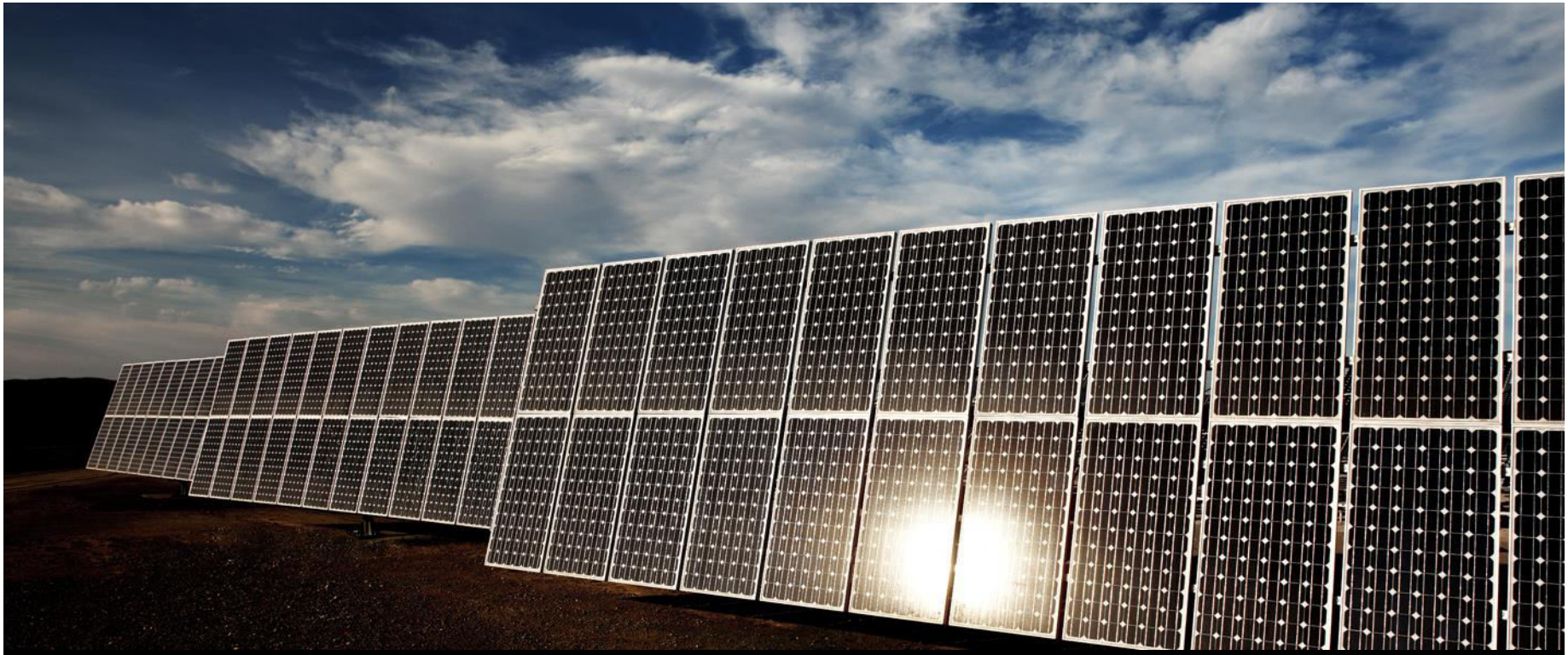


Pietro Raboni, R&D engineer, BU DMPC PG Solar

Integration of PhotoVoltaic Plants, the ABB experience
Lessons learned and case studies

ESCWA Workshop, Amman, 2nd-3rd September 2015

Power and productivity
for a better world™

List of the contents

- Introduction to ABB
- An R&D Forward-Thinking approach:
  - Grid code compliance and customer satisfaction
  - PVIs model portfolio
- Our Utility Scale PV Plant Engineering experience:
  - Services
  - Plant capability fulfilment: Q sources and related issues
  - Step-up transformer choice
  - Short circuit current limitation and our skid
  - Energization and Harmonic studies
  - Centralized Vs Decentralized solutions
- Conclusions

A global leader in power and automation technologies
Leading market positions in main businesses

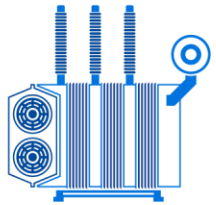
~150,000 employees

$42 billion
In revenue (2013)

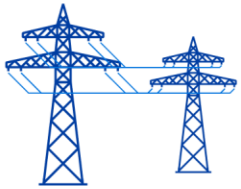
Present in +100 countries

Formed in 1988
merger of Swiss (BBC, 1891) and Swedish (ASEA, 1883) engineering companies

