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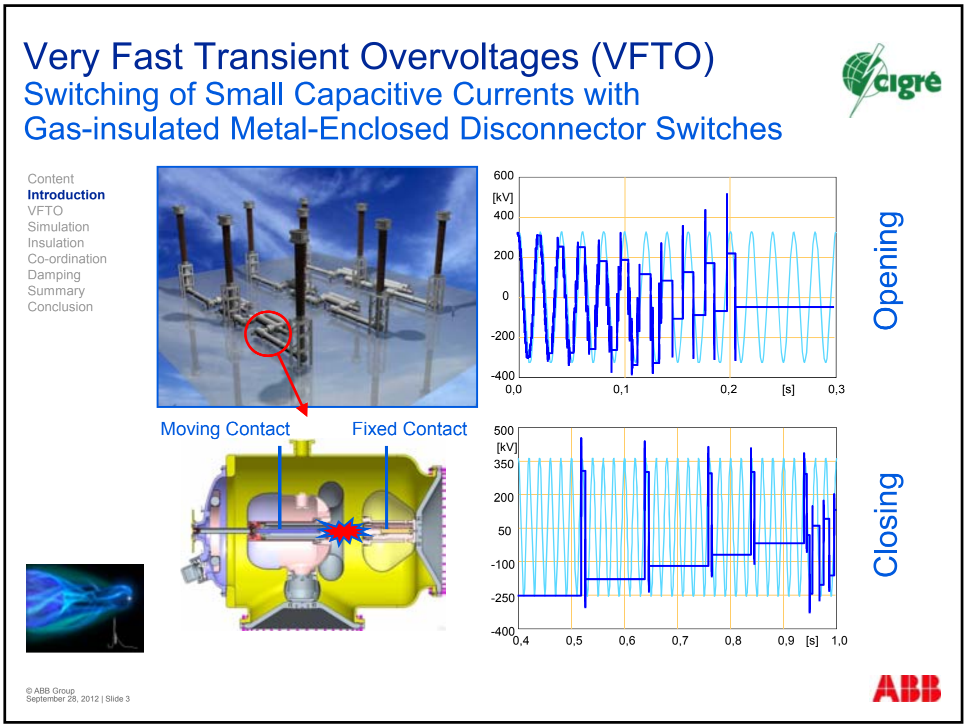
Uwe Riechert, ABB Switzerland Ltd, High Voltage Products, 2012-10-04

Very Fast Transient Overvoltages (VFTO) in Gas-Insulated EHV & UHV Substations

Tutorial of CIGRÉ Working Group A3.22 / A3.28
Technical Requirements for UHV and EHV Substation Equipment

Power and productivity for a better world™

Contents


Very Fast Transient Overvoltages (VFTO)
Switching of Small Capacitive Currents with
Gas-insulated Metal-Enclosed Disconnector Switches
cigré
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Moving Contact
Fixed Contact
Opening
Closing
[kV]
[s]
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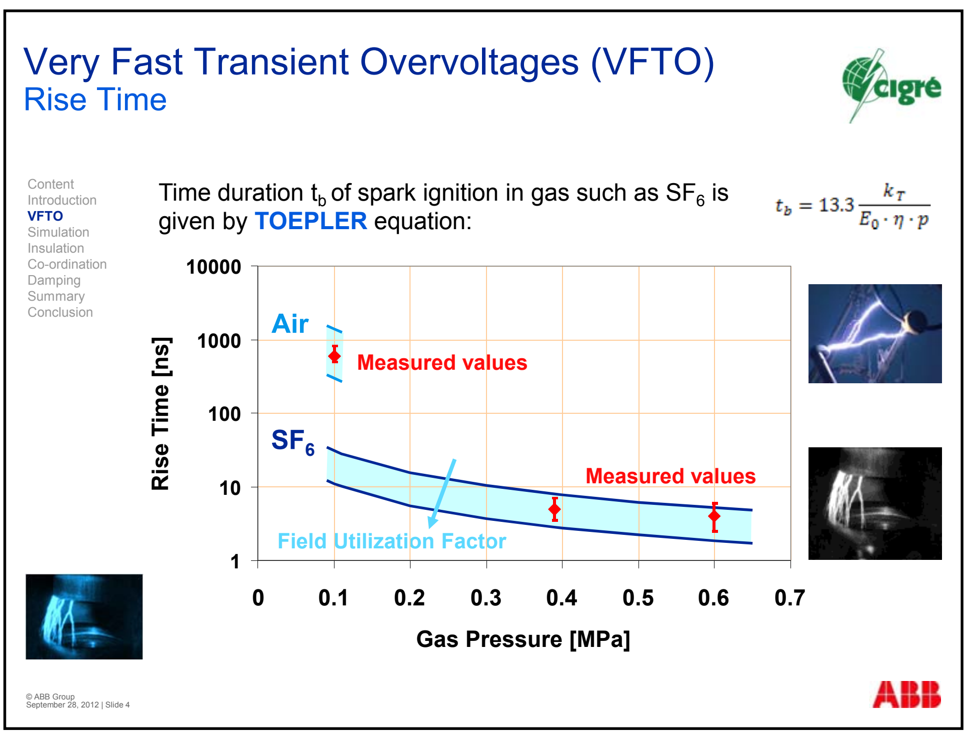
Very Fast Transient Overvoltages (VFTO)
Rise Time
cigré
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Time duration t_b of spark ignition in gas such as SF_6 is given by TOEPLER equation:
$t_b = 13.3 \frac{k_T}{E_0 \cdot \eta \cdot p}$
Air
Measured values
SF_6
Measured values
Field Utilization Factor
Rise Time [ns]
Gas Pressure [MPa]
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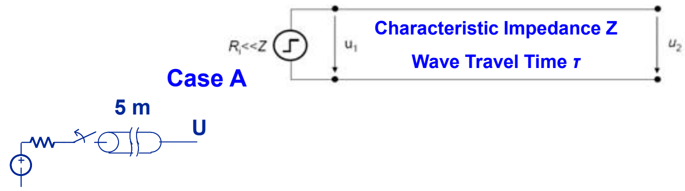
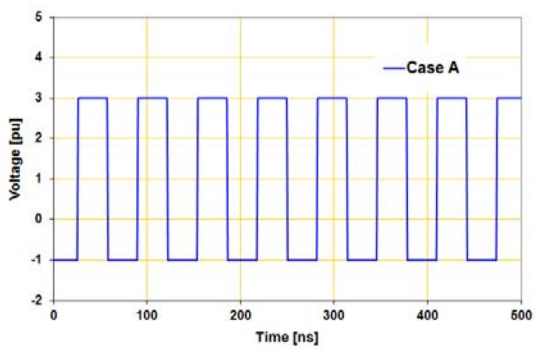
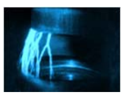
VFTO - Amplitude
Principle – Case A



