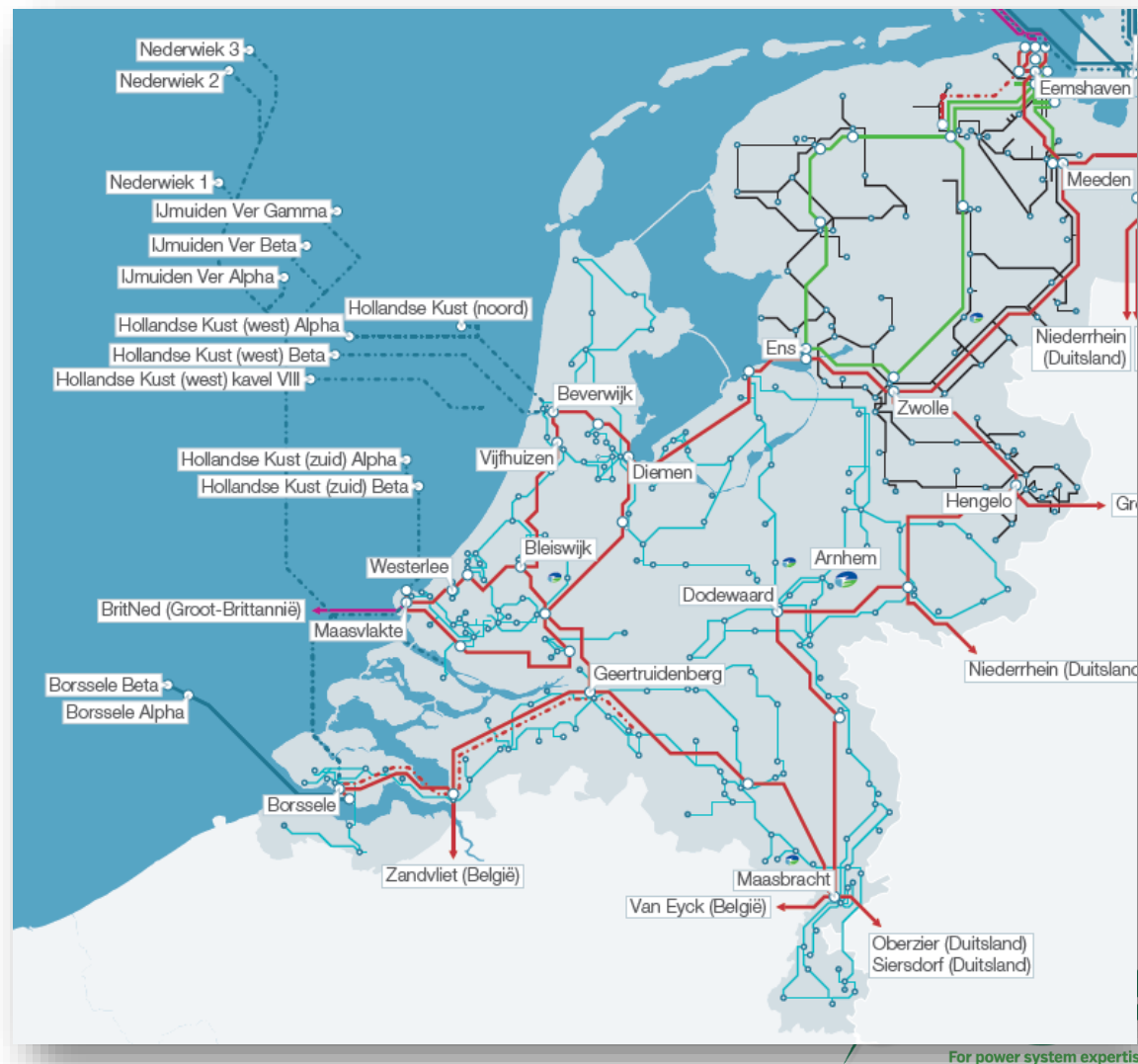
Failure Investigation Analysis

Shunt Reactor Switching by Means of Vacuum Circuit Breaker

IPST Paper 2023: 33 kV Cable Connector Failures due to Shunt Reactor Switching by Means of Vacuum Circuit Breaker– A Thorough Investigation & Mitigation Analysis

Background information

- TenneT NL Transmission Grid
- Offshore wind developments
 - ✓ 21 GW by 2030
 - ✓ 4.9 GW standard AC connections by 2026
 - ✓ From 2028 standard DC connections



