Paris Session
2022

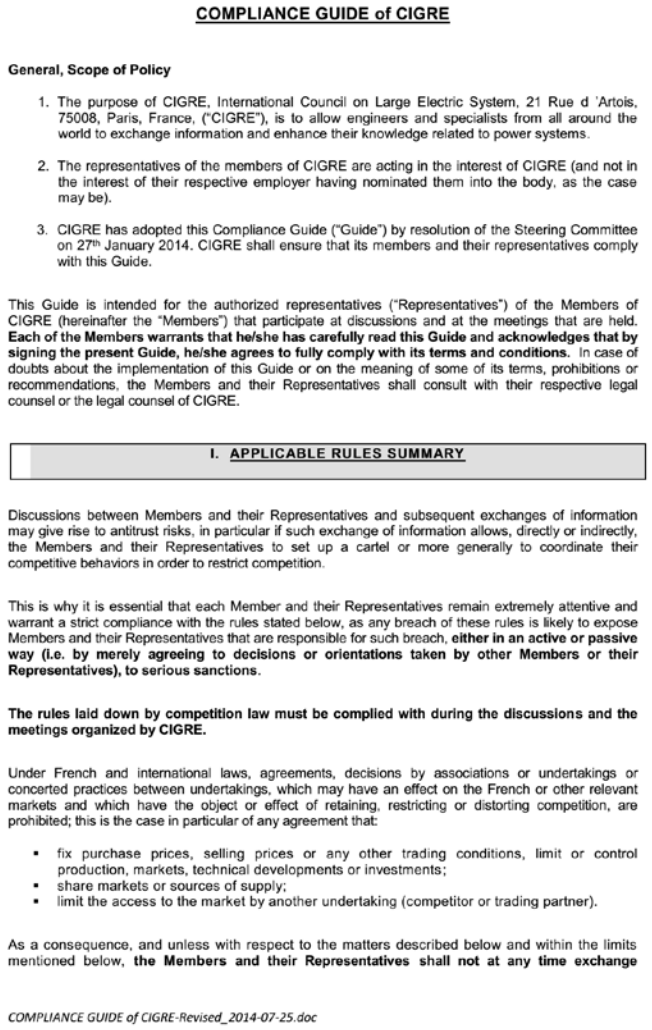
# Study Committee C4 Tutorial
# System Technical Performance
# Evaluation of Temporary Overvoltages in Power Systems due to Low Order Harmonic Resonances

31 August 2022

**Zia Emin – SC Chair**

# CIGRE Antitrust Guidelines

https://www.cigre.org/GB/about/cigre-compliance-regulations



## COMPLIANCE GUIDE of CIGRE

**General, Scope of Policy**

1. The purpose of CIGRE, International Council on Large Electric System, 21 Rue d 'Artois, 75008, Paris, France, ("CIGRE"), is to allow engineers and specialists from all around the world to exchange information and enhance their knowledge related to power systems.

2. The representatives of the members of CIGRE are acting in the interest of CIGRE (and not in the interest of their respective employer having nominated them into the body, as the case may be).

3. CIGRE has adopted this Compliance Guide ("Guide") by resolution of the Steering Committee on 27th January 2014. CIGRE shall ensure that its members and their representatives comply with this Guide.

This Guide is intended for the authorized representatives ("Representatives") of the Members of CIGRE (hereinafter the "Members") that participate at discussions and at the meetings that are held. **Each of the Members warrants that he/she has carefully read this Guide and acknowledges that by signing the present Guide, he/she agrees to fully comply with its terms and conditions.** In case of doubts about the implementation of this Guide or on the meaning of some of its terms, prohibitions or recommendations, the Members and their Representatives shall consult with their respective legal counsel or the legal counsel of CIGRE.

### I. APPLICABLE RULES SUMMARY

Discussions between Members and their Representatives and subsequent exchanges of information may give rise to antitrust risks, in particular if such exchange of information allows, directly or indirectly, the Members and their Representatives to set up a cartel or more generally to coordinate their competitive behaviors in order to restrict competition.

This is why it is essential that each Member and their Representatives remain extremely attentive and warrant a strict compliance with the rules stated below, as any breach of these rules is likely to expose Members and their Representatives that are responsible for such breach, **either in an active or passive way (i.e. by merely agreeing to decisions or orientations taken by other Members or their Representatives), to serious sanctions.**

**The rules laid down by competition law must be complied with during the discussions and the meetings organized by CIGRE.**

Under French and international laws, agreements, decisions by associations or undertakings or concerted practices between undertakings, which may have an effect on the French or other relevant markets and which have the object or effect of retaining, restricting or distorting competition, are prohibited; this is the case in particular of any agreement that:

- fix purchase prices, selling prices or any other trading conditions, limit or control production, markets, technical developments or investments;
- share markets or sources of supply;
- limit the access to the market by another undertaking (competitor or trading partner).

As a consequence, and unless with respect to the matters described below and within the limits mentioned below, **the Members and their Representatives shall not at any time exchange**

*COMPLIANCE GUIDE of CIGRE-Revised_2014-07-25.doc*

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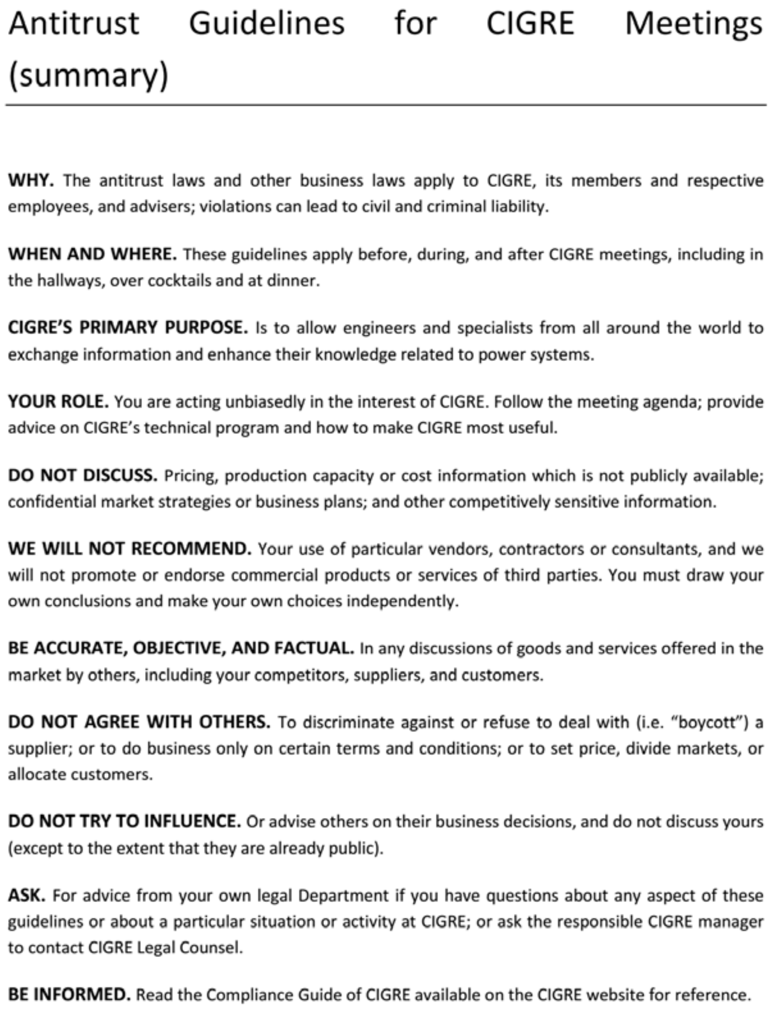

## Antitrust Guidelines for CIGRE Meetings (summary)

**WHY.** The antitrust laws and other business laws apply to CIGRE, its members and respective employees, and advisers; violations can lead to civil and criminal liability.

**WHEN AND WHERE.** These guidelines apply before, during, and after CIGRE meetings, including in the hallways, over cocktails and at dinner.

**CIGRE'S PRIMARY PURPOSE.** Is to allow engineers and specialists from all around the world to exchange information and enhance their knowledge related to power systems.

**YOUR ROLE.** You are acting unbiasedly in the interest of CIGRE. Follow the meeting agenda; provide advice on CIGRE's technical program and how to make CIGRE most useful.

**DO NOT DISCUSS.** Pricing, production capacity or cost information which is not publicly available; confidential market strategies or business plans; and other competitively sensitive information.

**WE WILL NOT RECOMMEND.** Your use of particular vendors, contractors or consultants, and we will not promote or endorse commercial products or services of third parties. You must draw your own conclusions and make your own choices independently.

**BE ACCURATE, OBJECTIVE, AND FACTUAL.** In any discussions of goods and services offered in the market by others, including your competitors, suppliers, and customers.

**DO NOT AGREE WITH OTHERS.** To discriminate against or refuse to deal with (i.e. "boycott") a supplier; or to do business only on certain terms and conditions; or to set price, divide markets, or allocate customers.

**DO NOT TRY TO INFLUENCE.** Or advise others on their business decisions, and do not discuss yours (except to the extent that they are already public).

**ASK.** For advice from your own legal Department if you have questions about any aspect of these guidelines or about a particular situation or activity at CIGRE; or ask the responsible CIGRE manager to contact CIGRE Legal Counsel.

**BE INFORMED.** Read the Compliance Guide of CIGRE available on the CIGRE website for reference.

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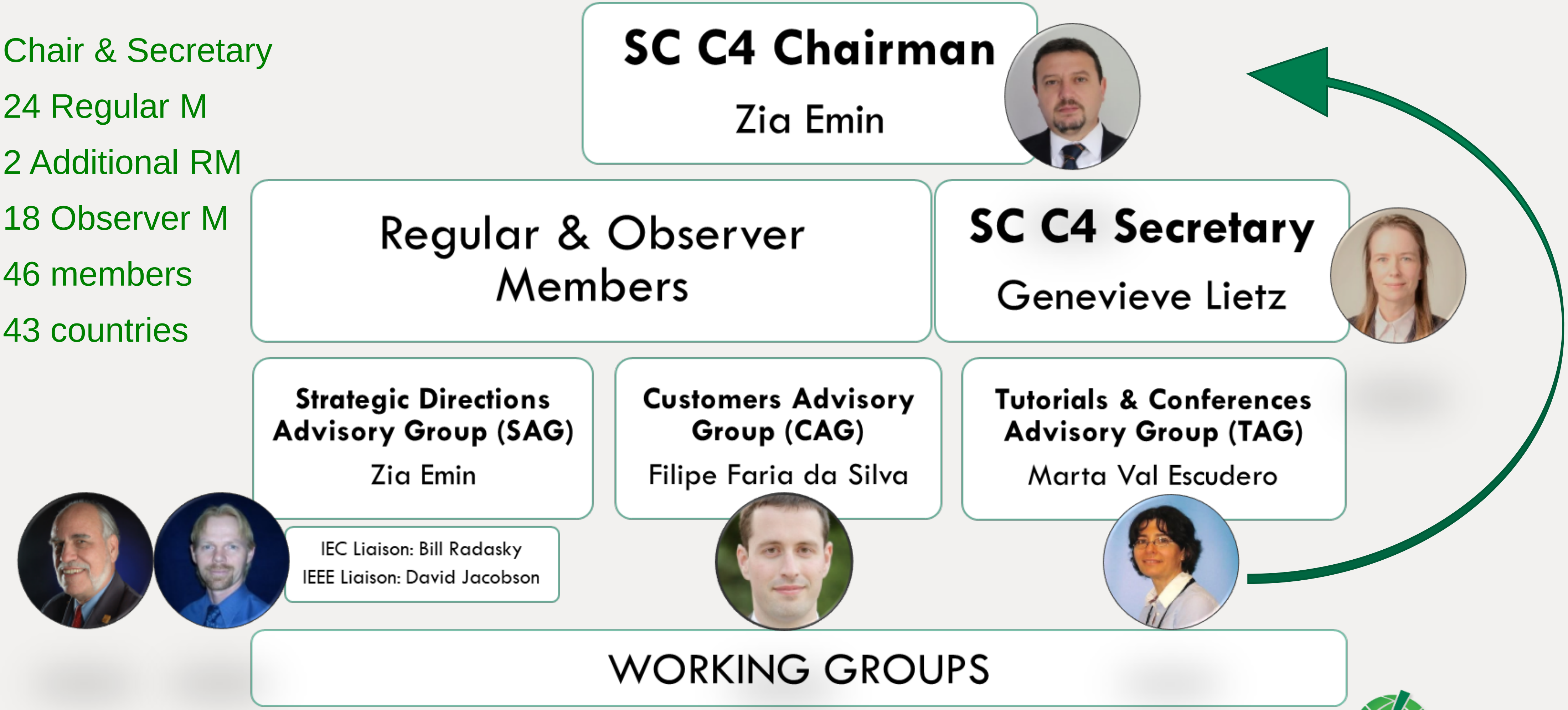
# SC C4 SCOPE

SC C4 deals with methods and tools for analysis related to the technical performance of power systems, with particular reference to dynamic and transient conditions and to the interaction between the power system and its apparatus/sub-systems. We cover system technical performance phenomena that range from nanoseconds to many hours, in the following fields:

- **Power Quality**
- **Electromagnetic Compatibility (EMC)**
- **Insulation Co-ordination**
- **Lightning**
- **Power System Dynamics and Numerical Analysis**

# SC C4 STRUCTURE

- Chair & Secretary
- 24 Regular M
- 2 Additional RM
- 18 Observer M
- 46 members
- 43 countries



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Zia Emin

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**SC C4 Secretary**

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WORKING GROUPS

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# SC C4 ACTIVE WORKING GROUPS

| WG # | WG TITLE | CONVENER |
|---|---|---|
| WG C4.36 | Winter Lightning – Parameters and Engineering Consequences for Wind Turbines | M. Ishii (Japan) |
| JWG C4.40/CIRED | Revisions to IEC Technical Reports 61000-3-6, 61000-3-7, 61000-3-13, and 61000-3-14 | M. Halpin (USA) |
| JWG C4.42/CIRED | Continuous assessment of low-order harmonic emissions from customer installations | I. Papič (Slovenia) |
| WG C4.43 | Lightning problems and lightning risk management for nuclear power plants | T. Shindo (Japan) |
| WG C4.44 | EMC for Large Photovoltaic Systems | E. Salinas (Sweden) |
| WG C4.46 | Evaluation of Temporary Overvoltages in Power Systems due to Low Order Harmonic Resonances | F. F. da Silva (Denmark) |
| WG C4.47 | Power System Resilience (PSR WG) | M. Panteli (Cyprus) |
| WG C4.49 | Multi-frequency stability of converter-based modern power systems | Ł. Kocewiak (Denmark) |
| WG C4.50 | Evaluation of Transient Performance of Grounding Systems in Substations and Its Impact on Primary and Secondary Systems | B. Zhang (China) |
| WG C4.51 | Connection of Railway Traction Systems to Power Networks | D. Vujatovic (UK) |
| JWG C4/B4.52 | Guidelines for Sub-synchronous Oscillation Studies in Power Electronics Dominated Power Systems | C. Karawita (Canada) |
| JWG C4/A3.53 | Application Effects of Low-Residual-Voltage Surge Arresters in Suppressing Overvoltages in UHV AC Systems | J. He (China) |
| WG C4.54 | Protection of high voltage power network control electronics from the High-altitude Electromagnetic Pulse (HEMP) | W.A. Radasky (USA) |
| WG C4.55 | EMC related very-fast transients in gas-insulated substations - EMC interferences, measured characteristics, modelling and simulations | A. Ametani (Japan) |
| WG C4.56 | Electromagnetic transient simulation models for large-scale system impact studies in power systems having a high penetration of inverter connected generation | B. Badrzadeh (Australia) |
| WG C4.57 | Guidelines for the Estimation of Overhead Distribution Line Lightning Performance and its Application to Lightning Protection Design Scope | K. Michishita (Japan) |
| JWG C4/C2.58/IEEE | Evaluation of Voltage Stability Assessment Methodologies in Transmission Systems | U. Annakkage (Canada) |
| JWG C4/C2.62/IEEE | Review of Advancements in Synchrophasor Measurement Applications | A. Rajapakse (Canada) |
| WG C4.59 | Real-time Lightning Protection of the Electricity Supply Systems of the Future | C. Tong (China) |
| WG C4.60 | Generic EMT-Type Modelling of Inverter-Based Resources for Long Term Planning Studies | A. Haddadi (USA) |
| WG C4.61 | Lightning transient sensing, monitoring and application in electric power systems | J. He (China) |
| WG C4.63 | Harmonic power quality standards and compliance verification – a comparative assessment and practical guide | N. Shore (UK) |
| WG C4.64 | Application of Real-Time Digital Simulation in Power Systems | C. Fang (Canada) |
| WG C4.65 | Specification, Validation and Application of Harmonic Models of Inverter Based Resources | J. David (Australia) |
| WG C4.66 | New concept for analysis of multiphase back-flashover phenomena of overhead transmission lines due to lightning | M. Miki (Japan) |
| WG C4.67 | Lightning Protection of Hybrid Overhead Lines | A. Piantini (Brazil) |
| WG C4.68 | Electromagnetic Compatibility (EMC) issues in modern and future power systems | P. Munhoz-Rojas (Brazil) |
| WG C4.69 | Quantifying the lightning response of tower-footing electrodes of overhead transmission lines: methods of measurement | S. Visacro (Brazil) |
| WG C4.70 | Application of space-based lightning detection in power systems | J. Montanyà (Spain) |
| WG C4.71 | Small signal stability analysis in inverter based resource dominated power system | S. Goyal (Australia) |
| JWG C4/B4.72 | Lightning and switching induced electromagnetic compatibility (EMC) issues in DC power systems and new emerging power electronics-based DC equipment | Q. Li (China) |
| JWG A2/C4.52 | High-frequency transformer and reactor models for network studies | B. Gustavsen (Norway) |
| JWG A1/C4.52 | Wind generators and frequency-active power control of power systems | N. Miller (USA) |
| JWG A1/C4.66 | Guide on the Assessment, Specification and Design of Synchronous Condensers for Power Systems with Predominance of Low or Zero Inertia Generators | D. K. Chaturvedi (India) |
| JWG B1/C4.69 | Recommendations for the insulation coordination on AC cable systems | T. du Plessis (South Africa) |
| JWG B4/B1/C4.73 | Surge and extended overvoltage testing of HVDC Cable Systems | M. Saltzer (Sweden) |
| JWG B4/C4.93 | Development of Grid Forming Converters for Secure and Reliable Operation of Future Electricity Systems | D. Kong (UK) |
| JWG B5/C4.61 | Impact of Low Inertia Network on Protection and Control | R. Zhang (UK) |
| JWG C1/C4.36 | Review of Large City & Metropolitan Area power system development trends taking into account new generation, grid and information technologies. | V. Jesus (Brazil)/S. Utts (Russia) |
| JWG B2/C4.76 | Lightning & Grounding Considerations for Overhead Line Rebuilding and Refurbishing Projects, AC and DC | William A. Chisholm (Canada) |
| JWG C1/C4.46 | Optimising power system resilience in future grid design | Christian Schaefer (Australia) |
| JWG B5/C4.79 | Protection Roadmap for Low Inertia and Low Fault Current Networks | Mukesh Nagpal (Canada) |