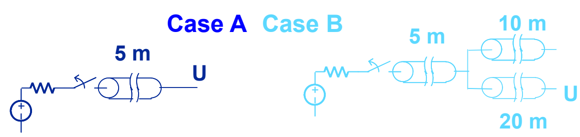


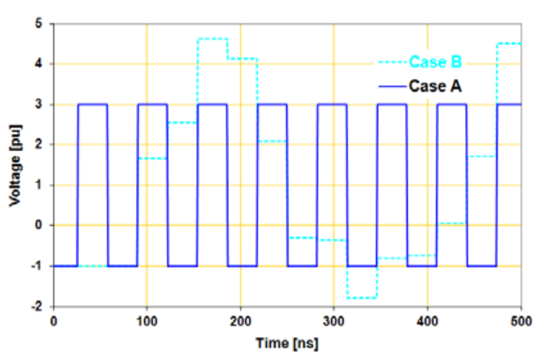


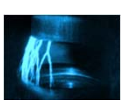
R = 0 Ω

U_{TC} = -1 pu

VFTO - Amplitude
Principle – Case B







R = 0 Ω

U_{TC} = -1 pu

VFTO - Amplitude
Principle – Damping Effect

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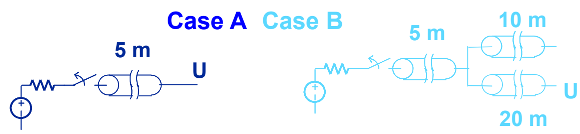

