Worley

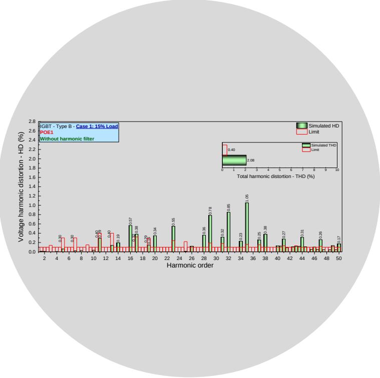
High-level Overview of Requested Power System Studies

Dr. Alireza Khakpour

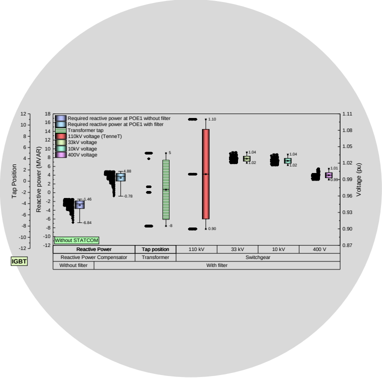
Friday, July 21, 2023

Hitachi Energy

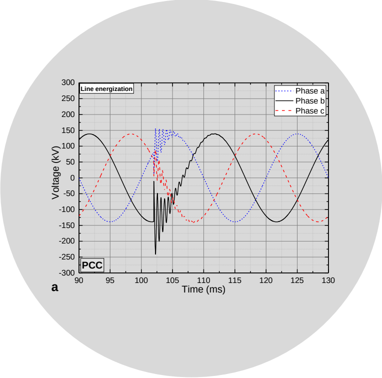
Agenda



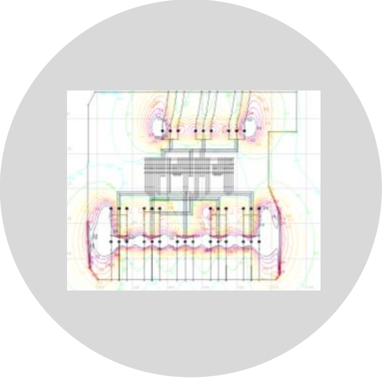
EMC Assessment



Power Factor Correction



Insulation Coordination



EMF Assessment

Arc Flash Study

Grid Compliance

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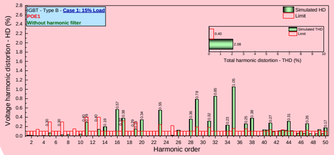
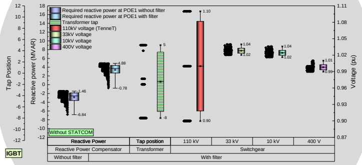
Harmonic

Resonance study



EMC Assessment



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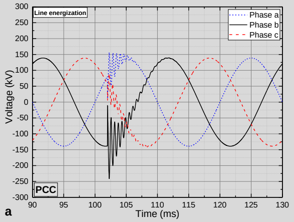

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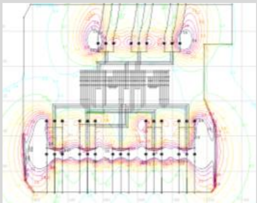

EMF Assessment

Arc Flash Study

Grid Compliance

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Power Quality Assessment – H2 Case Study

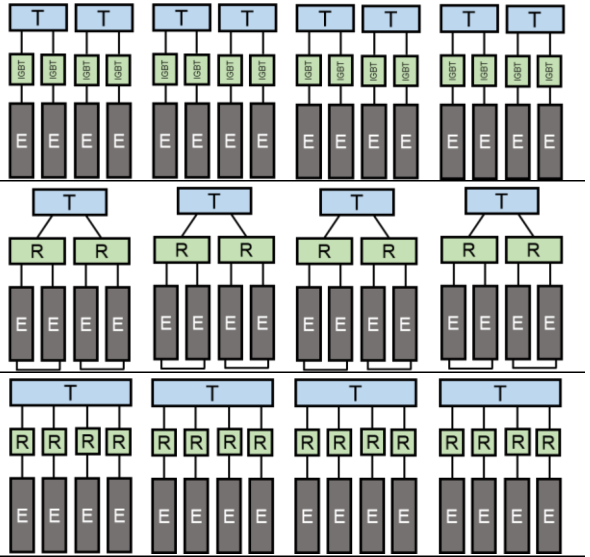
Impact of different project specific parameters /design

<u>General</u>

- Technology (Thyristor, IGBT, etc.)
- Topology (12 pulses, 24 pulses, Diode, IGBT chopper, etc.)
- Supplier
- Loading scenario
- Operating scenarios (contingencies)
- Grid Code requirement

Configuration of different topologies (T: Transformer, R: Rectifier, and E: Electrolyser)

IGBT solution (Design 1 and 2) 1 transformer with 2 rectifiers for 2 stacks in parallel	
12-pulse solution (Design 3 and 4) 1 transformer and 2 rectifiers for 2x2 stacks in series	
24-pulse solution (Design 5 and 6) 1 transformer and 4 rectifiers for 4 stacks in parallel	



Different operating cases of the TR's (contingencies in electrolysers)

Case	Topology	No. ELC's	Loading (%) Min	Loading (%) Max
1		16	15	100
2		12	20	100
3		8	30	100
4		14	17	100
5		12	20	100
6a		10	24	100
6b		10	24	100
7a 7b 7c		Depending on worst-case		

Power Quality Assessment – H2 Case Study

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Impact of different project specific parameters /design

Power Quality - Harmonic

- Technology (Thyristor, IGBT, etc.)
- Topology (12 pulses, 24 pulses, Diode, IGBT chopper, etc.)
- Supplier
- Loading scenario
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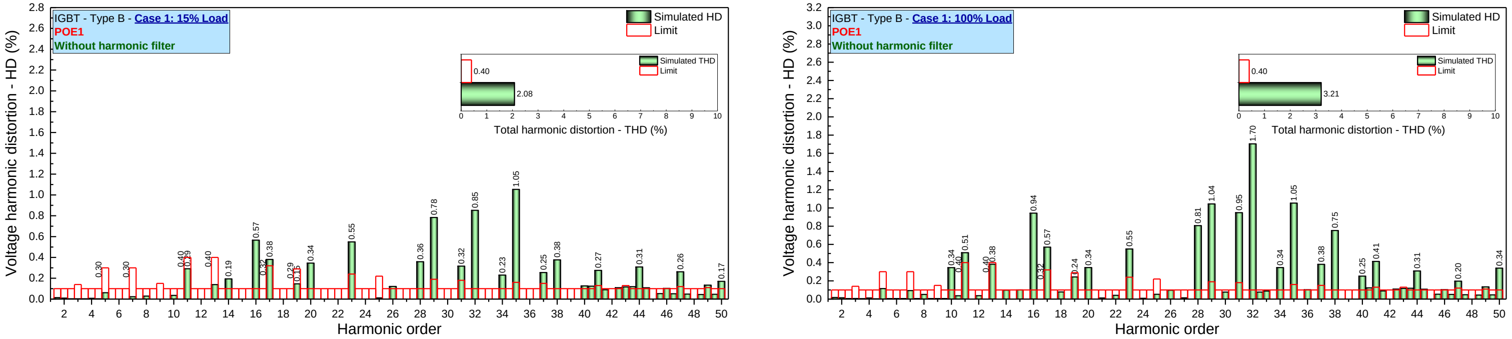
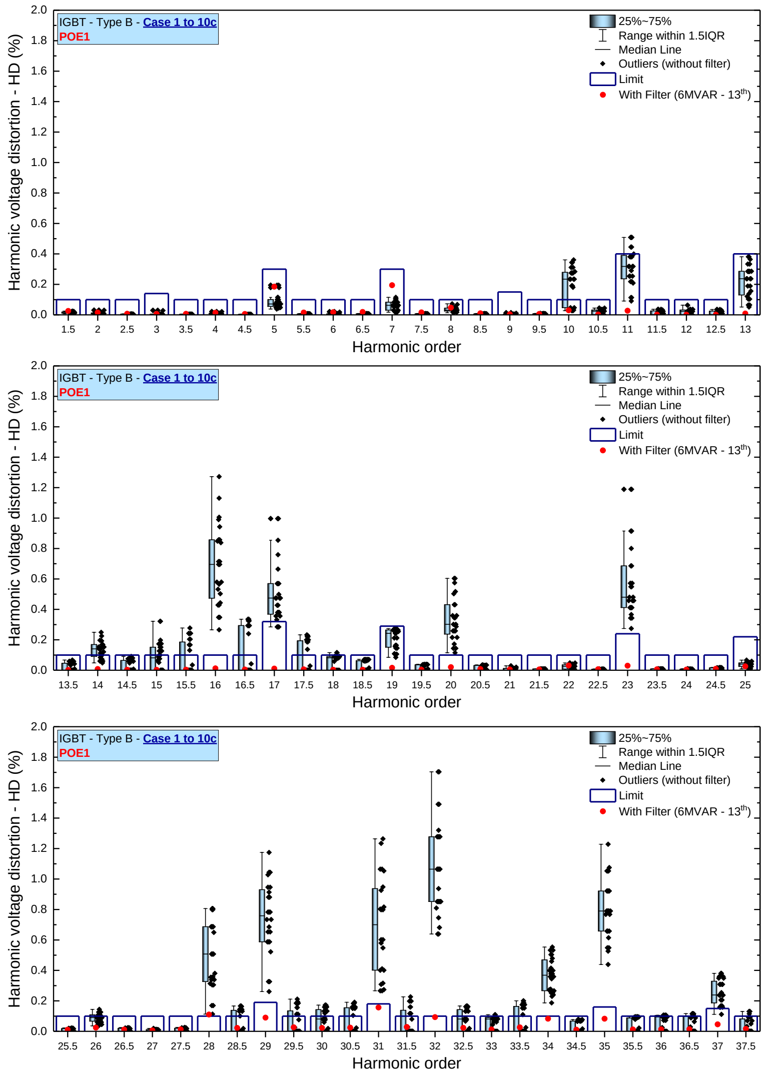
- Grid Code requirement



Impact of loading



Individual voltage harmonic distortions at POE1 for all possible cases (1 to 7c) and different loadings for IGBT solution

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Power Quality Assessment – H2 Case Study

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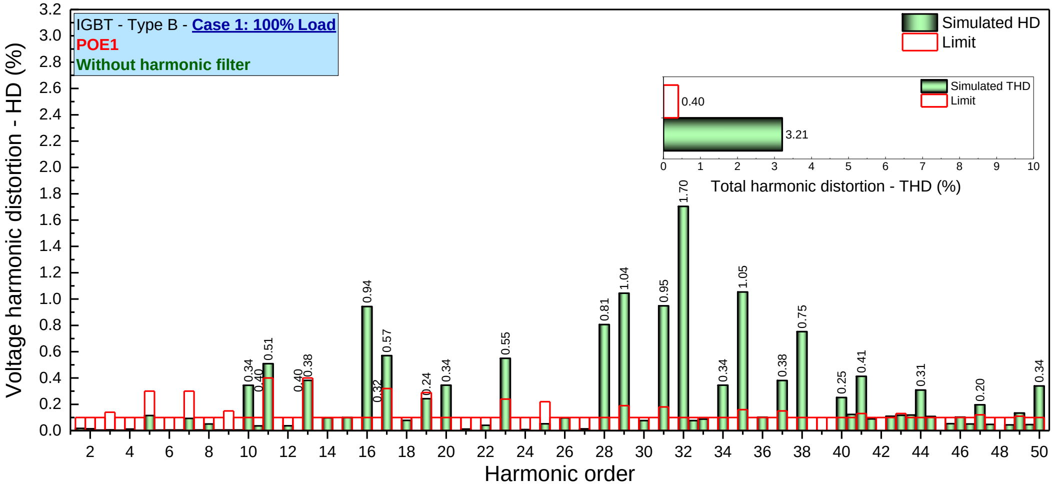
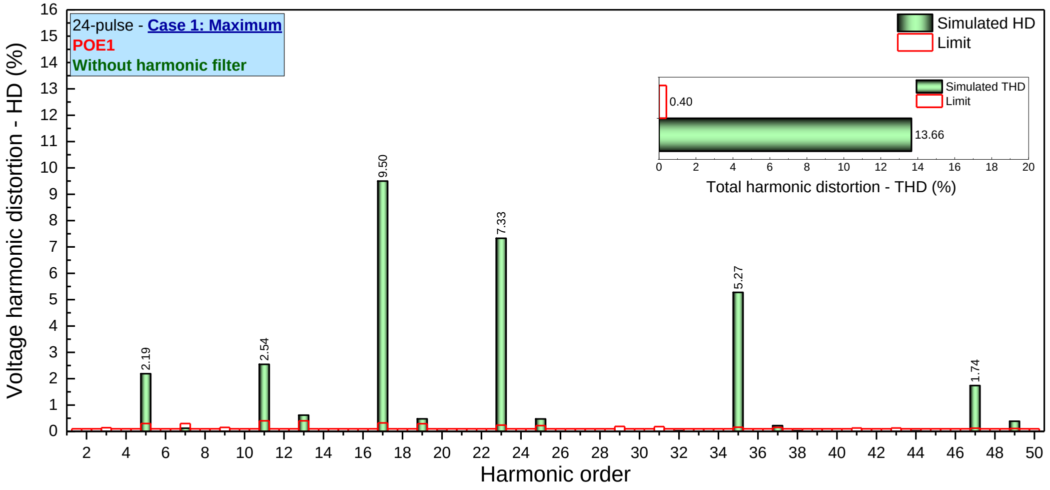
Impact of different project specific parameters /design

Power Quality - Harmonic

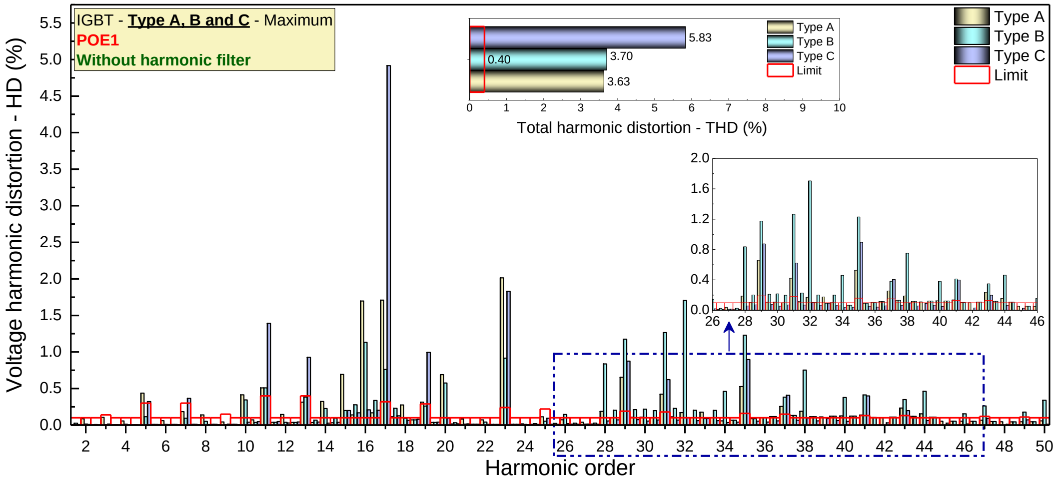
- Technology (Thyristor, IGBT, etc.)
- Topology (12 pulses, 24 pulses, Diode, IGBT chopper, etc.)
- Supplier
- Loading scenario
- Operating scenarios (contingencies)
- Grid Code requirement

Impact of topology/technology





Impact of IGBT supplier/technology



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Power Quality Assessment – H2 Case Study

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Impact of different project specific parameters /design

Power Quality - Harmonic

- Technology (Thyristor, IGBT, etc.)
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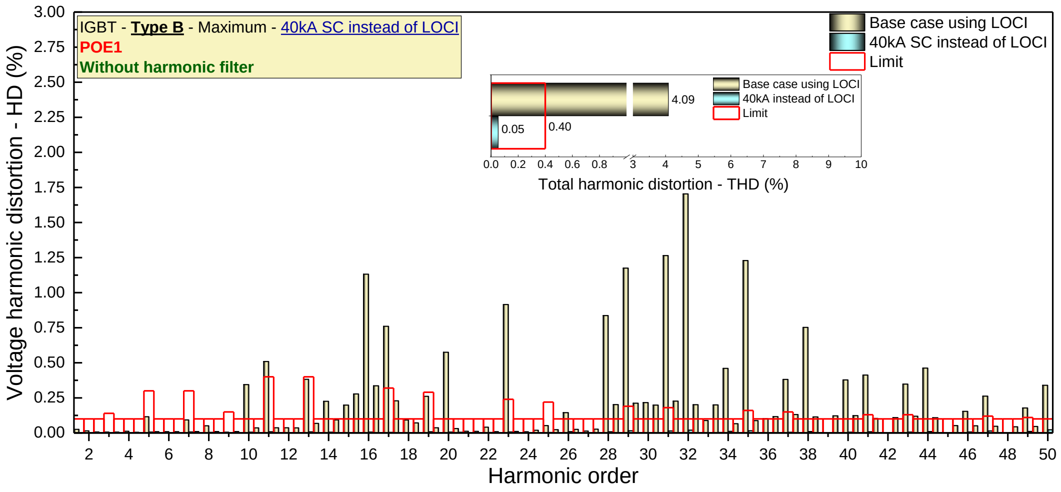
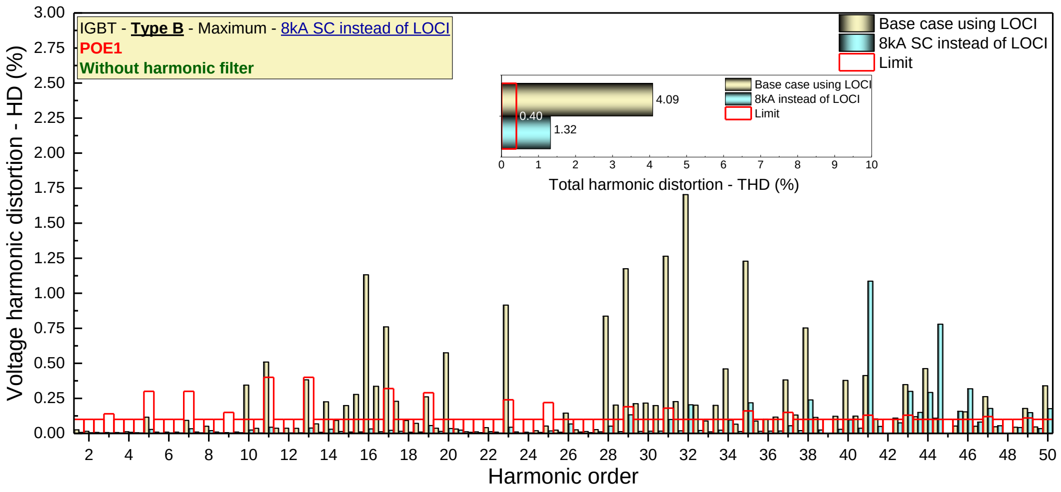
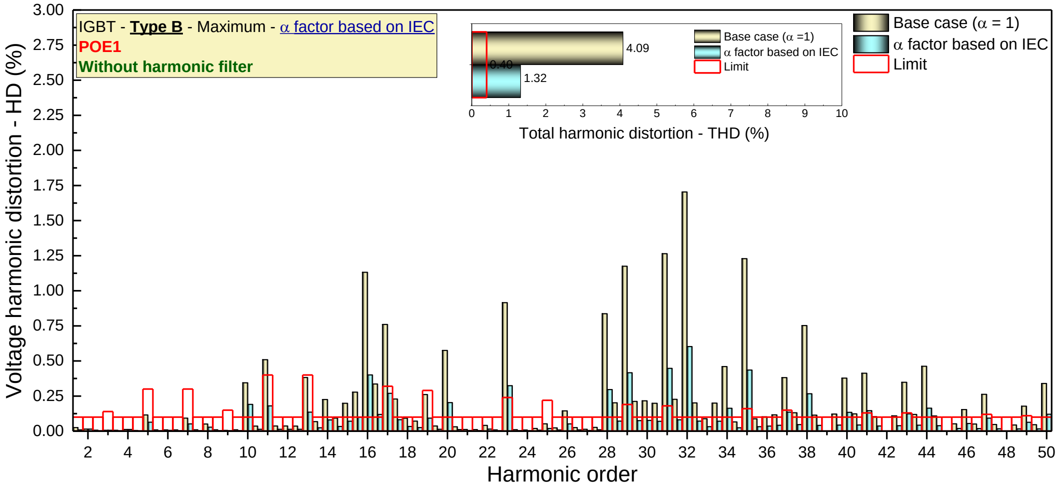
- Grid Code requirement

Impact of Grid Code – Impedance polygon (LOCI)





Impact of Grid Code – Summation method



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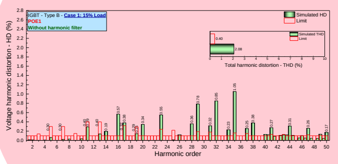
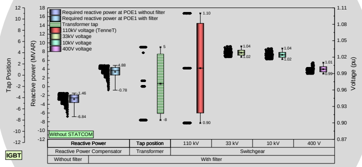
Harmonic

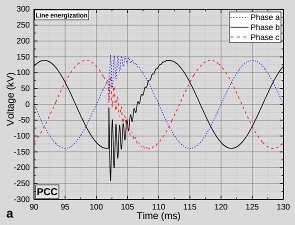


Resonance study

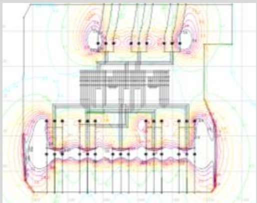
EMC Assessment



Power Factor Correction



Insulation Coordination



EMF Assessment

Arc Flash Study

Grid Compliance

Power Quality Assessment – Mitigation Solution

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Filter Design Criteria

- Filter type
  - Single-tuned,
  - Second order high-passed,
  - Double tuned filter,
  - C-Type
  - …
- Location
- Voltage level (HV or MV)
- Number of required filters
- Capacity
- Tuning Frequency
- Switchable?
- What about PQ capability at PCC?