For power system expertise

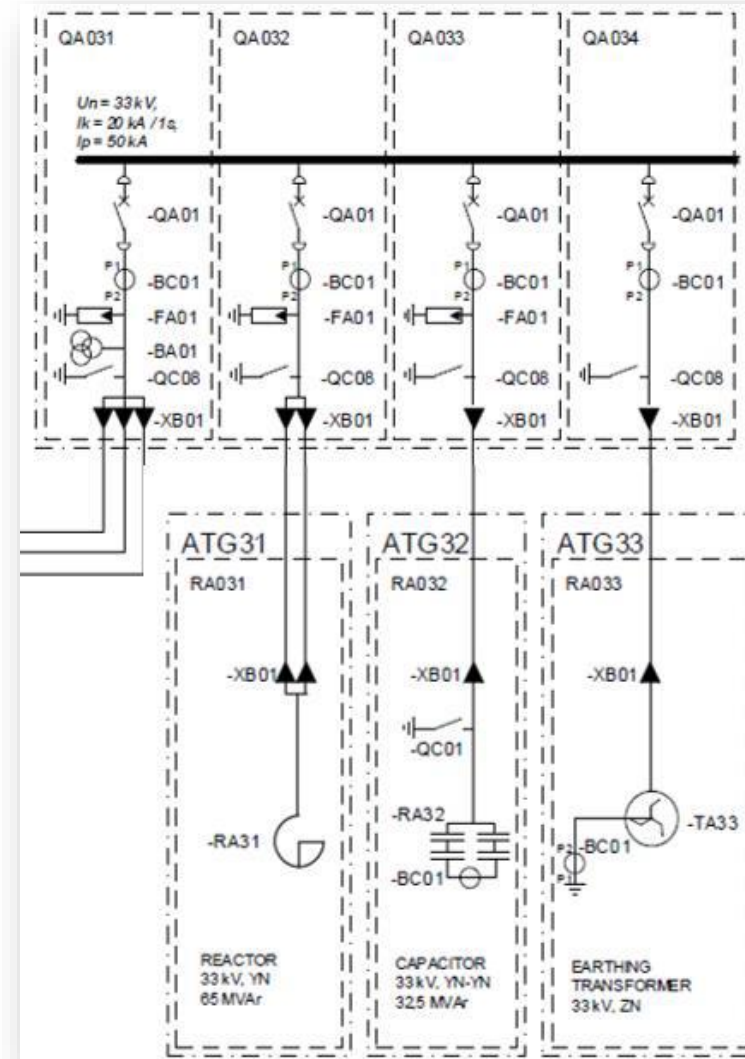
Background information

- 700 MW standard AC offshore connection



Background information

- 4x 33 kV tertiary installations
 - ✓ Provides reactive power compensation
 - ✓ Steps of 32.5 MVar
 - ✓ 65 MVar shunt reactor
 - ✓ 32.5 MVar capacitor bank

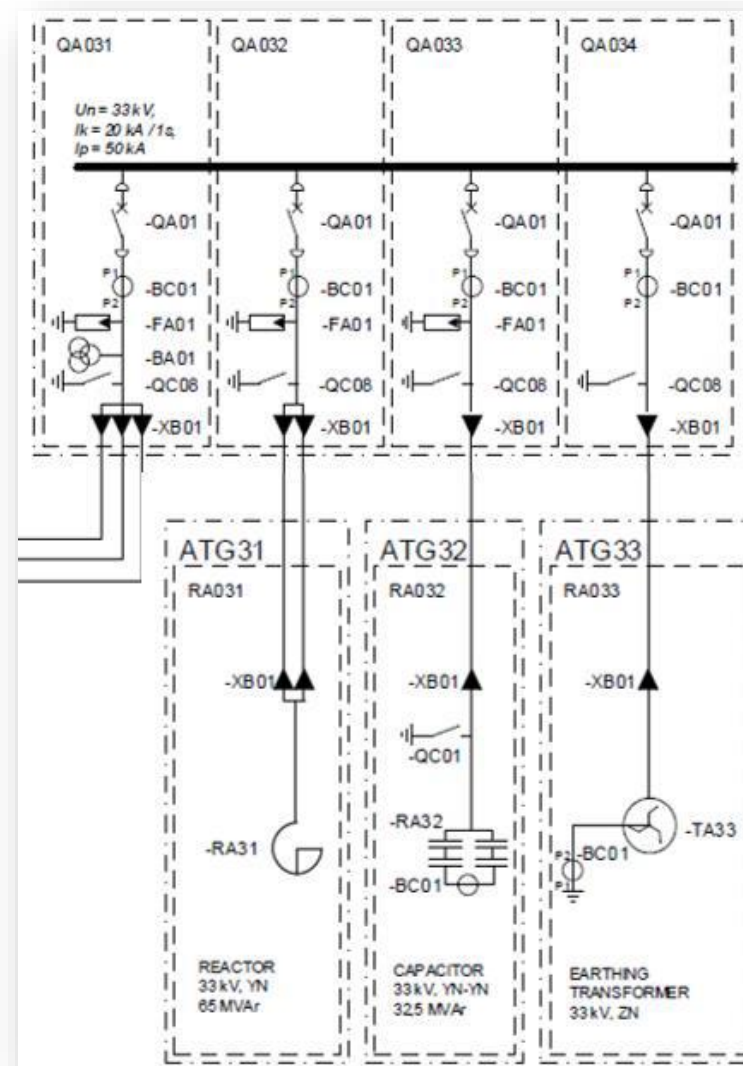


Background information

- 33 kV tertiary installation
- Short cable connections
- Vacuum circuit breakers