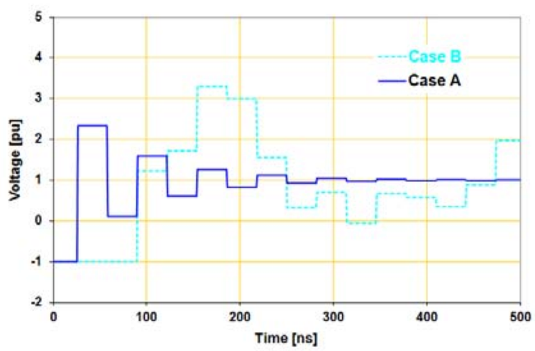

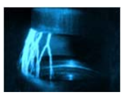

R = 10 Ω

U_{TC} = -1 pu

VFTO - Amplitude
Principle – Real Trapped Charge

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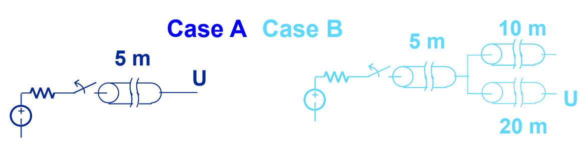
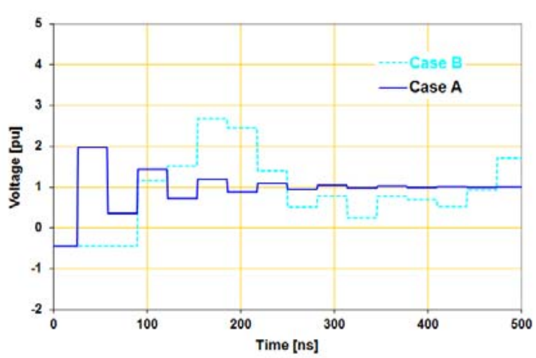
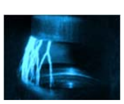
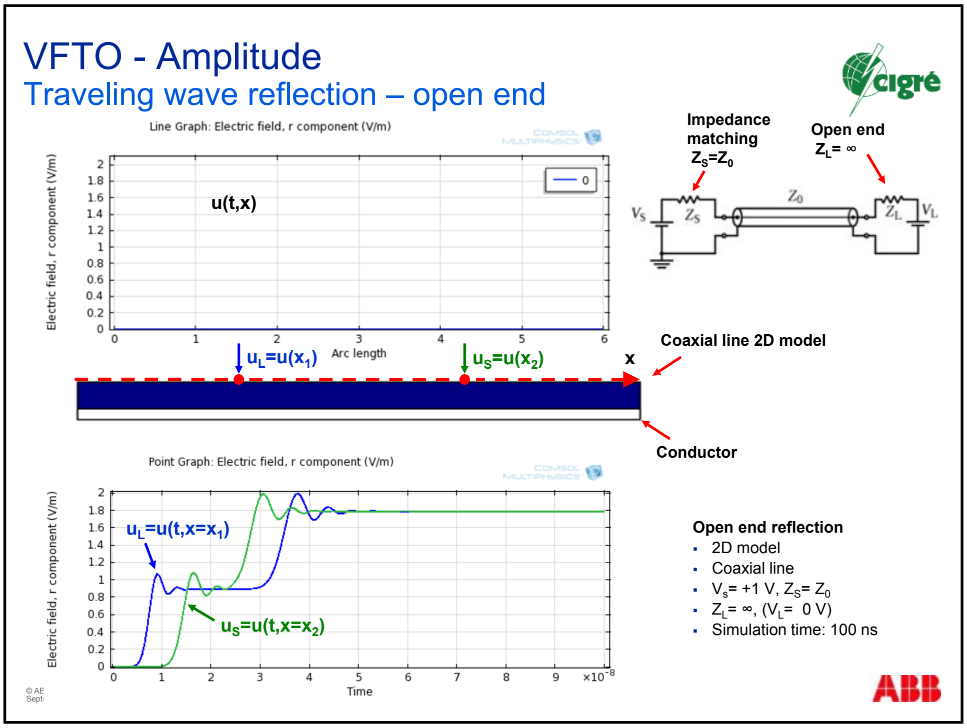






R = 10 Ω

U_{TC} = -0.45 pu


VFTO - Amplitude
Traveling wave reflection – open end
Line Graph: Electric field, r component (V/m)
Electric field, r component (V/m)
u(t,x)
Arc length
$u_L=u(x_1)$
$u_S=u(x_2)$
x
Impedance matching $Z_S=Z_0$
Open end $Z_L=\infty$
Coaxial line 2D model
Conductor
Point Graph: Electric field, r component (V/m)
$u_L=u(t,x=x_1)$
$u_S=u(t,x=x_2)$
Time
Open end reflection
2D model
Coaxial line
V_s= +1 V, $Z_S= Z_0$
$Z_L= \infty$, (V_L= 0 V)
Simulation time: 100 ns
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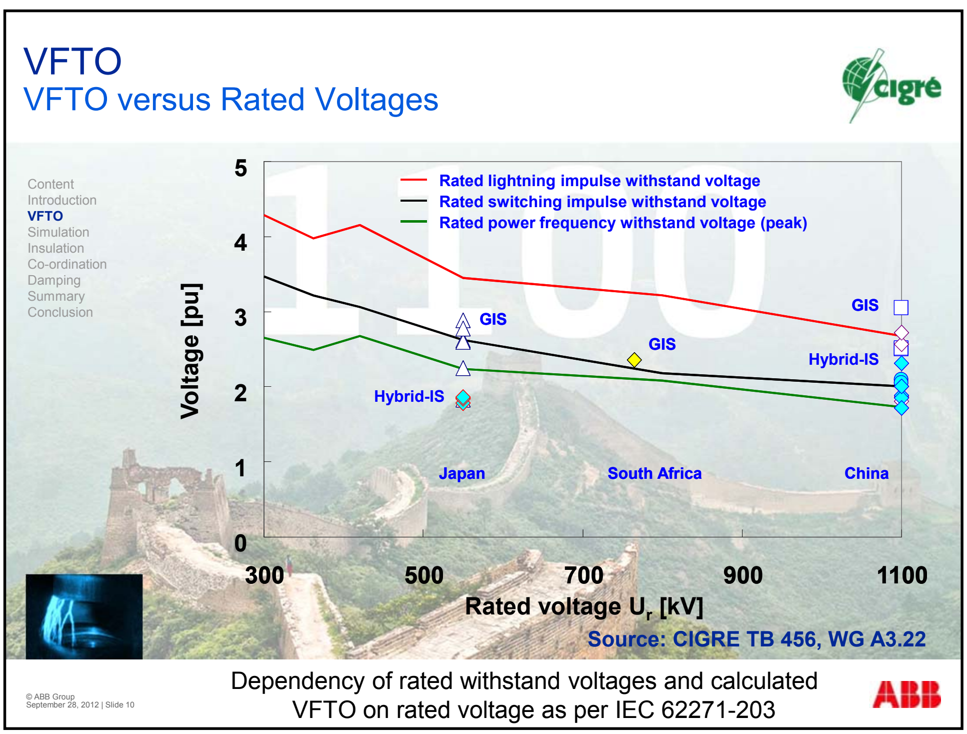
VFTO
VFTO versus Rated Voltages
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Rated lightning impulse withstand voltage
Rated switching impulse withstand voltage
Rated power frequency withstand voltage (peak)
Voltage [pu]
GIS
Hybrid-IS
Japan
South Africa
China
Rated voltage U_r [kV]
Source: CIGRE TB 456, WG A3.22
Dependency of rated withstand voltages and calculated VFTO on rated voltage as per IEC 62271-203
ABB