**42 JWG/WGs**

- **6 on PQ**
- **5 on EMC**
- **5 on IC**
- **10 on L**
- **16 on PSD**

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# Evaluation of Temporary Overvoltages in Power Systems due to Low Order Harmonic Resonances WG C4.46

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# INTERACTIVITY

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

WG C4.46 / PREPARED by
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Julien Michel

# Members of the WG C4.46

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# Agenda

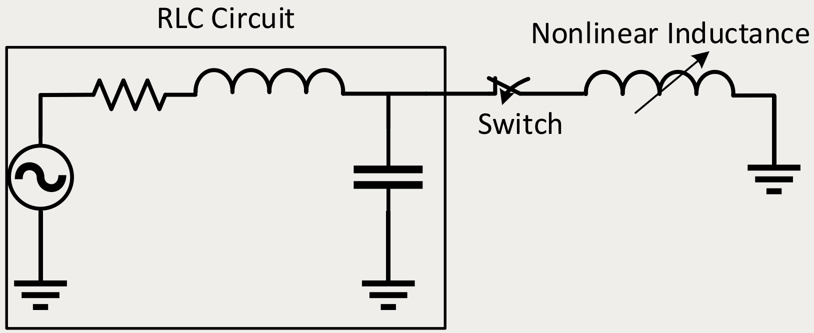
- Introduction and Motivation
- Harmonic TOV stresses in selected equipment
- Modelling Guidelines and Selected Cases
- Assessment Methods
- Comparison of Assessment Methods
- Mitigation Strategies
- Summary and Recommendations

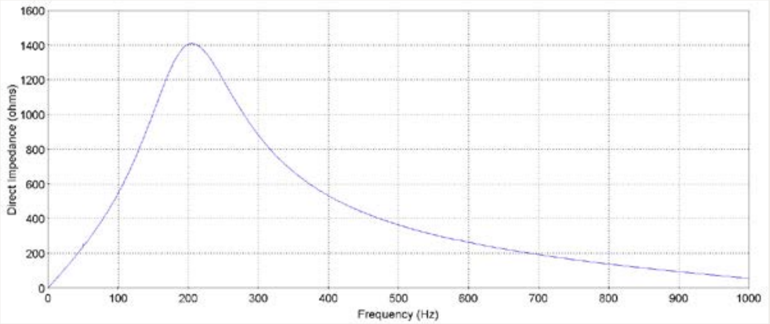
# Introduction and Motivation

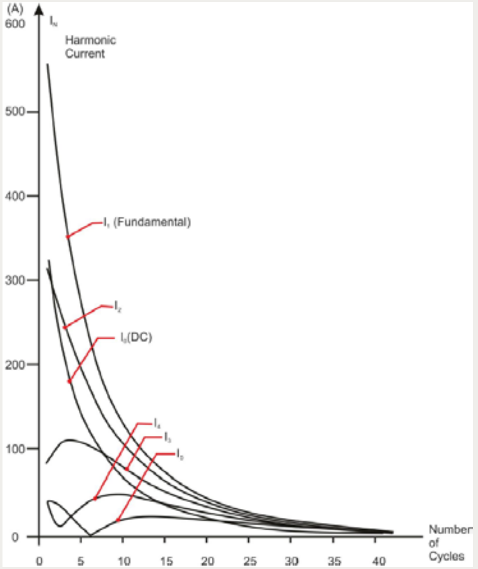
- Temporary Overvoltage (TOV) is a typical phenomenon accounted for in insulation coordination studies
- Defined by IEC as a "*power frequency overvoltage of relatively long duration*"
- The standard testing waveform follows this definition by consisting in a "*short-duration power frequency test*"
- 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







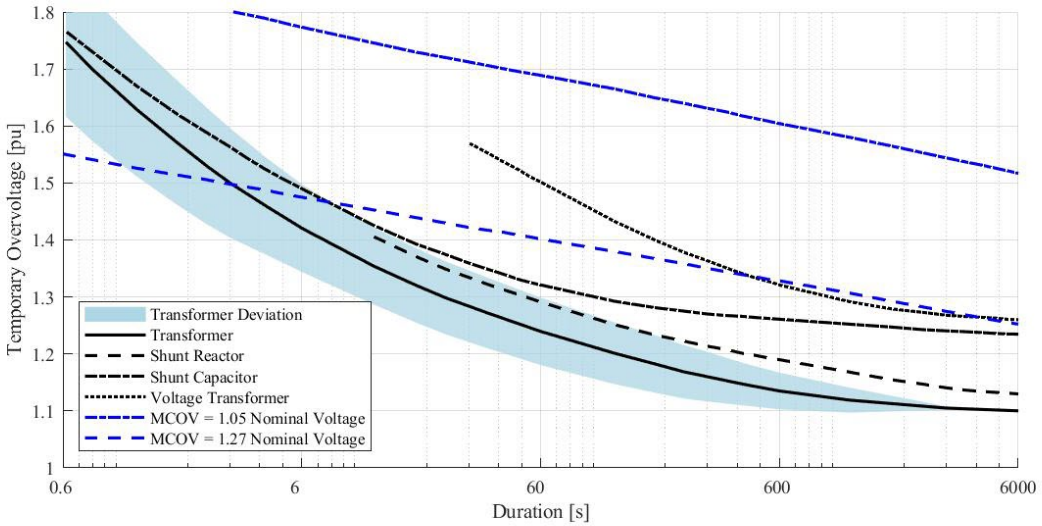
*Technical Brochure 568 (2014) Transformer Energization in Power Systems: A Study Guide, WG C4.307*

# 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 centres 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 WG C4.46



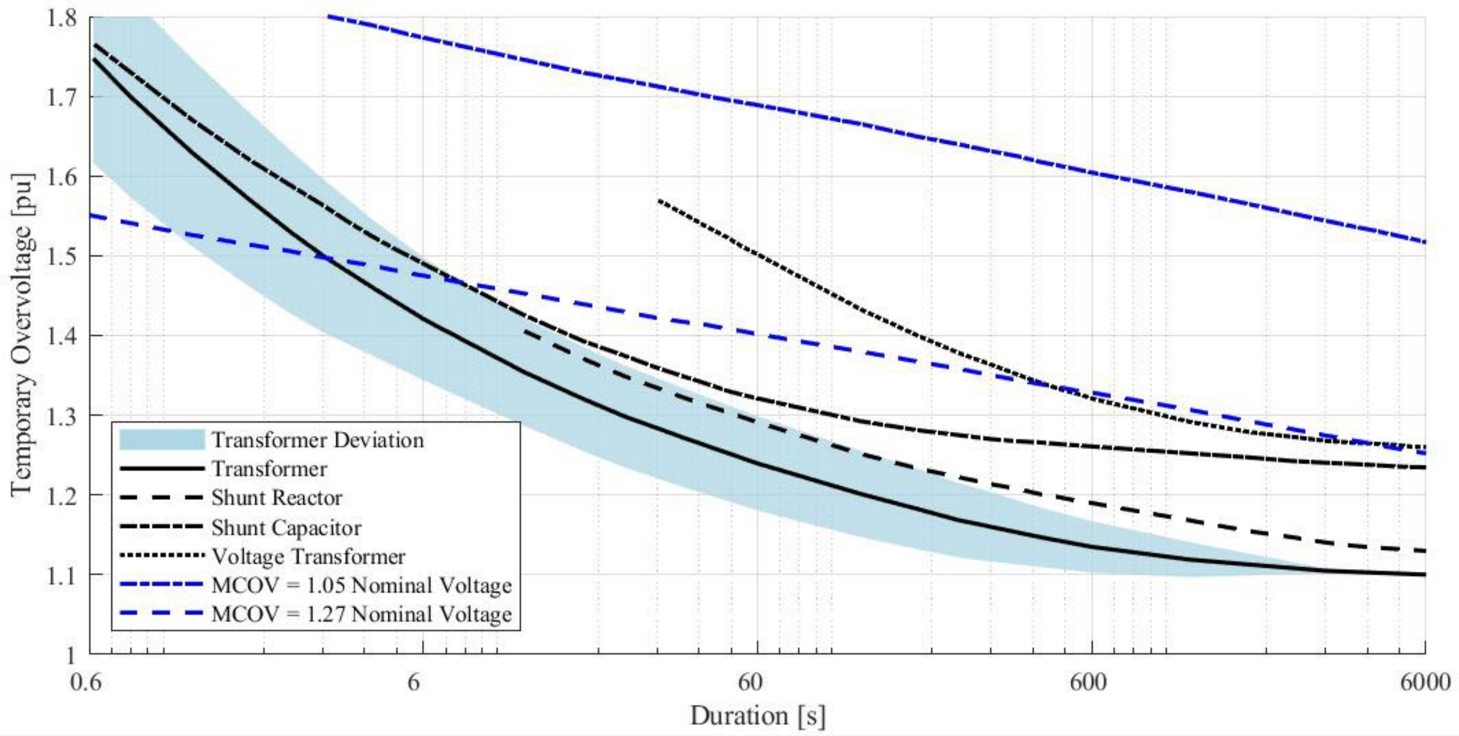
“Temporary Overvoltage Withstand Characteristics of Extra High Voltage Equipment”, Electra 179, August 1998, WG 33.10. (Figure redrawn by C4.46)

# Harmonic TOV stresses stresses in selected equipment

# Harmonic TOV stresses

- Harmonic TOVs can cause aging/deterioration or failure of components due to dielectric or thermal stresses
- Conventional (fundamental frequency) TOVs covered by standards such as IEC 60071 are not representative of the stresses caused by TOVs containing harmonic components
- Little information is available regarding withstand capabilities of equipment subject to TOVs with harmonic content

# Harmonic TOV stresses



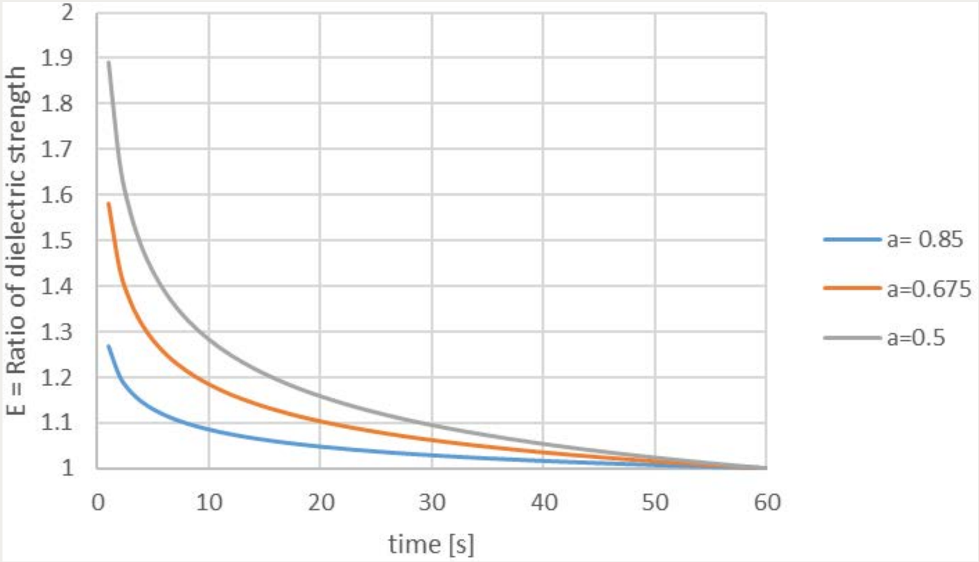
*“Temporary Overvoltage Withstand Characteristics of Extra High Voltage Equipment”, Electra 179, August 1998, WG 33.10. (Figure redrawn by C4.46)*

# Harmonic TOV stresses - transformers

- The strength-time curve of the insulating material can be represented by the following equation:

$$E_{b\_pf} = \left( a + \frac{1-a}{\sqrt[4]{t}} \right)$$

- The value of a depends on the dissipation factor (dielectric loss). The higher the dielectric loss the lower the dielectric strength.
- The higher the voltage the lower the time is to cause the breakdown.



*Relation of dielectric strength and time for different values of a*

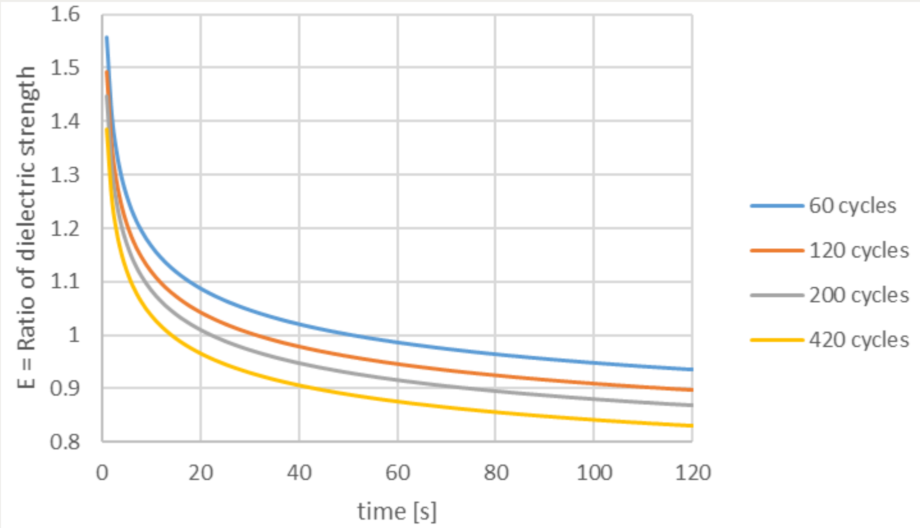
*Note: the breakdown strength as defined here is only applicable to oil immersed transformers*

# Harmonic TOV stresses - transformers

- The frequency of the applied voltage has a significant effect on the insulation strength; as the frequency increases, so does the dielectric loss and heating.
- The effect of frequency can be described by the following equation:

$$E_{b\_vf} = \frac{K}{f^n}$$

(K = 0.175 and n = 0.137 can be used as conservative values)



*Relation of dielectric strength and time for different frequencies*

*Note: the breakdown strength as defined here is only applicable to oil immersed transformers*

# Harmonic TOV stresses - transformers

- Combining the relations, the following is obtained for the dielectric strength of the transformer insulation:

$$E_b = E_{b\_pf} * E_{b\_vf} = \left(a + \frac{1-a}{\sqrt[4]{t}}\right) * \left(\frac{K}{f^n}\right)$$

- Typical values used for the equation in case data is unavailable:
  - a = 0.675, K = 0.175, n = 0.137
- *Eb* should be multiplied by the one-minute power frequency withstand voltage in order to obtain the adjusted withstand voltage

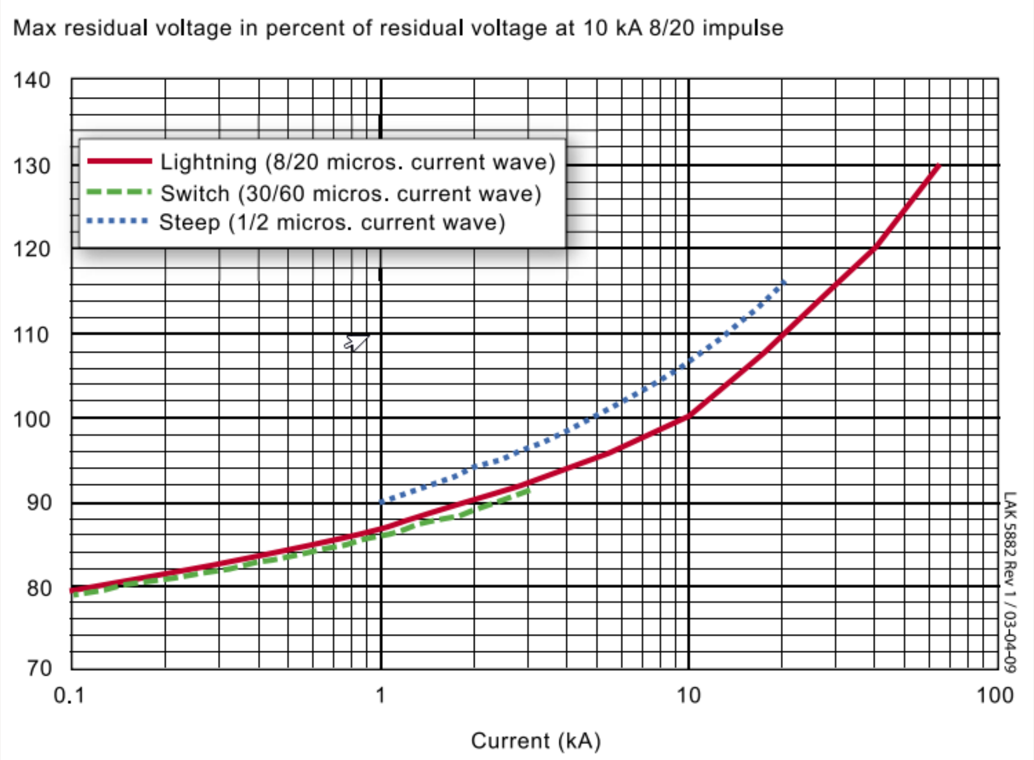
*Note: the breakdown strength as defined here is only applicable to oil immersed transformers*

# Harmonic TOV stresses - arresters

- Arresters are designed to protect HV equipment from transient overvoltages, without the arrester itself being damaged by TOVs.
- TOV curves provided by manufacturers are useful for selecting Ur when the TOV magnitude is known to be practically constant for a given duration (e.g., single-phase-to-ground faults).
- However, resonant overvoltages are typically composed of several, slowly damped, harmonic components of varying magnitude. Therefore, the curves provided by manufactures cannot be applied directly for analysis of TOV containing harmonic components.

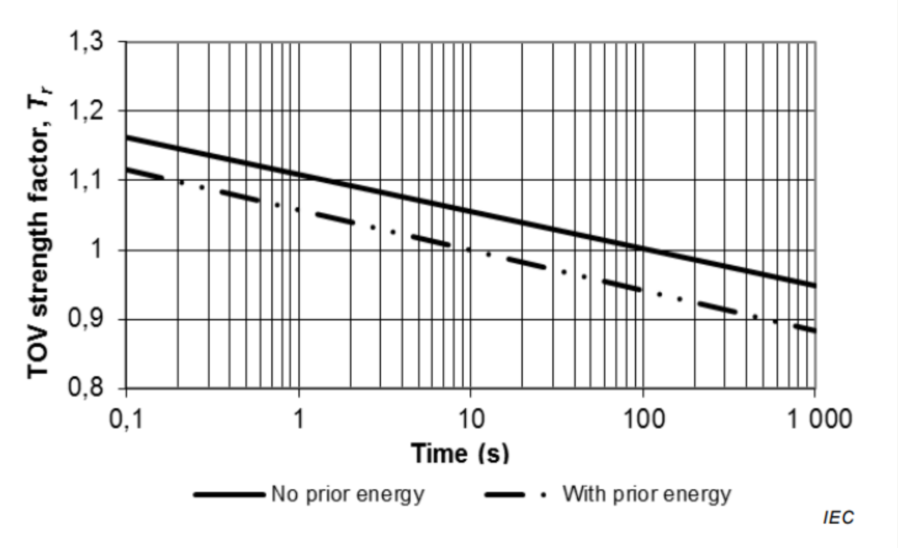
# Harmonic TOV stresses - arresters

- The primary task of the arrester is to protect other equipment against overvoltages.
- Residual voltage curves are used for calculating overvoltage levels due to, e.g., lightning or switching.
- The residual voltage curves represent the **maximum** V-I characteristic.