33 kV CABLES – MAIN INFORMATION

Connection	Cross Section [mm ²]	No. cables per section	Length [m]
Trfm – Swgr	800	3	60-80
Swgr – Rctr	630	2	40-45
Swgr – Cptr	630	1	50
Swgr – Earth. Trfm	240	1	30



Background information

- 33 kV tertiary installation
- Short cable connections
- Vacuum circuit breakers



Background information

- 33 kV tertiary installation
- MVAR controller concept

Generated power [pu]	Shunt reactor status	Capacitor bank status
[0...0.35]	<i>IN</i>	<i>OUT</i>
[0.35...0.52]	<i>IN</i>	<i>IN</i>
[0.52...0.8]	<i>OUT</i>	<i>OUT</i>
[0.8...1.0]	<i>OUT</i>	<i>IN</i>

SHUNT REACTOR & CAPACITOR BANK SWITCHING ACTIONS

Generated power [pu]	Shunt reactor status	Capacitor bank status
0.35 → 0.36	<i>Remains energized</i>	<i>To be energized</i>
0.52 → 0.53	<i>To be de-energized</i>	<i>To be de-energized</i>
0.8 → 0.81	<i>Remains de-energized</i>	<i>To be energized</i>
0.81 → 0.8	<i>Remains de-energized</i>	<i>To be de-energized</i>
0.53 → 0.52	<i>To be energized</i>	<i>To be energized</i>
0.36 → 0.35	<i>Remains energized</i>	<i>To be de-energized</i>

Failure investigation

- In total, 24 cable connectors in operation (transformer & shunt reactor)
- 5 failed units since February 2020
 - ✓ **All at the shunt reactor side**
 - ✓ **At three out of the four 33 kV installations**
 - ✓ **At different phases**
 - ✓ **Initial investigations**
- Electric activity marks indicating the presence of high electric fields
- Shunt reactor overcurrent protection triggered after a reactor was energized