Filter Design Process

- Script-based approach to check
  - Voltage distortion
  - Resonance in system
- Contingency/operating scenarios
- Filter detuning (detuning due to ageing, temperature, …)
- Secondary issues e.g., resonance in gird
- Overvoltage in case of switchable filter
- Reactive power requirement at PCC

Power Quality Assessment – Mitigation Solution

Single-Tuned or Notched Filter

The main characteristics of a notch filter

- It acts as a very low impedance at the tuned frequency, i.e. effectively shunts most of the harmonic current at the tuned frequency
- When the source impedance is inductive, there is a resonance peak at a frequency lower than the tuned frequency
- The impedance increases with frequency for frequencies above tuned frequency
- There is a sharp increase in impedance below the tuned frequency due to the proximity of the resonant frequency

Electric parameters

Impedance of the filter

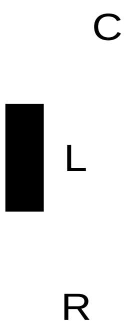
$$Z = R + j[\omega L - 1/\omega C]$$

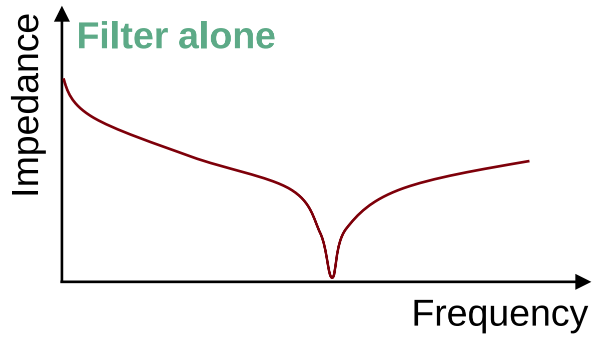
Tuning frequency

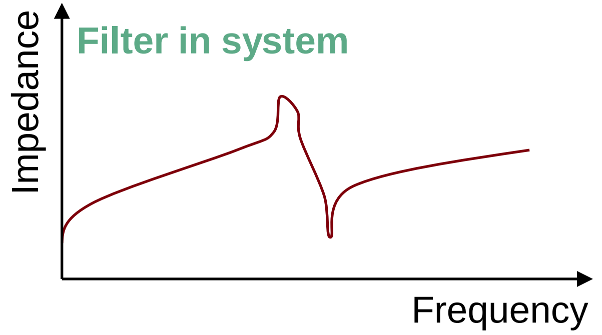
$$f = \frac{1}{2\pi(LC)^{0.5}}$$

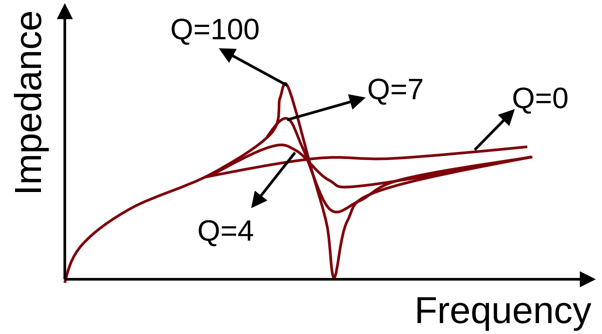
Quality factor

$$Q = \frac{\sqrt{L/C}}{R}$$









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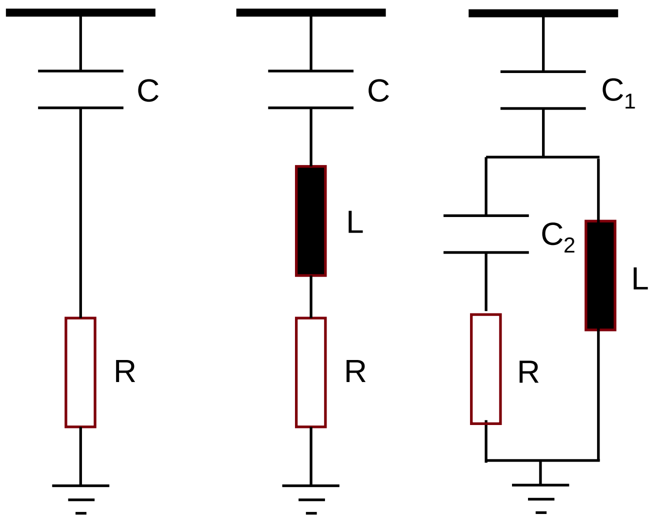
High-passed Filter

- It shunts a large percentage of all harmonics at or above the tuned frequency.
- It can be applied for filtering of all frequencies.



Electric parameters

Impedance of the filter (second order)

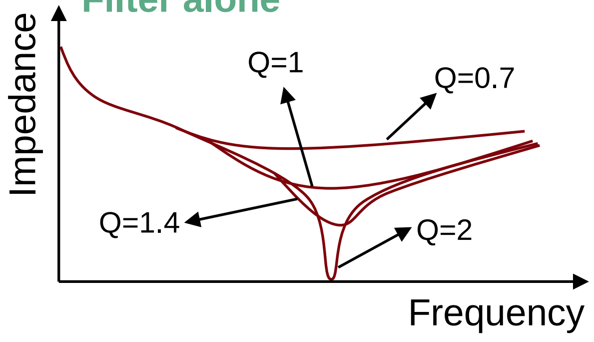
$$Z = \frac{1}{j\omega C} + \left(\frac{1}{R} + \frac{1}{j\omega L}\right)^{-1}$$

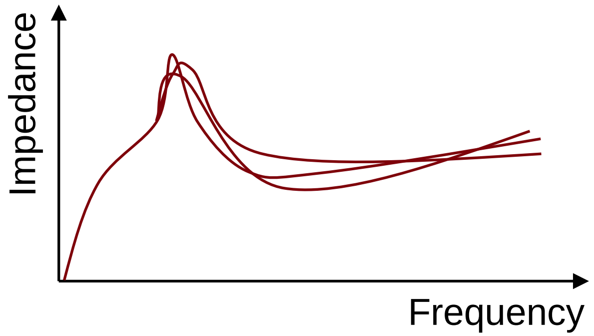
Tuning frequency

$$f = \frac{1}{2\pi(LC)^{0.5}}$$

Quality factor

$$Q = \frac{R}{(L/C)^{0.5}}$$





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C-type Filter or MSCDN

- C-Type Filter or MSCDN (Mechanical Switched Capacitor Damping Network)
- At the tuned frequency the LC_2 branch is opened, so the harmonic current at the tuned frequency passes through the resistor (R_p).
- At power frequency the impedance of LC_2 is lower than R_p. Therefore, the resistive losses of C-type filter at power frequency are very low.

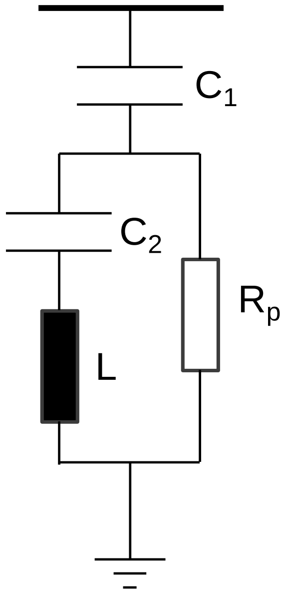
Electric parameters

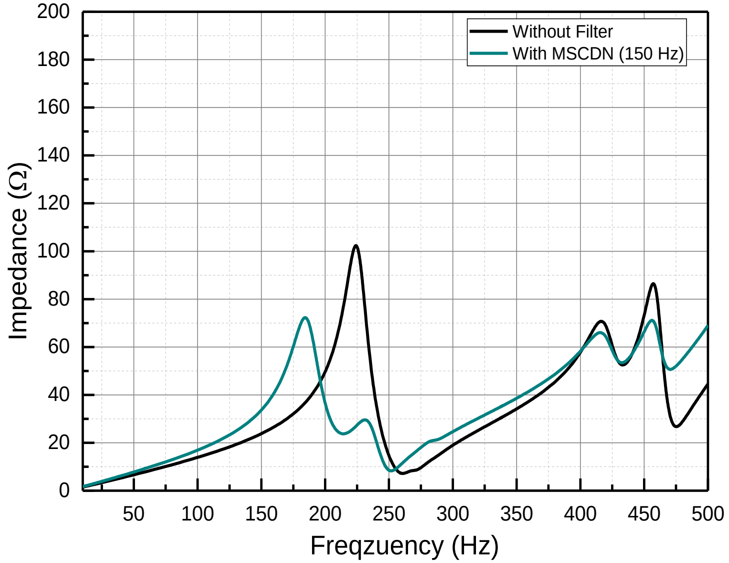
Impedance of the filter (second order)

$$Z = \frac{\left(j\omega L - j\frac{1}{\omega C_2}\right) R_p}{R_p + j\omega L - j\frac{1}{\omega C_2}} - j\frac{1}{\omega C_1}$$

Quality factor

$$Q = \frac{R_p}{(2\pi f_{tune})L}$$





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Power Quality Assessment – Mitigation Solution

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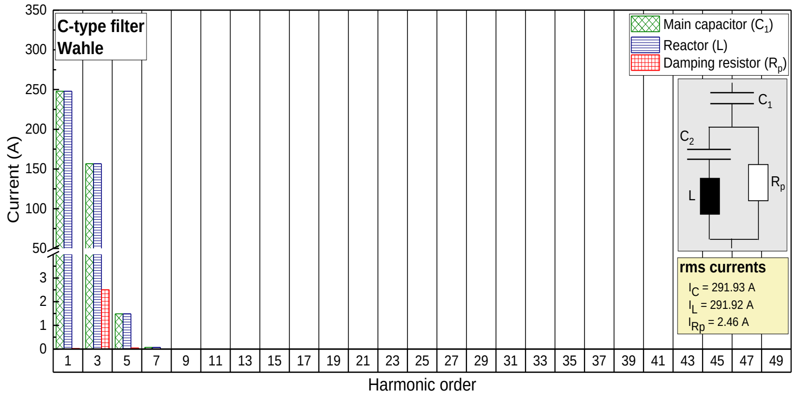
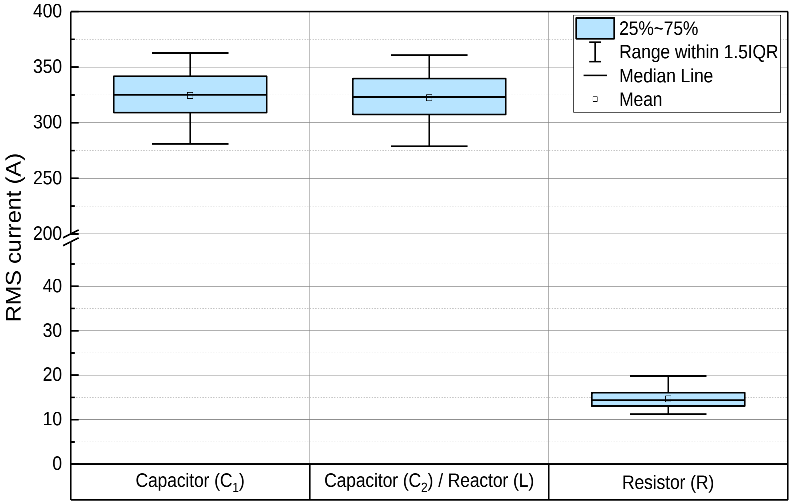
Harmonic order	Current (A)			
	Capacitor (C_1)	Capacitor (C_2)	Inductor (L)	Resistor (R_p)
1	336.097	336.097	336.097	0.000
2	0.000	0.000	0.000	0.000
3	16.957	16.490	16.490	3.952
4	0.000	0.000	0.000	0.000
5	1.662	1.526	1.526	0.660
6	0.000	0.000	0.000	0.000
7	0.279	0.237	0.237	0.147
8	0.000	0.000	0.000	0.000
9	0.027	0.021	0.021	0.022
10	0.000	0.000	0.000	0.000
11	0.022	0.012	0.012	0.012
12	0.000	0.000	0.000	0.000
13	0.003	0.002	0.002	0.002
14	0.000	0.000	0.000	0.000
15	0.003	0.002	0.002	0.003
16	0.000	0.000	0.000	0.000
17	0.011	0.006	0.006	0.009
18	0.000	0.000	0.000	0.000
19	0.005	0.002	0.002	0.004
20	0.000	0.000	0.000	0.000
21	0.001	0.000	0.000	0.001
22	0.000	0.000	0.000	0.000
23	0.004	0.002	0.002	0.003
24	0.000	0.000	0.000	0.000
25	0.014	0.006	0.006	0.013
26	0.000	0.000	0.000	0.000
27	0.002	0.001	0.001	0.002
28	0.000	0.000	0.000	0.000
29	0.003	0.001	0.001	0.003
30	0.000	0.000	0.000	0.000
31	0.004	0.001	0.001	0.004
32	0.000	0.000	0.000	0.000
33	0.002	0.001	0.001	0.002
34	0.000	0.000	0.000	0.000
35	0.000	0.000	0.000	0.000
36	0.000	0.000	0.000	0.000
37	0.002	0.000	0.000	0.002
38	0.000	0.000	0.000	0.000
39	0.001	0.000	0.000	0.001
40	0.000	0.000	0.000	0.000
41	0.000	0.000	0.000	0.000
43	0.001	0.000	0.000	0.001
45	0.001	0.000	0.000	0.001
47	0.000	0.000	0.000	0.000
49	0.000	0.000	0.000	0.000
I_{rms}	336.53	336.50	336.50	4.00

rms Current





Current and voltage rating

$$U_\Sigma = U_1 + U_2 + U_3 + \cdots + U_7 + \sqrt{\sum_{k=8}^{50} (U_i)^2}$$

$$I_\Sigma = I_1 + \sqrt{\sum_{k=2}^{50} (I_i)^2}$$

The tolerances of components and frequency deviation

Components	Value
Frequency deviation	(47.5 – 50 – 51.5) Hz
Capacitor (C_1 and C_2)	± 5 %
Reactor (L)	± 1 %
Resistor (R)	± 5 %

Total rms voltage for different components

Frequency (Hz)	Total rms voltage (kV)			
	Capacitor (C_1)	Capacitor (C_2)	Reactor (L)	Resistor (R)
47.5	267.395	15.251	51.551	37.689
50	266.372	15.196	50.868	35.679
51.5	265.177	15.176	50.667	35.498

The total rms current for different components

Frequency (Hz)	Total rms current (A)		
	Capacitor (C_1)	Reactor (L)	Resistor (R)
47.5	373.843	371.427	21.016
50	383.411	381.133	18.172
51.5	389.987	387.778	18.756

Current and Voltage ranges

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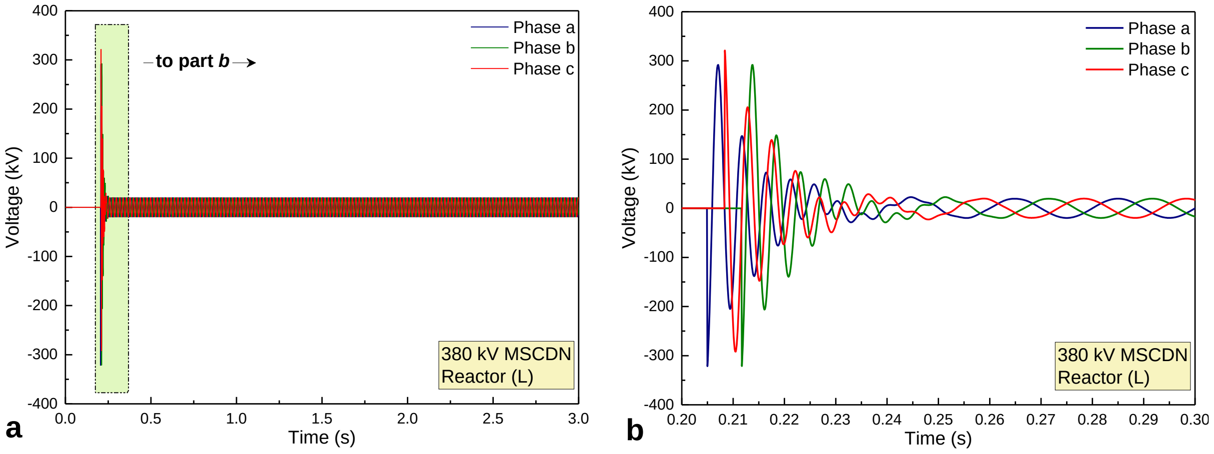
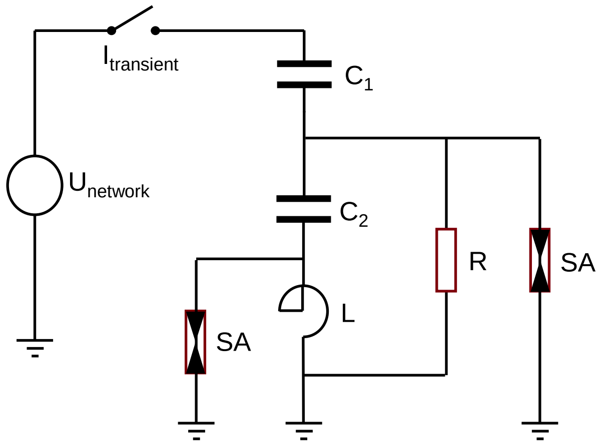
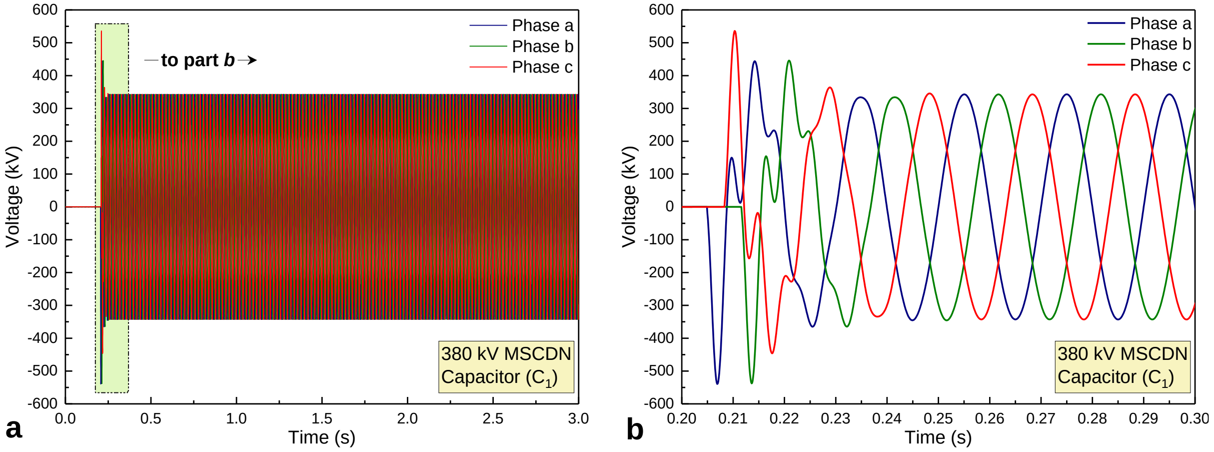
Power Quality Assessment – Mitigation Solution



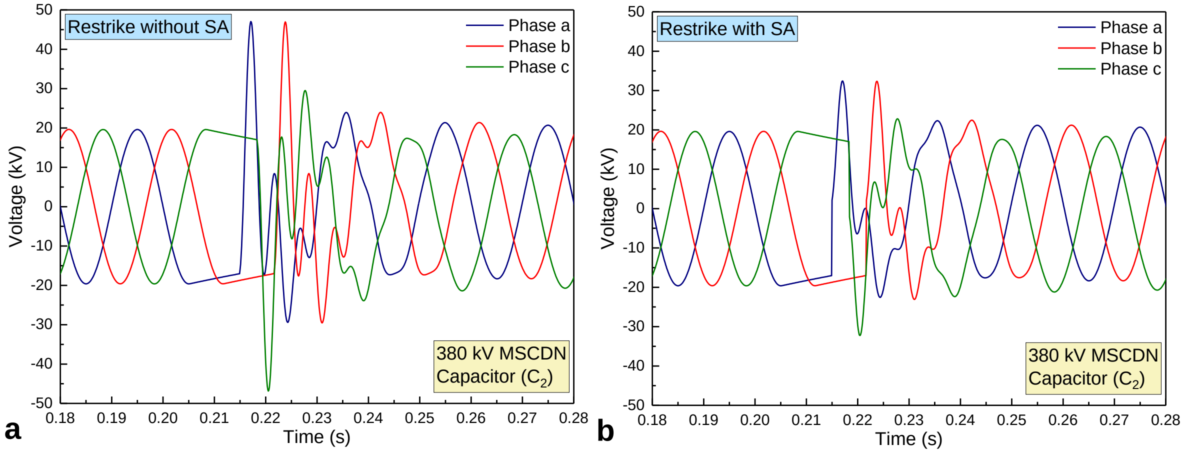
The voltage across reactor (L) during energization of MSCDN

Description	Value
Nominal Voltage	380 kV
Rated reactive power	200 MVAR
Tuned frequency	215 Hz
Capacitor (C_1)	3.98 µF
Capacitor (C_2)	69.59 µF
Inductance (L)	145.6 mH
Resistor (R)	1000 Ω