VFTO
Classification in High Voltage GIS Substation

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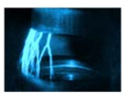
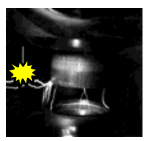
Origin	**switching operation in gas-insulated HV substations** ↓ **Very fast transients in gas-insulated substations VFTO**			
Propagation	**Internal transient voltages**	**External transient voltages**		
	Travelling waves between inner conductor and enclosure	**Transient enclosure voltage TEV**	**Transient electromagnetic fields EMF**	**Travelling waves on overhead lines**
Effect	**Stresses in insulation**	**Stresses in secondary equipment**		**Stresses in air-insulated operating equipment**





Leader branching

design,
free moving particles,
DC stress

control circuits, EMC,
personnel safety

Transformer, bushings

ABB

IEC 62271-102 Annex F
Requirements for switching of bus-charging currents by disconnectors for rated voltages 72.5 kV and above

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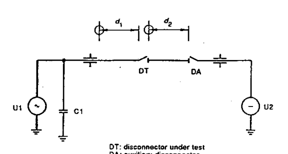
- Test Duty TD 1: Switching of a very short section of busbar duct
  - Normal type test and mandatory for DS
  - The circuits for DS testing were chosen in such a way, that maximum pu (per unit) values for VFT peak were generated and it was assumed that they would also be the highest possible in the GIS.
  - The test circuit has to be arranged in such a way, that the measured peak voltage to ground without a trapped charge voltage at the load side and 1 pu at the source side is higher than 1.4 pu. The time to first peak should be less than 500 ns.

IEC



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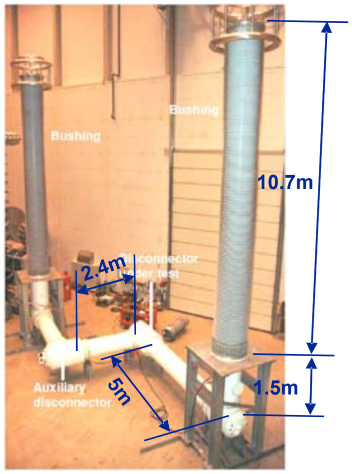
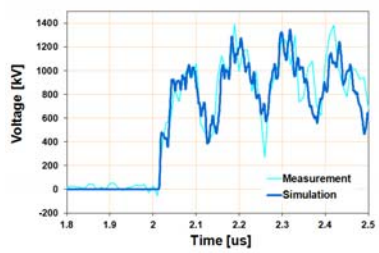
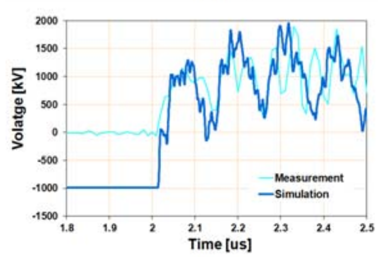
VFTO Measurement
Test Set-up TD 1

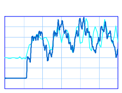


VFTO Simulation
Calculation and Measurement of VFTO

- **Conventional single spark approach**
  - EMTP- electromagnetic transient program
- **The accuracy of the simulation model must be verified**
- VFTO calculation and measurement when switching busbars with a GIS DS as per IEC 62271-102
  - without pre-charging
  - with pre-charging
- The measured voltage progressions coincide very well with the simulation.

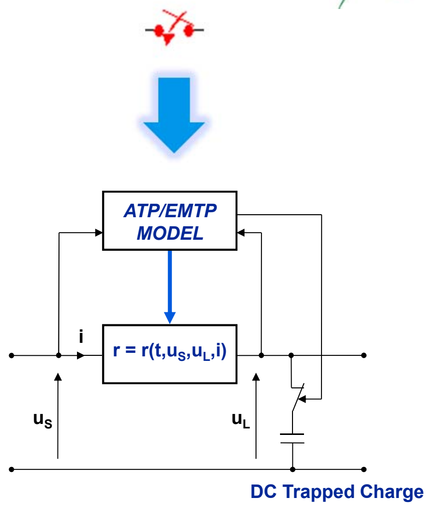






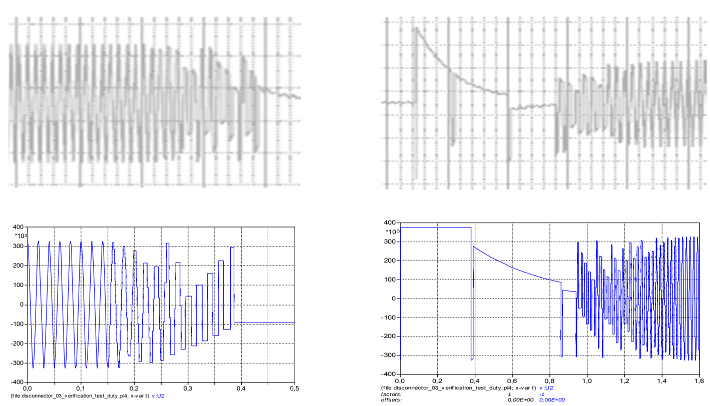
VFTO Simulation
Extended Disconnector Model