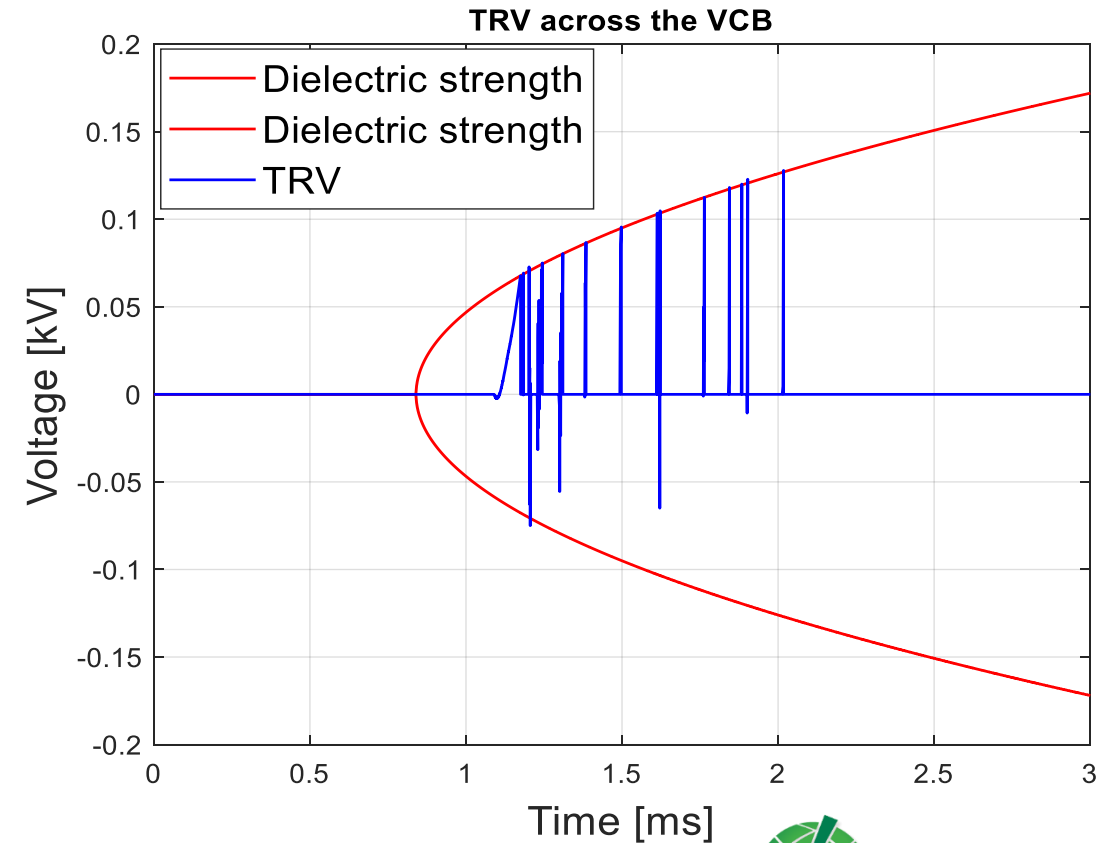
Failure investigation

- In total, 24 cable connectors in operation (transformer & shunt reactor)
- 5 failed units since February 2020
 - ✓ All at the shunt reactor side
 - ✓ At three out of the four 33 kV installations
 - ✓ At different phases
 - ✓ Initial investigations
- Initial hypothesis
 - ✓ Dielectric failures could be the result of overvoltages due to the switching actions in the 33 kV installation



Failure investigation – EMT Analysis

- EMT analysis – VCB re-ignitions due to shunt reactor switching
 - ✓ **Detailed model of the VCB**
 - Dielectric withstand characteristic of the gap under contact separation
 - Quenching capability
 - Arcing time
 - VCB logic developed in MODELS in ATP



Failure investigation – EMT Analysis

- EMT analysis – VCB re-ignitions due to shunt reactor switching

RE-IGNITIONS & OVERVOLTAGES DUE TO SHUNT REACTOR SWITCHING

Component under de-energization	No. re-ignitions	dV/dt [kV/ μ s]	Ph-Gr [kV _{peak}]
Shunt reactor	28	102	40.9
Shunt Reactor & Capacitor bank	32	177	60.0

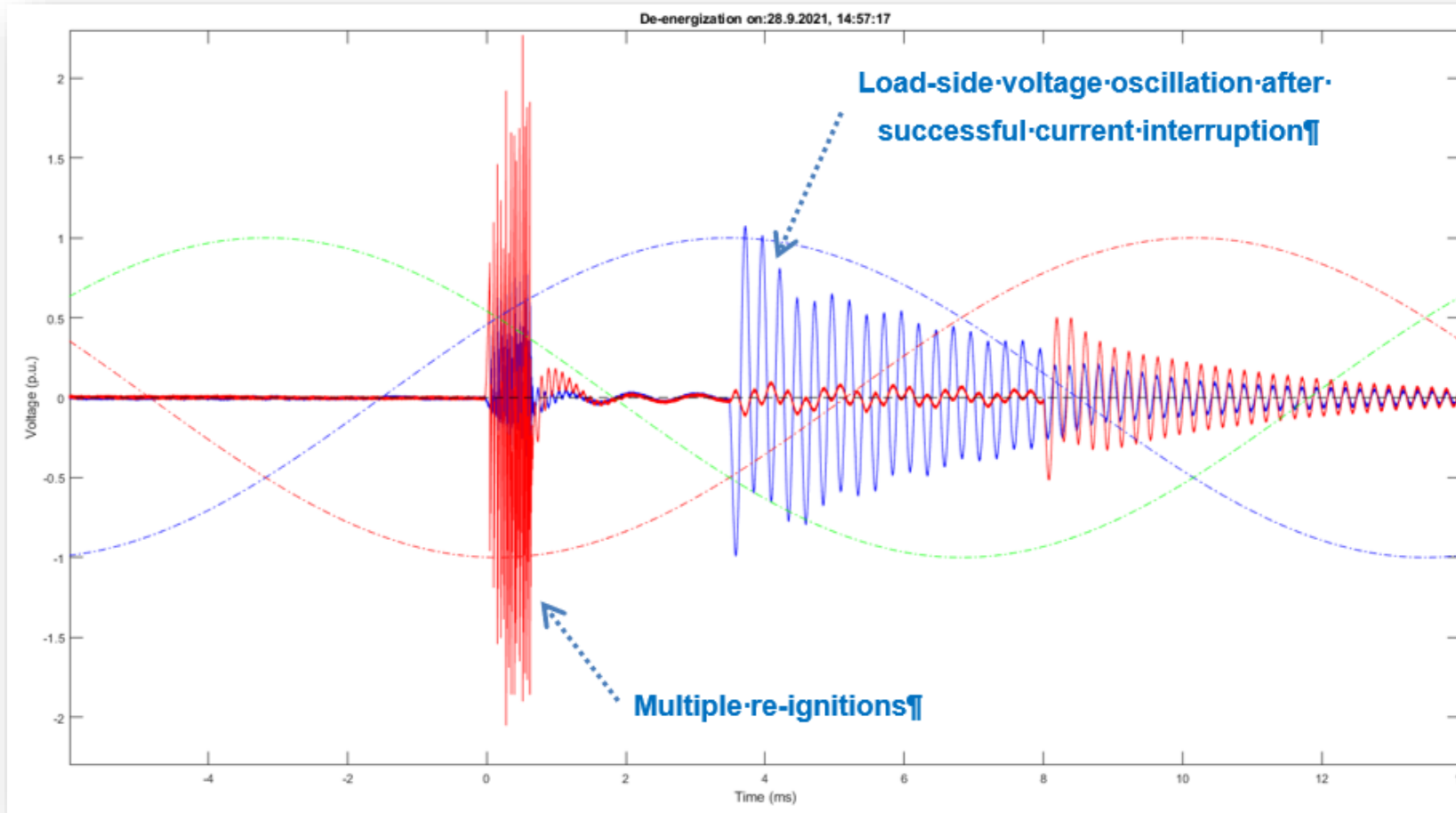
Failure investigation – Field Measurements