The voltage across capacitor (C_1) during energization of MSCDN

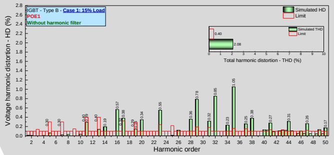


The voltage across capacitor (C_2) of MSCDN due to restrike without and with surge arrester

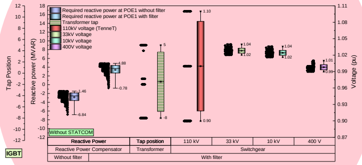
Agenda

Harmonic

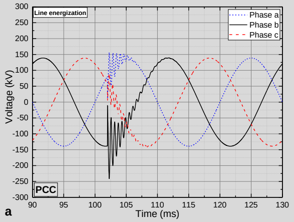
Resonance study



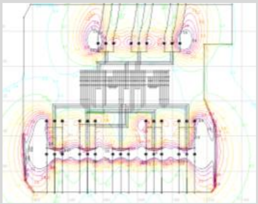
EMC Assessment



Power Factor Correction



Insulation Coordination



EMF Assessment

Arc Flash Study

Grid Compliance

Power Factor Correction Study

Motivations

- To control the voltage profile considering
  - Grid Code Requirement i.e., required available reactive power at PCC
  - Specific plant requirements
- Control losses

Approach

- Steady-state model development
- Reactive power requirements
- Defining different operating scenarios
  - In terms of grid code i.e., voltage at PCC (0.9pu – 1.1pu)
  - Contingency inside plant
- Load-flow study during normal and different contingencies as well as grid operation
- Design of reactive power compensator, i.e., size, location, type (fixed or FACTS-based)
- Tap changer range optimization
- Switching study and energization evaluation (it will be done as part of trainset study)

Power Quality Assessment – H2 Case Study

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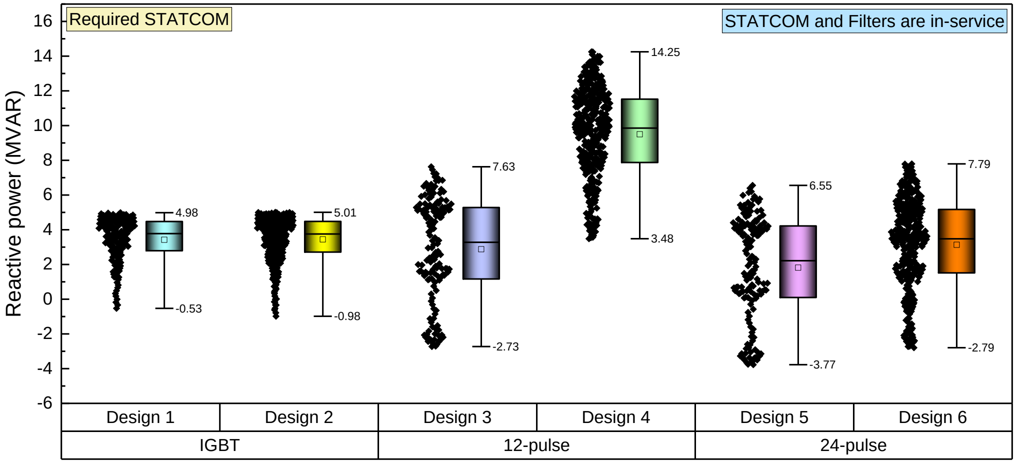
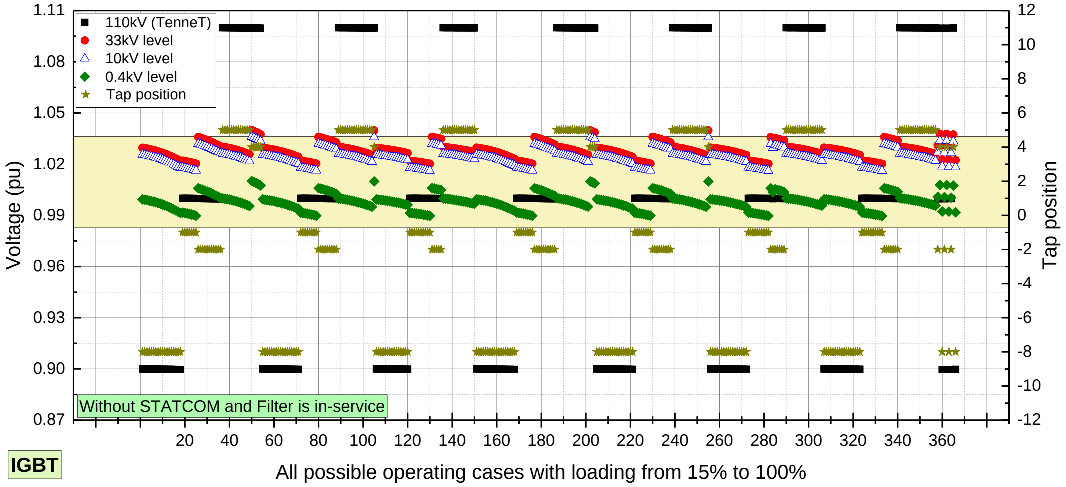
Impact of different project specific parameters /design
Steady-state – Reactive Power Requirements

- Technology (Thyristor, IGBT, etc.)
- Topology (12 pulses, 24 pulses, Diode, IGBT chopper, etc.)
- Supplier
- Loading scenario
- Operating scenarios (contingencies)
- Grid Code requirement

Reactive power requirements at PCC

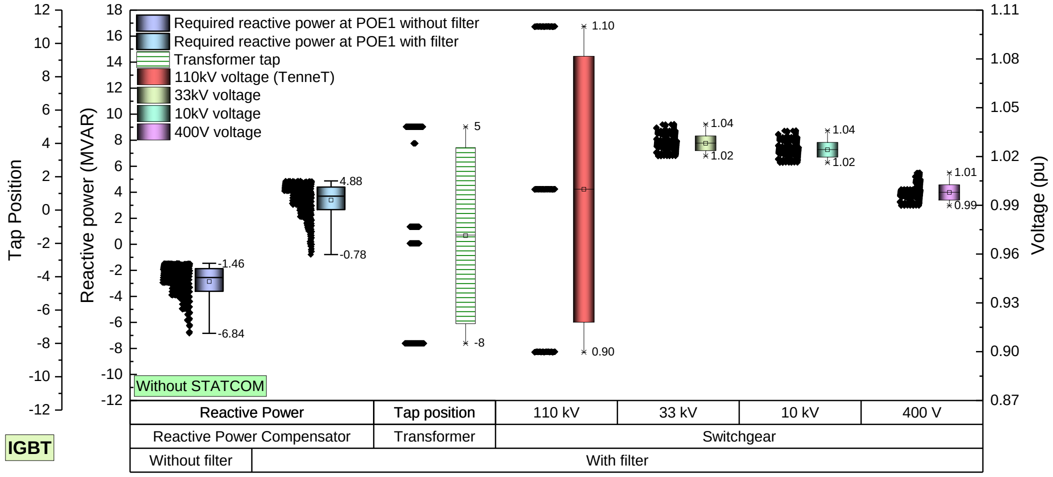


Voltage and tap position



IGBT

Reactive power requirements, transformer design, voltage quality



IGBT

Internal

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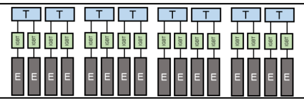
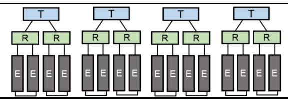
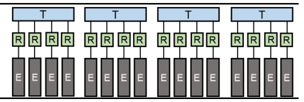
Power Quality Assessment – H2 Case Study

System Design

- Reactive power compensation i.e., fixed capacitor, reactor, STATCOM, etc.
- Harmonic assessment
- Tap changer philosophy
- Reliability of system
- Efficiency
- Footprint
- Economic evaluation
- Availability
- etc.

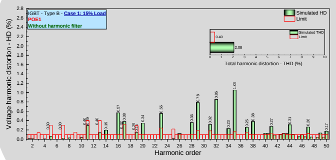
The summary of technical evaluations for selection of different technologies/topologies

Topology schematic representation								
Technology			IGBT active front-end		Thyristor 12-pulse		Thyristor 24-pulse	
Design			Design 1	Design 2	Design 3	Design 4	Design 5	Design 6
Design cases	1		x	x	x	x	x	x
	2		x	x	x	x	x	x
	3		x	x	x	x	x	x
	6			x		x		x
	5			x		x		x
	6			x		x		x
	7			x		x		x
Technical criteria	Efficiency (%)		98.91	98.91	98.32	97.87	98.12	98.31
	Harmonic filter	Type	HP: C-Type	HP: C-Type	HP: C-Type	HP: C-Type	HP: C-Type	HP: C-Type
		Size (MVAR)	6	6	7 5	5 7 6	3 4 4	6 3 3
		Tuning frequency (Hz)	650	650	550 650	250 550 650	250 550 650	250 550 650
	STATCOM (MVAR)		5.0	5.0	7.7	14.3	6.6	7.8
	Availability (%)		99.87	99.87	99.89	99.86	99.87	99.86
	Tap changer status		Constant	Constant	Constant	Constant	Constant	Constant
Overall evaluation	Ranking	HD and THD	5	5	2	2	3	3
		Demand of harmonic filter	5	5	3	3	3	3
		Power factor	5	5	3	3	3	3
		Efficiency	5	5	5	5	5	5
		Availability	5	5	5	5	5	5
		Proven technology	4	4	5	5	5	5
		Availability the rectifier in market	4	4	5	5	5	5

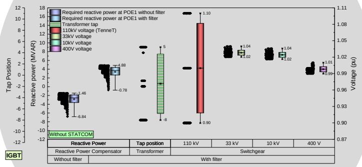
Agenda

Harmonic

Resonance study



EMC Assessment



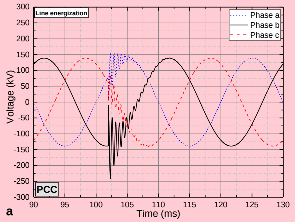
Power Factor Correction

Switching

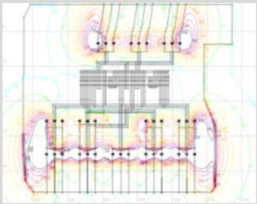
Lightning

Mitigation

etc.



Insulation Coordination



EMF Assessment

Arc Flash Study

Grid Compliance

Background

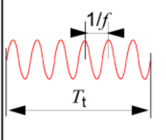
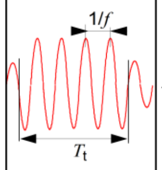
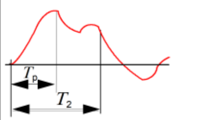
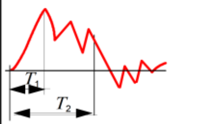
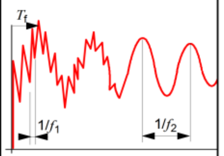
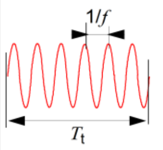
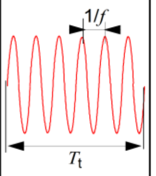
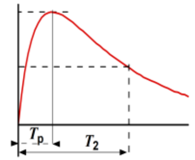
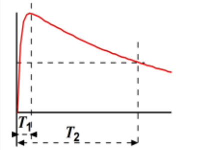
Depending on relevant event different types of overvoltage can occur in system:

- Power frequency or temporary overvoltage (TOV)
- Slow-front transient overvoltage (SFO)
- Fast-front overvoltage (FFO)
- Very-fast front overvoltage (VFTO)
- Ferro-resonance overvoltage

Depending on grid topology and evaluated event(s) one or several types of overvoltage can occur. The following can affect the type, duration, and amplitude of overvoltage:

- Grid topology e.g., cable dominated, transformer-based event(s), combination of inductive and capacitive, etc.
- Switching time instant i.e., voltage peak or zero (theoretically over 10 ms timespan for 50Hz system)
- Initial state of system e.g., residual flux in transformer or trapped charge, etc.
- Fault initiation time (for fault-based events)
- Switching/energization sequence
- etc.

Classes and shapes of overvoltages according to IEC 60071-4

Class	Low frequency		Transient		
	Continuous	Temporary	Slow-front	Fast-front	Very-fast-front
Voltage or over-voltage shapes					
Range of voltage or over-voltage shapes	f = 50 Hz or 60 Hz $T_t \geq 3$ 600 s	10 Hz < f < 500 Hz 0,03 s $\leq T_t \leq$ 3 600 s	20 µs < $T_p \leq$ 5 000 µs $T_2 \leq$ 20 ms	0,1 µs < $T_1 \leq$ 20 µs $T_2 \leq$ 300 µs	3 ns < $T_f \leq$ 100 ns 0,3 MHz < f_1 < 100 MHz 30 kHz < f_2 < 300 kHz
Standard voltage shapes	 f = 50 Hz or 60 Hz T_t 1)	 48 Hz $\leq f \leq$ 62 Hz T_t = 60 s	 T_p = 250 µs T_2 = 2 500 µs	 T_1 = 1,2 µs T_2 = 50 µs	1)
Standard withstand test	1)	Short-duration power frequency test	Switching impulse test	Lightning mpulse test	1)

1) To be specified by the relevant apparatus committees.

Insulation Coordination Study

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Approach

- Screening the project specific data e.g., SLD, equipment type, etc. and determine relevant events
- Model preparation relevant for different events e.g., slight deviation between required model for TRV is different for VFTO or ferro-resonance, etc.
- Define events and assumptions e.g., switching time instant, fault types, sensitivity, initial conditions (e.g., residual fluxes, trap charged, etc.)
- Conducting the simulations based on defined events and corresponding sequence e.g., fault incretion, energization, lightning strike, etc.
- Calculate overvoltage at different locations and relevant for different components
- Compare the calculated value with admissible rating based on equipment datasheet or relevant standards e.g., IEC 60071
- Select appropriate equipment
- If applicable to propose mitigation solution(s) e.g., surge arrester, snubber, syncswitch, etc.

Goals

- To select appropriate insulation level for all equipment
- To avoid any over-design/under-design in project
- To avoid any probable future failure
- Reduce the design cost
- To comply with Grid Code

Some events results in overvoltages according to IEC 60071-4

	Temporary overvoltages	Transient overvoltages		
		Slow-front overvoltages	Fast-front overvoltages	Very-fast-front overvoltages
	TOV	SFO	FFO	VFFO
Load rejection (see 2.3.2.2 in IEC 60071-2)	X			
Transformer energization	X	X		
Parallel line resonance	X			
Uneven breaker poles	X			
Backfeeding	X			
Line fault application (see 2.3.3.2 in in IEC 60071-2)	X	X		
Fault clearing (see 2.3.3.2 in in IEC 60071-2)	X	X		
Line energization (see 2.3.3.1 in in IEC 60071-2)	X	X		
Line re-energization	X	X		
Line dropping	X	X		
AIS busbar switching			X	[1)]
Switching of inductive and capacitive current (see 2.3.3.4 in IEC 60071-2)	X	X	X	
Back flashover			X	
Direct lightning stroke (see 2.3.3.5 in IEC 60071-2			X	
Switching inside GIS substation				X
SF_6 circuit-breaker inductive and capacitive current switching	X	X	X	[1)]
Flashover in GIS substation				X
Vacuum circuit-breaker switching			X	X

[1)] In the case of short distance busbars and low damping, very-fast-front overoltages can also occur.

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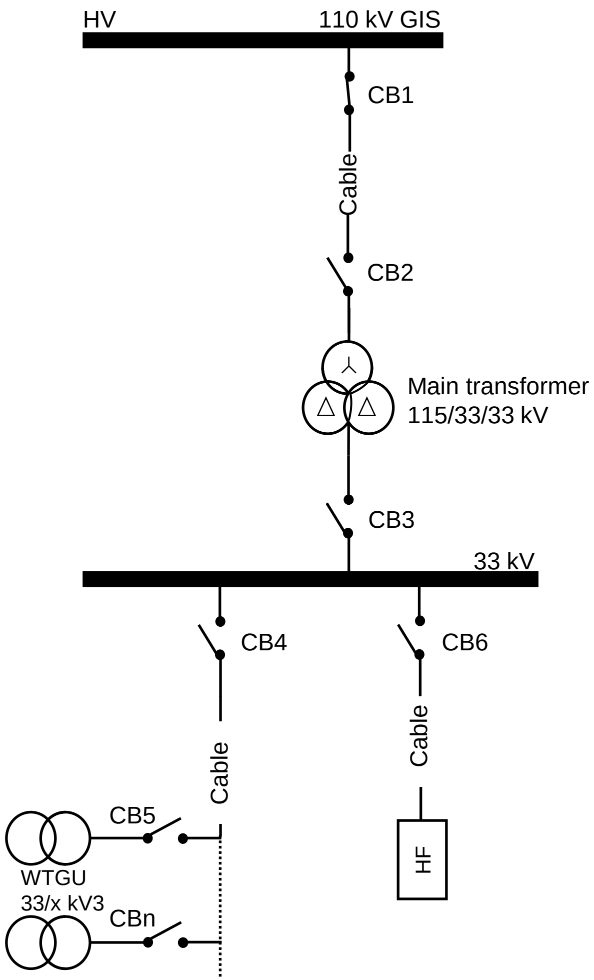
Temporary overvoltage

Energization of power transformer

– Energization process
  - Closing CB2 (when CB1 is closed and CB3 is open)

Single line diagram



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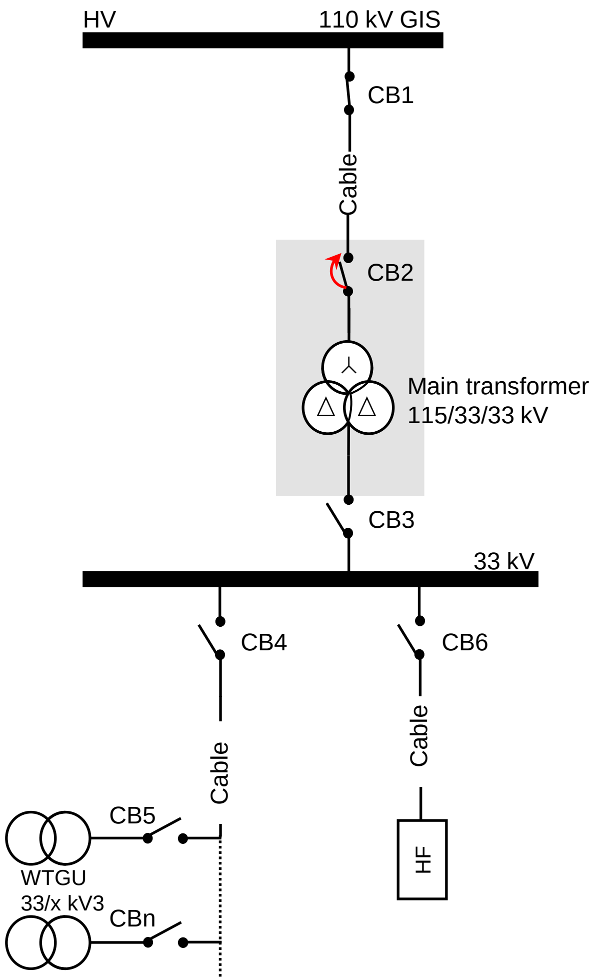
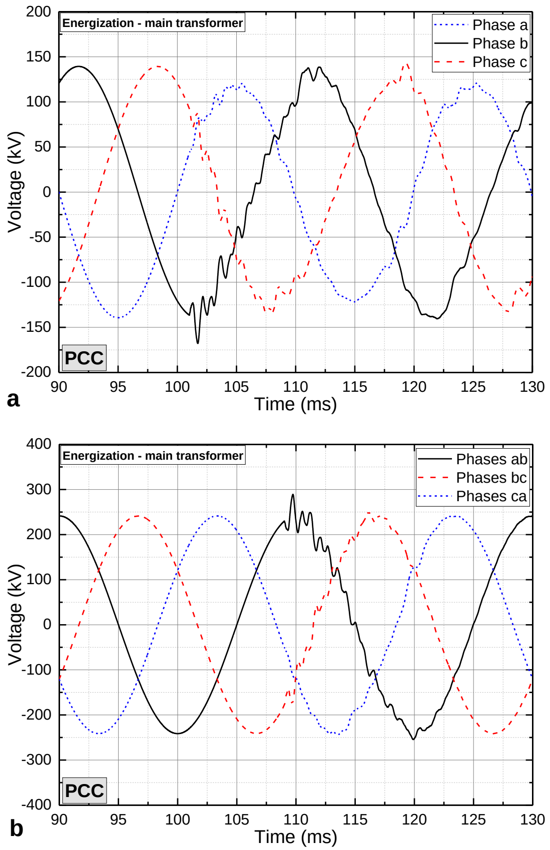
Temporary overvoltage

Energization of power transformer

- Energization process
  - Closing CB2 (when CB1 is closed and CB3 is open)
- The shape of overvoltage depends on
  - Closing time instant
  - Residual fluxes in transformer
  - Transformer size
  - Transformer saturation curve