- **Simulation of the entire process**
  - Consideration of the dielectric behavior of the DS
  - Simulation of all pre-strikes and re-strikes
- **Calculation**
  - Trapped Charge (DC)
  - Pre- and Re-strike duration
  - Number of strikes
- **As basis for the insulation coordination**

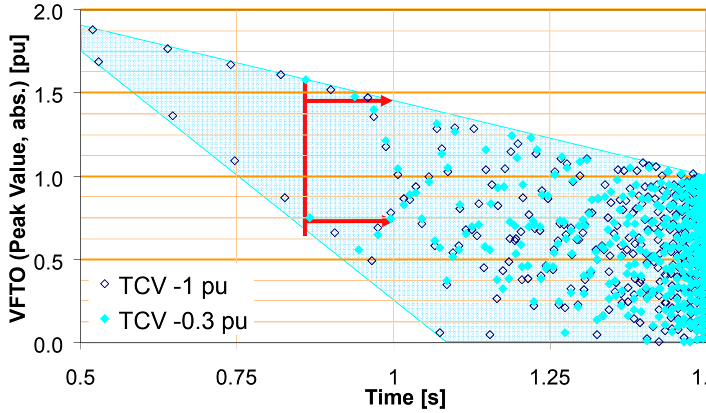


VFTO – Full DS Operation
Comparison of Calculation and Measurement (Tests)

- A comparison between simulation and measurement can verify the accuracy of the simulation.



VFTO Simulation – Extended Model
Calculation of Number of pre-strikes during one Closing



VFTO Simulation – Extended Model
Trapped Charge Voltage TCV

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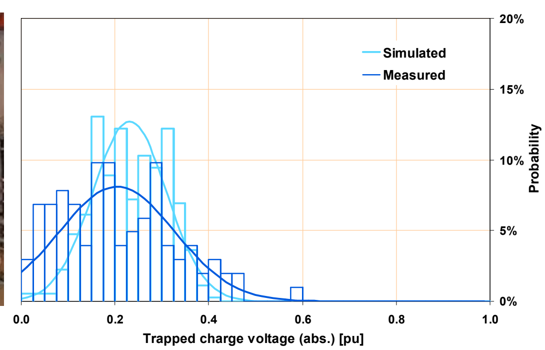
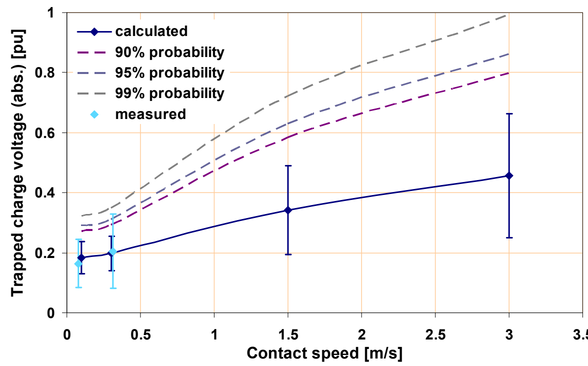
- Use of real trapped charge behavior of the disconnector, if known.
- Otherwise the worst case assumption of a trapped charge voltage of -1 pu should be used for the simulation.



VFTO Simulation – Extended Model
TCV Distribution

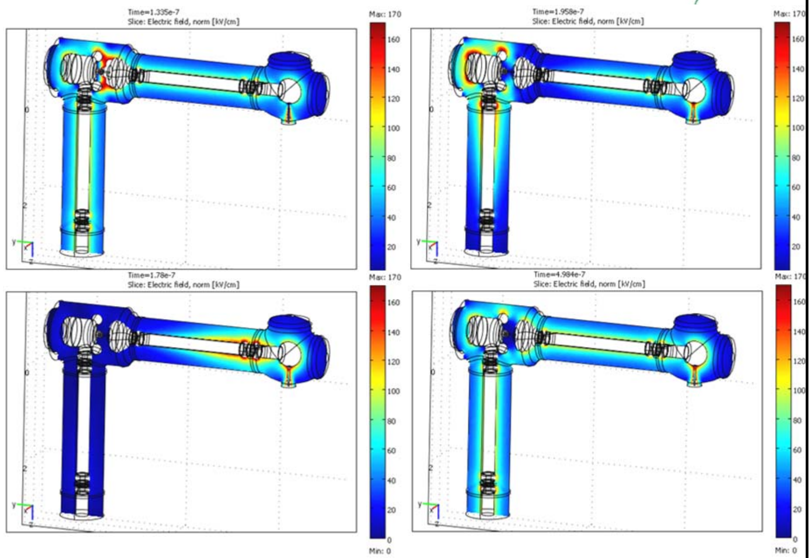
- The TCV distribution depends strongly on the contact speed.
- The TCV is specific for each design and could be analyzed during type testing or simulated with high accuracy.