- Transient measurements
 - ✓ 3-week period, capture the switching actions of the MVar controller
 - ✓ Multiple re-ignitions during the de-energization of the shunt reactor

RE-IGNITIONS & OVERVOLTAGES DUE TO SHUNT REACTOR SWITCHING

No. measurement	No. re-ignitions	Ph-Gr [pu]
1	0	1.0
2	21	1.8
3	0	1.0
4	13	2.2
5	0	1.0
6	21	1.9
7	0	1.0
8	15	3.1
9	0	1.0
10	15	Unknown ⁽¹⁾

Failure investigation – Field Measurements



Mitigation Analysis

- Common practice RC surge suppressor
 - ✓ Parametric EMT analysis
 - ✓ Evaluate the effectiveness of an RC circuit
 - ✓ Define standard R, C values
 - ✓ Define preferred location

Various RC topologies

No. configuration	Simplified single line diagram
A0 (reference case)	
A1 RC circuit connected to the sending end of the load-side cables	
A2 RC circuit connected to the receiving end of the load-side cables	

Outage Investigation Analysis

Unidentified & bird related outages on a 110kV overhead transmission line

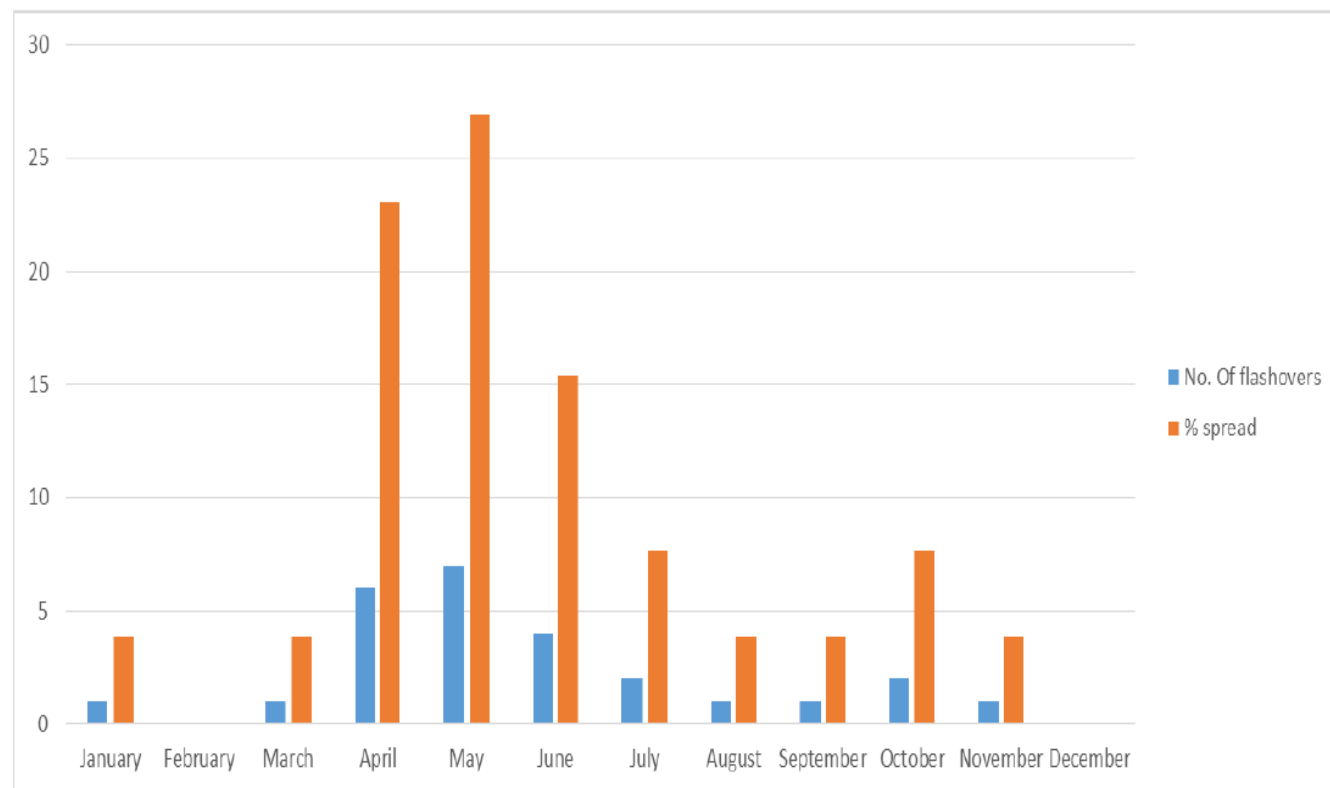
Background information

- Few 110kV overhead lines suffer from single-phase “unidentified” outages
- Power quality issues due to the resulting voltage dips in the system