Switching sequence and resulting overvoltage





The phase-to-earth and b) phase-to-phase voltages at the HV

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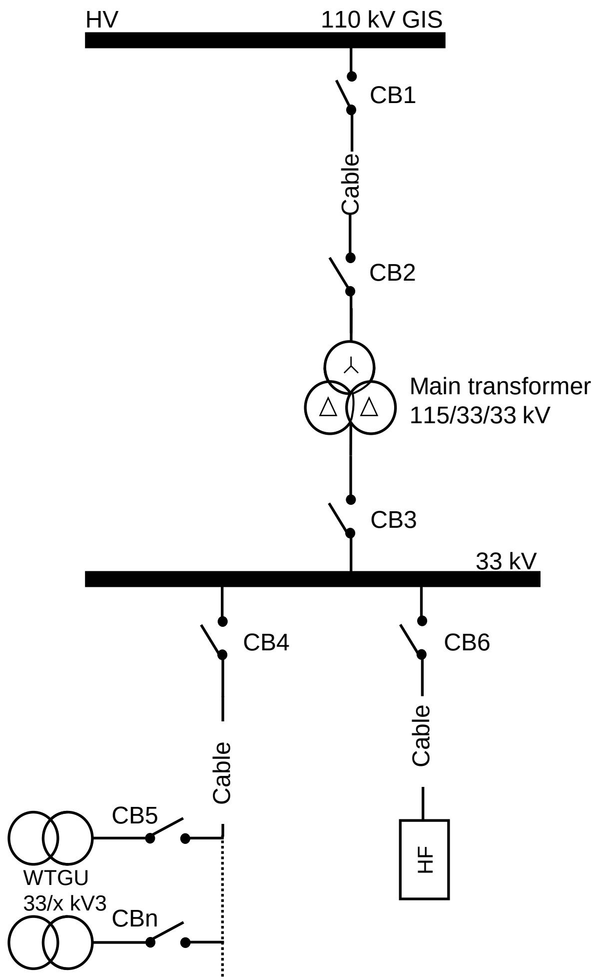
Slow-front overvoltage

Energization of cable or transmission line

- Energization process
  - Closing CB1 (when CB2 is open)

Single line diagram



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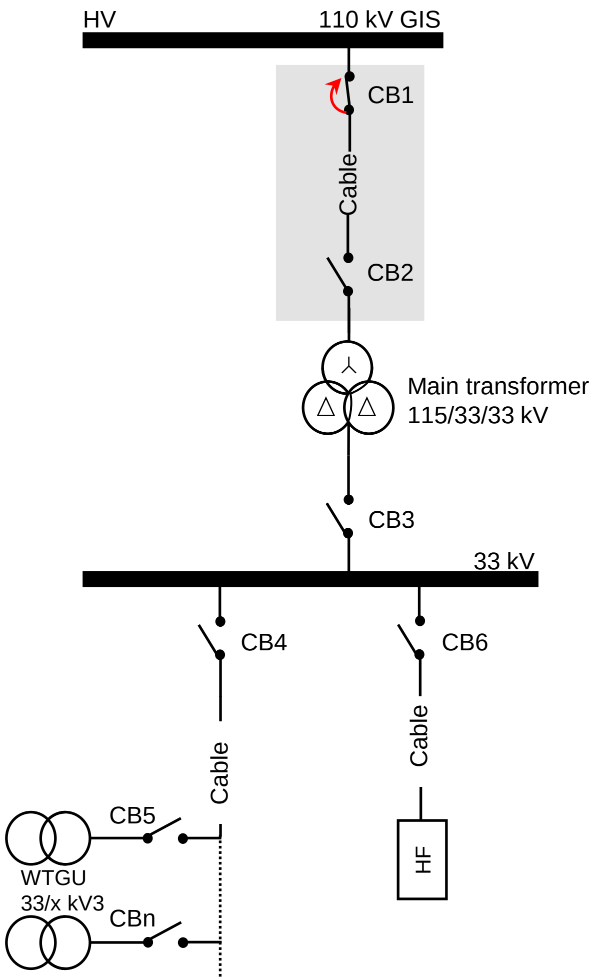
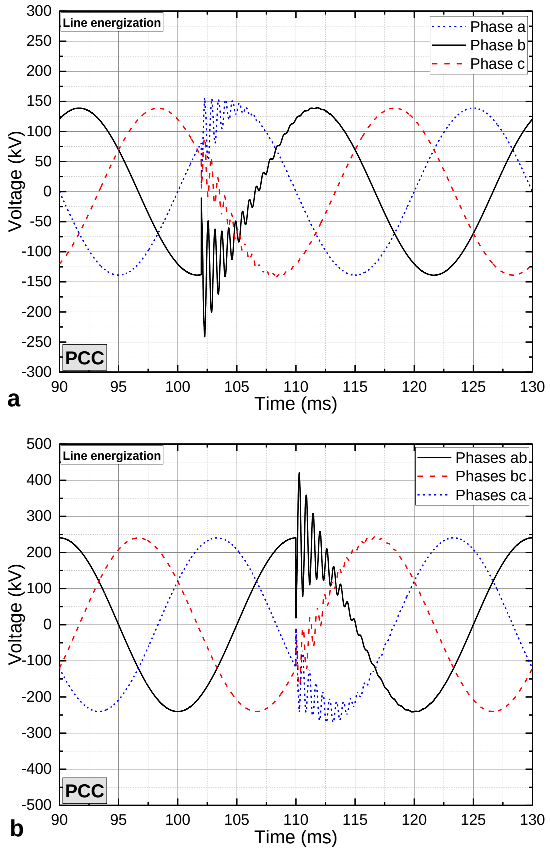
Slow-front overvoltage

Energization of cable or transmission line

- Energization process
  - Closing CB1 (when CB2 is open)
- The shape of overvoltage depends on
  - Closing time instant
  - Cable length
  - Residual charging in cable

Switching sequence and resulting overvoltage





The phase-to-earth and b) phase-to-phase voltages at the HV

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Insulation Coordination Study

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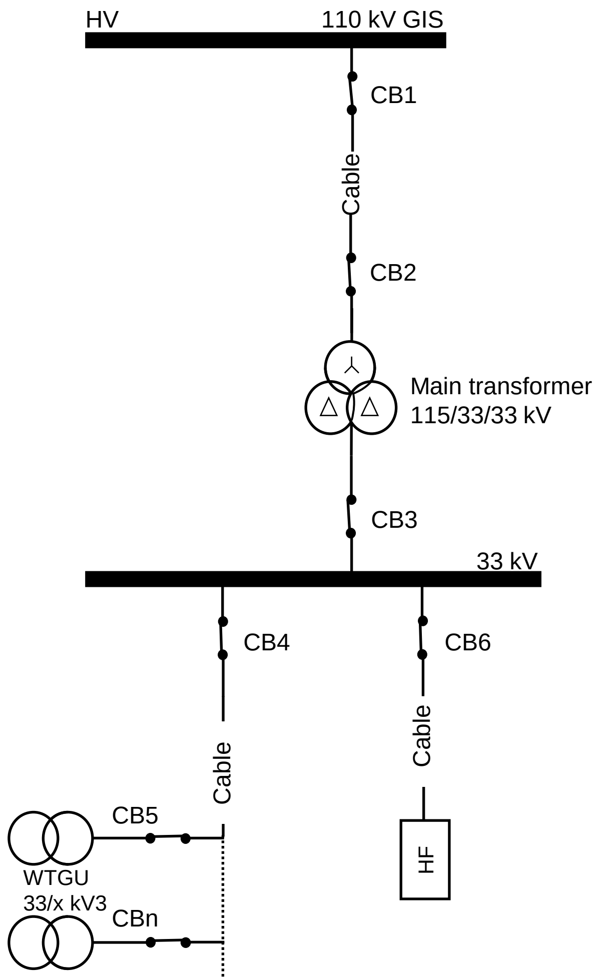
Temporary/Slow-front overvoltage

Fault clearance

– Event evolution
  - System operates i.e., all CBs are closed
  - Fault occurs e.g., at HV side of transformer
  - CB2 will open

Single line diagram



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Temporary/Slow-front overvoltage

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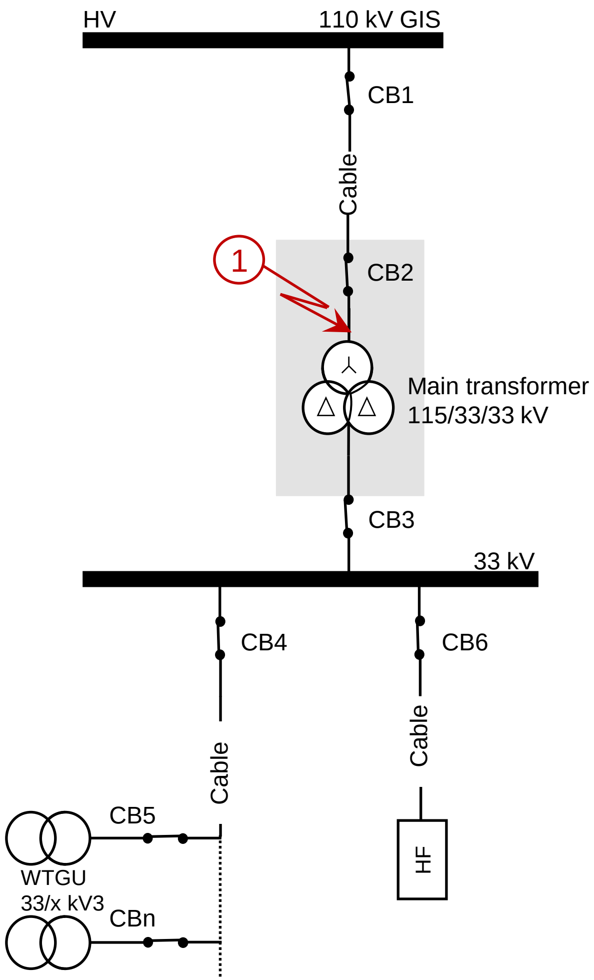
Event sequence



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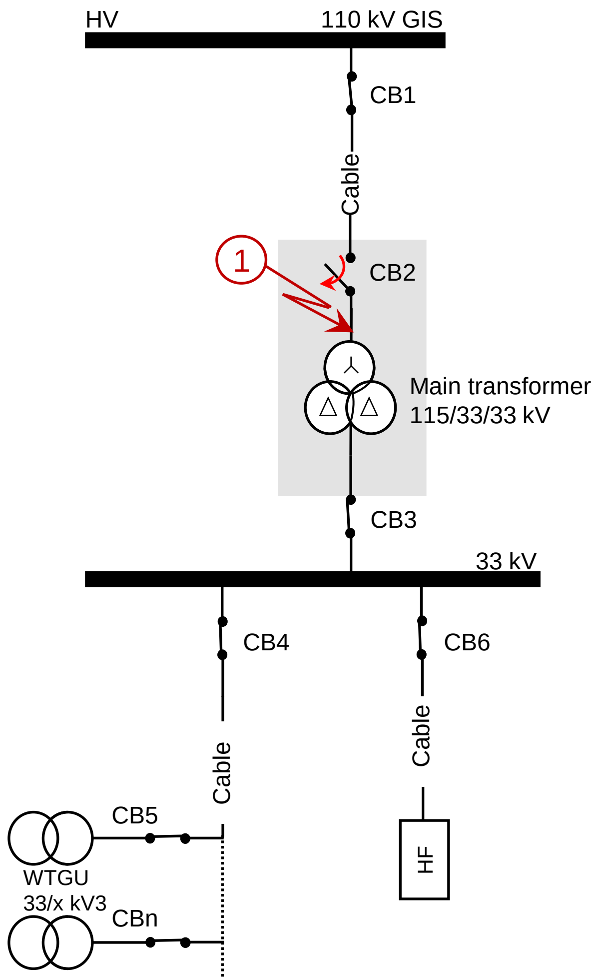
Insulation Coordination Study

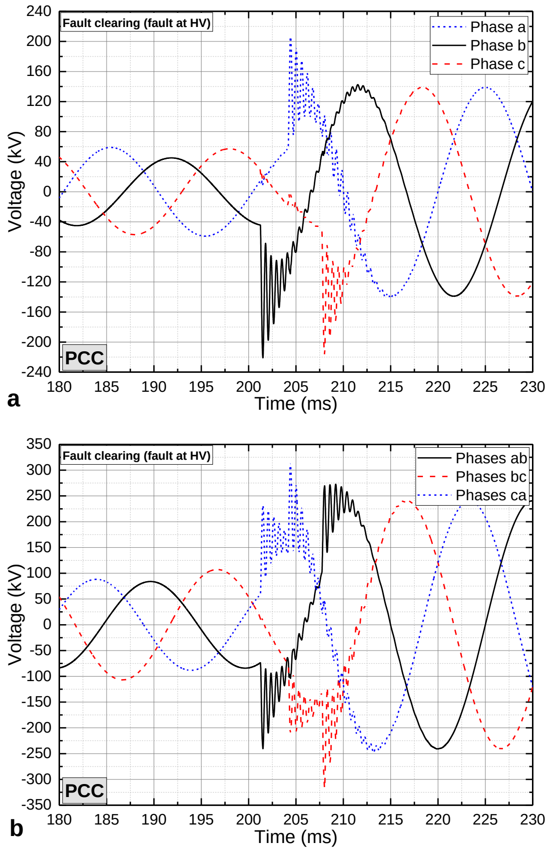
Temporary/Slow-front overvoltage

Fault clearance

- Event evolution
  - System operates i.e., all CBs are closed
  - Fault occurs e.g., at HV side of transformer
  - CB2 will open
- The shape of overvoltage depends on
  - Fault insertion time
  - Fault clearance time
  - Fault type, single-phase, three-phase, etc.

Event sequence and resulting overvoltage





The phase-to-earth and b) phase-to-phase voltages at the HV

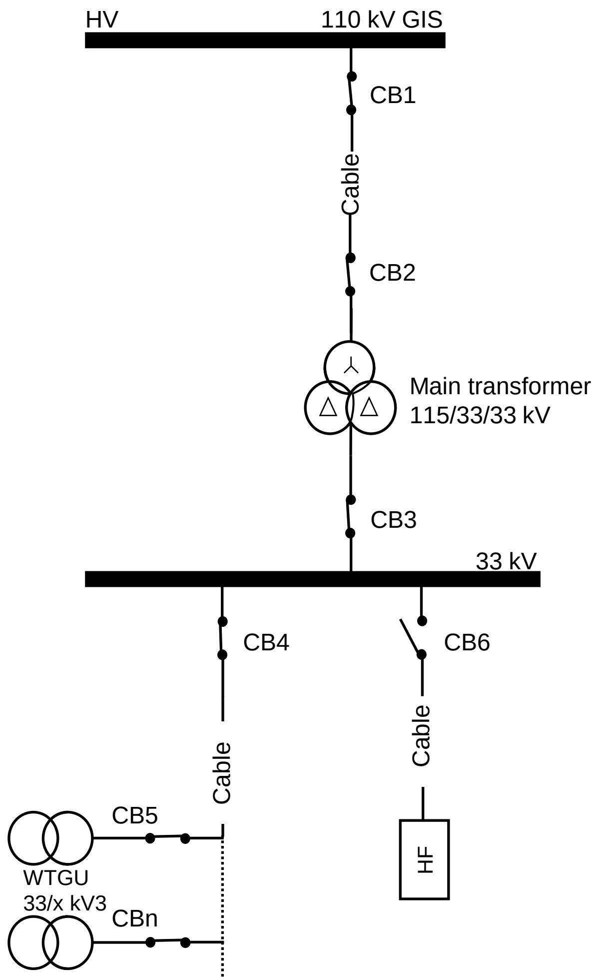
Insulation Coordination Study

Temporary/Slow-front overvoltage

Energization of harmonic filter

- Energization process
  - Closing CB6 (when CB1, CB2, and CB3 are closed)
- The shape of overvoltage depends on
  - Closing time instant
  - Electrical parameters of filter

Single line diagram



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Temporary/Slow-front overvoltage

Energization of harmonic filter

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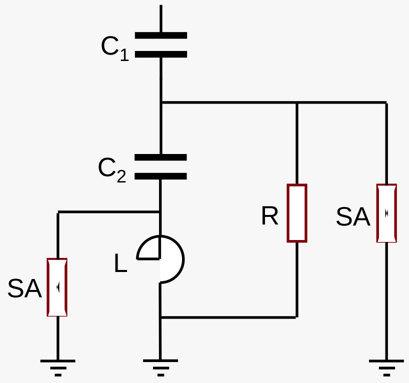
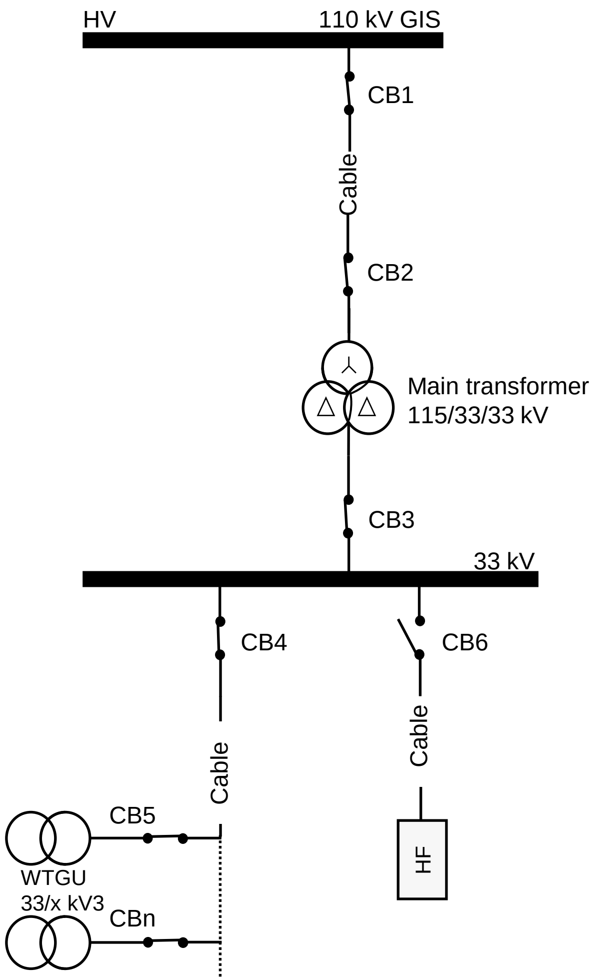
  - Closing CB6 (when CB1, CB2, and CB3 are closed)
– The shape of overvoltage depends on
  - Closing time instant
  - Electrical parameters of filter

Description	Value
Nominal Voltage	380 kV
Rated reactive power	200 MVAR
Tuned frequency	215 Hz
Capacitor (C_1)	3.98 µF
Capacitor (C_2)	69.59 µF
Inductance (L)	145.6 mH
Resistor (R)	1000 Ω



Single line diagram



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Insulation Coordination Study

Temporary/Slow-front overvoltage

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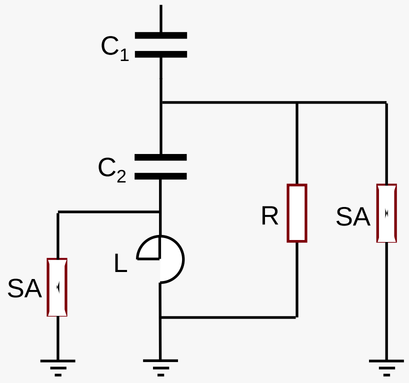
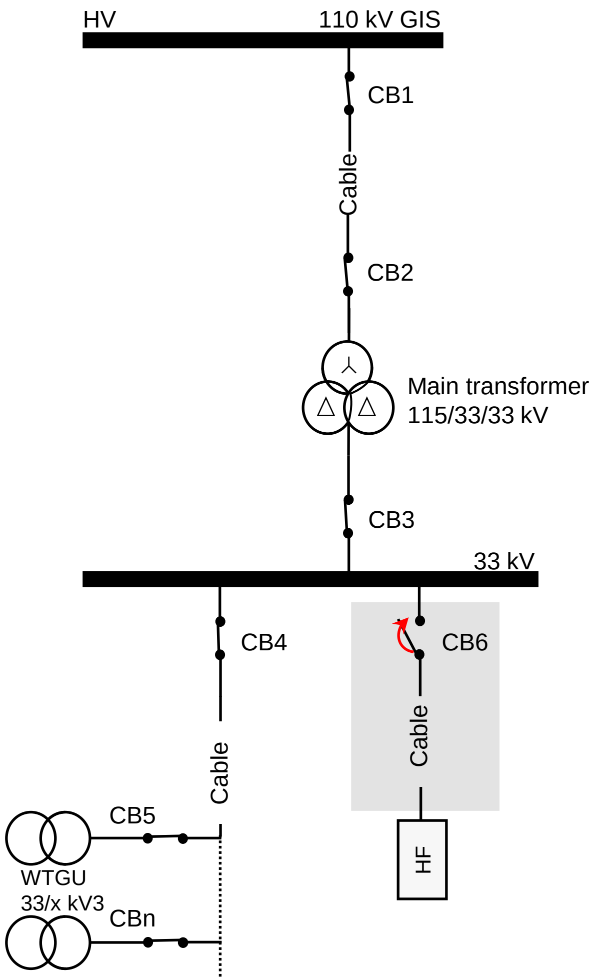
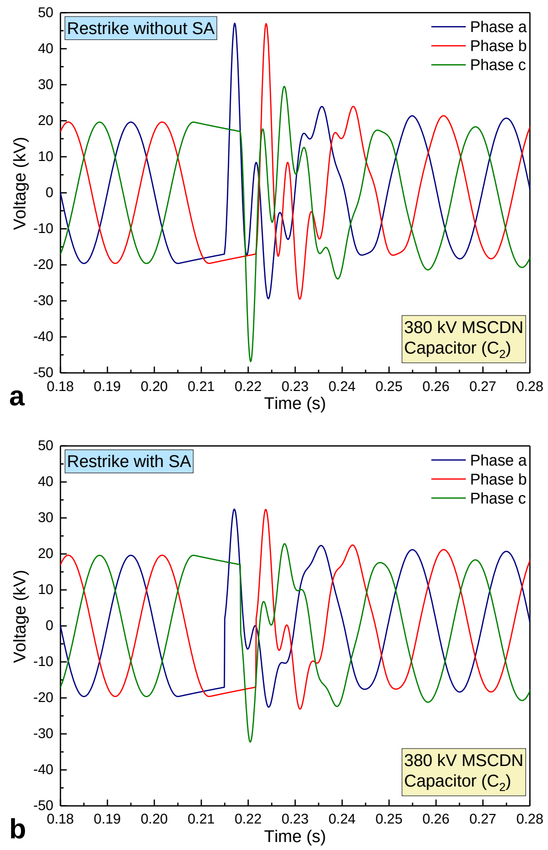


Switching sequence and resulting overvoltage





The phase-to-earth and b) phase-to-phase voltages at the HV

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Fast-front overvoltage

Lightning strike

- Event sequence
  - Direct or indirect strike on transmission line
- The shape of overvoltage depends on
  - Impulse shape
  - Tower geometry
  - Soil parameter
  - etc.