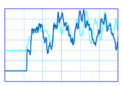


VFTO 3D Simulation
Full-Maxwell Simulation Approach

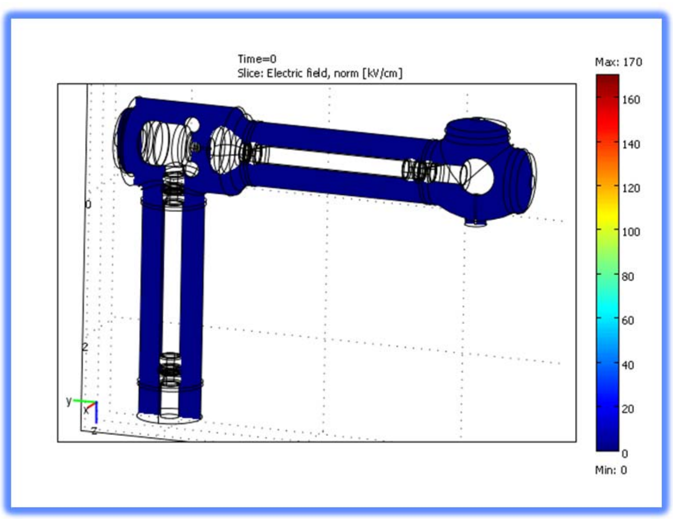
- **Full-Maxwell simulation approach (vector FEM implemented in COMSOL)**
- Full-Maxwell time-domain simulation approach offers the following advantages:
  - Very fast transients can be visualized and its wave character can be better understood
  - Local field values are available over the 3D GIS geometry
  - Critical places of the GIS design can be reliably detected
  - Sensitivity study with small geometrical changes is possible
  - Design optimization is possible

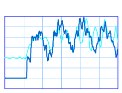
VFTO 3D Simulation
Example



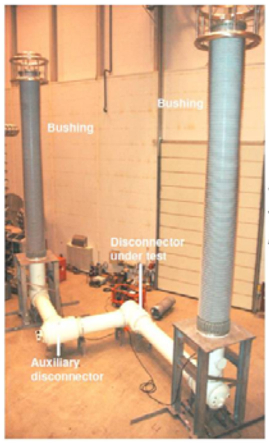


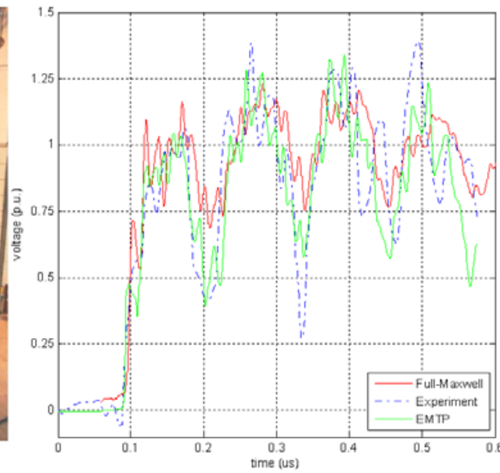
VFTO 3D Simulation
Simulation Results

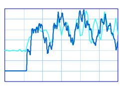




VFTO 3D Simulation
Experimental Verification of the Results







VFTO Simulation
Comparison of Simulation Methods

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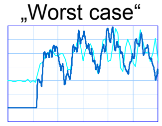
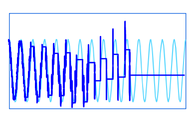
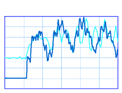
	Conventional Model	Extended EMTP Model	3D Model
Description	One Strike „Worst case“ 	Entire process 	Detailed Calculation of GIS 
Insulation coordination	Amplitude Rise Time Accuracy > 95%		
Considaration of		Trapped Charge Pre- and Re-striking Times	
Design			Visualization Local Field Strength Internal Mitigation Studies Optimization



Insulation Co-ordination Approach
Overview according to IEC 60071-1

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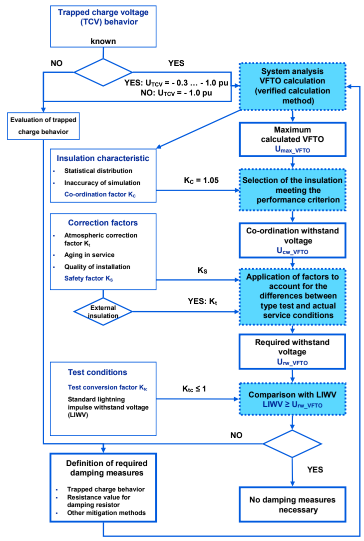
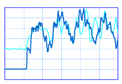


Step 1 Calculation of VFTO (peak value and rise time)

Step 2 Comparison of calculated VFTO values with LIWV level for the different equipment by using:

- Co-ordination factor K_c
- Safety factor K_s
- Test conversion factor K_{tc}

Step 3 Definition of measures according to the insulation co-ordination



VFTO Co-ordination: Step 2
Comparison of calculated VFTO values with LIWV level

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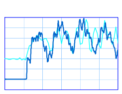
- Calculation of the required VFTO withstand voltage U_{CW_VFTO} for the different equipment by using:
  - Co-ordination factor K_c (statistical distribution, inaccuracy of simulation, frequency of occurrence) ➔ 1.05 (1.0 … 1.1)
  - Safety factor K_s (atmospheric correction, aging behavior in service, quality of installation) ➔ 1.15 (1.05 for air insulation)
  - Test conversion factor K_{tc} (for a given equipment or insulation configuration, describes the different withstand behavior under VFTO stress compared to the stress with standard LI voltages) ➔ 1.0 (0.95 for SF_6)
- Comparison of calculated required VFTO withstand voltage values with LIWV level



Insulation Co-ordination Approach
Definition of Damping Measures

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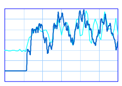
- Definition of measures according to the insulation co-ordination
  - No damping measure required
  - Damping measure required
    - DS with low TCV
    - **Damping resistor**

      Definition of required resistance value
    - **Other mitigation methods**

      Magnetic damping or resonators



VFTO Mitigation – Damping Resistor
Principles

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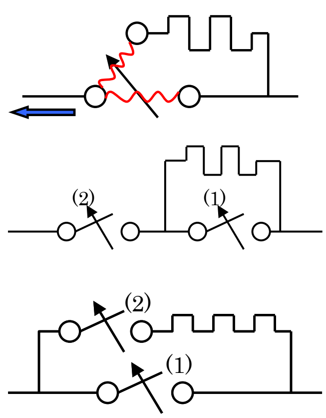
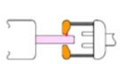
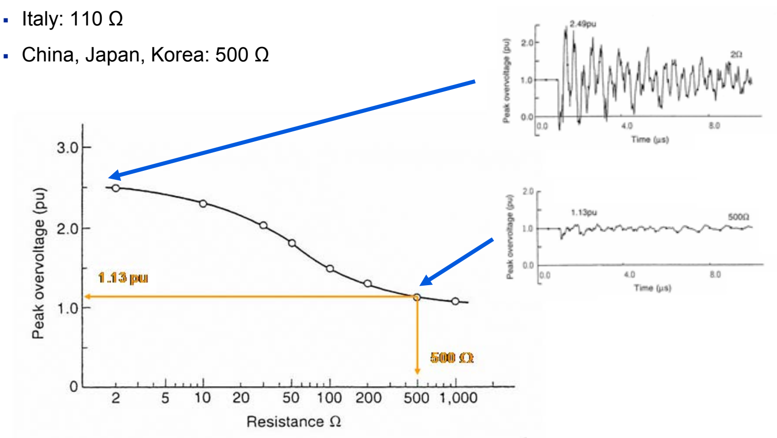
- Arc commutation
- Series resistor (contact)
- Parallel resistor (contact)





VFTO Mitigation – Damping Resistor
Effect

- Italy: 110 Ω
- China, Japan, Korea: 500 Ω



VFTO Mitigation – Damping Resistor
Working Principle and Structure

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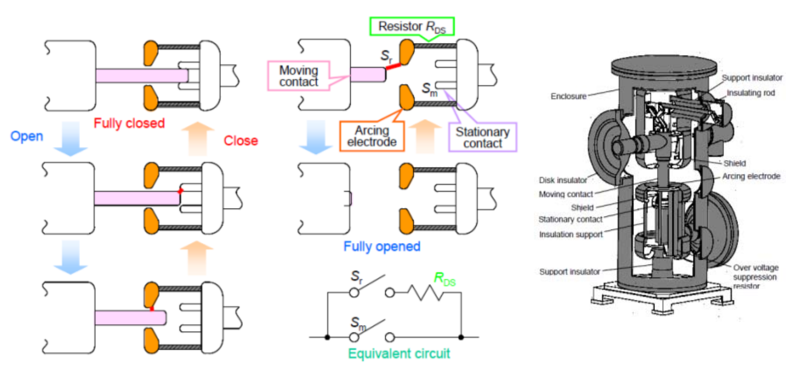
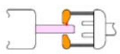


VFTO Mitigation – Damping Resistor
Requirements for the Resistor

- Voltage withstanding characteristic and energy absorption capability of the resistor in case of re-strikes and pre-strikes between the moving contact and the arcing electrode of the resistor.
- A flashover across the resistor may lead to high VFTO and has to be avoided. A higher resistance value leads to a higher voltage stress across the switching resistor. The rate of rise of the voltage across the resistor could be very high and depends on the set-up and the capacitances on the load and source side.
- The thermal absorption capability of damping resistor is defined to withstand the thermal stress of one close-open operation. During the switching a lot of re-strikes or pre-strikes occur. The absorption energy of each strike must be added to get the whole absorption energy for one operation.