# Harmonic TOV stresses - arresters

- The TOV withstand of arresters is determined by the **minimum** V-I characteristic.
- The minimum characteristic has to do with arrester manufacturing tolerances and is not generally available.
- A method has been proposed to estimate the minimum characteristic from the arrester TOV curve.
- The minimum characteristic can be used to directly evaluate the energy stress on arresters due to TOVs in EMT software.



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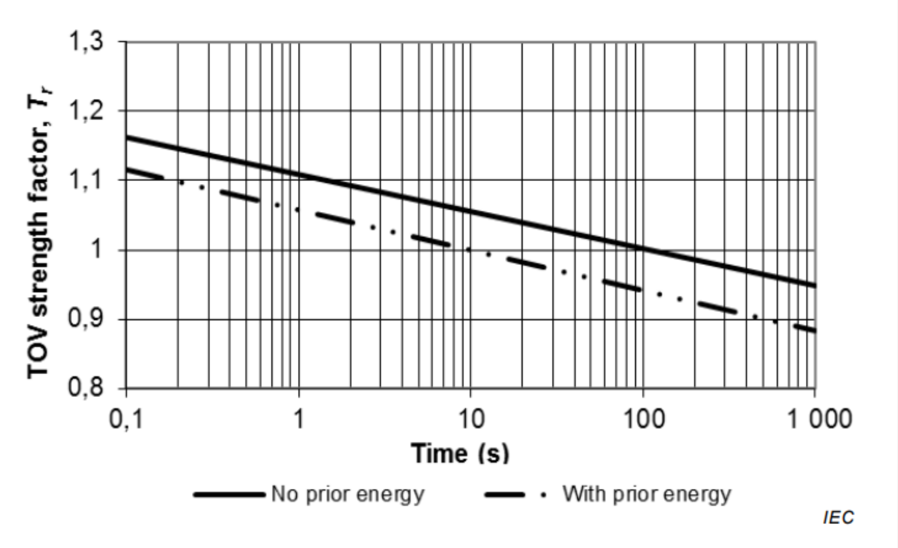
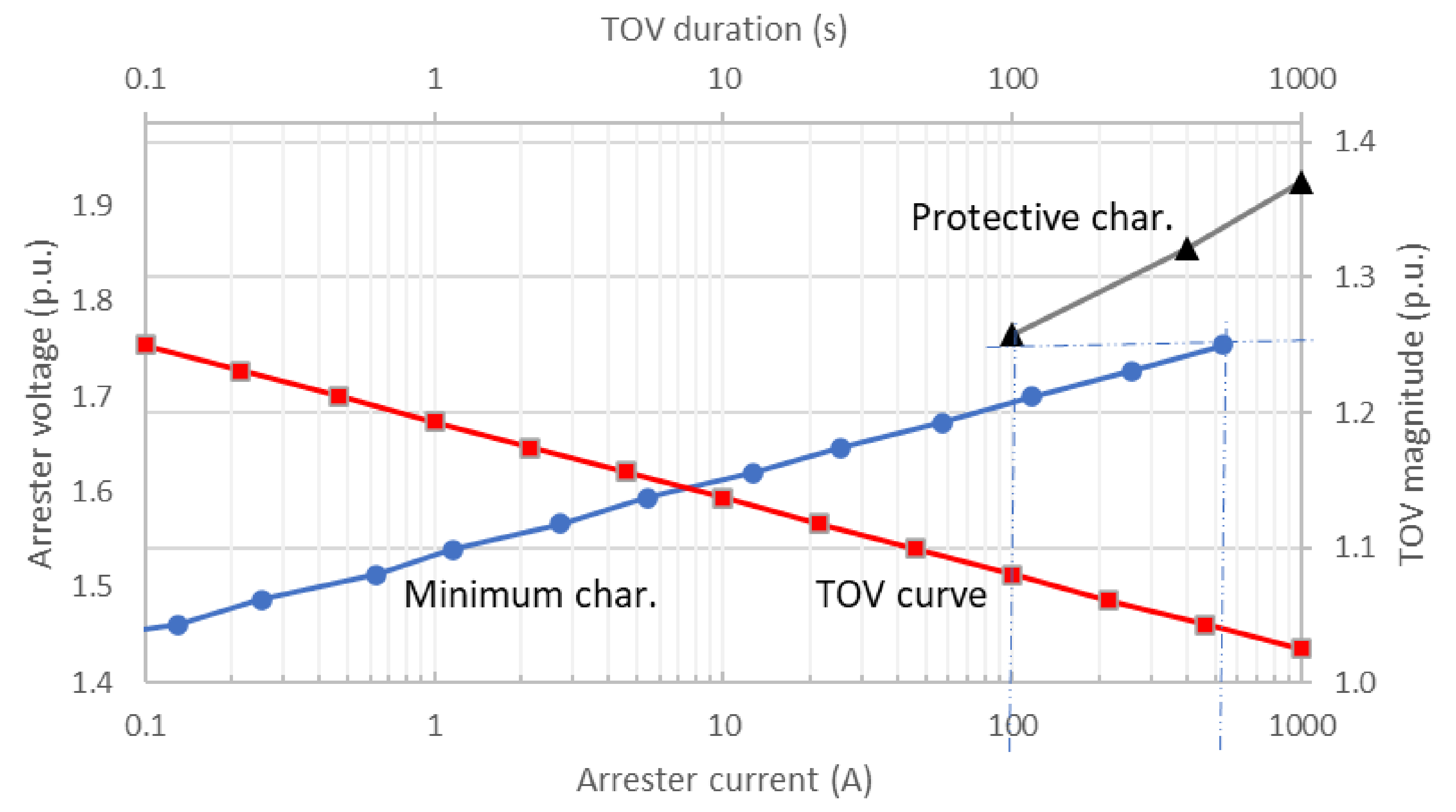
# Harmonic TOV stresses - arresters

- The TOV curve without prior energy absorption is used to establish the minimum VI-characteristic.
- The minimum characteristic is unchanged for TOV durations up to 10 seconds since:
  - Arrester currents during TOVs shorter than 10 s are in the range 1 - 1000 A. In this range, the characteristic is independent of temperature and frequency.
  - For TOVs lasting up to 10 s, cooling of the metal-oxide resistors can be disregarded.



# Harmonic TOV stresses - arresters



# Modelling Guidelines & Selected Cases

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# Modelling Guidelines & Selected 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 PoI

# Modelling Guidelines & Selected Cases

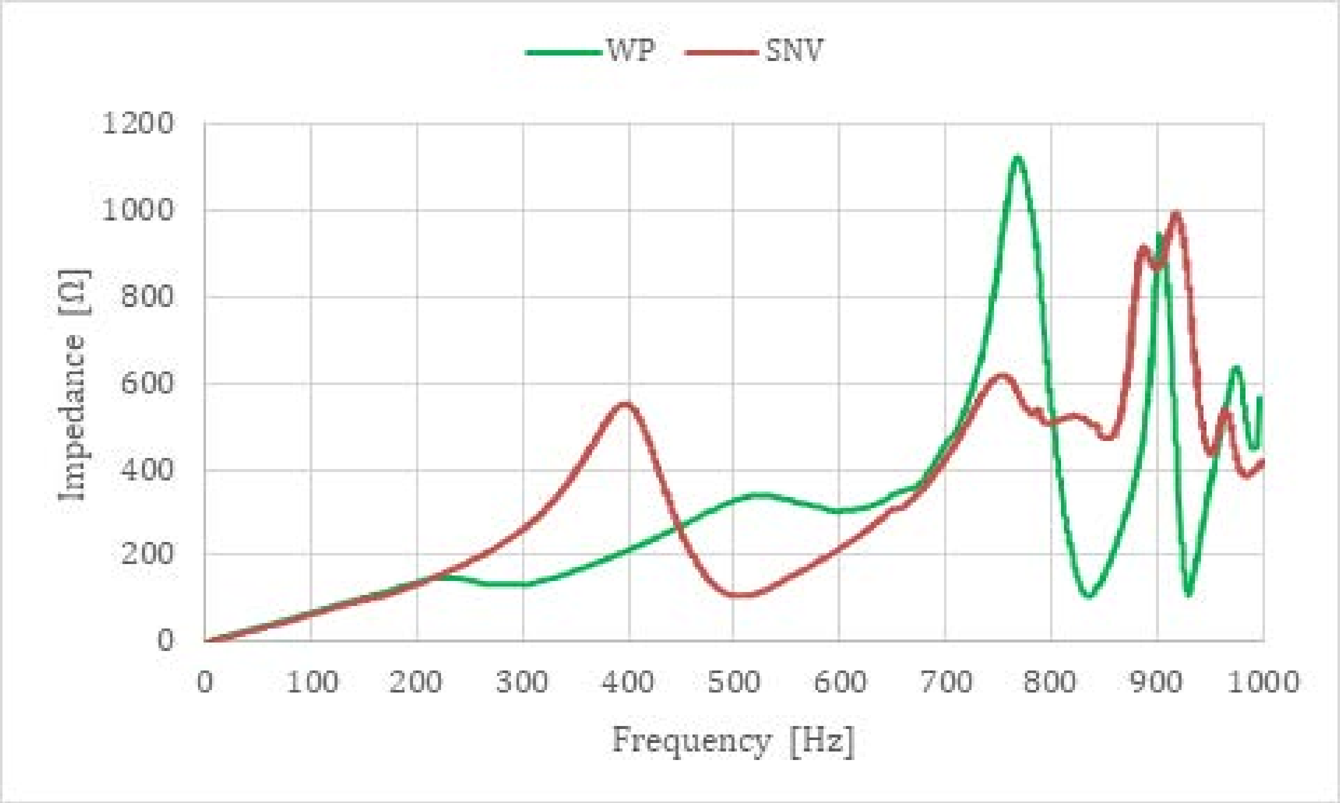
- Frequency scans form an initial screening process to identify and select relevant/ onerous system conditions that require further investigation in the time domain

- 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



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# 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

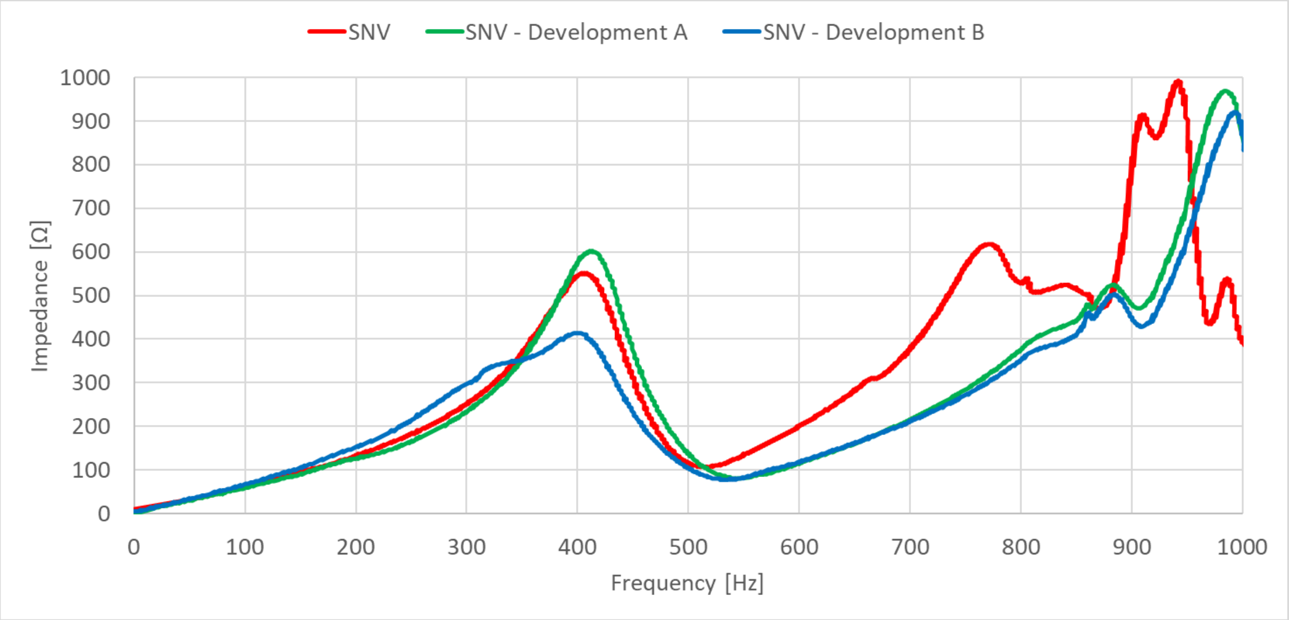
- Various approaches on the modelling detail of the upstream and downstream networks

- Example 1: RTE (French TSO)
  - Modelling of the complete primary transmission grid
  - Detailed modelling of the study zone
  - Network equivalents at the boundaries
    - Simplified Thévenin equivalent
    - FDNE model

# Modelling Guidelines & Selected Cases

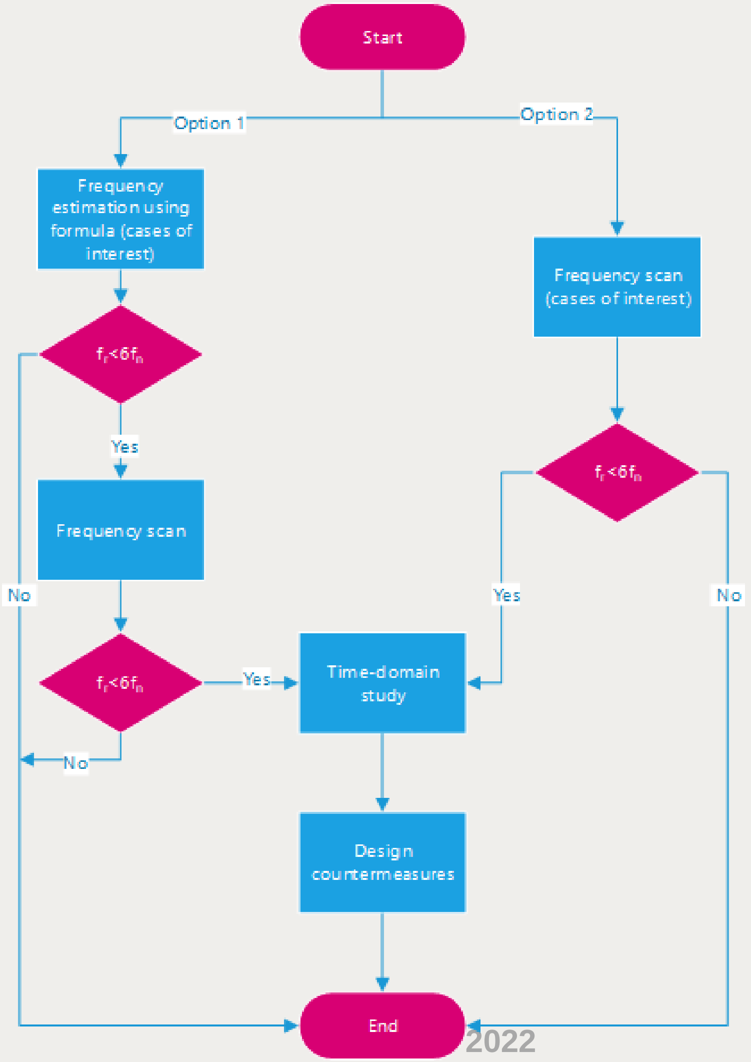
- Various approaches on the modelling detail of the upstream and downstream networks

- Example 2: Other



# Modelling Guidelines & Selected Cases

- In a nutshell:



Start

Option 1

Frequency estimation using formula (cases of interest)

$f_r<6f_n$

Yes

Frequency scan

$f_r<6f_n$

Yes

No

No

Option 2

Frequency scan (cases of interest)

$f_r<6f_n$

Yes

No

Time-domain study

Design countermeasures

End

# Modelling Guidelines & Selected Cases

- Selected cases in the time domain:
    - o Power transformer energization
        - Remanent flux
        - Statistical switching
    - o Fault clearing
        - Single-phase and three-phase faults
        - Fault instant, fault clearing time & auto-reclosing
    - o Islanding
        - Distributed generation

# Assessment Methods

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# 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”

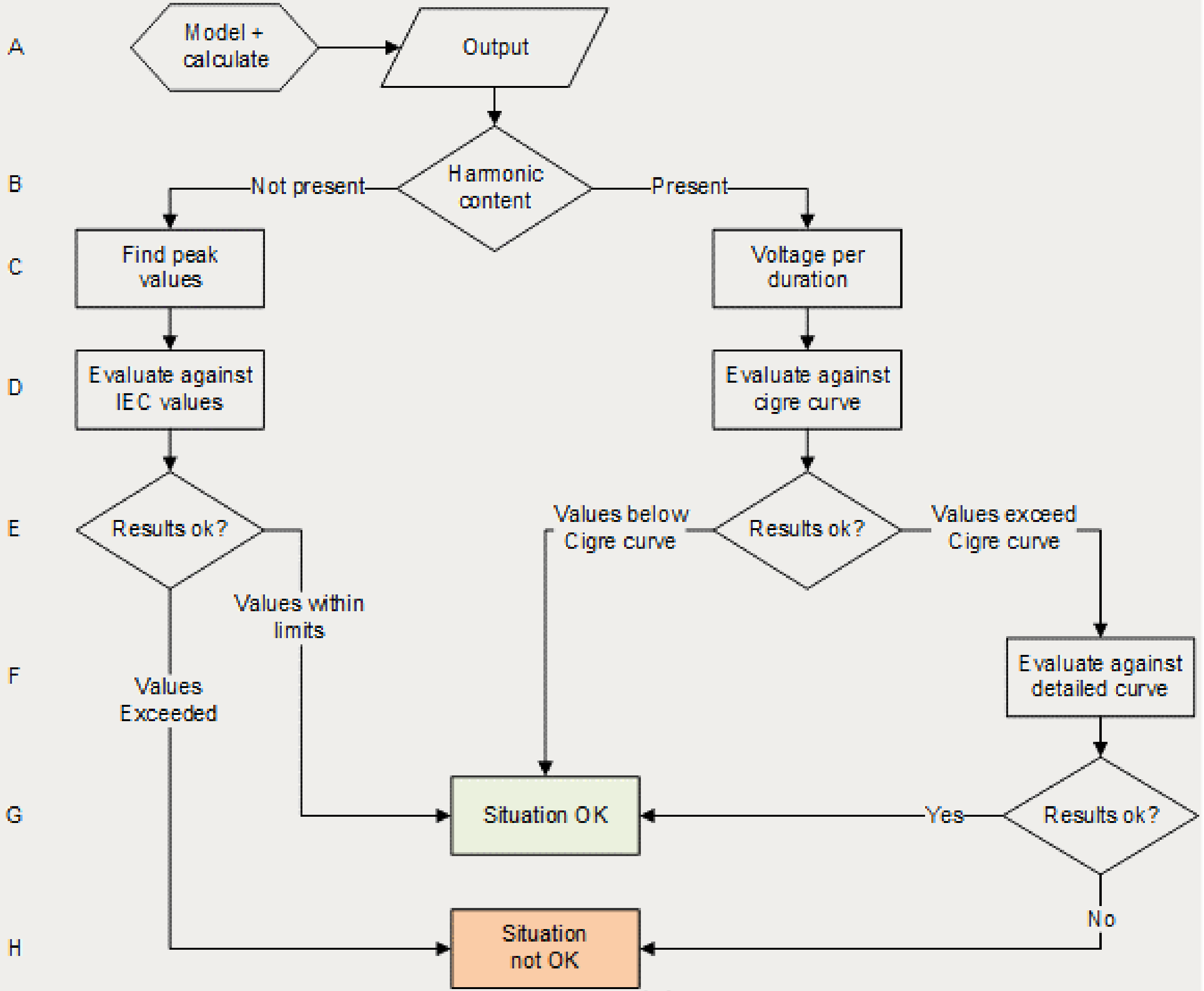
# Assessment methods

Existing TOV withstand characteristics are defined for

- constant amplitude
- constant frequency

C4.46 presents methods for assessing TOVs with

- varying amplitude
- harmonic content



A

Model + calculate

Output

B

Harmonic content

Not present

Present

C

Find peak values

Voltage per duration

D

Evaluate against IEC values

Evaluate against cigre curve

E

Results ok?