Switching sequence and resulting overvoltage

Hitachi Energy

Fast-front overvoltage

Lightning strike

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  - Direct or indirect strike on transmission line
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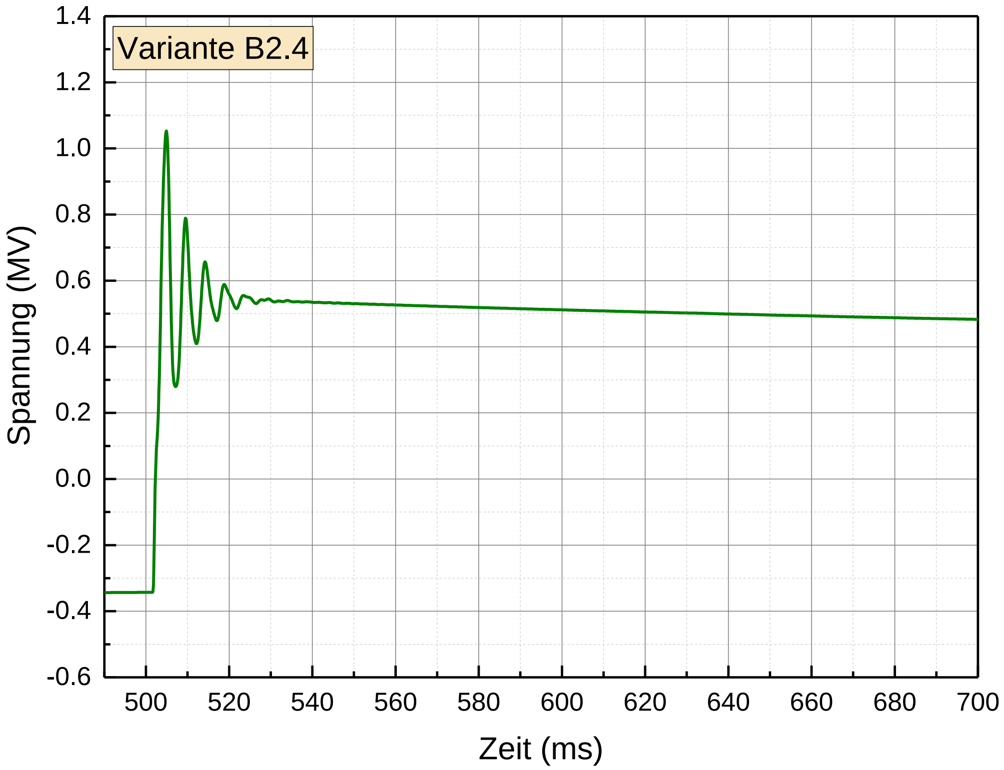
Switching sequence and resulting overvoltage



Very-fast-front overvoltage

Switching inside GIS (operating of disconnector switch)

Representation of GIS 380kV switchgear

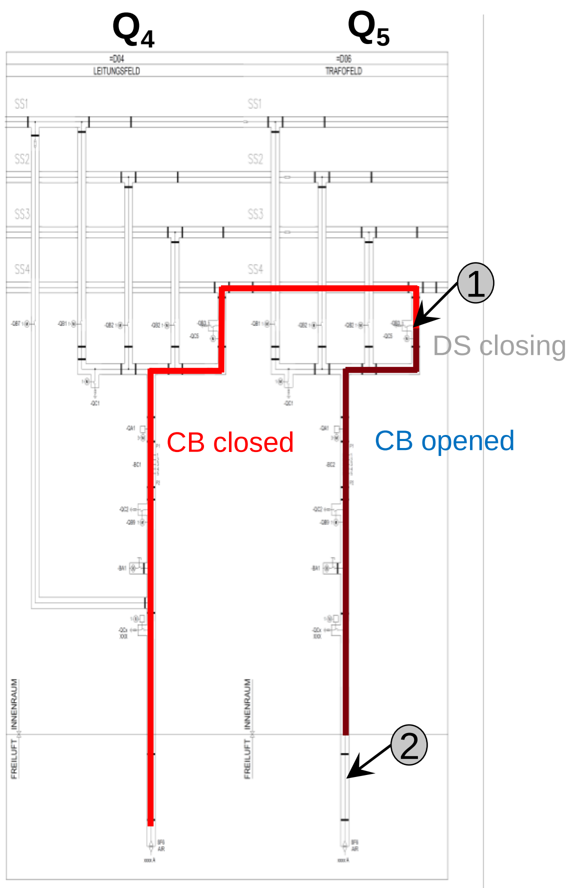
380kV GIS switchgear

Very-fast-front overvoltage

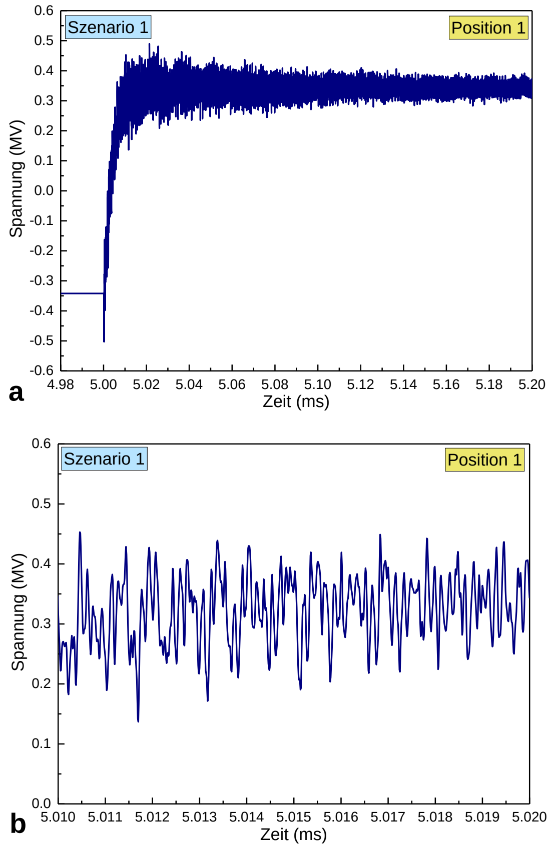
Switching inside GIS (operating of disconnector switch)

- Event sequence
  - Opening of DS (disconnector switch) while CB is opened form one side and is closed from other side
- The shape of overvoltage depends on
  - Closing time instant
  - Voltage level of switchgear
  - Residual voltage

Switching sequence and resulting overvoltage



Two adjacent GIS feeders



The phase-to-earth voltage at position 1 and 2

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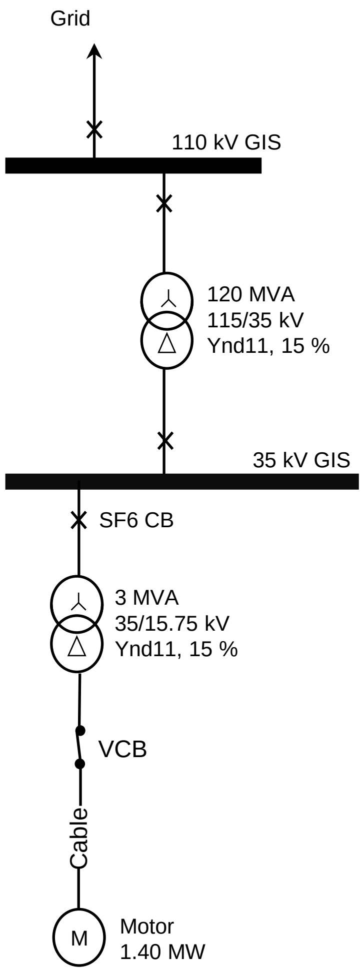
Very-fast-front overvoltage

Switching inductive current with vacuum interrupter

- Event sequence
  - Opening of VCB (vacuum circuit breaker)
- The shape of overvoltage depends on
  - Opening time instant
  - Arcing time
  - Vacuum interrupter design, electrode diameter, material, etc.

Switching sequence and VCB representation



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Very-fast-front overvoltage

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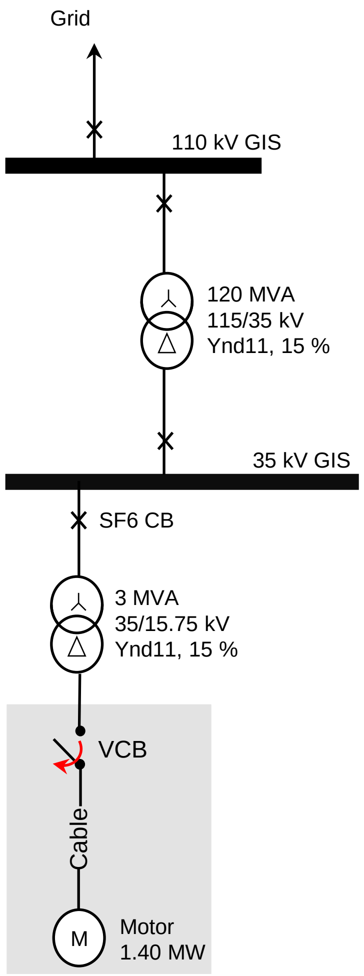
Switching sequence and VCB representation



Very-fast-front overvoltage

Switching inductive current with vacuum interrupter

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  - Opening of VCB (vacuum circuit breaker)
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  - Opening time instant
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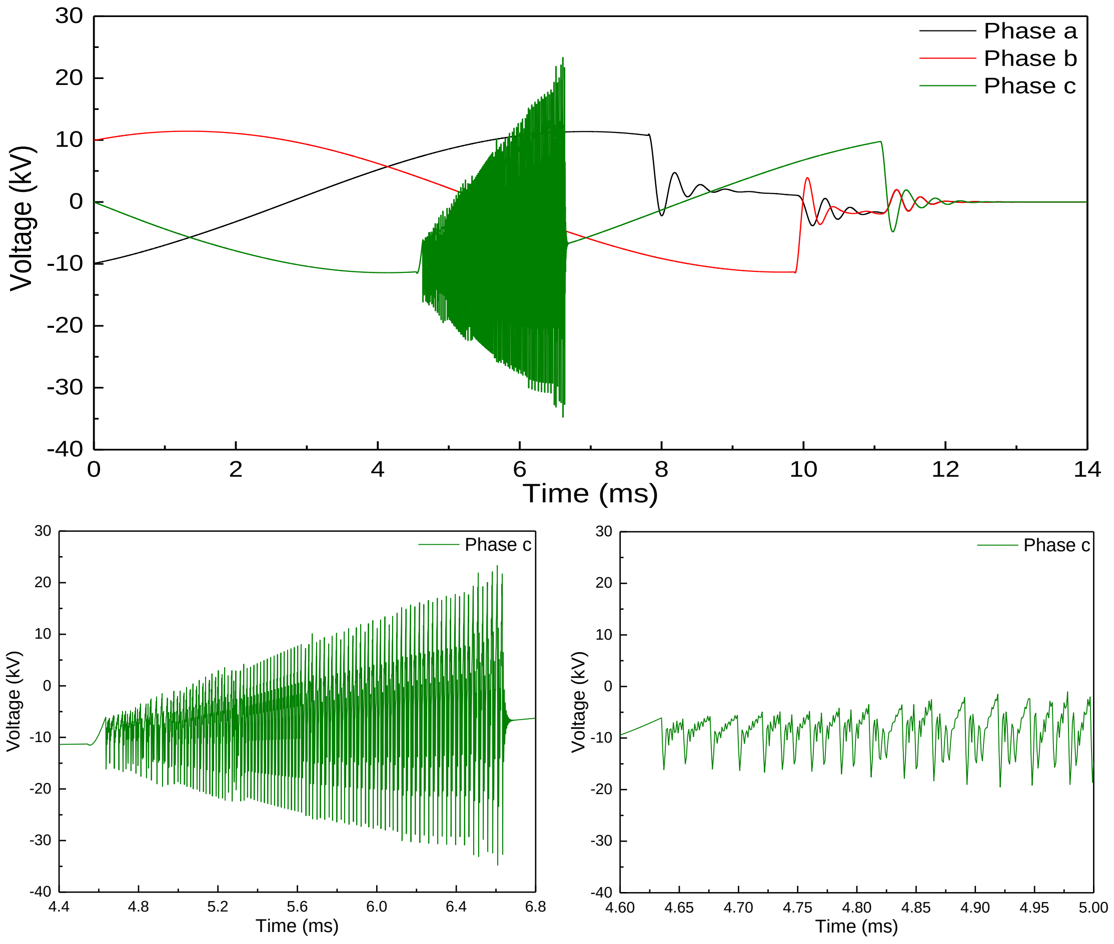
Resulting overvoltage



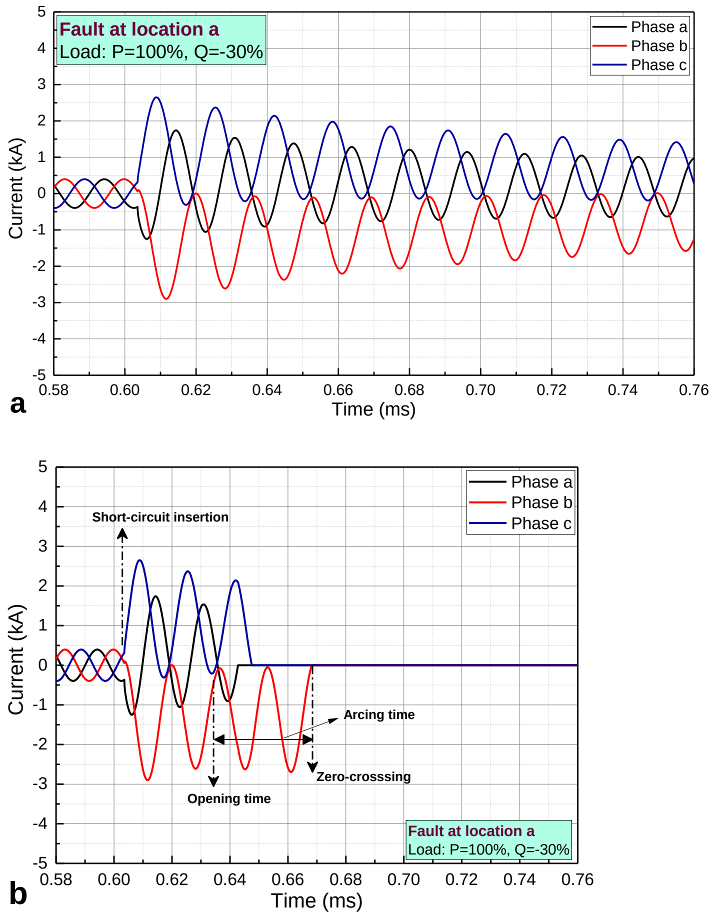
The phase-to-earth voltage at Terminal of VCB

Insulation Coordination Study

Missing zero-crossing evaluation

- Missing zero-crossing might occur when circuit breaker needs to interrupt a current with high DC component.
- Depending on circuit breaker (voltage level, type, insulation, etc.) this might lead to serious failure of circuit breaker and endanger system.
- Theoretically it occurs when circuit breaker interrupting current with very high offset DC.
- Practically missing zero-crossing can occur:
  - Interrupting reactor shortly after its energization,
  - Interrupting long cable circuit,
  - Interrupting short-circuits at GIS of generator when generator operated in under-excited mode

Resulting overvoltage



An example of missing zero-crossing and long arcing time due to interrupting short-circuit current with high DC component when fault occurs at GIS and generator operated in under-excited mode

Ferro-resonance evaluations

- Ferro-resonance is a non-linear oscillation due to the interaction of an iron core inductance e.g., magnetic voltage transformer, saturable reactor or power transformer, with a capacitance (cable, grading capacitance of circuit breaker, etc.).

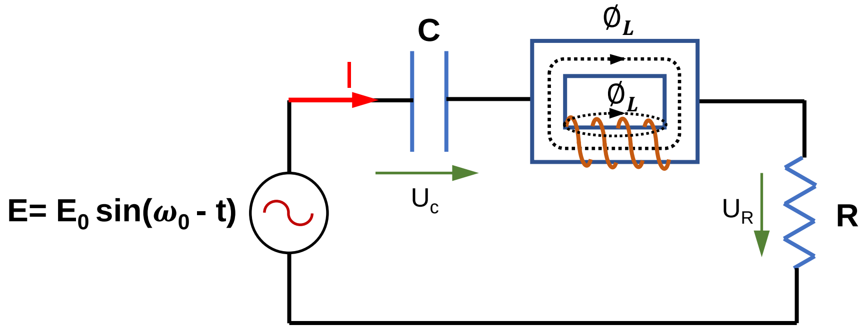
- The combination of the following elements can be identified as cause for ferro-resonance
  - Non-linear inductance
  - Capacitance
  - An external voltage or current source
  - Low Losses or low resistive system

- Network inductances are constant and independent to the current, when the magnetic field flows preponderantly in air e.g., in overhead lines, underground cables or in leakage paths of rotating machinery and transformers

General

- Th network inductance is no longer constant, if the magnetic field flows entirely or to great extent through iron e.g., in magnetic cores of power transformers, instrument transformers and reactors, which made of saturable **ferromagnetic** materials

- Capacitances are present in long transmission lines, underground cables, GIS, grading capacitors of circuit breakers, series capacitors, shunt capacitor banks, etc.



Insulation Coordination Study

Typical Ferro-resonance cases

- Power transformers accidentally energized in only one or two phases.
- Voltage or power transformers energized through grading capacitors of open circuit breakers.
- Lightly loaded power transformer connected to a series compensated transmission line.
- Voltage transformers connected to an isolated or resonant neutral system.
- Capacitor voltage transformer.
- Voltage and power transformers connected to a de-energized transmission line running in parallel with one or more energized lines.
- Lightly loaded power transformers connected to a cable network or long transmission line with low short circuit power.

Ferro-resonance waveforms

- Periodic Ferro-resonant Modes
- Quasy-Periodic Ferro-resonant Modes
- Chaotic Ferro-resonant Modes

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Risky configurations – VT based events

1) Busbars VTs

- The ferro-resonance can occur when busbars are de-energized by opening the circuit breakers in all the feeders.
- **When?** e.g. a busbar fault clearing or a maintenance outage.
- **Required conditions:**
  - Presence of inductive VTs in the isolated Busbar section.
  - The feeder circuit-breakers (all or some of them) are equipped with grading capacitors.
- The capacitance C_g represents the grading capacitance of each open circuit breaker and n is the number of feeders. Cs represents the capacitance to ground of the disconnected section of busbar. R and L represent the VT losses and magnetizing inductance respectively.

Risky configurations – VT based events

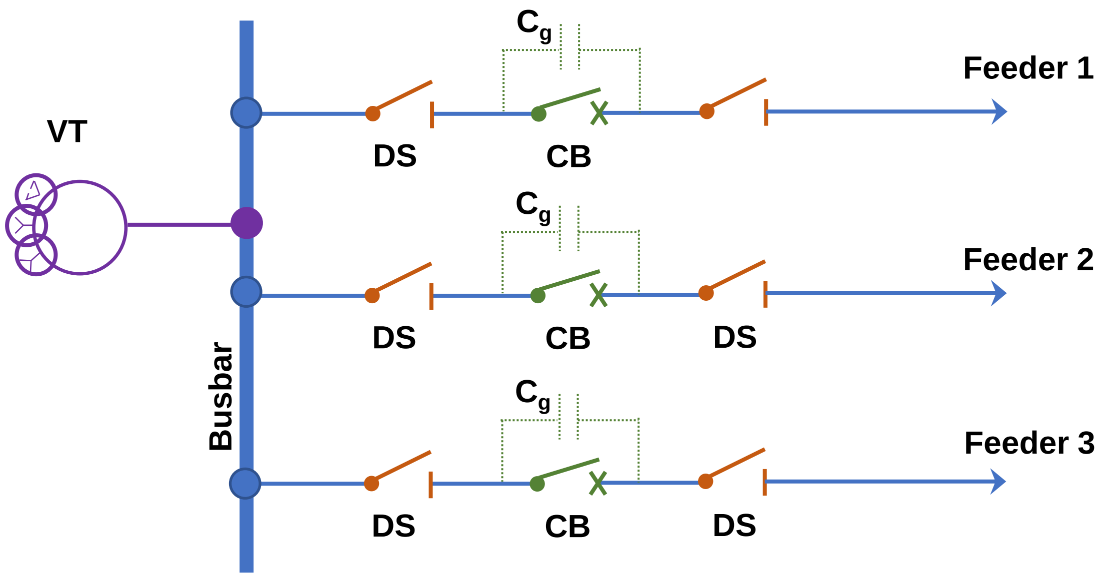

Figure 1:Risky configuration: Busbar VT

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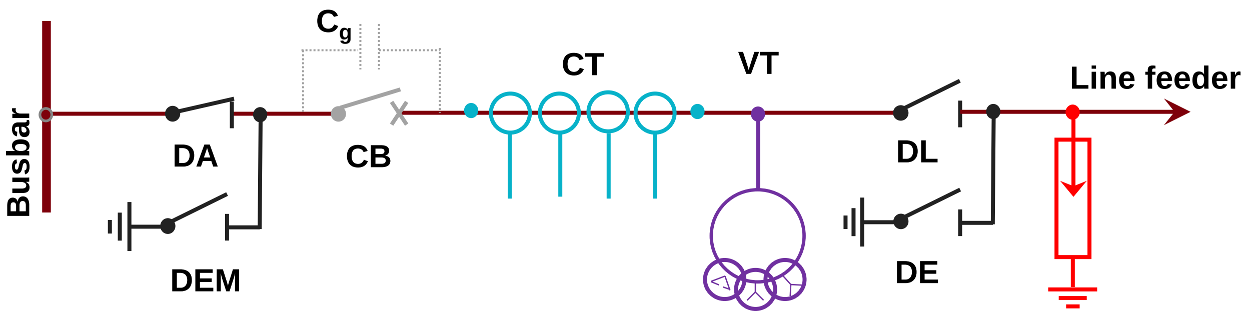
Risky configurations – VT based events

2) Lint VTs

- The ferro-resonance can occur when line VTs are de-energized.
- **When?** It can be occurred frequently.
- **Required conditions:**
  - The line circuit-breaker is equipped with grading capacitors.
  - The bus disconnector is closed, and the line disconnector is open.
  - Inductive VTs are installed between the circuit breaker and the line disconnector.
- An example is shown in Figure 1. The capacitance C_g represents the grading capacitance of the circuit breaker, C_s represents the capacitance to ground of the disconnected line bay, R and L represent the VT losses and magnetizing inductance, respectively.
- Ferro-resonance may occur as a result of a line de-energization by opening the circuit breaker with the bus disconnector DA closed and DL open.