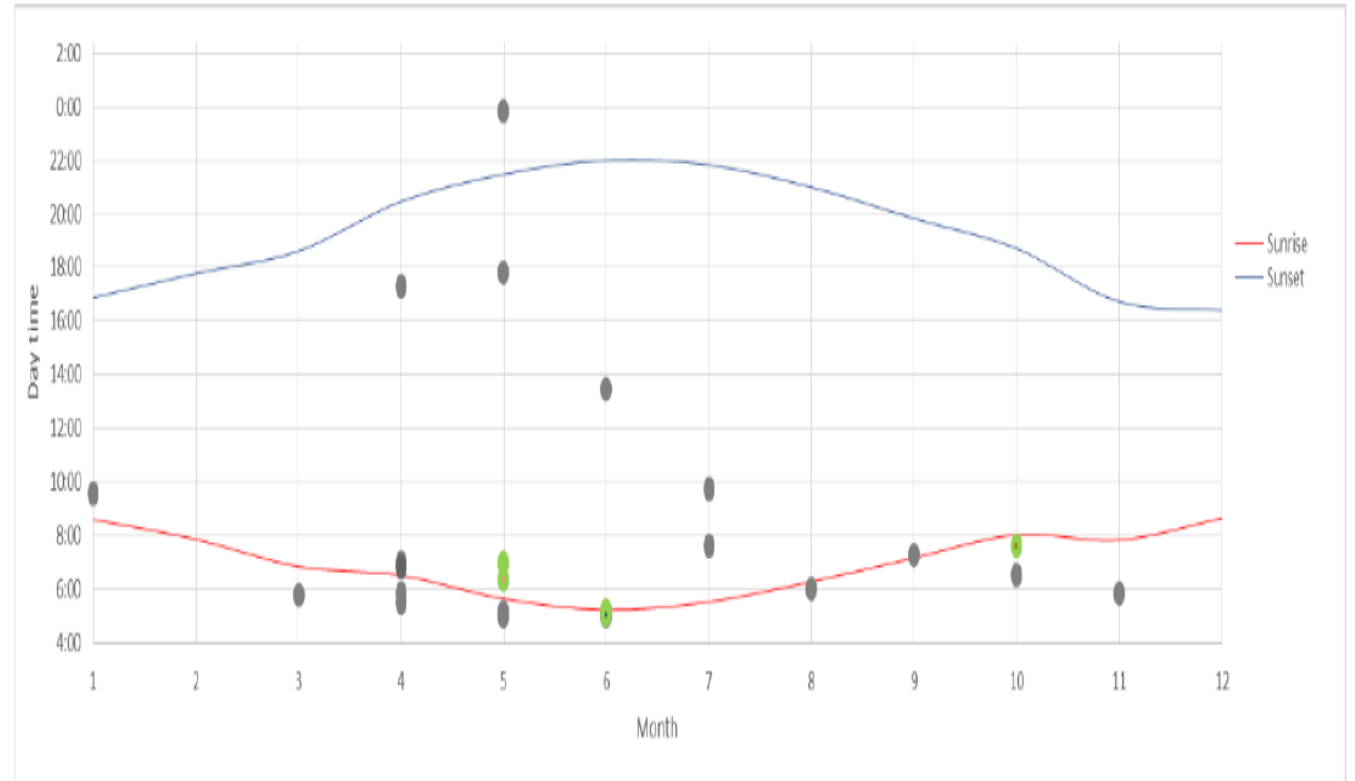
Background information

- Analysis of the outages with respect to the month of occurrence