Values within limits

Values below Cigre curve

Results ok?

Values exceed Cigre curve

F

Values Exceeded

Evaluate against detailed curve

G

Situation OK

Yes

Results ok?

H

Situation not OK

No

# TOV at power frequency

For TOVs without harmonic content and time independent.

Apply the IEC 60071 conversion formulas of relevant insulation levels to TOV withstand.

Compare identified peak values or rms (√2 conversion) to the equipment insulations levels.

Example of converted reference $TOV_{50Hz}$ as RMS value.

| a | b | C | d | e | f | g |
|---|---|---|---|---|---|---|
| **Un (kV)** | Um (kV) | LIWL (kV) | (converted) SIWL (kV) | Reference SIWL (kV) | PFWV (kV) | Reference $TOV_{50Hz}$ (kV) |
| **380** | 420 | 1425 | 1050 | 913 | 630 | 548 |
| **220** | 245 | 1050 | 840 | 730 | 460 | 400 |
| **150** | 170 | 750 | 600 | 513 | 325 | 283 |
| **110** | 123 | 550 | 440 | 373 | 230 | 200 |

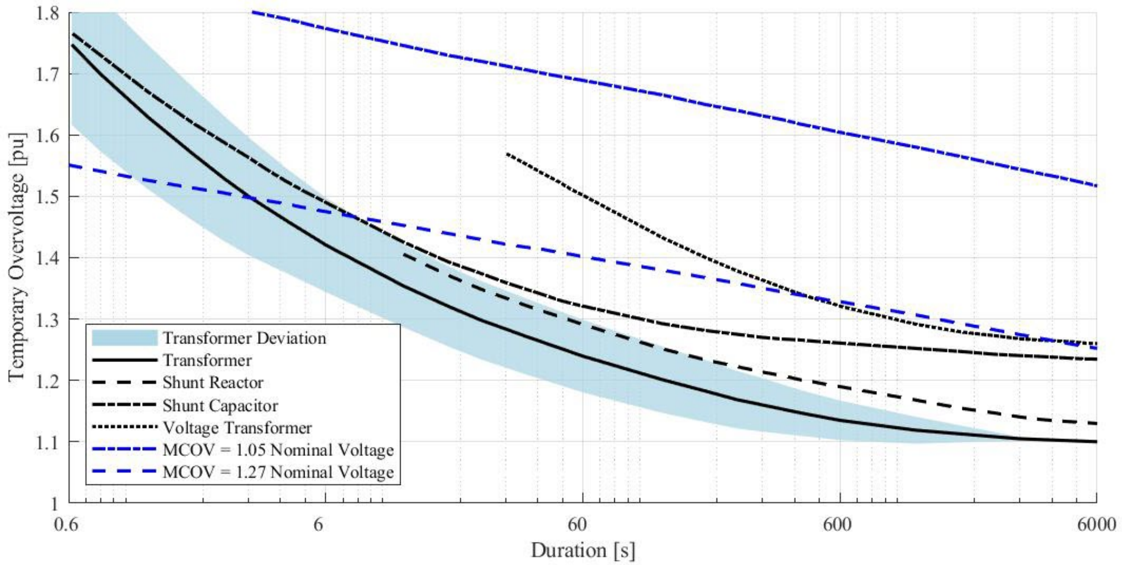
Note 1: the lightning insulation withstand level (LIWL) and switching insulation withstand level (SIWL) are peak values, and the power frequency withstand voltage (PFWV) and temporary over voltage (TOV) are rms values.
Note 2: Switching impulse withstand levels for grids with Um lower than 245 kV are converted from lightning impulse withstand levels

# TOV with harmonic components

An alternative to the time independent IEC limits are the CIGRE voltage-duration curves.

These provide a relationship between TOV magnitude and duration in terms of withstand capability.

The curves are derived for TOV without harmonic content. Hence it is with a degree of uncertainty, these are applied in some of the following TOV assessment methods



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

# Moving window method - RMS

Calculating RMS voltages of TOV voltage-time signal

Apply a series of calculation window sizes.

Window sizes are integer multiples of the power frequency period.

The calculation window is shifted through the waveform by a fixed time step e.g. half a period.

Save max. RMS value calculated for each window size.

Increase window ($t_{period}$)

First RMS value

$$N = \frac{t_{period}}{t_{step}}$$

$$RMS_1 = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(u\left(t_i\right)^2\right)}$$

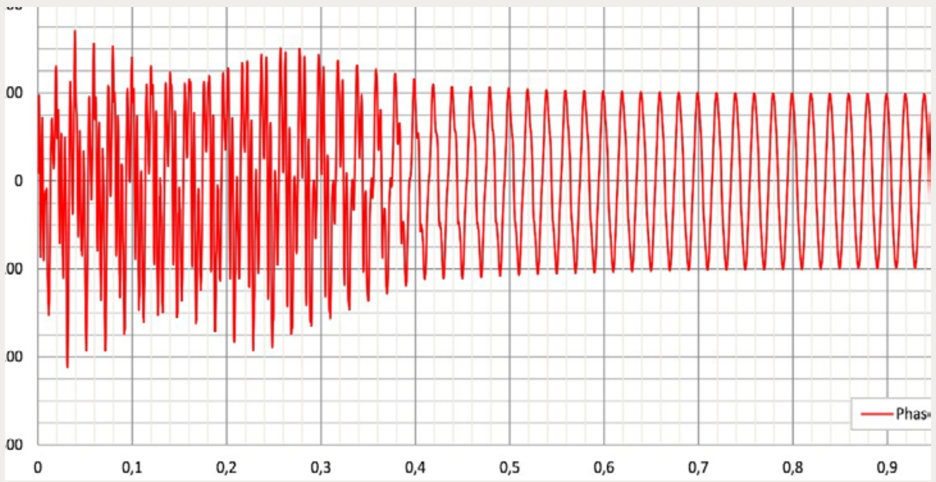
Second RMS value

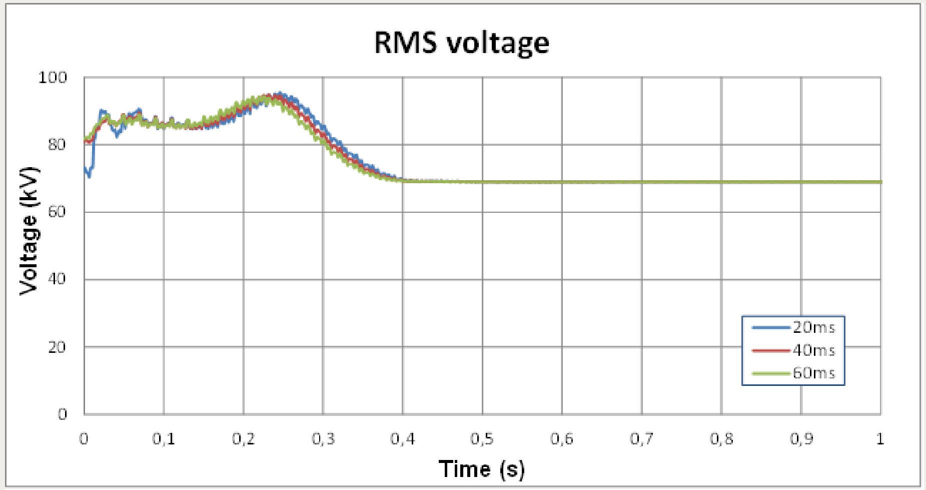
$$N_{shift} = \frac{t_{period}}{2t_{step}}$$

$$RMS_2 = \sqrt{\frac{1}{N}\sum_{i=N_{shift}}^{N+N_{shift}}\left(u\left(t_i\right)^2\right)}$$

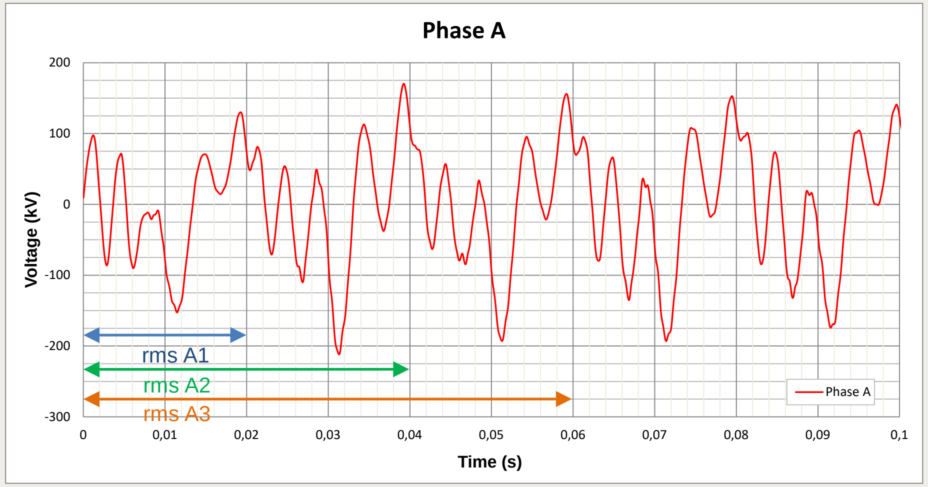
Continue to end

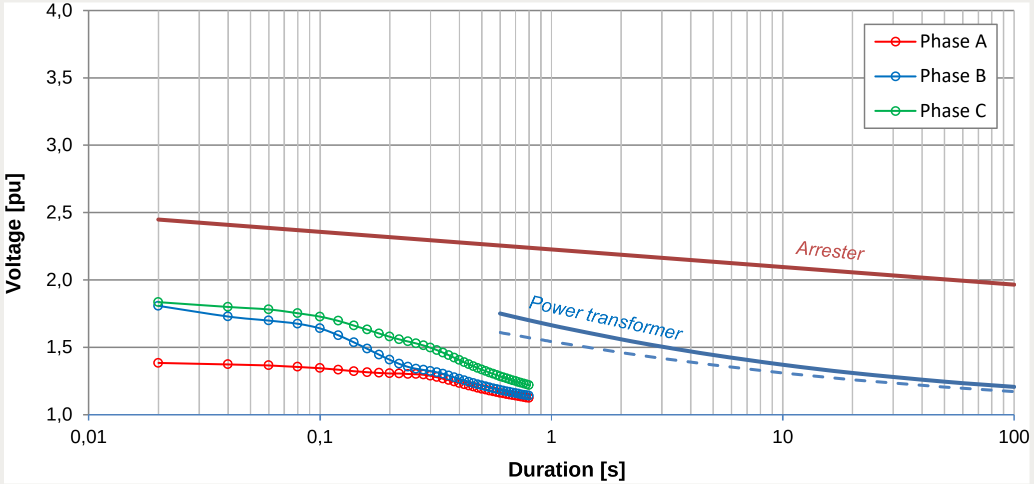
# Moving window method - RMS





| Window | Max. RMS |
|---|---|
| 20 ms | 95.5 kV |
| 40 ms | 94.8 kV |
| 60 ms | 94.2 kV |
| 80 ms | 93.5 kV |
| 100 ms | 92.8 kV |





# Moving window method - peak

Window size is initially one power frequency period

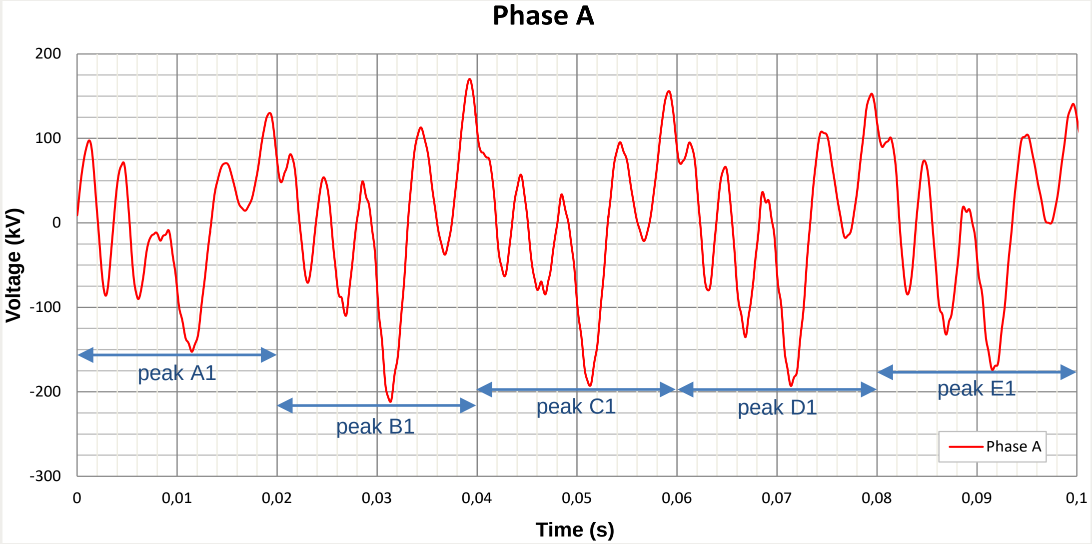
Window is shifted by a full power frequency period

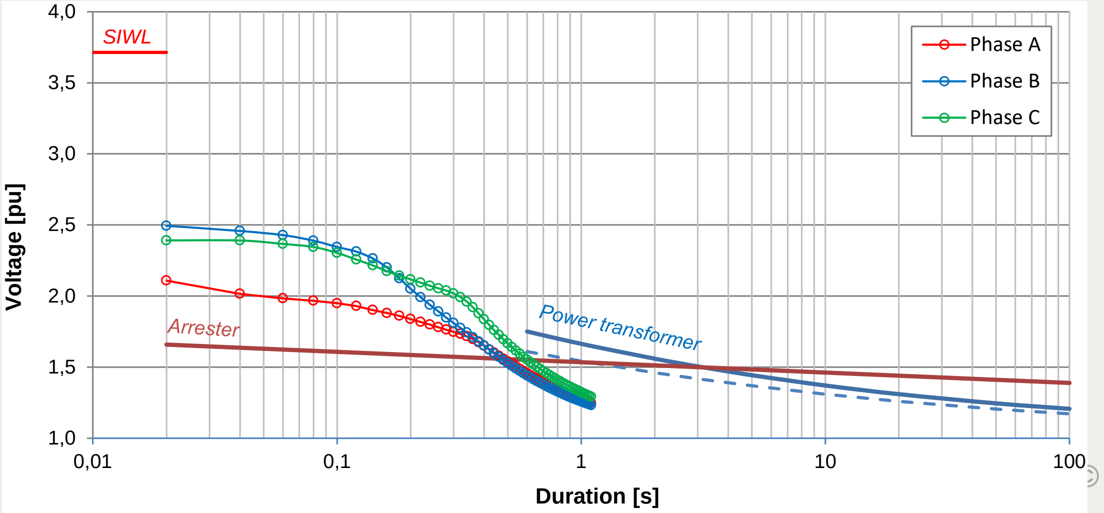
The peak value is obtained for each window (absolute instantaneous voltage)

No overlap between windows, as there is no averaging for peak values

Increase window size and average peak values within window

# Moving window method - peak





A. Determine maximum absolute value per cycle. For an example with 5 cycles:

| | |
|---|---|
| Pk A1 | 152.6 |
| Pk B1 | 211.9 |
| Pk C1 | 192.9 |
| Pk D1 | 193.1 |
| Pk E1 | 174.1 |

B. Sort the maximum values per cycle (descending). For an example with 5 cycles:

| | |
|---|---|
| 152.6 | 211.9 |
| 211.9 | 193.1 |
| 192.9 | 192.9 |
| 193.1 | 174.1 |
| 174.1 | 152.6 |

C. Determine average value per number of cycles (duration 1 to n). For an example with 5 cycles:

Peak A2 = average (Peak A1, Peak B1)

Peak B2 = average (Peak B1, Peak C1)

Peak A3 = average (Peak A1, Peak B1, Peak C1)

Etc.

| 20ms | 40ms | 60ms |
|---|---|---|
| Pk A1 | Pk A2 | Pk A3 |
| Pk B1 | Pk B2 | Pk B3 |
| Pk C1 | Pk C2 | Pk C3 |
| Pk D1 | Pk D2 | -- |
| Pk E1 | -- | -- |

| 20ms | 40ms | 60ms |
|---|---|---|
| **211.9** | **202.5** | **199.3** |
| 193.1 | 193.0 | 186.7 |
| 192.9 | 183.5 | 173.2 |
| 174.1 | 163.4 | -- |
| 152.6 | -- | -- |

D. Determine maximum value per duration

| 20ms | 40ms | 60ms | 80ms | 100ms |
|---|---|---|---|---|
| 211.9 | 202.5 | 199.3 | 193.0 | 184.9 |

# Frequency-Based Assessment for Transformers

Breakdown strength of transformer insulation is influenced by heat storage and dissipation.

AC voltage will cause hysteresis and dielectric losses.

The heat from losses will lead to temperature rising until thermal equilibrium is reached.

Insulation temperature increase will lead to increased currents through insulation. If this increase sufficiently the breakdown point will be reached.

$$E_{b\_pf} = \left( a + \frac{1-a}{\sqrt[4]{t}} \right)$$

$E_{b\_pf}$ = breakdown strength at power frequency, any time T with respect to 1-minute value ($V_t/V_{1m}$)

a = constant for insulating medium ($V_{inf}/V_{1m}$)

t = duration of overvoltage in minutes

$V_t$ = breakdown strength, any time t

$V_{1m}$ = breakdown strength, 1-minute (t=1)

$V_{inf}$ = breakdown strength, infinite time

Note: The variables are renamed from the reference for a better understanding.

# Frequency-Based Assessment for Transformers

The power frequency withstand voltage is converter by the ratio of dielectric strength $E_b$.

The duration and frequency is derived from the simulations.