Risky configurations – VT based events



Risky configuration: Line VT

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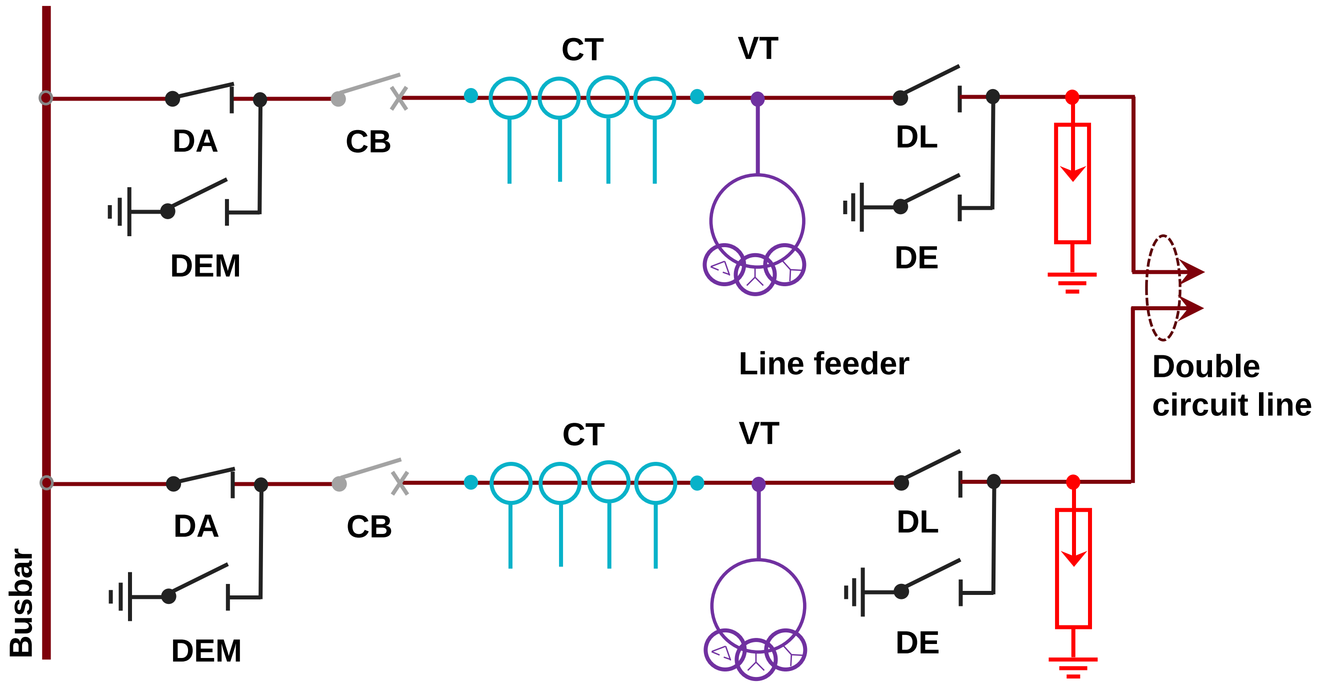
Risky configurations – VT based events

3) Line VTs in double-circuit construction

- The ferro-resonance can occur when one circuit in a double-circuit line is disconnected, while the other one remains energized.
- The ferro-resonant condition is sustained by the capacitive coupling with the energized circuit.
- Circuit Breaker grading capacitance is not necessary to maintain the oscillation.
- **When?** Double circuit lines under specific operating condition.
- **Required conditions:**
  - One circuit in a double-circuit line is disconnected.
  - The other one remains energized.
  - Inductive VTs are installed between the circuit breaker and the line disconnector.

Risky configurations – VT based events



Risky configuration: Line VTs in double-circuit construction

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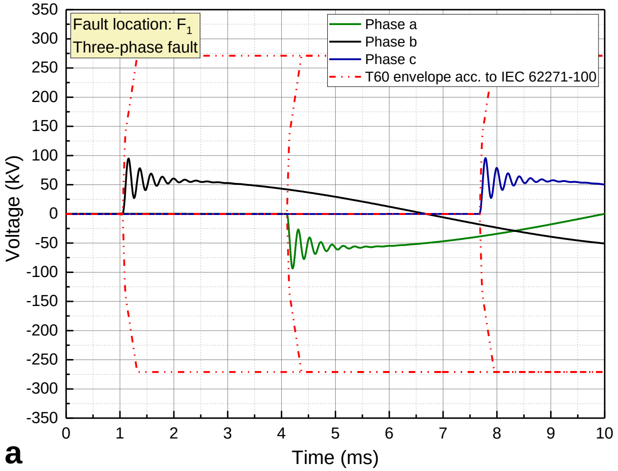
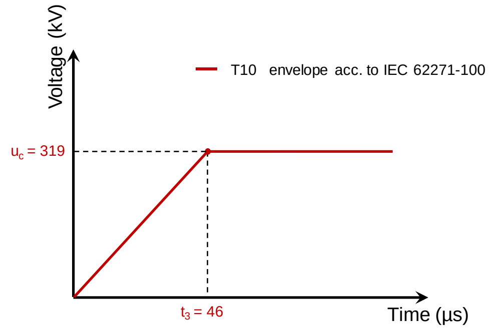
Circuit breaker capability – TRV calculations

- In case of a fault at the busbar the circuit breaker must switch off high short-circuit currents.
- If the fault is close to the transformer e.g., a busbar fault, a high rate-of-rise of the transient recovery voltage is expected.
- The steepness of the voltage is mainly affected by the natural frequencies of the transformer
- Transient recovery voltage is defined in the “IEEE Standards Dictionary: Glossary of Terms & Definitions” as “the voltage transient that occurs across the terminals of a pole of a switching device upon interruption of the current”.
- The transient recovery voltage is the voltage to which the circuit breaker terminals are exposed following interruption.
- A circuit breaker TRV capability is sufficient, if the two or four parameter envelopes drawn with the rated parameters as specified in IEEE Std C37.06-2012 is higher than the two or four parameter envelope of the system TRV at the point of application.

location	Type	Circuit breaker current			Envelopment	Calculated		standard values acc. to IEC 62271-100	
		Rated I_{CB} [kA]	Calculated I_K” [kA]	ratio I_K”/I_{CB} [%]		TRV peak [kV]	RRRV [kV/µs]	TRV peak [kV]	RRRV [kV/µs]
F1	Three-phase	50	23.5	47.0	T60	95.3	1.18	135	3
F1	Single-phase	50	23.6	47.2	T60	95.2	0.86		



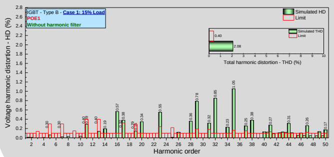


An example of characteristic of TRV for the ELK-04/170 circuit breaker

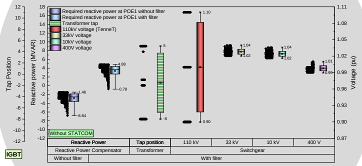
Agenda

Harmonic

Resonance study



EMC Assessment



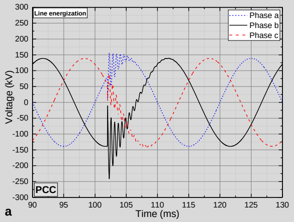
Power Factor Correction

Switching

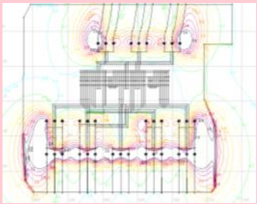
Lightning

Mitigation

etc.



Insulation Coordination



EMF Assessment

Arc Flash Study

Grid Compliance

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EMF – Electric and Magnetic Filed Calculations

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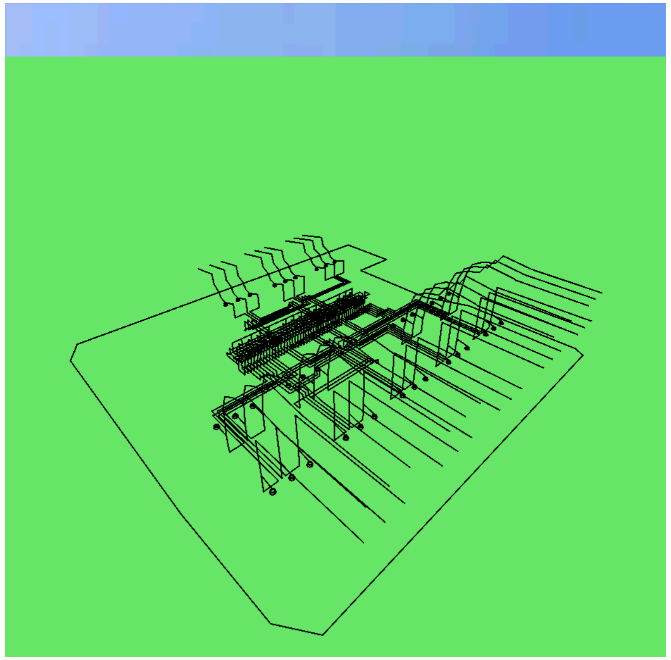
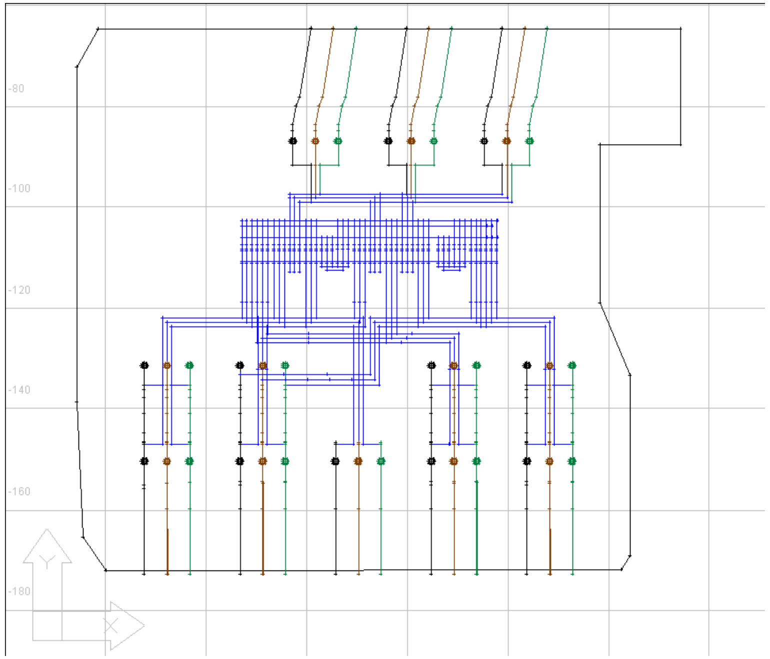
Motivation

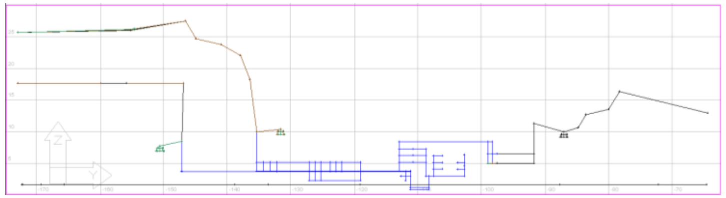
– Calculation of electric and magnetic filed at different project zones

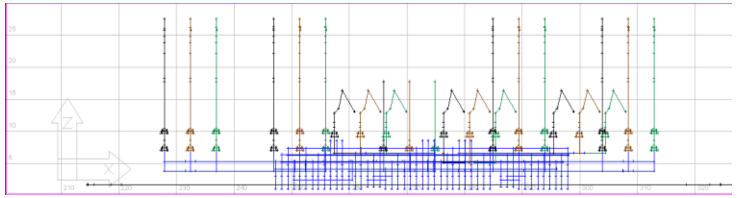
Approach

– 3D model preparation based on voltage and current of active part
– Define relevant zone
– Initial condition and operating voltage/current definition
– Comparing calculated value with appropriate admissible levels
– Mitigation solution, if required









An example of 3D model of high voltage switchgear for EMF calculations

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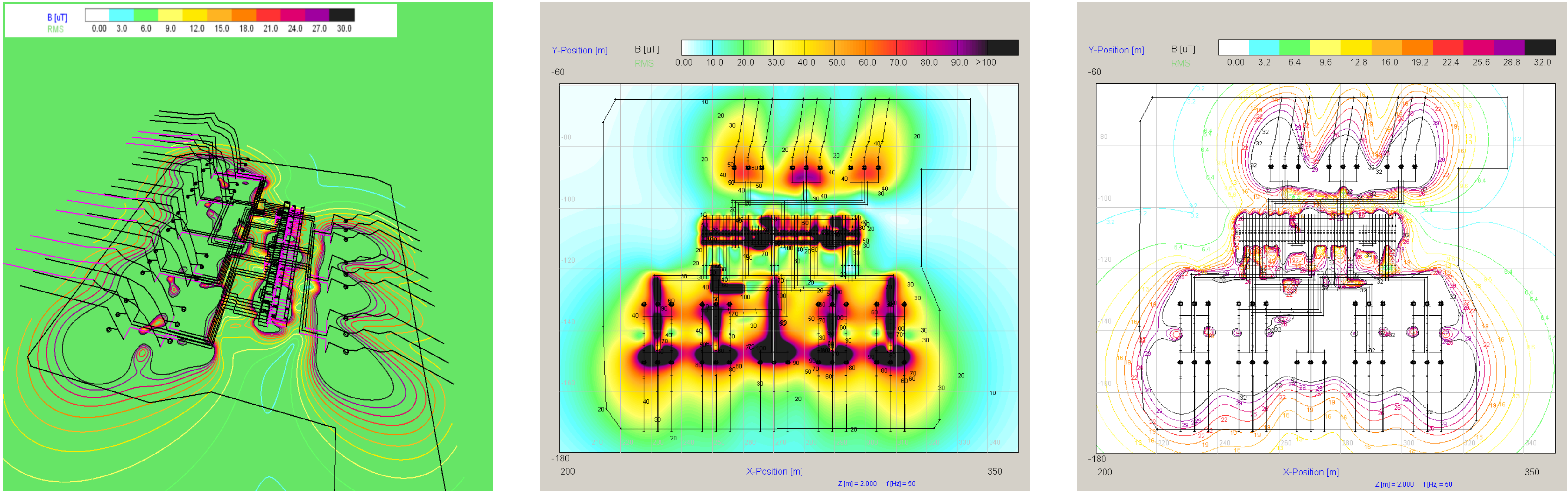
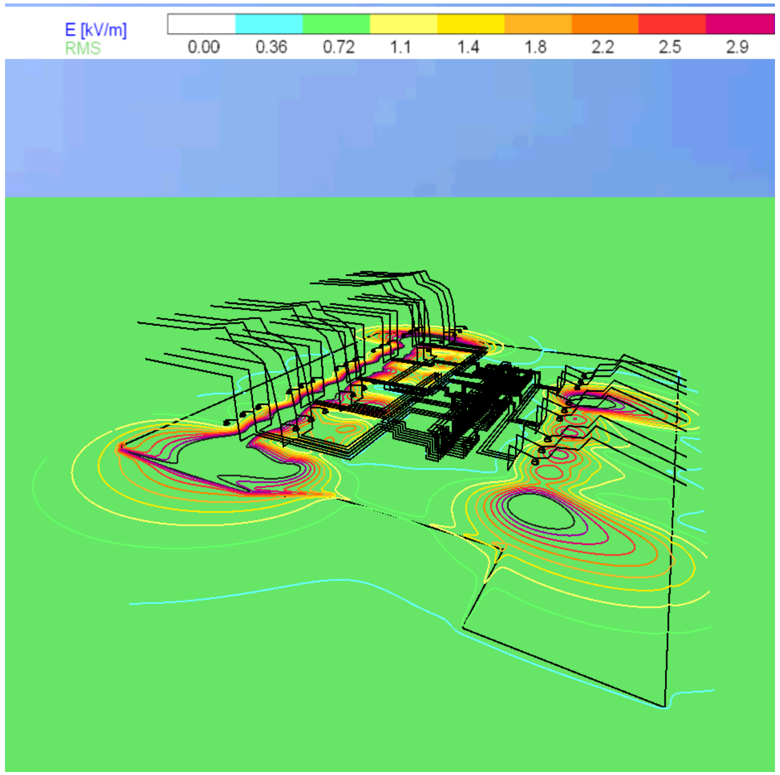
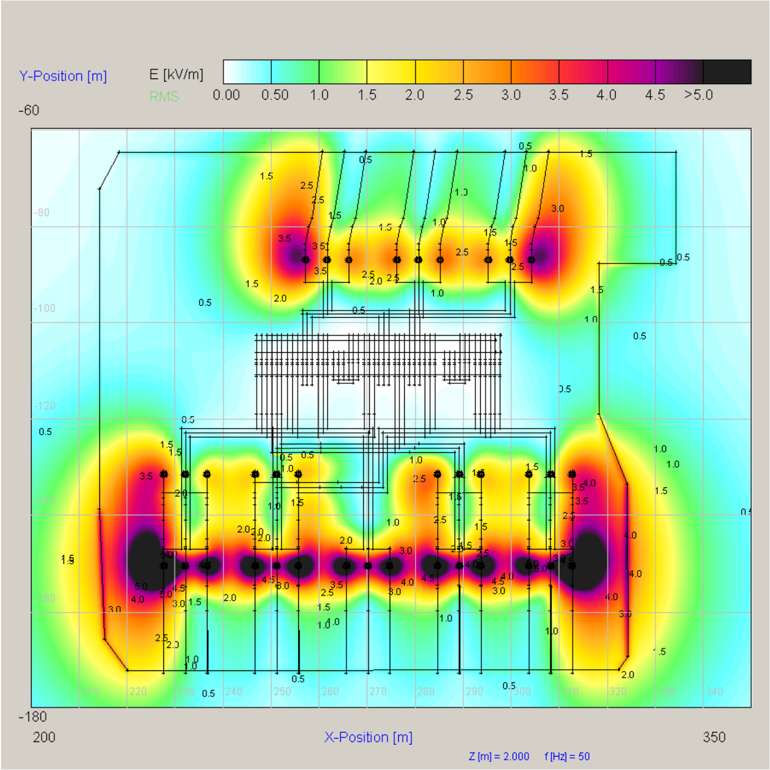
EMF – Electric and Magnetic Filed Calculations

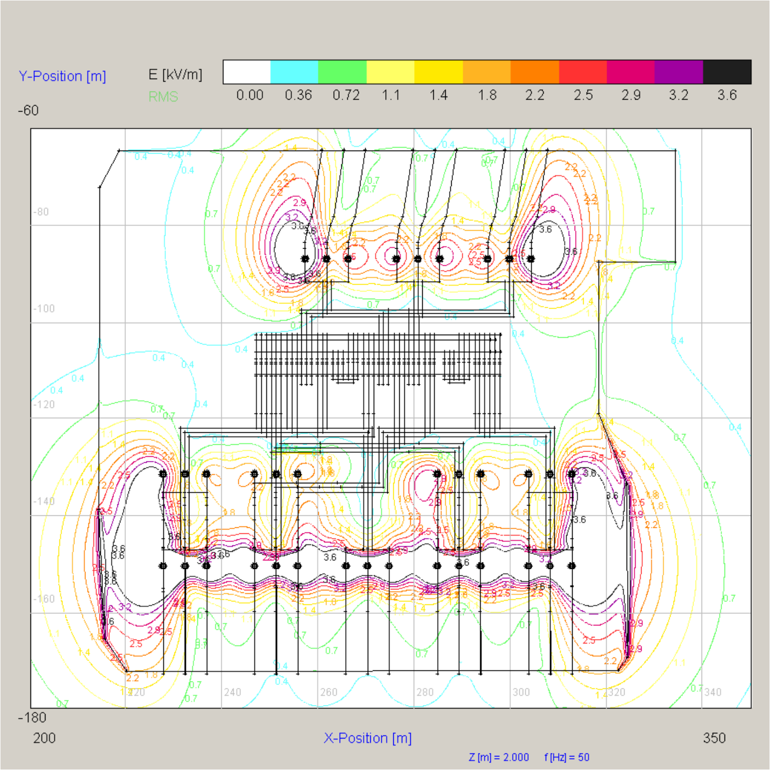


An example of calculated magnetic field

EMF – Electric and Magnetic Filed Calculations





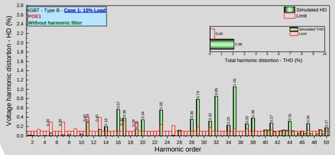


An example of calculated electric field

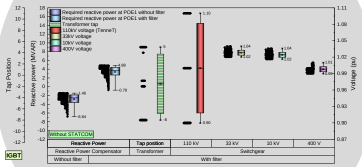
Agenda

Harmonic

Resonance study



EMC Assessment



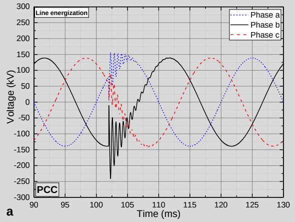
Power Factor Correction

Switching

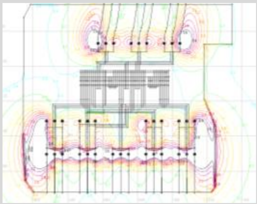
Lightning

Mitigation

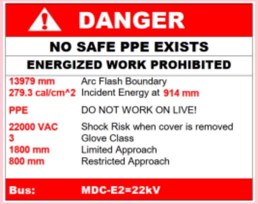
etc.