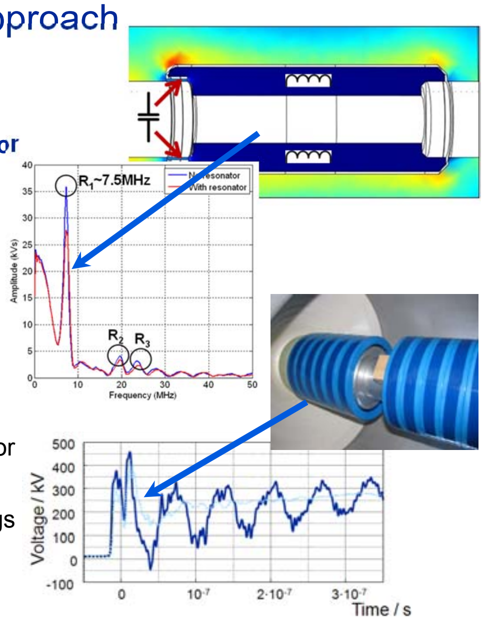
Insulation Co-ordination Approach
New Mitigation Methods

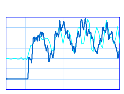
High frequency RF resonator

- Low quality factor designed to cover a wider frequency range
- Tuned to the dominant harmonic component
- 20 % damping

Nano-crystalline material

- Placed around the conductor
- Depending on number, material and size of the rings
- 20 % damping





Summary

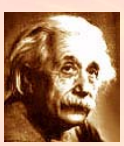
Summarizing the different experiences an insulation co-ordination procedure with three steps is proposed, following the general insulation co-ordination approach.

The trapped charge voltage is specific for each design and could be analyzed during type testing or simulated with high accuracy and has to be used for the insulation coordination.

Required damping measures could be defined for the specific project.

Conclusions

China UHV — A New Milestone in the World's Power Grid History



Everything should be as simple as it is
-
but not simpler.

Albert Einstein

CIGRÉ

UHV Working Groups

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(1) CIGRÉ WG A3.22: ***Technical Requirements for Substation Equipment Exceeding 800 kV – TB 362 & TB 456***

(2) CIGRÉ WG B3.22: ***Technical Requirement for Substations Exceeding 800 kV – TB 400***

(3) CIGRÉ Ad Hoc TF of SC D1: ***VFTO in UHV GIS Systems***

(4) CIGRÉ WG D1.36: ***Special Requirements for Dielectric Testing of Ultra High Voltage (UHV) Equipment***

(5) CIGRÉ WG C4.306: ***Insulation Coordination for UHV AC Systems***

(6) CIGRÉ WG A3.28: ***Switching phenomena and testing requirements for UHV & EHV equipment***

(7) CIGRÉ WG B3.27: ***Field tests technology on UHV substation during construction and operation***

Summary

Outlook – EHV & UHV AC World Map

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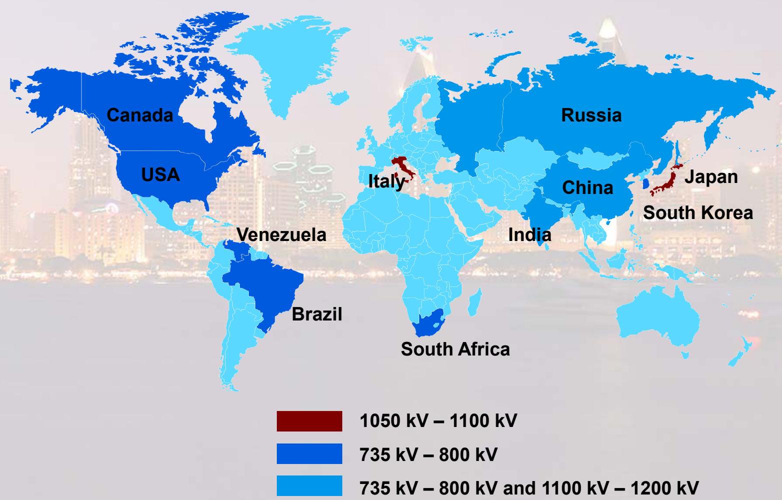

Source: CIGRÉ WG C4.306 / highest voltages

Author

CV Dr.-Ing. Uwe Riechert

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- Studies in electrical engineering at the Dresden Technical University
- Research assistant at the Dresden Technical University
  - Diagnostics and dielectric properties of polymeric insulated cables for ac and dc applications
  - PhD on the topic of polymeric insulated HVDC cables in 2001
- Since 1999 ABB Switzerland Ltd
  - Up to 2001: test engineer in the high voltage laboratory
  - Since 2001: switchgear development, responsible for partial discharge diagnostic and monitoring, solid insulating materials, dielectric design, patents, testing, product certification and cooperation with research centers and universities
  - Since 2004: development project manager (e.g. 1100 kV circuit-breaker)
  - 2008: senior manager
  - 2009-2011: high current systems (generator circuit breaker) development
  - Since 2011: gas insulated switchgear development
- Membership
  - DKE (German Commission for Electrical, Electronic & Information Technologies of DIN and VDE)
  - Swiss Electrotechnical Committee (CES) TK42 (convener) and TK115 (convener)
  - CIGRÉ working groups (AG D1.03, WG A3.28, WG D1.25, WG D1.28, WG C4.306).
  - Convener of CIGRÉ working group D1.36: Special requirements for dielectric testing of Ultra High Voltage (UHV) equipment
  - IEC TC42/WG19
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