The maximum simulation RMS value is compared to the calculated insulation voltage withstand capability.

$$E_{b\_vf} = \frac{K}{f^n}$$

$E_{b\_vf}$: ratio of dielectric strength at variable frequency

K: constant, depending on the relative strengths of material

f: frequency in Hz

$$E_b = E_{b\_pf} * E_{b\_vf} = \left(a + \frac{1-a}{\sqrt[4]{t}}\right) * \left(\frac{K}{f^n}\right)$$

Insulation voltage withstand capability:

$$V_{TOV,max} = E_b * V_{\mathrm{PFWV}}$$

# “Gauge method” - definitions

- A “gauge” correspond to a table which associates different overvoltage limits: from the higher to the lower, to an “acceptable” overvoltage duration.

| | Overvoltage duration | 1 ms | 10 ms | 100 ms | 1 s | 5 s | 10 s |
|---|---|---|---|---|---|---|---|
| ***Voltage phase to phase*** | Limit: acceptable level (pu) | 1,71 | 1,58 | 1,45 | 1,32 | 1,23 | 1,2 |

- The limits are defined in pu: e.g. 1 pu equal to 420*√2 kV for the 400 kV network
- For each transformer there is a *gauge* dedicated to the phase to phase and ground to phase voltages. The parameters depend on:
  - the voltage level (primary side) of the transformer
  - the transformer insulation level (normal or reduced)
  - the surge arrester type
- The main parameters have been calculated in 1998 in internal TSO studies based on dielectric normalized test, with also the participation of two manufacturers of transformers

# “Gauge method” – Evaluation of the consumption

- The 6 waveforms: 3 $PeakValues_{PhaseToGround}$ and 3 $PeakValues_{PhaseToPhase}$ are analysed.
- The signals are split in windows *w* (generally 10ms). For each windows $M_w = MAX\left|\frac{U(t)}{Uc}\right|$
- For each windows, if $M_w$ exceed one or many limits of the gauge, the quantity $K_{g,w}$ (equal to the duration *w* divided by the “acceptable overvoltage duration” of the partial gauge: e.g $d_1$ for the partial gauge $g_1$ ) is counted only for the most severe partial gauge: e.g $g_1$ is more severe than $g_2$ …

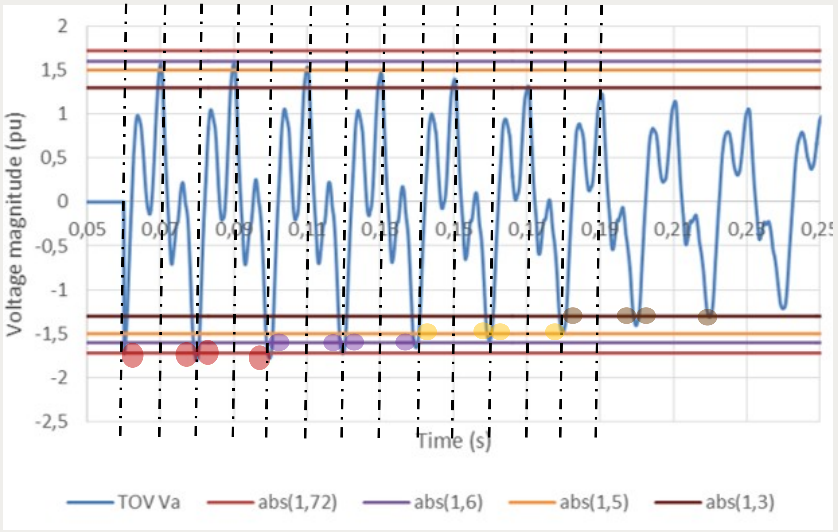
$$K_{g,w} = \begin{cases} 0, & if\ M_w < L_g\ or\ K_{g-1,w} > 0 \\ \frac{w}{d_g}, & if\ M_w \geq L_g \end{cases}$$

| Partial Gauges | $g_1$ | $g_2$ | $g_3$ | $g_4$ | $g_5$ | $g_6$ |
|---|---|---|---|---|---|---|
| **$D_g$=acceptable overvoltage duration (ms)** | $d_1$ | $d_2$ | $d_3$ | $d_4$ | $d_5$ | $d_6$ |
| **$L_g$=acceptable limit (pu)** | $L_1$ | $L_2$ | $L_3$ | $L_4$ | $L_5$ | $L_6$ |
| **$K_{g/w}$=weighting coefficient** | $K_{1/w}$ | $K_{2/w}$ | $K_{3/w}$ | $K_{4/w}$ | $K_{5/w}$ | $K_{6/w}$ |

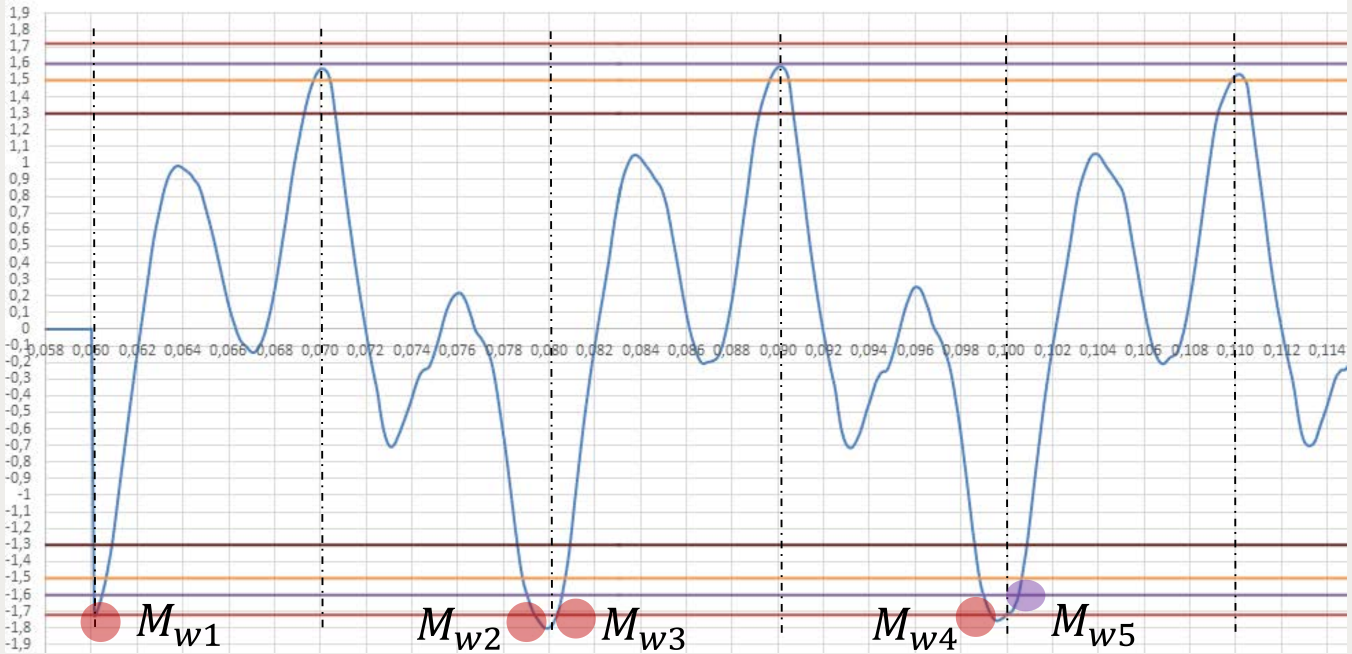
- The total consumption “C” is calculated by summing all partial gauges consumption: equal to the sum of its $K_{g,w}$. If C exceed 100% mitigations needs to be investigated.

$$C\ (\%) = 100 * \int_{Tevent+\alpha}^{Tevent+\alpha+10s} \sum_{g=1}^{g=6} K_{g,w}\, dw$$

# “Gauge method” – Example



Zoom for the first 50ms



| | Overvoltage duration acceptable | 1 ms | 10 ms | 100 ms | 1 s | 5 s | 20 s |
|---|---|---|---|---|---|---|---|
| Voltage phase to phase | Acceptable level (pu) | >1,88 | 1,8-1,88 | 1,72-1,8 | 1,6-1,72 | 1,5-1,6 | 1,3-1,5 |
| | Number of exceedances | 0 | 0 | 4 | 4 | 4 | 4 |
| | Overvoltage duration calculated (ms) | 0 | 0 | 40 | 40 | 40 | 40 |
| | Percentage of the "partial gauge" consumed (%) | 0 | 0 | 40 | 4 | 0,8 | 0,2 |

Overvoltage duration acceptable 1 ms 10 ms 100 ms 1 s 5 s 20 s
Acceptable level (pu)
Voltage phase to phase

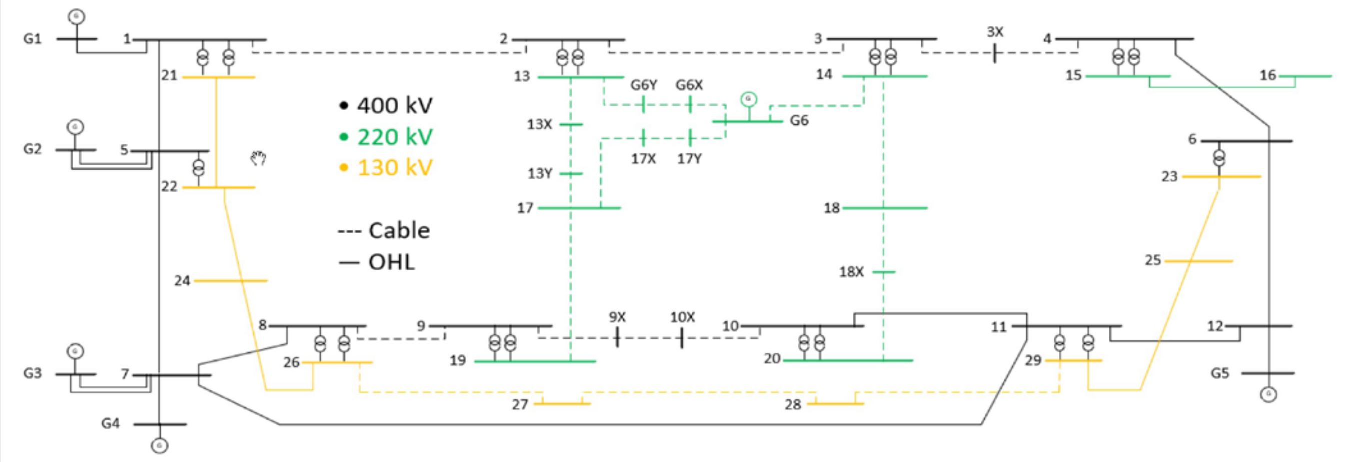
# “Gauge method” – conclusion of the example

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Voltage phase to phase | Overvoltage duration acceptable | 1 ms | 10 ms | 100 ms | 1 s | 5 s | 20 s |
| | Acceptable level (pu) | >1,88 | 1,8-1,88 | 1,72-1,8 | 1,6-1,72 | 1,5-1,6 | 1,3-1,5 |
| | Number of exceedances | 0 | 0 | 4 | 4 | 4 | 4 |
| | Overvoltage duration calculated (ms) | 0 | 0 | 40 | 40 | 40 | 40 |
| | Percentage of the "partial gauge" consumed (%) | 0 | 0 | 40 | 4 | 0,8 | 0,2 |

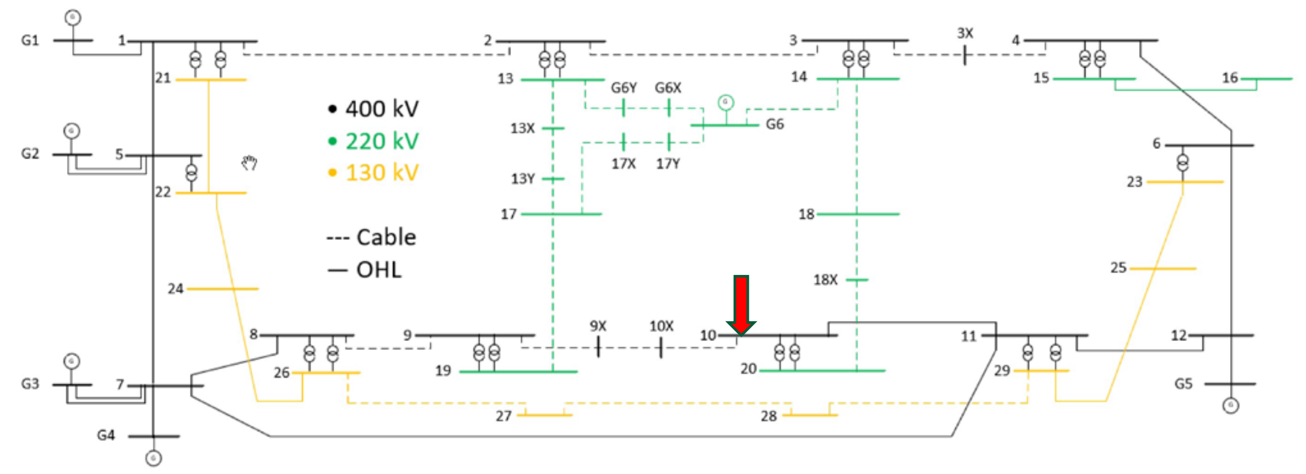
- The $“partial\ gauge\ consumption\colon\ C_p” = 100 * \frac{N_{excess} * w}{acceptable\ duration}$
- Total consumation: $C = \sum C_p = 45\%$ → $C < 100\%$ $\rightarrow$ TOV acceptable
- The operation is repeated for the 2 others phase-to-phase and the phase-to-ground voltages with another gauge adapted to the transformer

# Comparison of the methods – test cases

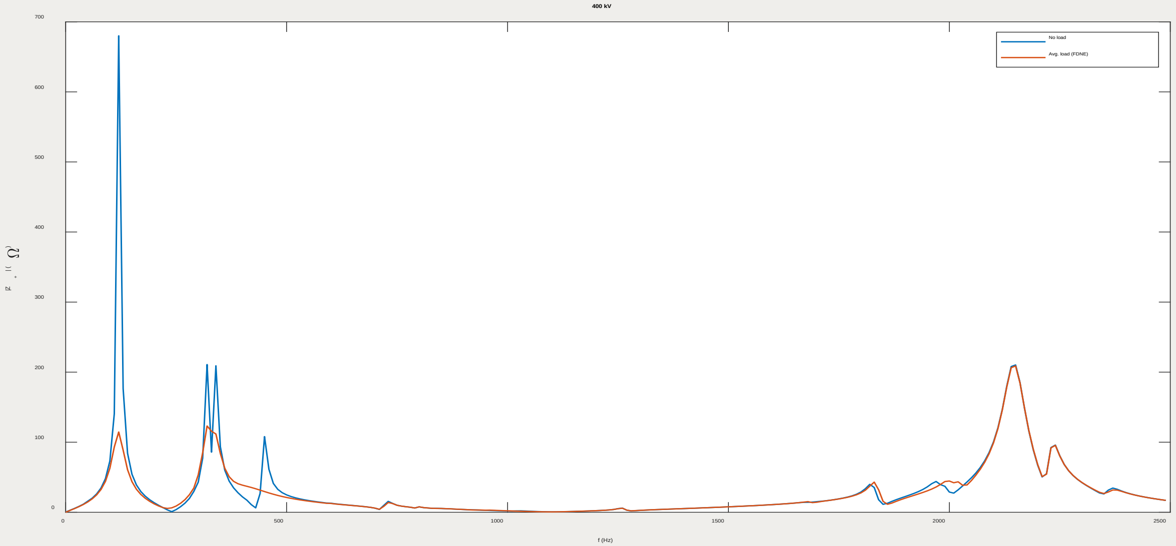
- To evaluate the previous methods with TOV waveforms, simulations were performed using an example grid described in detail in the TB. The network modeled is partially based on an existing network
- The example grid covers voltage levels from 400 kV to 400 V, with all relevant parameters included (e.g. data for detailed modelling of cables and lines, transformer saturation curves). The system is fed by large generation units (represented by Thévenin equivalents) located to the west and to the south, connected through long overhead lines
- Because the large share of cables (in dash line bellow), including parallel links, this system is characterized by having a first resonance frequency between 100 and 150 Hz at several locations



# Comparison of the methods – impedance of the network



The frequency impedance seen from bus 10, with and without loads and downstream network included in the model is characteristic of a parallel resonance. This resonance at approximately 120Hz is the nominal case and is poorly damped especially in the model without load.



# Comparison of the methods – fault clearing

- For the comparison of the assesment methods using the transformer energization after a fault clearing scenario, the following load are considered.

| Test case | Load level [MW] |
|---|---|
| 1 | 0 |
| 2 | 10 |
| 3 | 20 |
| 4 | 30 |
| 5 | 50 |
| 6 | 100 |
| 7 | 250 |
| 8 | 500 |

- Initially, the simulation model is set up to a parallel resonance seen from Bus 10 at 120 Hz. Another version of the model was set up, by adjusting the Thévenin equivalents so Bus 10 sees a parallel resonance directly at the 2nd harmonic, i.e. at 100 Hz.
- The sensitivity analysis showed that both the presence of a parallel resonance at the right frequency and remanent flux are important for significant TOV to occur. The worst cases are used for the comparison

# Comparison of the methods – fault clearing

| Load [MW] | Method A [RMS values] | Method B [RMS & Peak values] | Method C [Gauge] | Method D [FB transformers] |
|---|---|---|---|---|
| **0** | √ | X | X | √ |
| **10** | √ | X | X | √ |
| **20** | √ | X | X | √ |
| **30** | √ | X | X | √ |
| **50** | √ | √ | √ | √ |
| **100** | √ | √ | √ | √ |
| **250** | √ | √ | √ | √ |
| **500** | √ | √ | √ | √ |

- For the *gauge* method, which use peak values and the moving windows method with the use of peak values as well, the exceedance of the TOV limits will be observed in the cases with a load equal or less than 30MW.
- The 2 other methods: moving windows with RMS values only and frequency-based assessment for transformers would not show any critical TOV in the scenarios played.