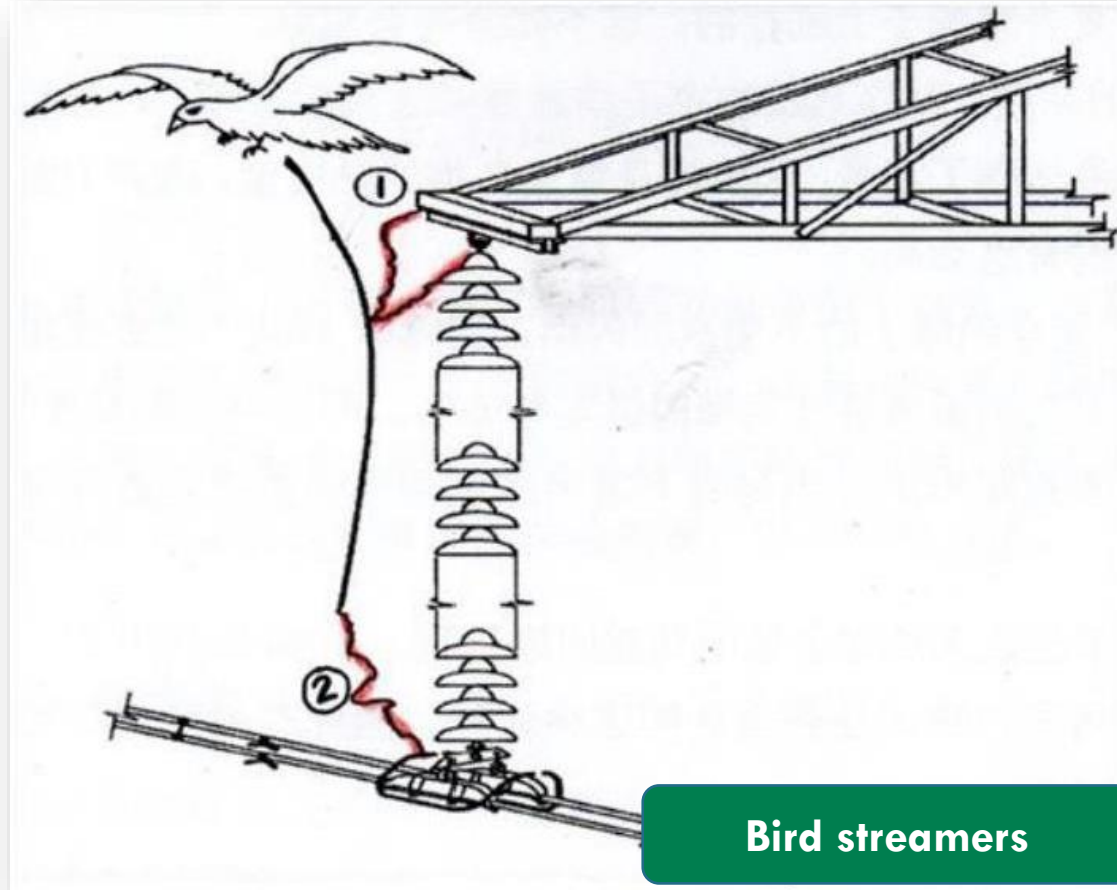
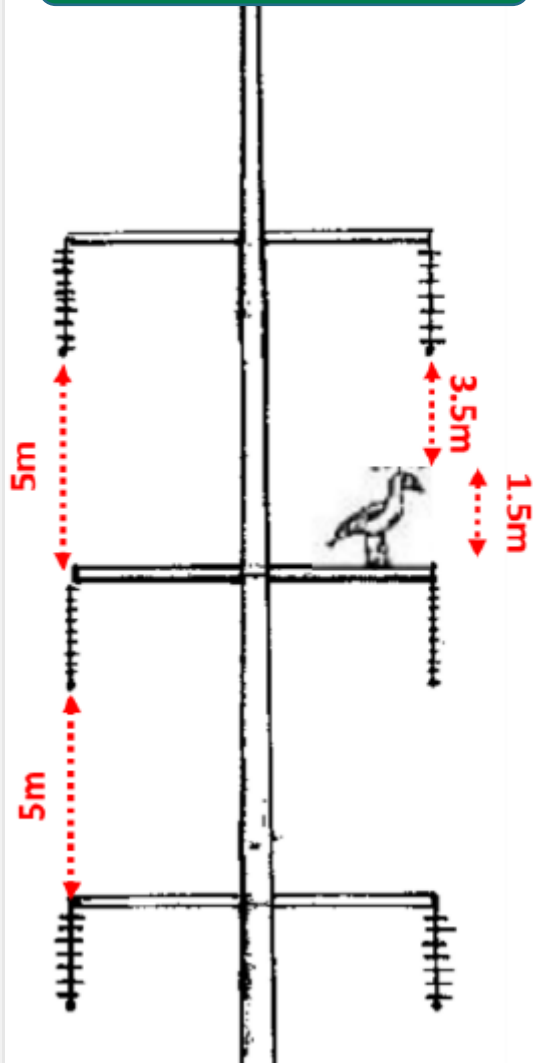
Background information