Insulation Coordination



EMF Assessment



Arc Flash Study

Grid Compliance

Arc Flash Study

Background

To determine a worker's exposure to arc flash incident energy.

To identify the Arc Flash Protection Boundary, which is the closest approach distance allowed before Personal Protective Equipment (PPE) must be worn.

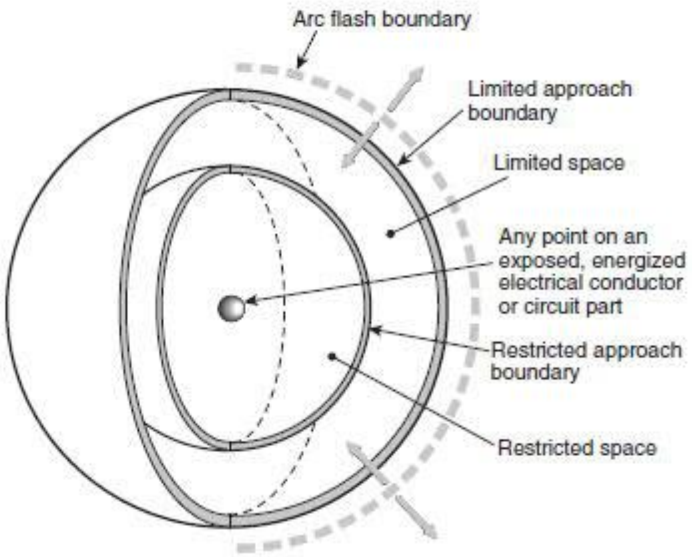
To determine the amount of incident energy during arcing faults, the short circuit fault current and protective device clearing times are required.

Protection devices (Fuses and Circuit Breakers) size and settings for the low voltage AC/DC Distribution System have been ascertained from the inherited power system model.

The amount of incident energy allows to establish the necessary site health and safety policies to manage the risk to their employees. I

f the control measure is determined to be arc-rated clothing, the Arc Flash study identifies the amount of energy available in each equipment and/or device, so that the proper combination of arc rated clothing is selected to perform energized work at each location.

The incident energy results are based on the fault current levels calculated in the short circuit study and the associated clearing times of the overcurrent protective devices.



Limits of Approach

Arc Flash Study – Case Study

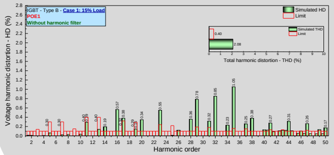
Arc Flash Study Results

Bus Name	Protective Device Name	Bus kV	Bus Bolted Fault (kA)	Bus Arcing Fault (kA)	Prot Dev Bolted Fault (kA)	Prot Dev Arcing Fault (kA)	Trip/ Delay Time (sec.)	Breaker Opening Time/Tol (sec.)	Equip Type	Electrode Config	Box Width (mm)	Box Height (mm)	Box Depth (mm)	Gap (mm)	Arc Flash Boundary (mm)	Working Distance (mm)	Incident Energy (cal/cm2)	PPE Level (Scenario)
MDC-E1=22kV	R-I/G_MDC-E1	22.00	23.03	23.03	23.03	23.03	0.65	0.0800	SWG	VCB	762	1143	762	152	13034	914	226.3	Dangerous! S2
MDC-E2=22kV	R-O/G_MCDE2-SDCE2-1	22.00	23.07	23.07	5.30	5.30	1.156	0.0800	SWG	VCB	762	1143	762	152	13979	914	262.7	Dangerous! S2
MDC-F1=22kV	R-I/G_MDC-F1	22.00	20.13	20.13	20.13	20.13	0.65	0.0800	SWG	VCB	762	1143	762	152	12188	914	197.9	Dangerous! S1
MDC-F2=22kV	R-I/G_MDC-F2	22.00	20.15	20.15	17.69	17.69	0.65	0.0800	SWG	VCB	762	1143	762	152	12193	914	198.0	Dangerous! S1
SDC-E1-1 22kV	R-O/G_MCDE1-SDCE1-1	22.00	22.04	22.04	22.04	22.04	0.45	0.0800	SWG	VCB	762	1143	762	152	11005	914	157.3	Dangerous! S2
SDC-E1-2 22kV	R-O/G_MCDE1-SDCE1-2	22.00	22.11	22.11	22.11	22.11	0.45	0.0800	SWG	VCB	762	1143	762	152	11022	914	157.8	Dangerous! S2
SDC-F1-1 22kV	R-O/G_MCDE1-SDCE1-1	22.00	20.36	20.36	20.36	20.36	0.45	0.0800	SWG	VCB	762	1143	762	152	10577	914	145.3	Dangerous! S2
SDC-F1-2 22kV	R-O/G_MCDF1-SDCF1-2	22.00	19.43	19.43	19.43	19.43	0.45	0.0800	SWG	VCB	762	1143	762	152	10333	914	138.7	Dangerous! S1
SDC_E2-1	R-O/G_MCDE2-SDCE2-1	22.00	22.55	22.55	17.19	17.19	0.45	0.0800	SWG	VCB	762	1143	762	152	9884	914	127.3	Dangerous! S2

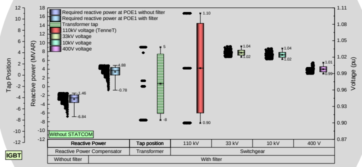
Agenda

Harmonic

Resonance study



EMC Assessment



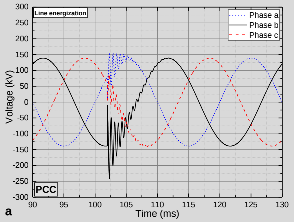
Power Factor Correction

Switching

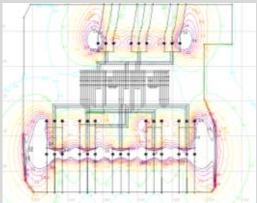
Lightning

Mitigation

etc.



Insulation Coordination



EMF Assessment

Arc Flash Study

Grid Compliance

Grid Code Compliancy Study

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Background

- As a requirement for grid connection
- To fulfill equipment compatibility in terms of
  - Insulation level
  - Operating voltage/current
  - Harmonic distortion
- Different type of study
- Reactive power requirement
- Short-circuit compatibility
  - Power quality (harmonic, rapid voltage change)
  - Dynamic stability
  - Insulation coordination

<u>Note, that power quality is selected for more detail presentation.</u>

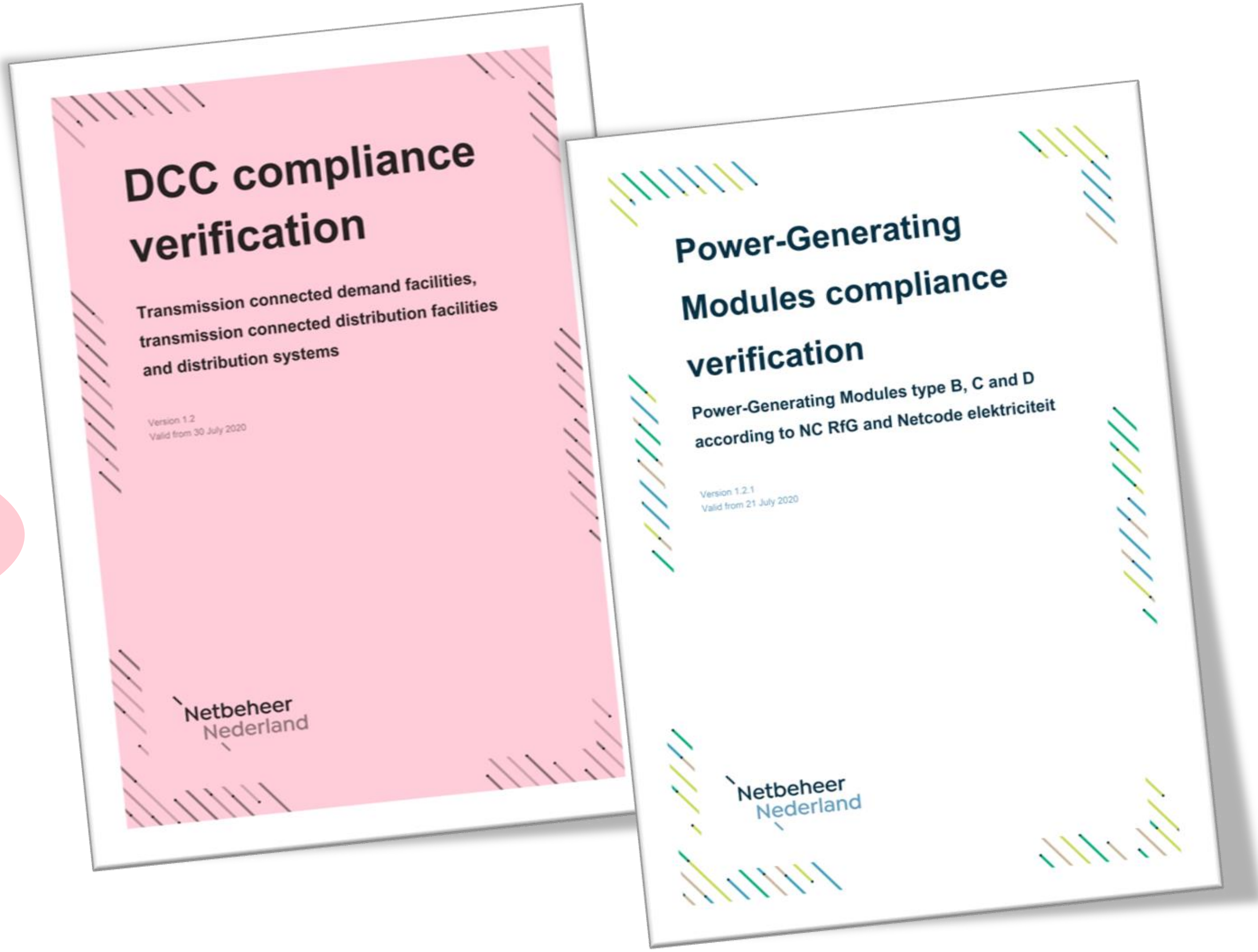
– Reactive Power Capability

– Harmonic Simulation

– Voltage fluctuating
  - Rapid voltage change
  - Flicker

Section 4.2.2 (Reactive Power Capability) and Section 4.2.14 (Power Quality) in
Transmission connected demand facilities, transmission connected distribution facilities and distribution systems

Section 4.2.8 (Reactive Power Capability) and Section 4.2.20 (Power Quality) in
Power-Generating Modules compliance verification Power-Generating Modules type B, C and D according to NC RfG and Netcode elektriciteit



Grid Code Compliancy Study – Case Study in The Netherlands

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– Reactive Power Capability

Netcode elektriciteit article 4.4, sub 1 a: If the connected party has not made any further contractual agreements with the transmission system operator, the power factor at the connection point varies **<u>between 0.9* (inductive) and 1.0 for a demand facility without onsite generation.</u>**

*depending on specific contractual agreement it can be 0.95 or etc.

– Harmonic Simulation

– Voltage fluctuating

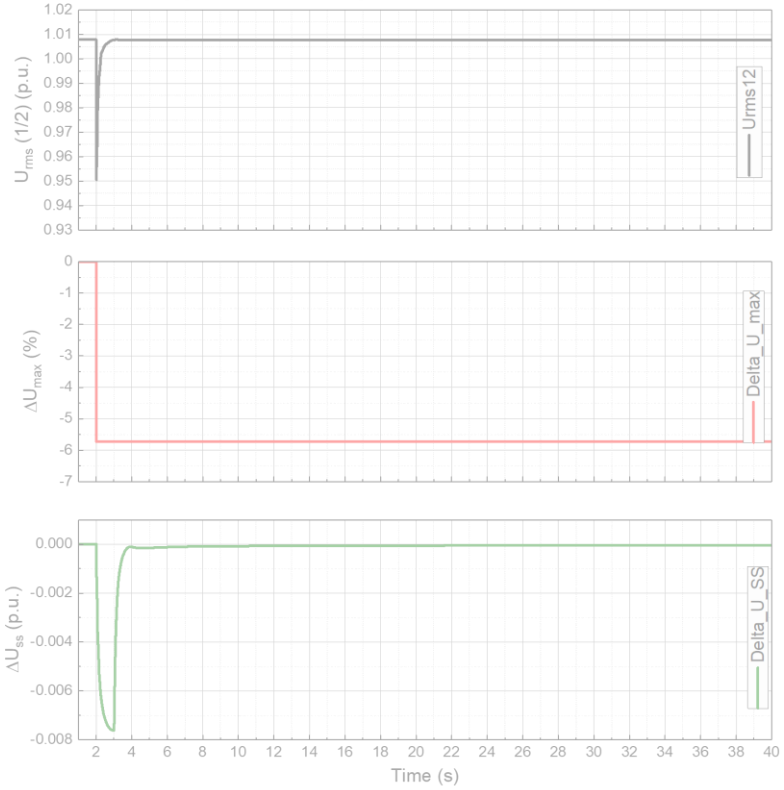
- Rapid voltage change
- Flicker

Harmonic Simulation (Comparison HDs and THD with limits)

Rapid Voltage Change

Number of accepted changes (n)	$\Delta U_{max}/U_n$ [%]
n ≤ 4 per day	5
n ≤ 2 per hour and n > 4 per day	3
2 < n ≤ 10 per hour	2.5

Voltage fluctuation during 120 MVA transformer energization



Flicker

P_{LT} Continuous Switching	P_{ST} Continuous Switching
0.25	0.35

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– **Reactive Power Capability**

Netcode elektriciteit article 4.4, sub 1 a: If the connected party has not made any further contractual agreements with the transmission system operator, the power factor at the connection point varies **between 0.9* (inductive) and 1.0 for a demand facility without onsite generation.**

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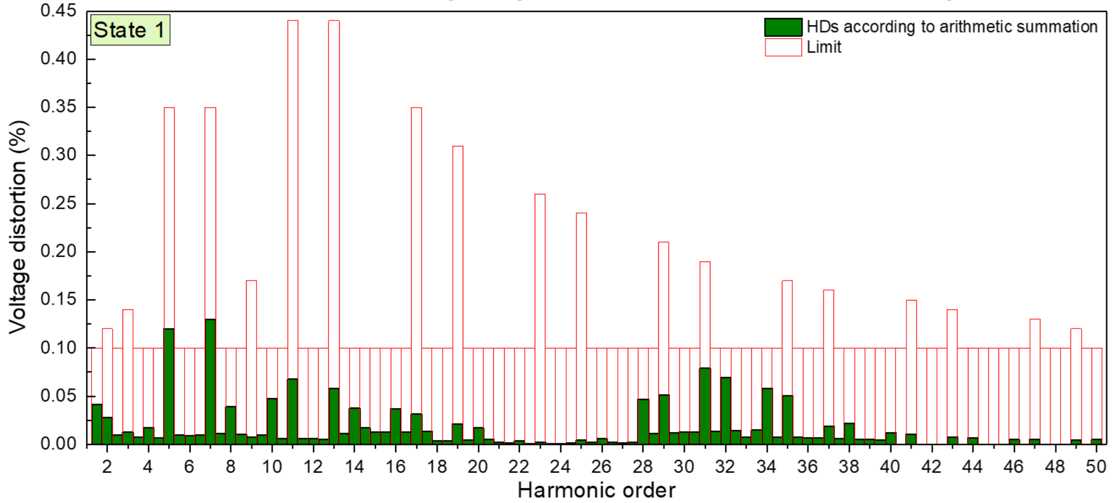
  - Rapid voltage change
  - Flicker

Harmonic Simulation (Comparison HDs and THD with limits)



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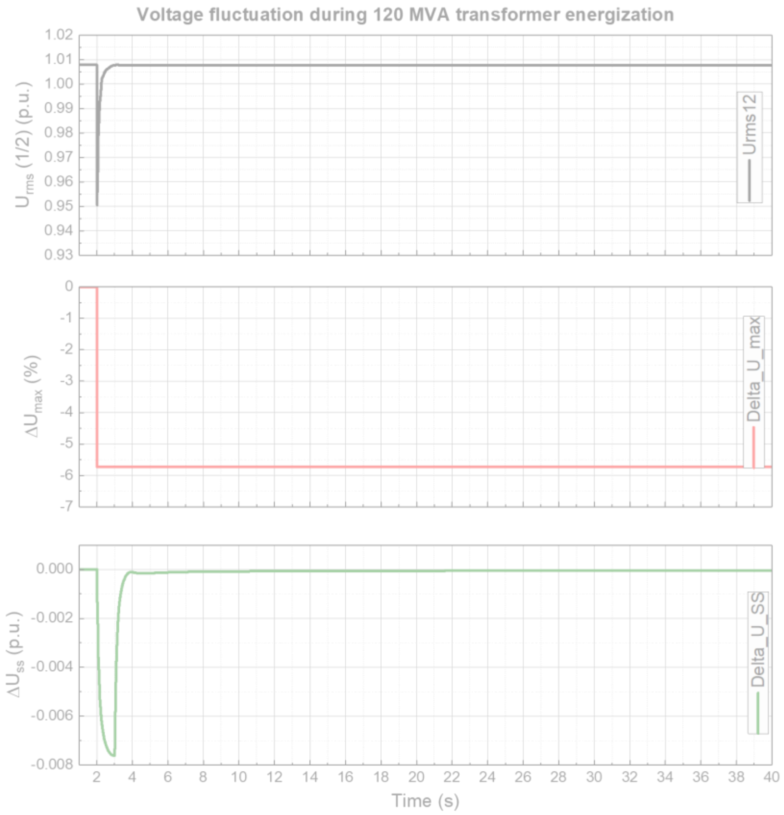

Flicker

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Grid Code Compliancy Study – Case Study in The Netherlands

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– **Reactive Power Capability**

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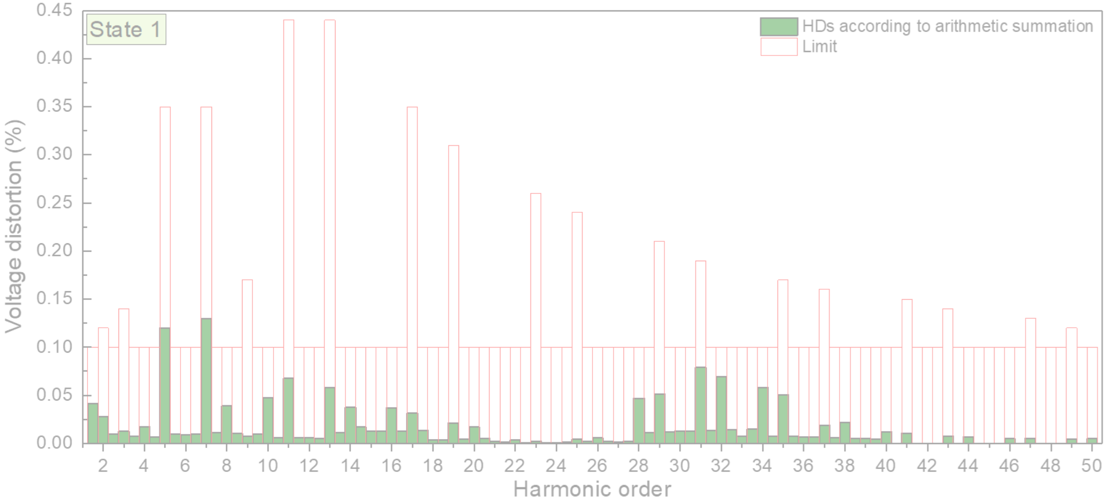
– **Harmonic Simulation**