# Additional test cases in the TB

- Transformer energisation:
  - Energisation with a parallel resonance at the busbar
  - With / without remanence
  - Energisation at zero-crossing / peak voltage;
  - Variation of the load
- Fault clearing
- Reclosure
- Parametric studies

# Mitigation strategies

For power system expertise

CIGRE Session 2022

# 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

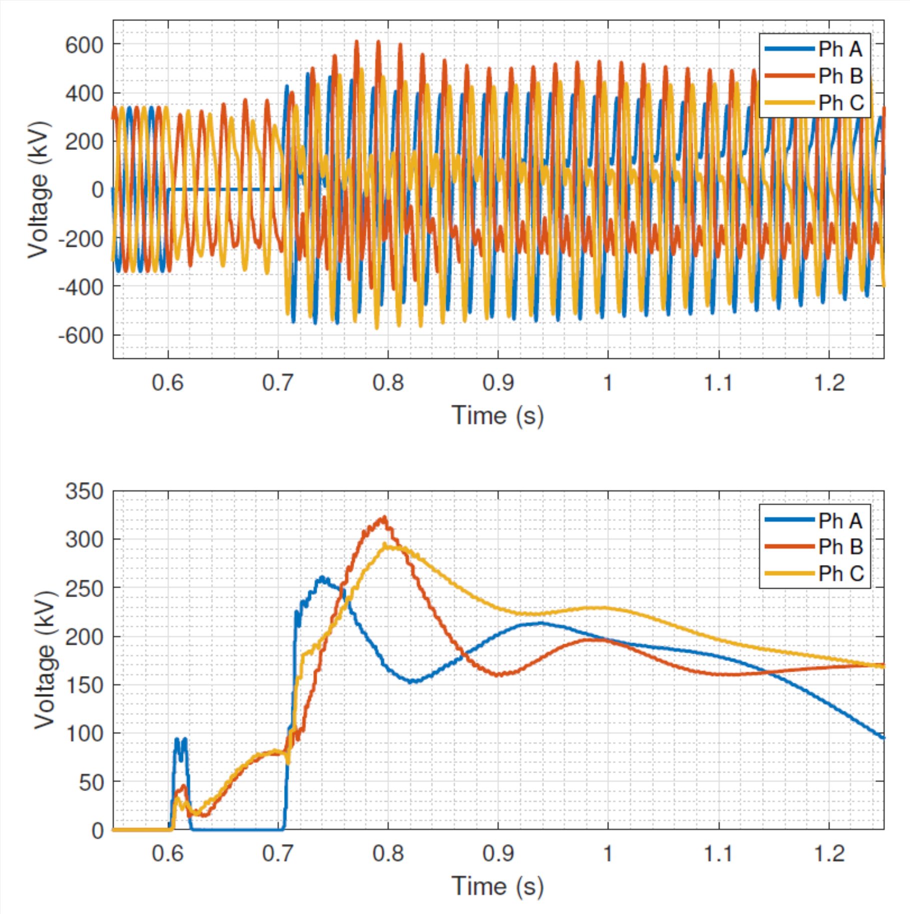
# Operational constraints

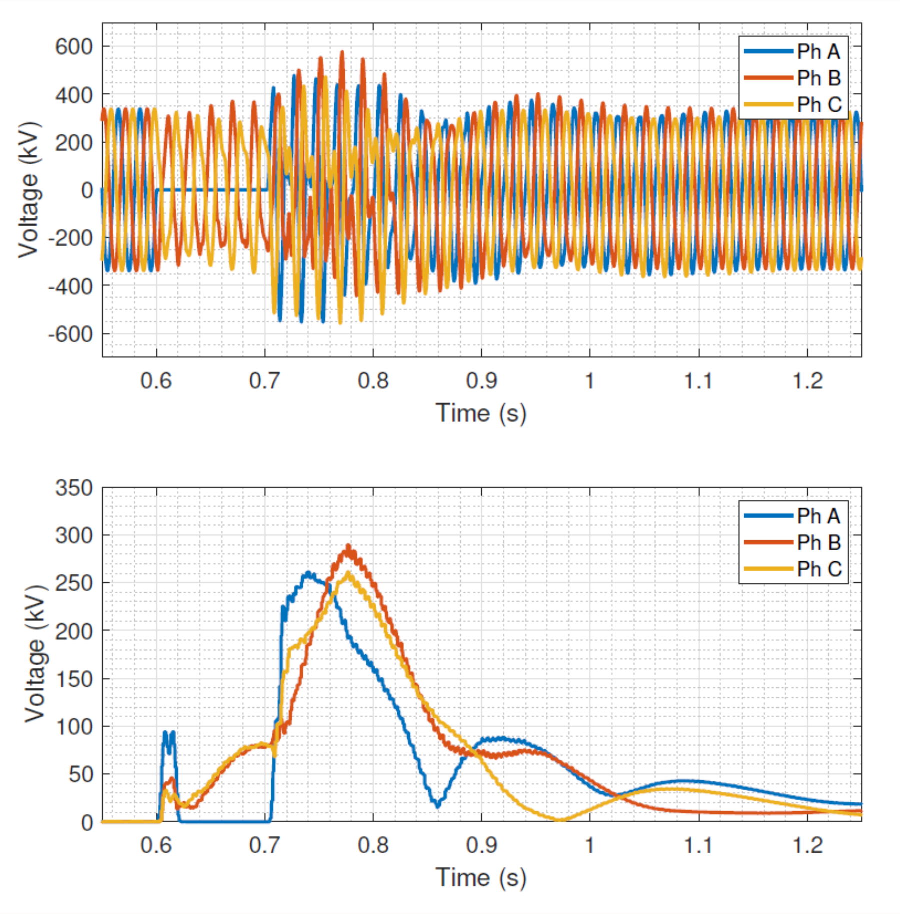
- **Pre-emptive constraints** can be used to reduce the TOV but will not prevent it from occurring in the first place
  - Reduction of pre-energization busbar voltage
  - Changing the tap changer position
- **Preventive constraints** aim to avoid low-order resonances which coincide with harmonic content of transformer inrush
  - For example: Disconnection of certain lines/cables before energization
  - Requires careful analysis of relevant grid configurations on beforehand
  - Following energization, the network configuration is restored

# Temporary Detuning of Cablified Networks

- A system-level approach based on the disconnection of cables to shift the system resonances
- The principle of the method can be summarized as follows:
  1. If the harmonic voltage at a given frequency exceeds a specified threshold for a given duration, cables are disconnected according to a predetermined scheme.
  2. Due to the disconnection of the cables, the resonance frequency of the system is shifted, thereby reducing the duration of the resonant TOVs.
  3. After the inrush current has decayed, the cables can be connected again following normal energization procedures.
- **The method is applicable to energization and fault clearing**

# Temporary Detuning of Cablified Networks





# Temporary Detuning of Cablified Networks

- The proposed method reduces the duration of the TOV, and thereby the stress on equipment.
- The method has no impact on the system during normal operation and acts only when resonant overvoltages are detected.
- The method requires cables that can be disconnected which have a large enough impact on the resonance frequency.
- The impact on the remainder of the system must be evaluated considering, e.g., stability, reactive compensation, and the risk of overloading other equipment.

# Synchronized Switching

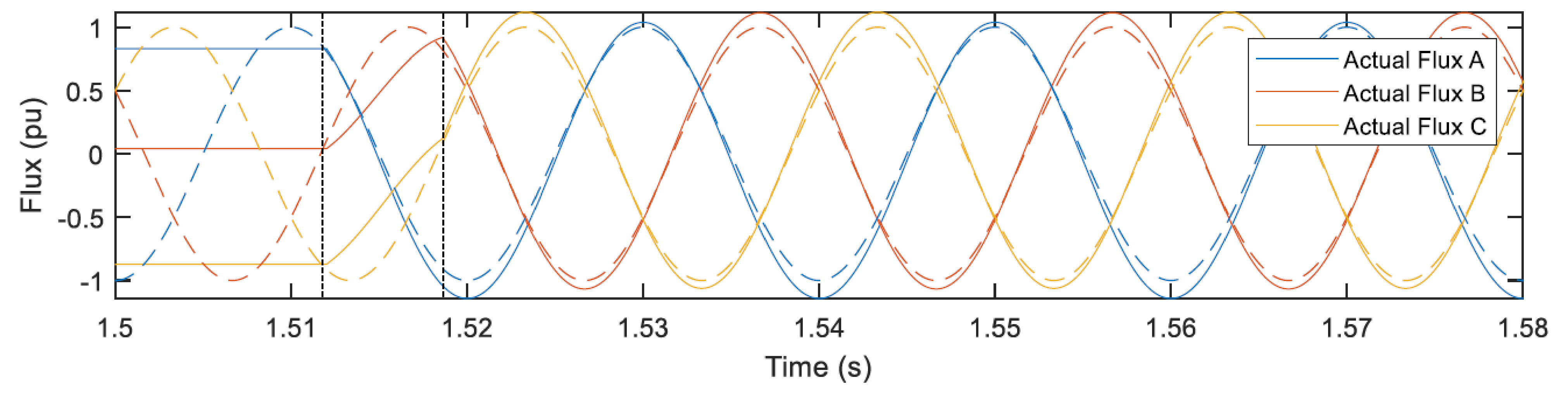
- Commonly used to minimize inrush current (and thereby the risk of resonant TOVs) when energizing power transformers

- The goal is to minimize the difference between the remanent flux in the transformer (if any) and the flux imposed by the grid voltage at the switching instant. The remanent flux can be obtained in two ways:
  - Controlled opening to achieve a predictable pattern in the remanent flux
  - Calculation based on the voltages at disconnection

- **N/A to resonant TOVs caused by fault clearing**

# Synchronized Switching

- Ideal closing targets depend on type of transformer (vector group, no. of limbs, etc.)
- Mechanical scatter etc. must be considered



*Example of synchronized energization of transformer with remanence*

# Synchronized Switching - example

- Comparison of calculated TOV using random and synchronized switching, without remanence
- Results from example network (100 Hz resonance with minimal damping)

| Case | Vmax (pu) | % > 1.2 pu | % > 1.4 pu | % > 1.6 pu |
|---|---|---|---|---|
| Random | 1.75 | 100 | 100 | 98 |
| Synchronized | 1.17 | 0 | 0 | 0 |

# Pre-insertion resistors

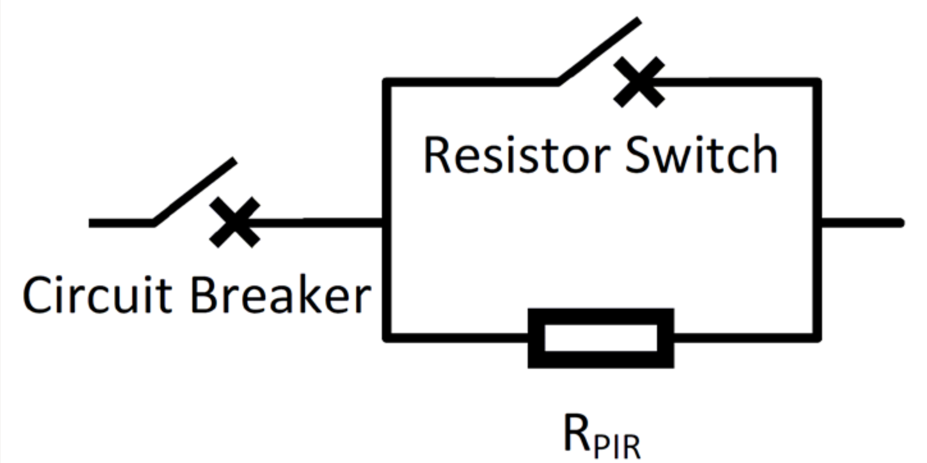
- Typical applications:
    - Long EHV lines for the suppression of the switching overvoltages
    - Power transformers for the mitigation of voltage dips
    - Cable/shunt reactor configurations for the suppression of current zero-miss phenomena

- With respect to TOVs, PIRs form a mitigation strategy when applied to power transformers
    - Suppression of inrush currents
    - **Only** effective under transformer energization **NOT** under fault clearing conditions

# Pre-insertion resistors

- Operational concept:
  - At $t_{energization}$ the main circuit breaker closes and the resistor is energized in series with the power transformer
  - At $t_{bridge}$, the auxiliary breaker closes and the resistor is bridged

- Detailed analysis is required to define the resistor value and insertion time for an effective TOV suppression



# C-type harmonic filters

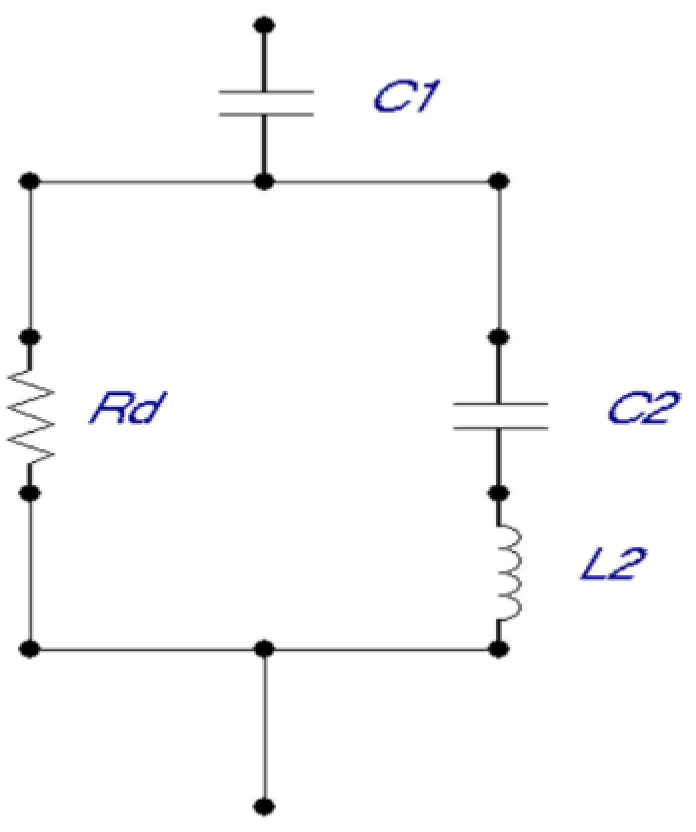
- Harmonic filters are used as a mitigation against background harmonic distortion, by changing the harmonic impedance of the network at and close to the PoI

- With respect to TOVs, harmonic filters offer a permanent de-tuning of the resonance

- For resonances at or close to 2nd and 3rd harmonics, C-type harmonic filters are preferred over other LC-type topologies

# C-type harmonic filters

- $C_1$: main capacitor, defines the filter MVAr
- $C_2$ and $L_2$ are shorted at 50 Hz
- $R_d$: filter damping resistance
- $C_1$, $C_2$ and $L_2$ are shorted at the tuning frequence $f_t$



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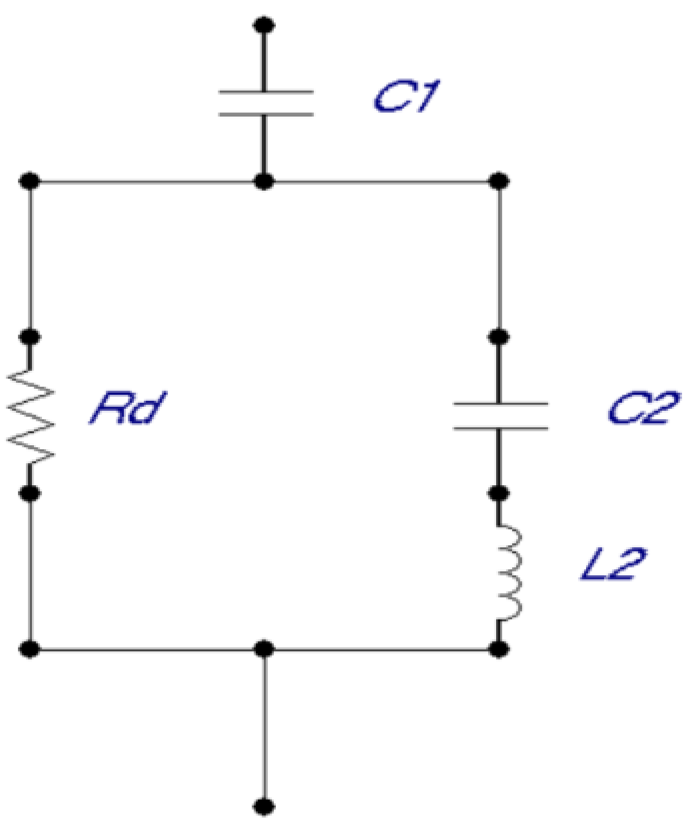
# C-type harmonic filters

- Driving equations
    - $C_1$: main capacitor, defines the filter MVAr

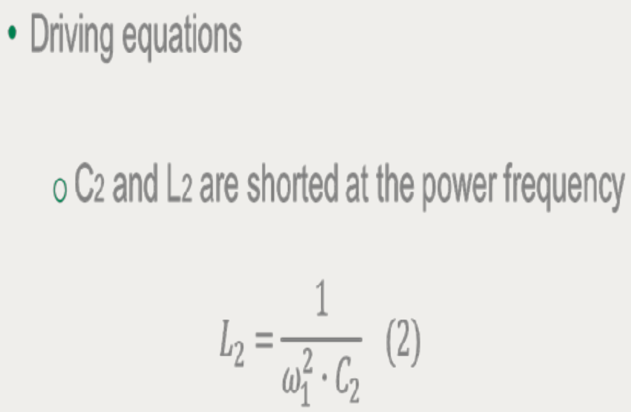
$$C_1 = \frac{Q_F}{\omega_1 \cdot U^2} \quad (1)$$



# C-type harmonic filters

- Driving equations
    - C2 and L2 are shorted at the power frequency

$$L_2 = \frac{1}{\omega_1^2 \cdot C_2} \quad (2)$$



- Driving equations
    - C2 and L2 are shorted at the power frequency

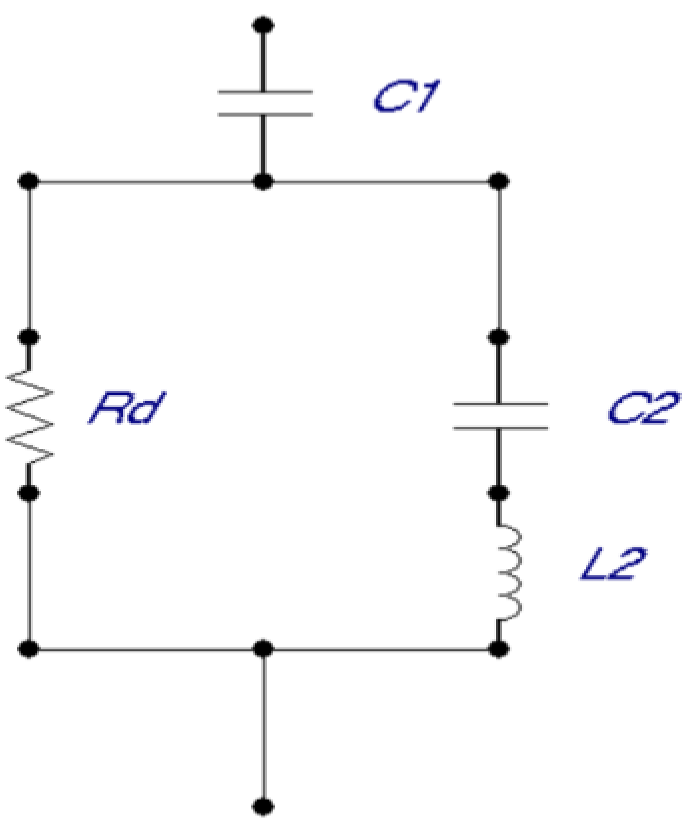
$$L_2 = \frac{1}{\omega_1^2 \cdot C_2} \quad (2)$$

# C-type harmonic filters

- Driving equations
  - $C_1$, $C_2$ and $L_2$ are shorted at the tuning frequency $f_t$