- Analysis of the outages with respect to the time in a day



Bird-related flashovers on a transmission line

Electrocution



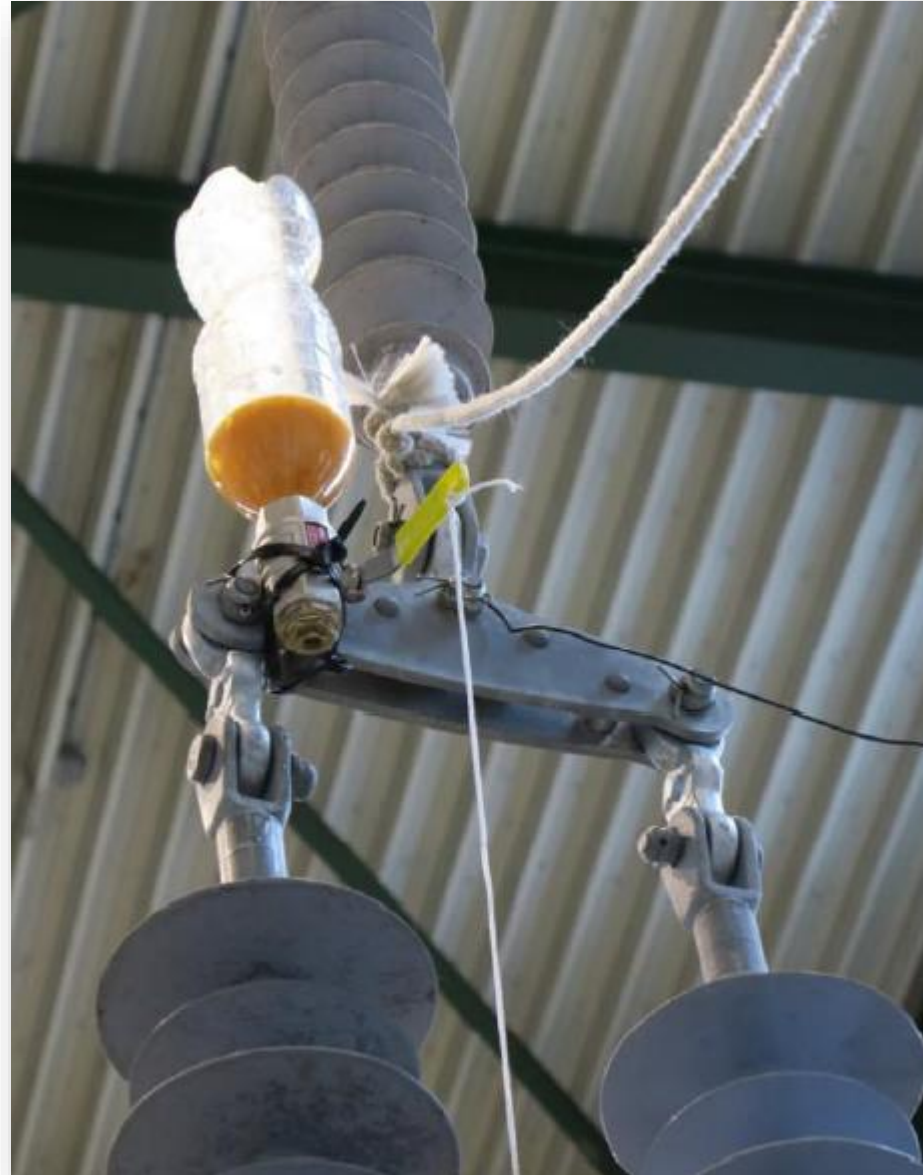
Bird-related flashovers on a transmission line

- Field line inspection
 - ✓ Hints that could indicate bird-related behavior (e.g., polluted insulators, streamers on the tower, etc.)
 - ✓ Identification of bird species in the vicinity of the line
 - ✓ Archive on bird populations in the area of interest

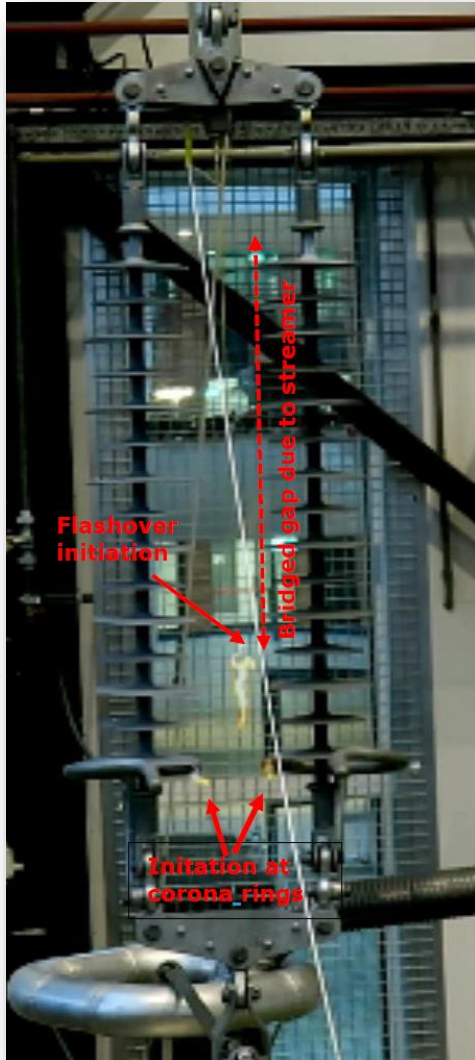


High Voltage Lab Testing

- AC voltage test (Ph-Gr)



High Voltage Lab Testing



Thank you for your attention

Questions?