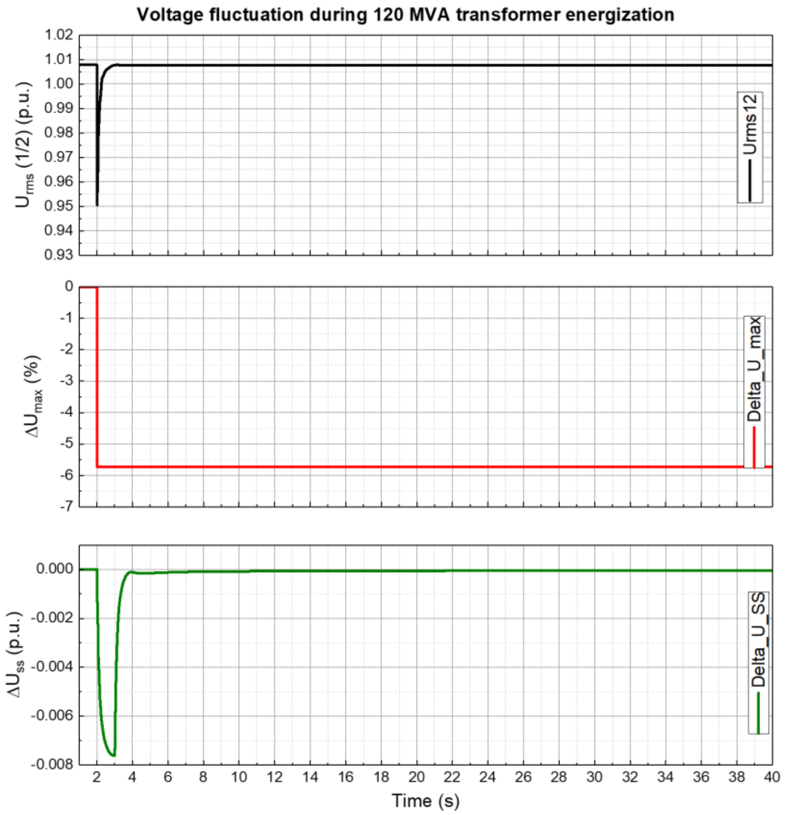
– Voltage fluctuating
- Rapid voltage change
- Flicker

Harmonic Simulation (Comparison HDs and THD with limits)



Rapid Voltage Change

Number of accepted changes (n)	$\Delta U_{max}/U_n$ [%]
n ≤ 4 per day	5
n ≤ 2 per hour and n > 4 per day	3
2 < n ≤ 10 per hour	2.5



Flicker

P_{LT} Continuous Switching	P_{ST} Continuous Switching
0.25	0.35

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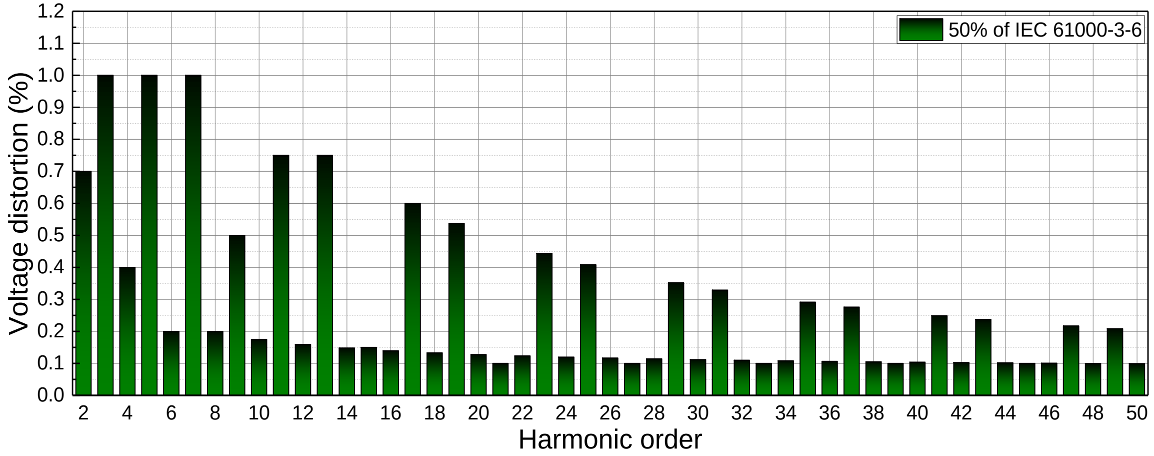
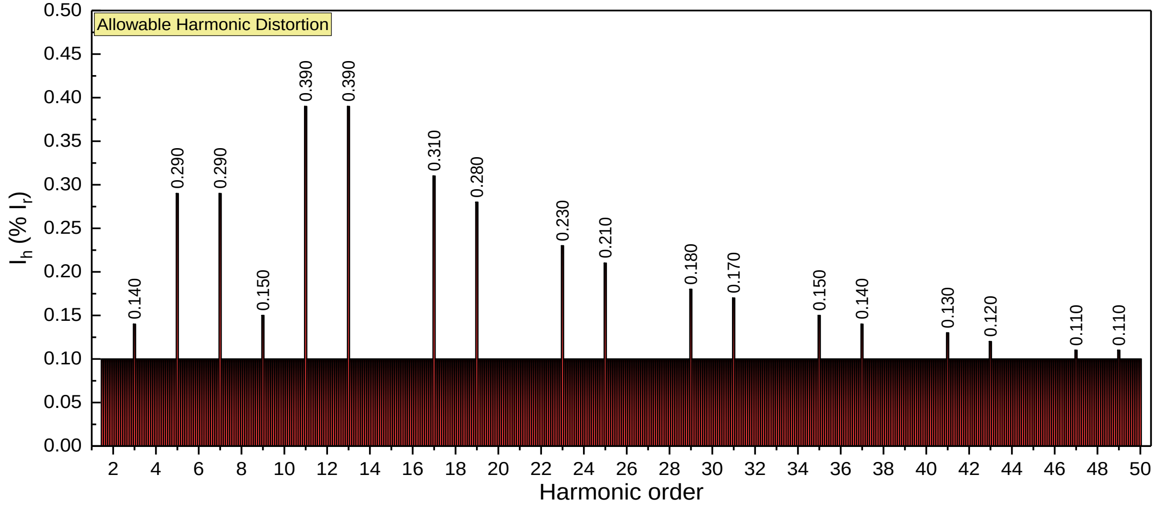
Power quality - Challenges

- Relatively low limit
- Grid strength (Impedance polygon at PCC)
- Frequency dependent model development
- Summation method



Odd harmonics non-multiple of 3			Odd harmonics multiple of 3			Even harmonics		
Harmonic order h	Harmonic voltage (%)		Harmonic order h	Harmonic voltage (%)		Harmonic order h	Harmonic voltage (%)	
	MV	HV-EHV		MV	HV-EHV		MV	HV-EHV
5	**5**	**2**	**3**	**4**	**2**	**2**	**1.8**	**1.4**
7	**4**	**2**	**9**	**1.2**	**1**	**4**	**1**	**0.8**
11	**3**	**1.5**	**15**	**0.3**	**0.3**	**6**	**0.5**	**0.4**
13	**2.5**	**1.5**	**21**	**0.2**	**0.2**	**8**	**0.5**	**0.4**
22 ≤ h ≤ 49	$1.9 \cdot \frac{22}{h} - 0.2$	$1.2 \cdot \frac{22}{h}$	**21 < h ≤ 45**	**0.2**	**0.2**	**10 ≤ h ≤ 50**	$0.25 \cdot \frac{10}{h} + 0.22$	$0.19 \cdot \frac{10}{h} + 0.16$



Internal

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Grid Code Compliancy Study – Case Study in The Netherlands

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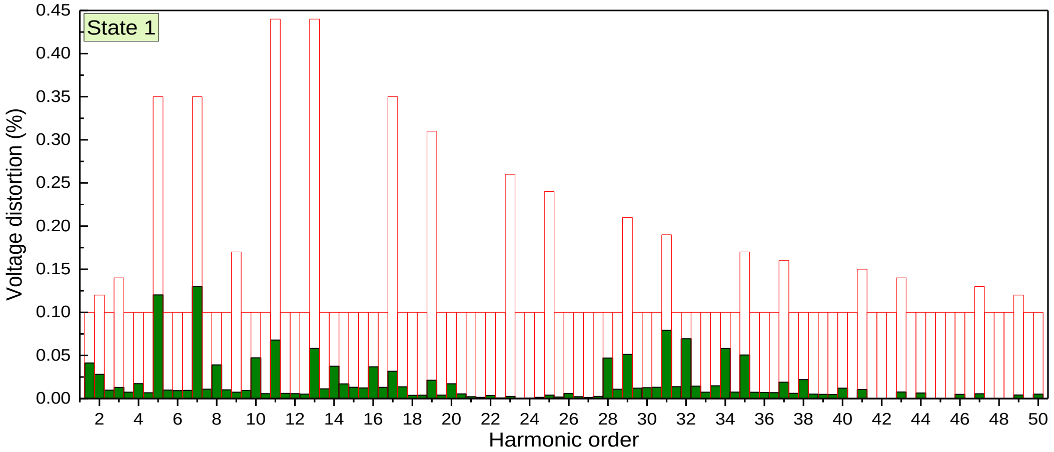
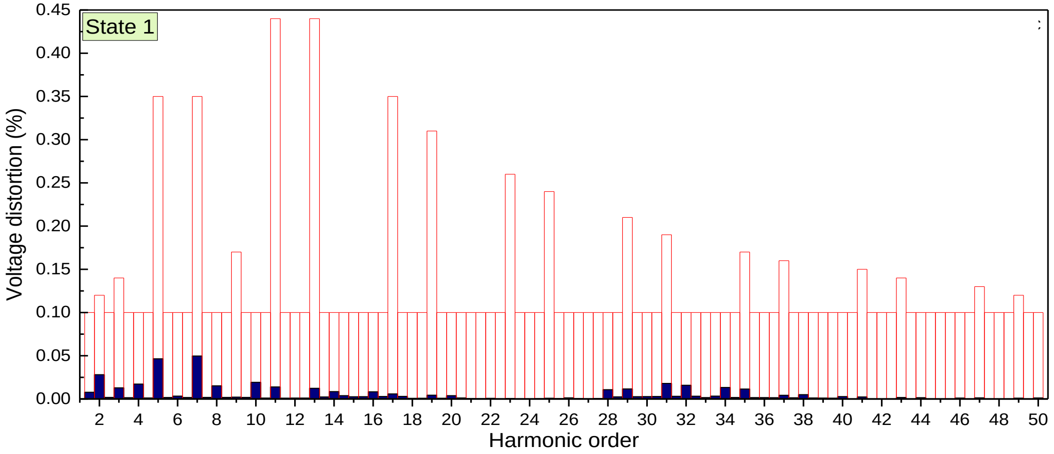
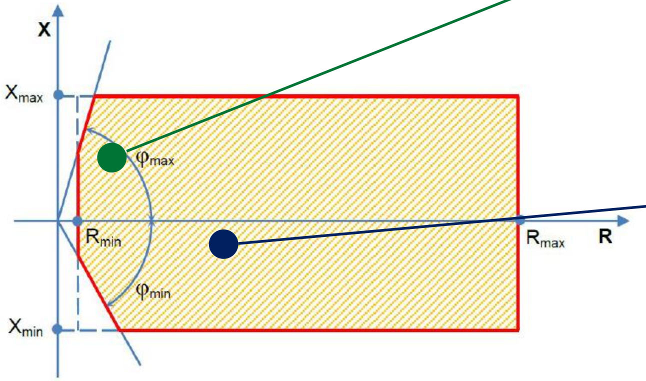
Power quality - Challenges

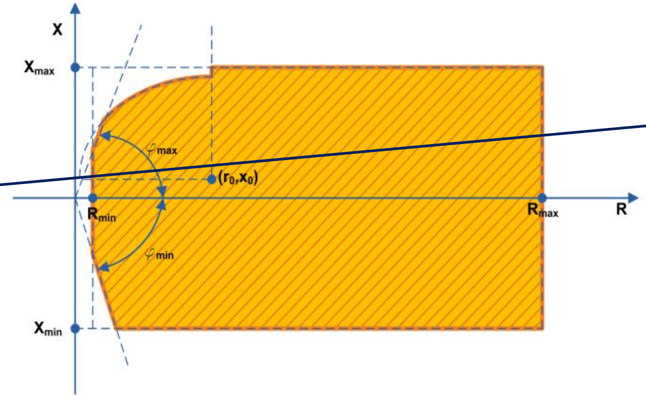
- Relatively low limit
- Grid strength (Impedance polygon at PCC)
- Frequency dependent model development
- Summation method

Amplification / reduction effects









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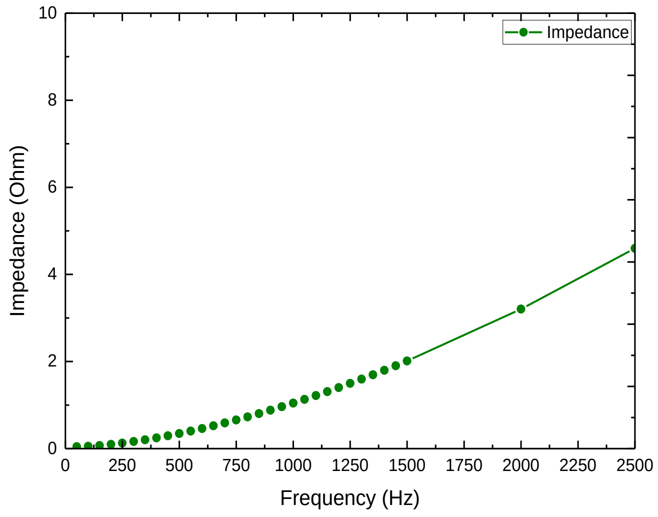
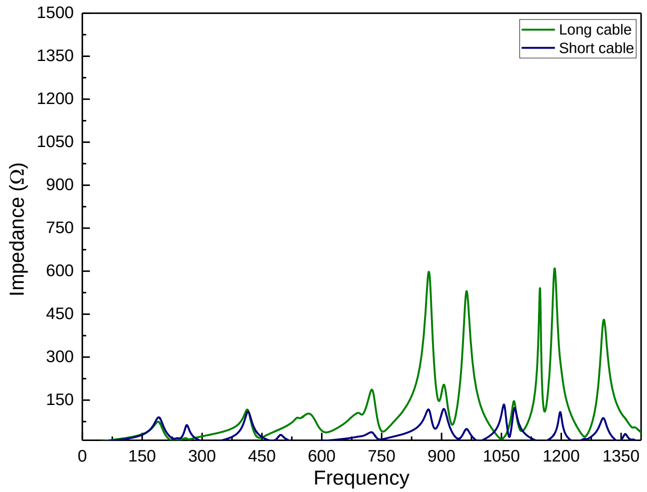
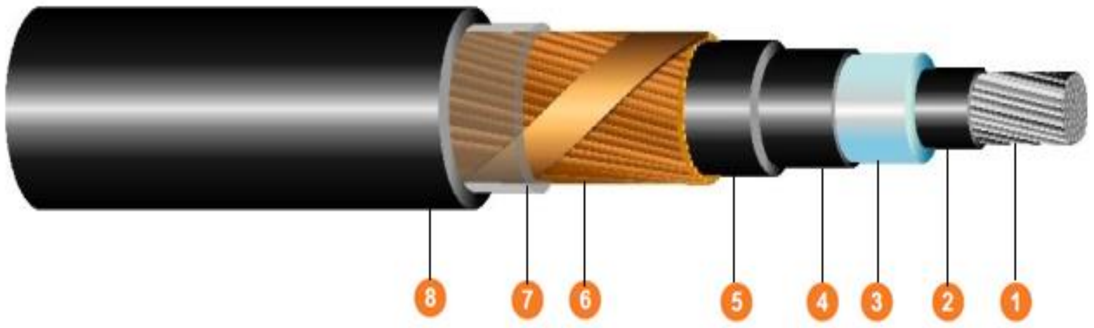
Power quality - Challenges

- Relatively low limit
- Grid strength (Impedance polygon at PCC)
- Frequency dependent model development
- Summation method





- **Cable modeling impact**
  - The frequency dependent behavior of cable impedances
  - Using Geometric data of cable or
  - Resistance / inductance for each frequency



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Power quality - Challenges

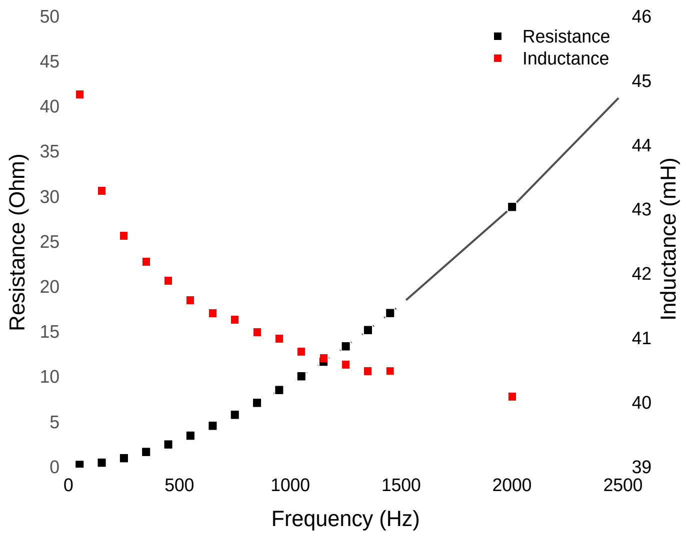
- Relatively low limit
- Grid strength (Impedance polygon at PCC)
- **Frequency dependent model development**
- Summation method

$$R(f) = R_n \cdot \left(1 + A_r \cdot \left(\frac{f}{f_n} - 1\right)^{B_r}\right)$$

$$L(f) = L_n \cdot A_l \cdot \left(\frac{f}{f_n}\right)^{B_l}$$

R(f)	HV winding effective resistance at given frequency
L(f)	HV winding effective air core inductance at given frequency
R_n	Winding resistance at nominal frequency
L_n	Air core inductance at nominal frequency
F	frequency
f_n	Nominal frequency
A_r	0.28
B_r	1.6
A_l	1
B_l	-0.03

- **Transformer modeling impact**
  - Higher resistance and reactance is expected



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Harmonics from each order were summed using the following technique:

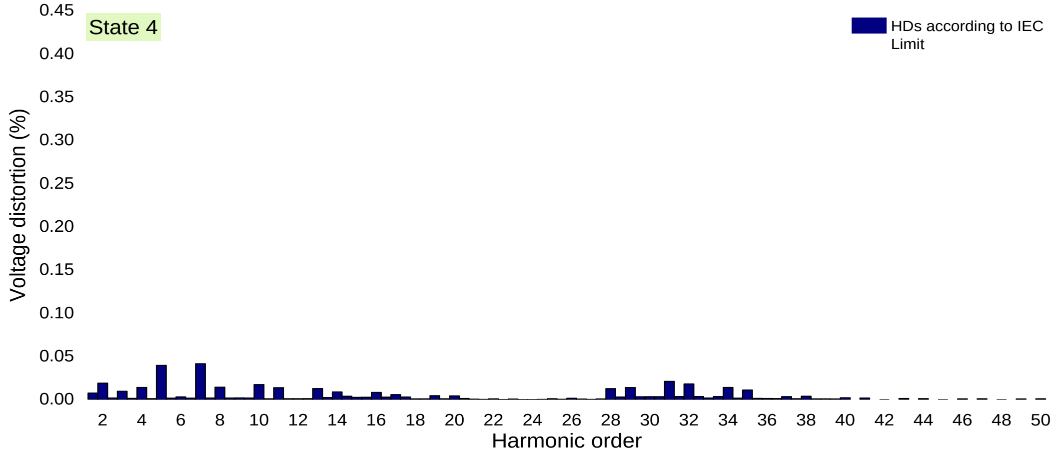
$$U_h = \sqrt[\alpha]{\sum_i U_{hi}^{\alpha}}$$

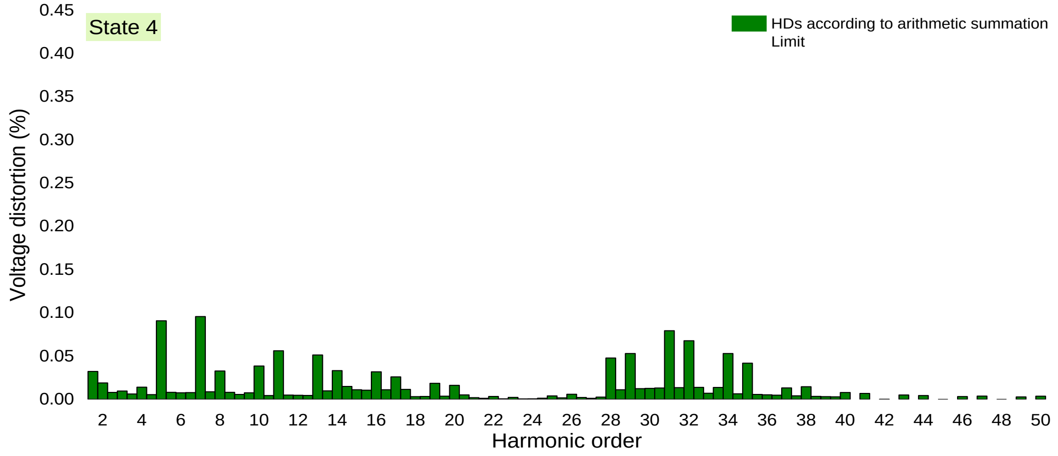
U_h – Magnitude of the corresponding harmonic voltage at a given harmonic "h"

U_{hi} – Magnitude of the individual emission level at a given harmonic "h"

α – Exponent to account for improved cancelation a higher harmonic order

Harmonic order	IEC (Appendix C) α	Arithmetic α
h ≤ 4	1	1
4 < h ≤ 10	1.4	1
h > 10	2	1





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