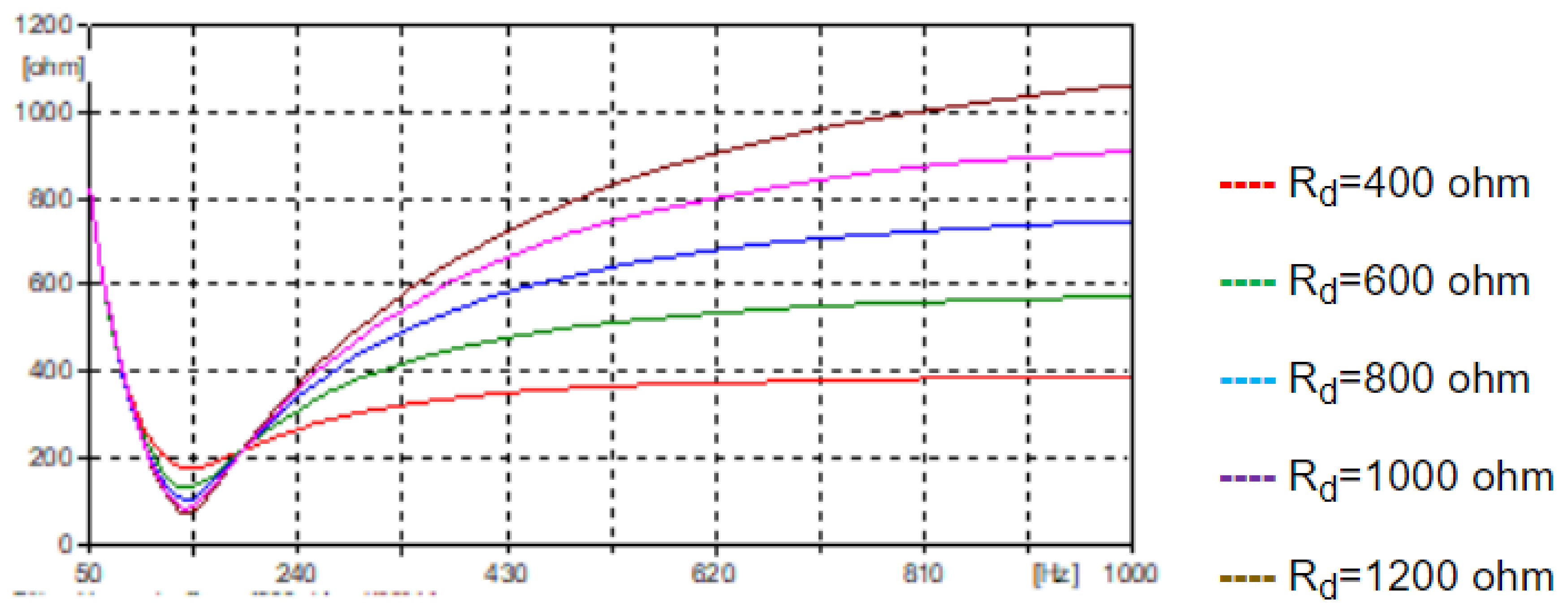
$$\omega_t = \frac{1}{\sqrt{L_2 \cdot \frac{C_1 \cdot C_2}{C_1 + C_2}}} \quad (3)$$

$$C_2 = \frac{C_1}{\omega_t^2 \cdot L_2 \cdot C_1 + 1} \quad (4)$$



# C-type harmonic filters

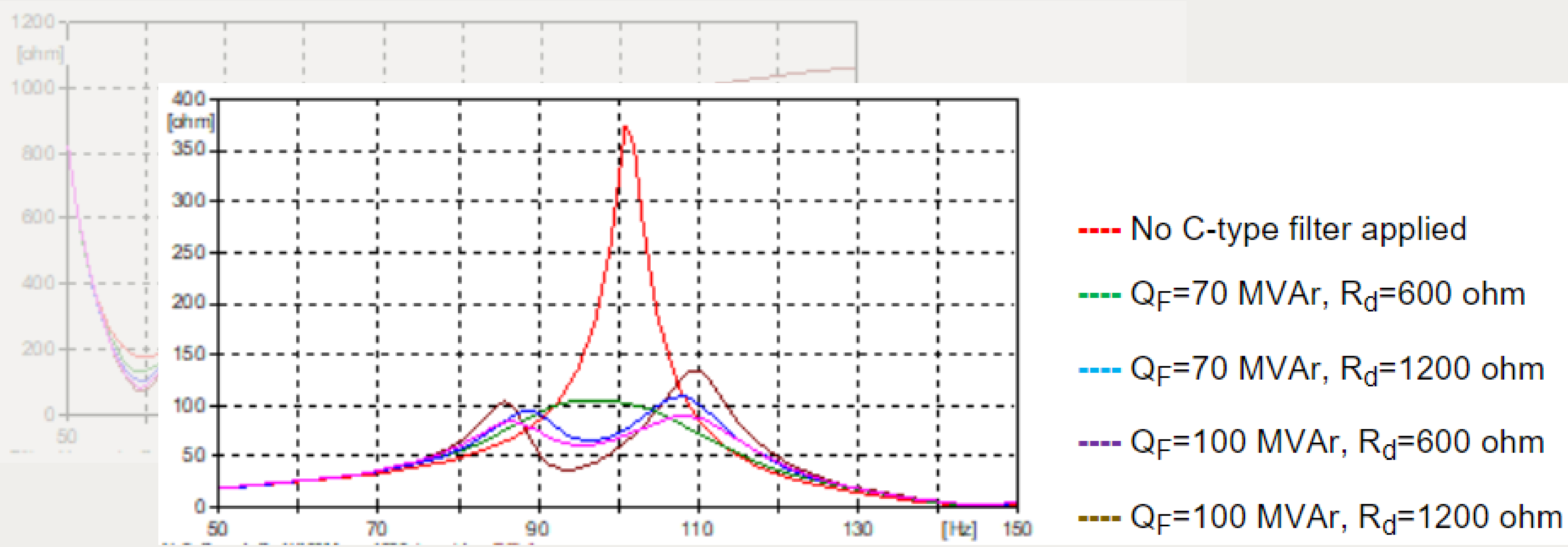
- Example case



*C-type filter harmonic impedance characteristic*

# C-type harmonic filters

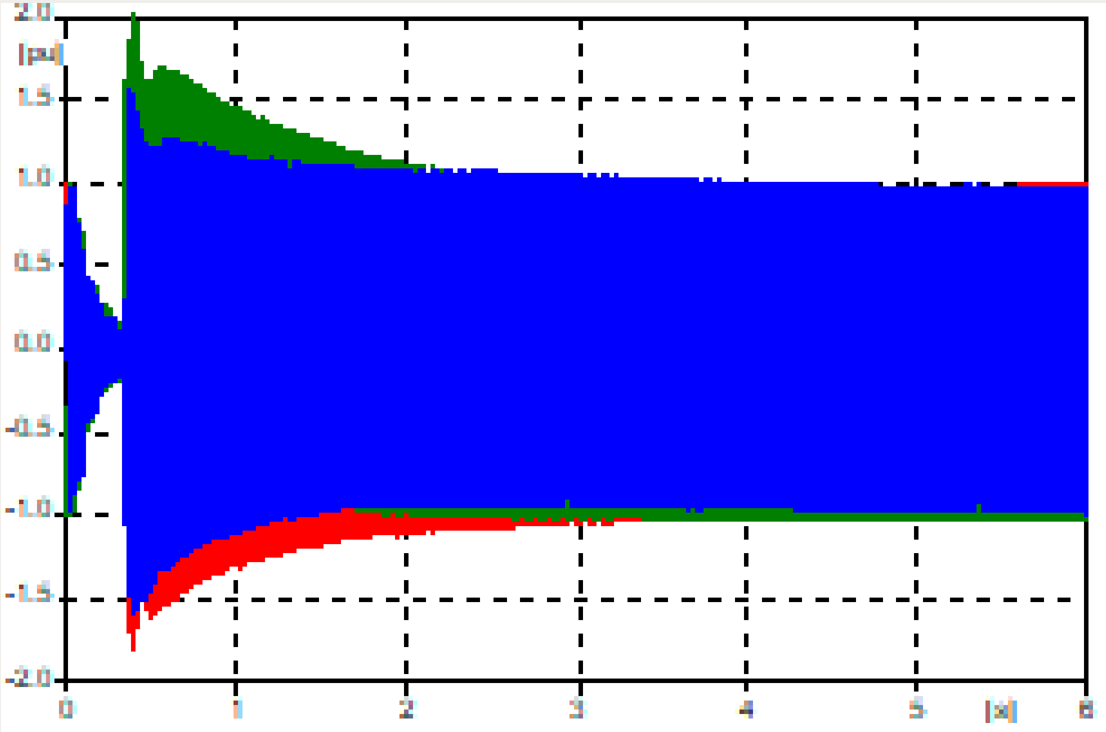
- Example case



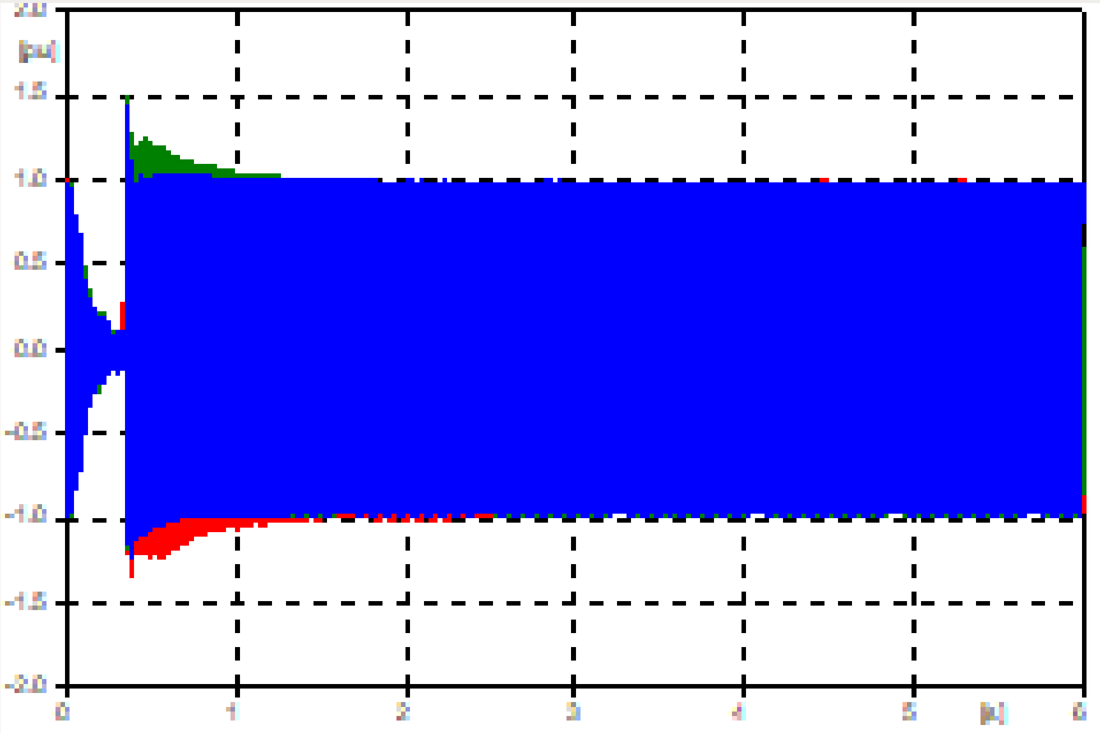
*Network harmonic impedance characteristic*

# C-type harmonic filters

- Example case



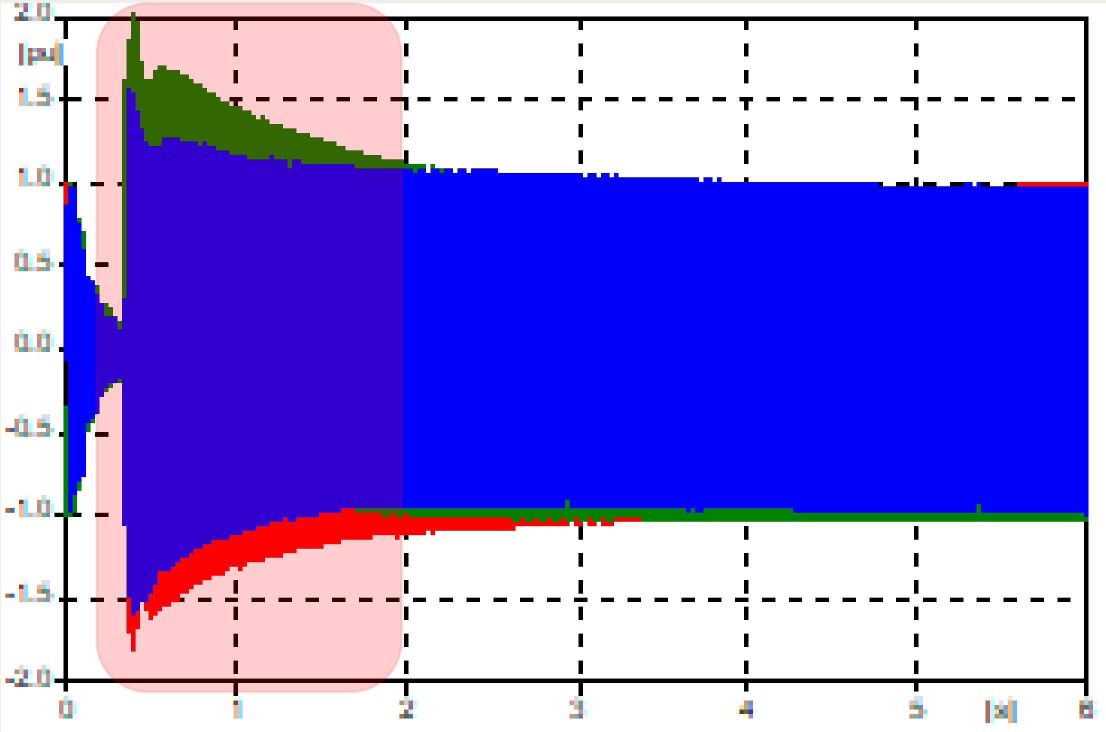
*Ph-Gr voltages: Without C-type filter*



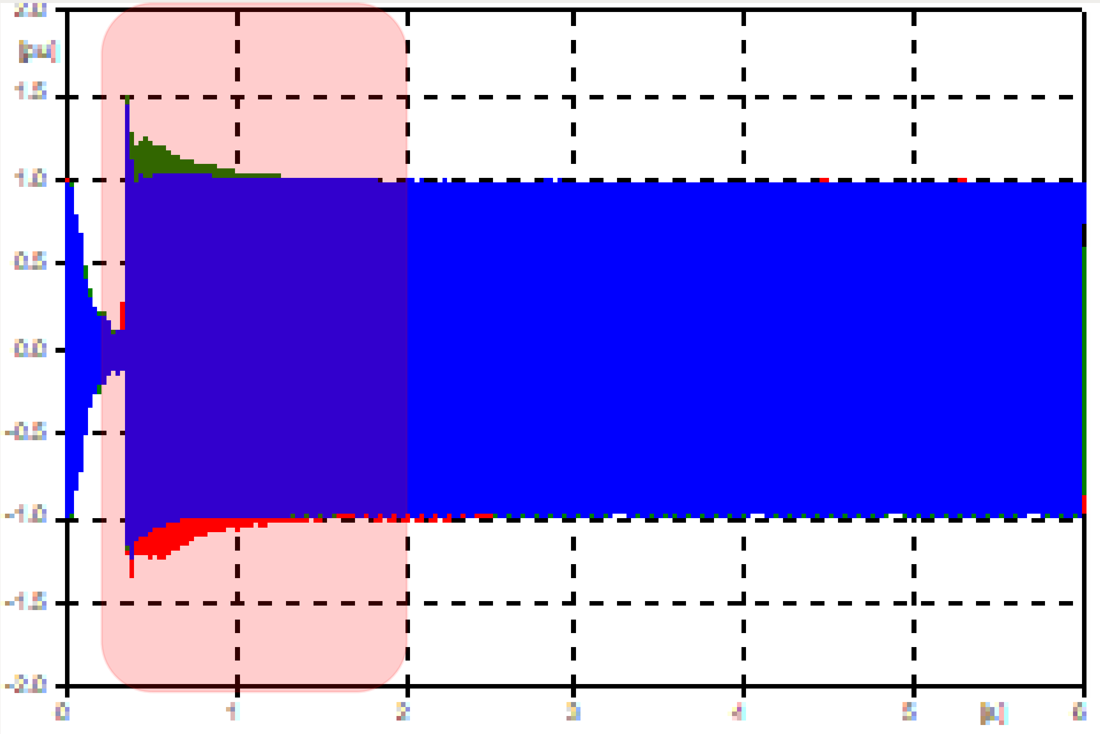
*Ph-Gr voltages: With 70 MVAr C-type filter*

# C-type harmonic filters

- Example case



*Ph-Gr voltages: Without C-type filter*



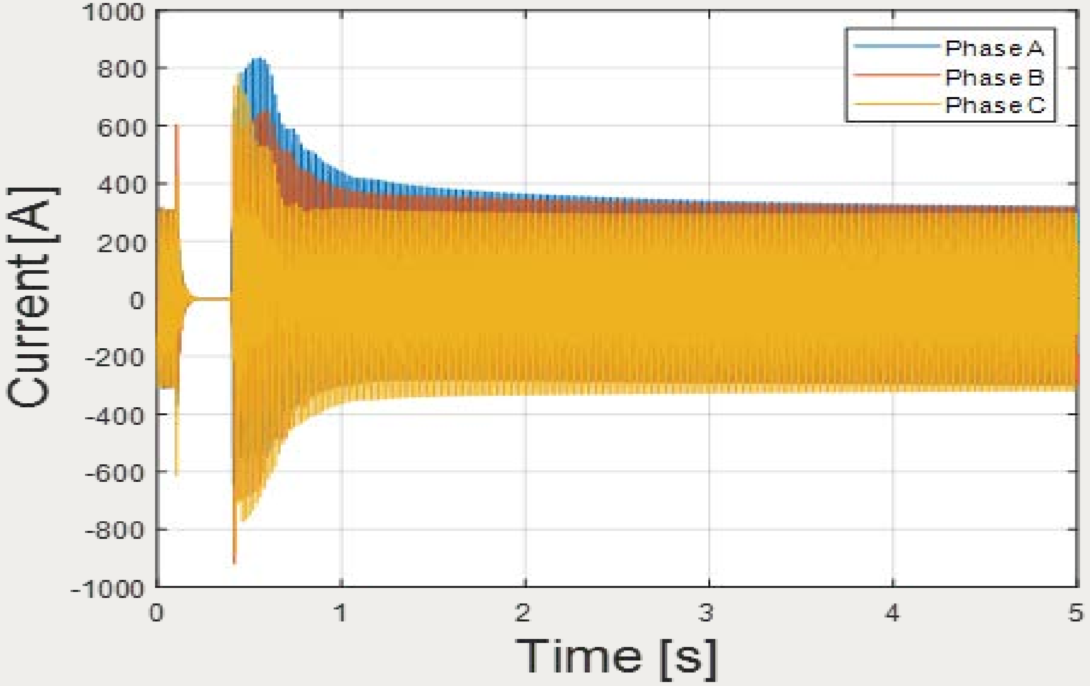
*Ph-Gr voltages: With 70 MVAr C-type filter*

# C-type harmonic filters

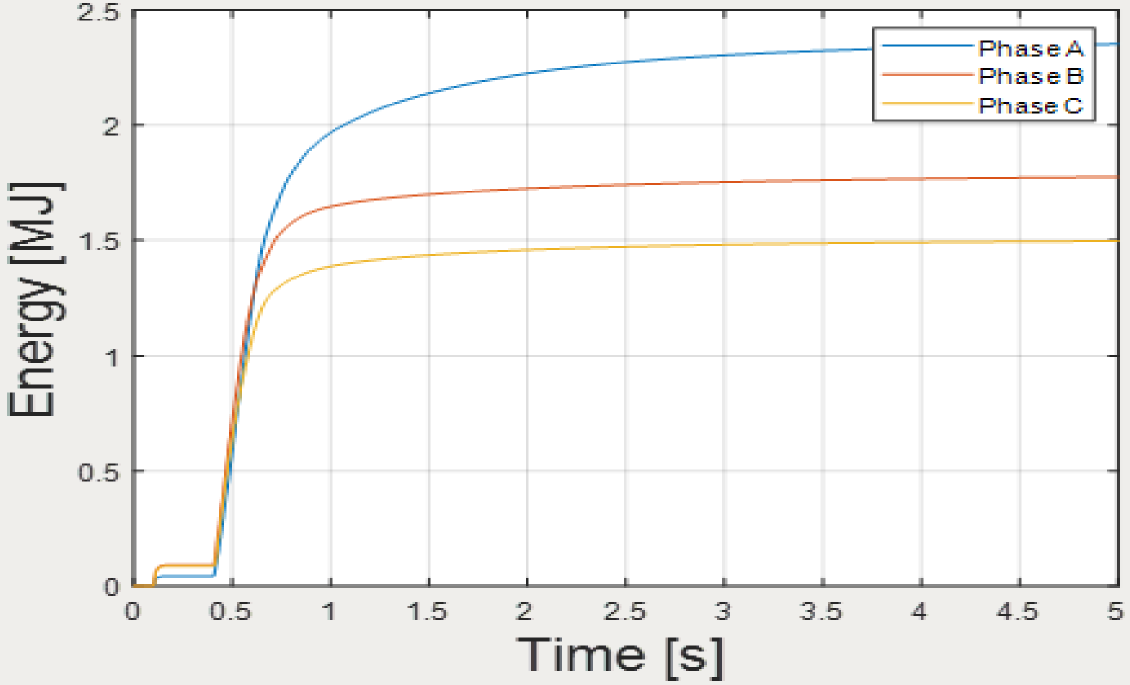
- Important aspects to be considered when designing a TOV C-type filter
    - Filter resistor losses, much higher than the typical steady state harmonic losses
    - Selection of filter surge arrester(s) with respect to energy handling and charge transfer ratings
    - Filter protection coordination (e.g. resistor overcurrent protection, etc.)

# C-type harmonic filters

- Example case



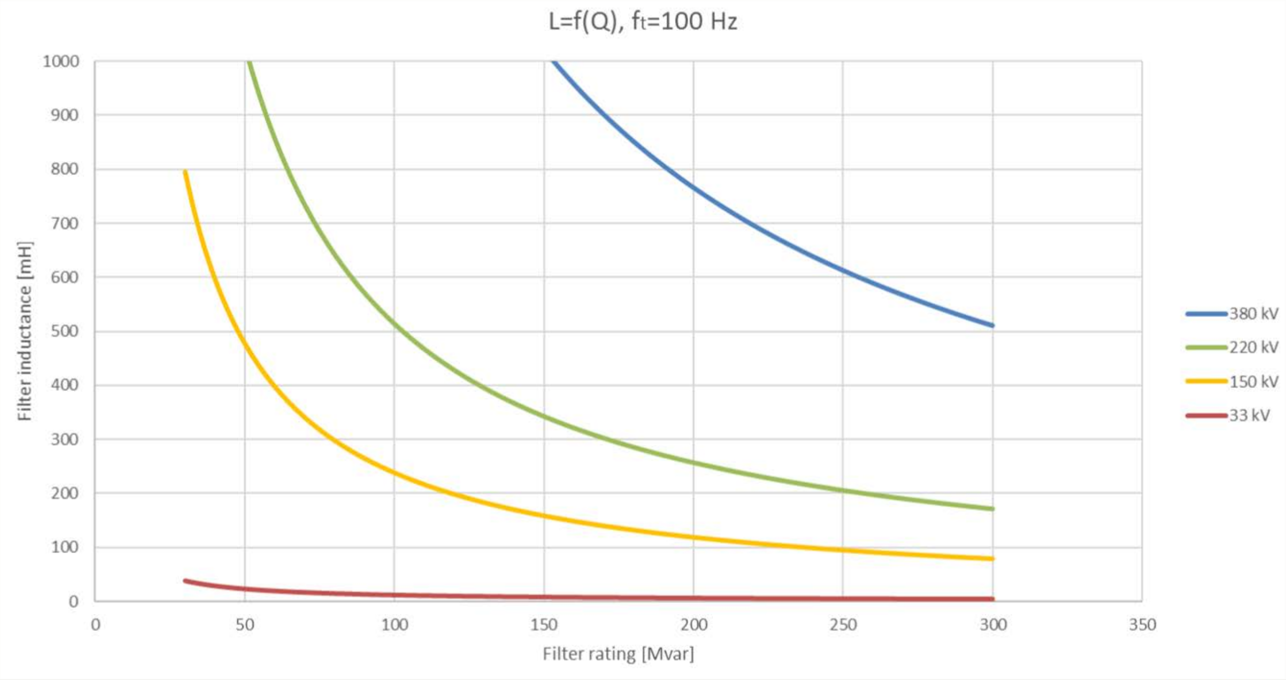
*Filter resistor currents*



*Filter resistor energy dissipation*

# C-type harmonic filters

- Important aspects to be considered when designing a TOV C-type filter
  - Filter components footprint
  - Reactive power compensation



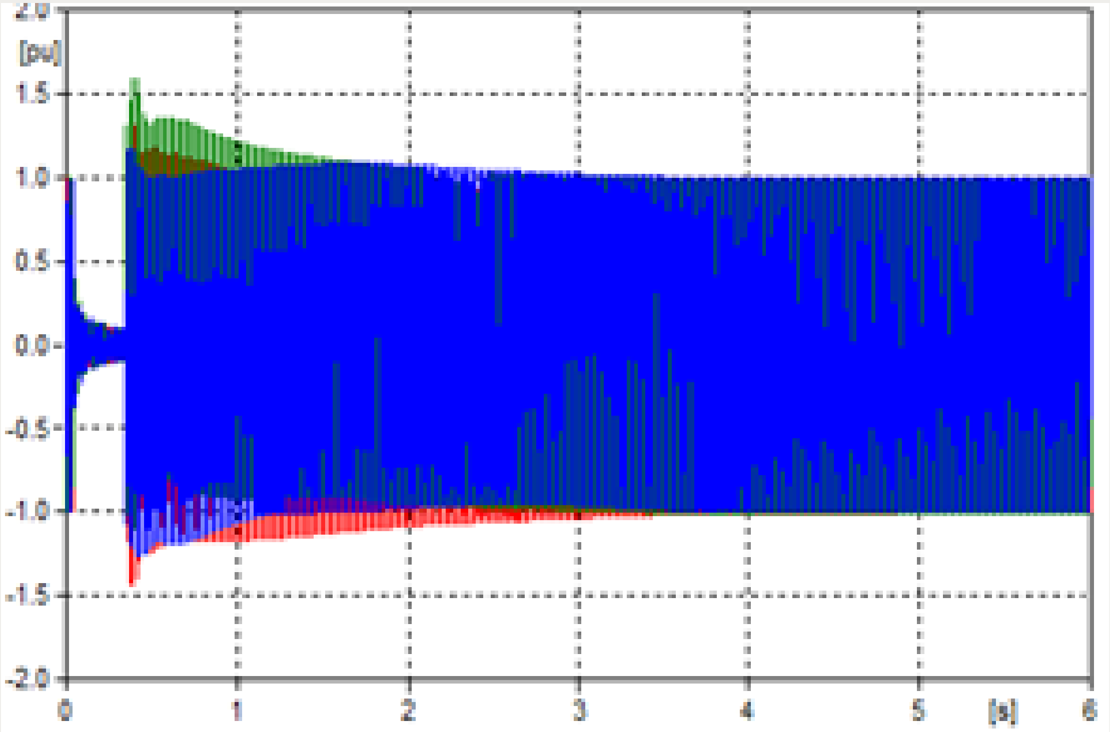
# Disconnection of power transformers

- Fault clearance directly at or at close proximity to the PoI leads (multiple) power transformers to be “virtually” re-energized

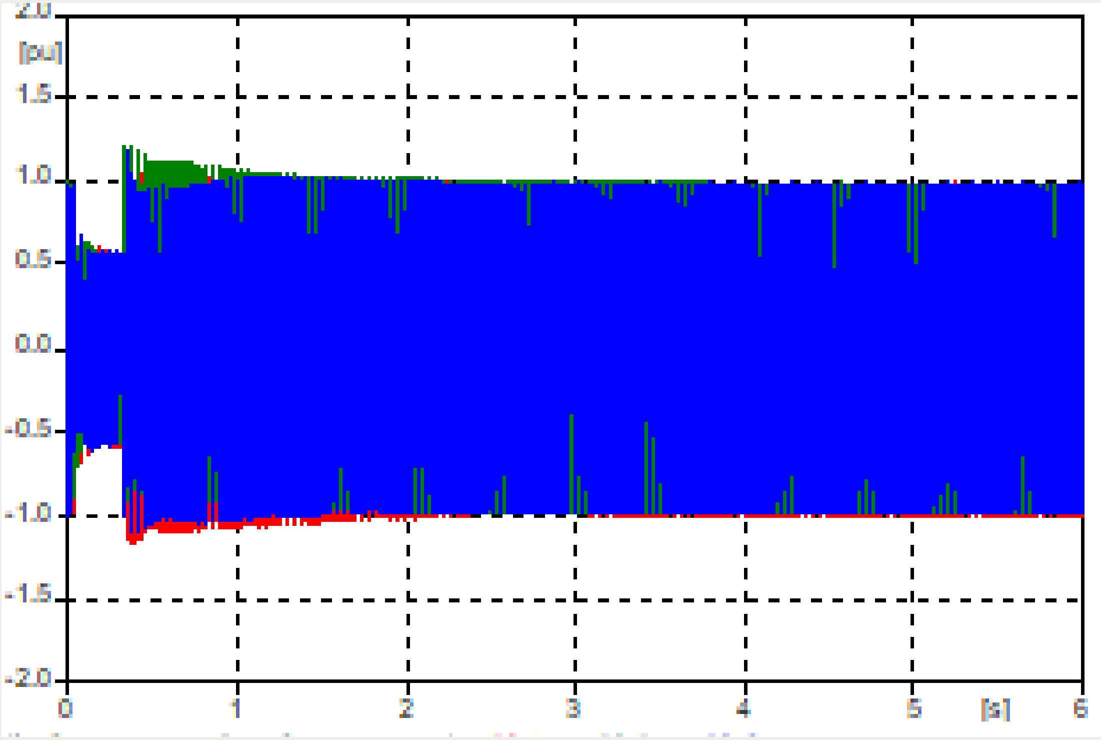
- For greater distances of the fault to the PoI:
    - smaller voltage sags compared to faults at or close to the PoI
    - lower inrush currents due to the smaller voltage recovery as “seen” by the power transformers
    - lower levels of the excited TOVs

# Disconnection of power transformers

- Example case



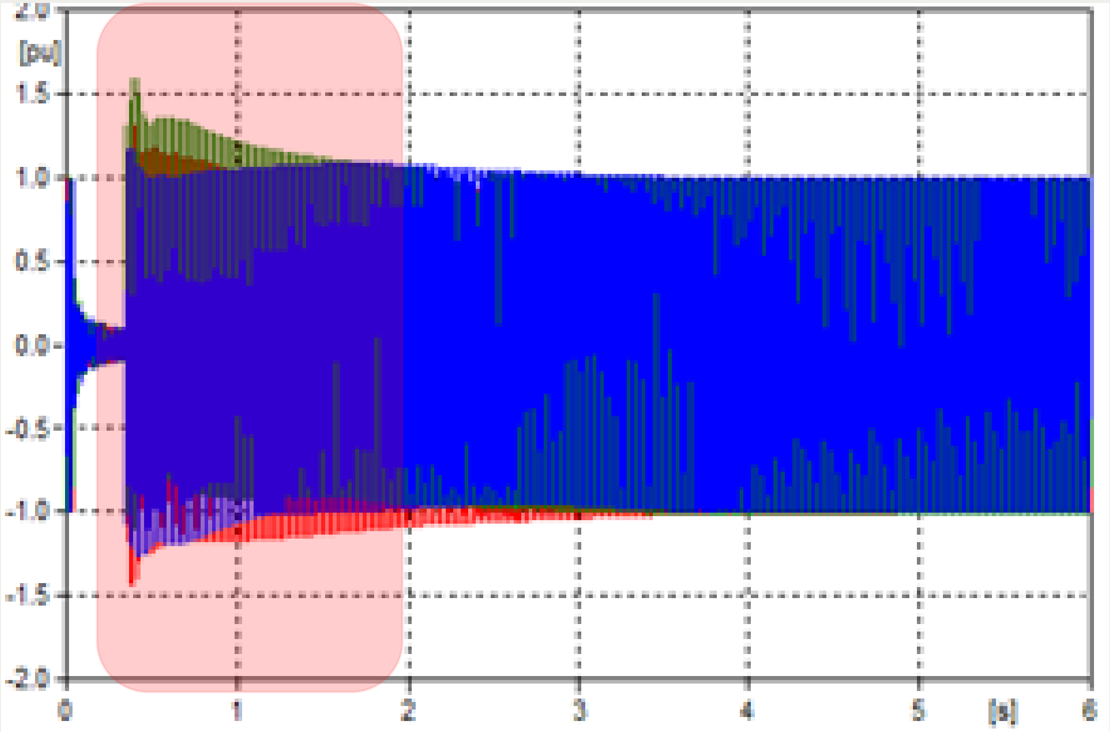
*Ph-Gr voltages: Fault at the PoI*



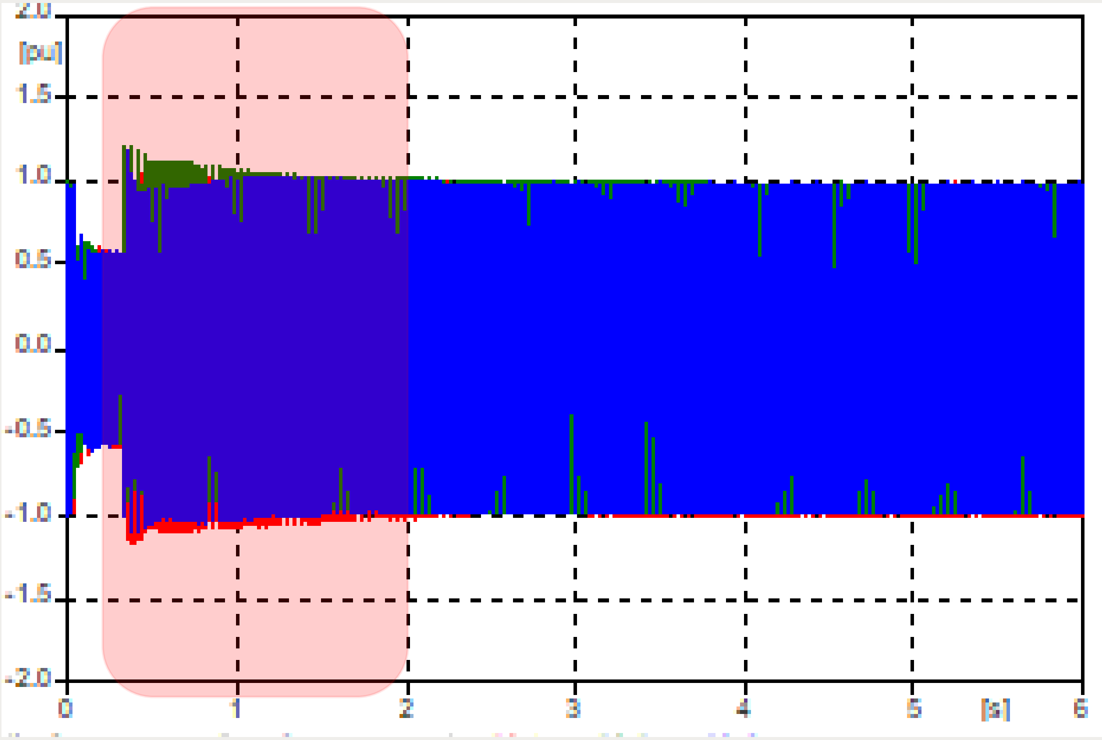
*Ph-Gr voltages: Fault at a 50-km distance to the PoI*

# Disconnection of power transformers

- Example case



*Ph-Gr voltages: Fault at the PoI*



*Ph-Gr voltages: Fault at a 50-km distance to the PoI*

# Disconnection of power transformers

- Undervoltage protection forms a preventive strategy against TOVs
    - If the voltage level at the PoI goes out of the defined limits, tripping signals are generated for the circuit breakers of the power transformers
    - Detailed analysis should a) define the minimum undervoltage levels that result in unacceptable TOVs and b) select the power transformers once critical undervoltage conditions occur

# 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<br>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<br>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<br>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<br>Fault clearing | | Risk of repeated fault clearing | Mature (in other applications) |

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# Summary and Recommendations

# Summary (1/2)

- Recently changes in the design of transmission grids are introducing resonances at low frequencies
  - TOV may contain both power frequency and harmonic content
  - More likely at some locations, e.g., adjacent to long radial cable links
- Energisation of a transformer is the mostly likely source of harmonics currents
  - Uncontrollable energisation after fault clearing is of special concern
- The characteristics of this type of TOV deviate from the standard test waveshape
- Existing standards do not provide any methods on how to evaluate TOVs due to harmonic resonances

# Summary (2/2)

- We try to provide various assessment methods for evaluation
- Guidelines for simulation are introduced
  - Different approach for the modelling of surge arresters
  - Simulation test cases showing different type of TOVs
- A list of mitigation measures
  - Some specific for this type of TOV, as the usage of filter or the detuning of the resonance frequency
- A description on the impact of harmonic resonance TOVs on the dielectric and thermal withstand of selected components

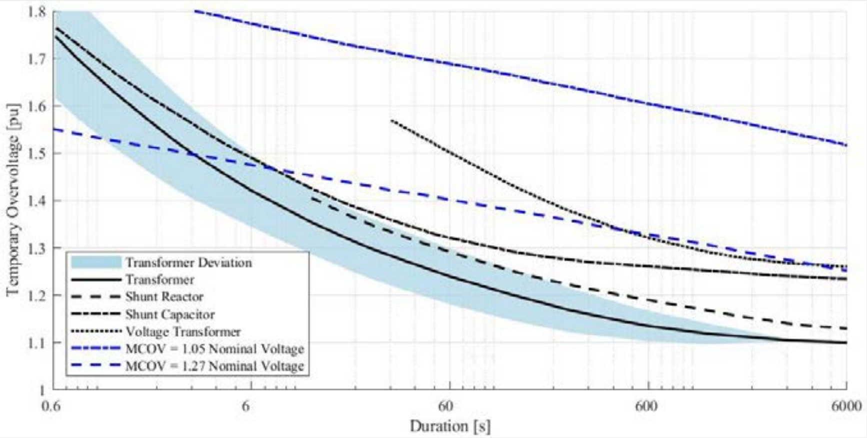
# Recommendations for future work (1/2)

- To bridge the gap between the standard testing procedure and the withstand characteristic of this type of TOVs
- A JWG combining the knowledge from experts with backgrounds on different apparatuses to update the TOV withstand curves
- The new JWG should consider durations below 600 ms, which lack presently, and provide detailed information on how the limits are obtained
- The impact of aging on the withstand curves is not clear

# Recommendations for future work (2/2)

- More public information on the impact of harmonic components on the degradation of insulation would be beneficial

- Power system technical performance experts could use all this new knowledge to improve the existing assessment methods



New

Changes in manufacturing

t < 600 ms

Aging

Harmonic stress and insulation

# Thank you for your attention

Questions?

For power system expertise