How ABB is organized
Five global divisions



Power Products



Power Systems

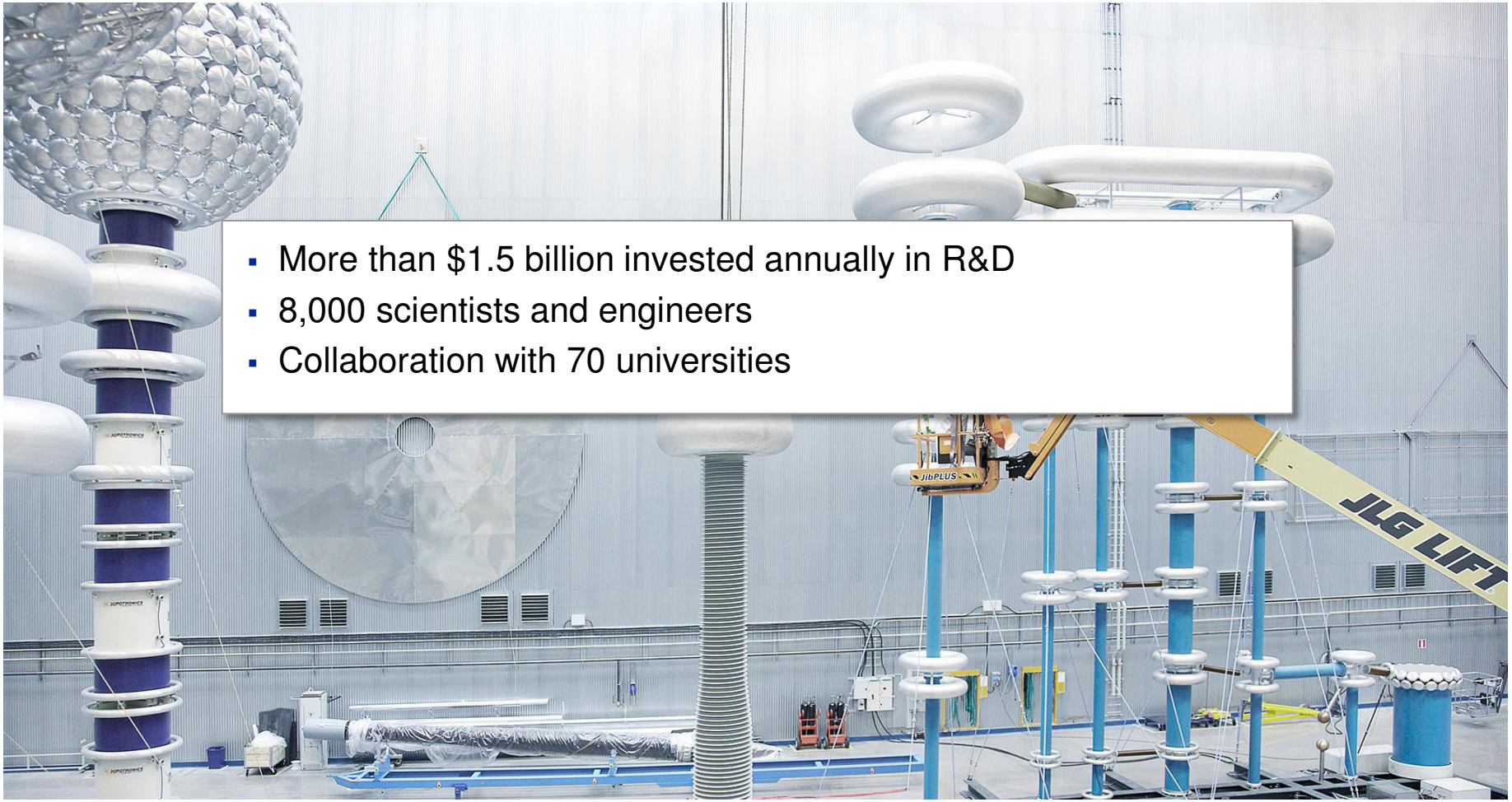
Discrete Automation and Motion

Low Voltage Products

Process Automation

© ABB

Innovation is key to ABB's competitive advantage
Leadership built on consistent R&D investment



- More than $1.5 billion invested annually in R&D
- 8,000 scientists and engineers
- Collaboration with 70 universities

ABB reinforces its commitment to solar
Power-One Renewable: a strategic acquisition

The largest and more capillary presence

Over 100 countries covered

The widest inverter portfolio

From 250W up to 2MW

A complete offer for renewables

Switchgears

Transformers

Protection devices

SCADA

PLCs and meterings

ABB DMPC PG Solar
Central PV Inverters

- CORE 1000
- PVS 800
- ULTRA 1400

Almost 1.6 GW of ULTRA installed

Wide V_{DC} range

Technical Data	ULTRA-1400-TL-OUTD
MPP Input Voltage Range	470-900 Vdc
Rated Power MPP Input Range	585-850 Vdc
Maximum Power MPP Input Range	645-850 Vdc
Max. Input Voltage	1000 Vdc
Number of Independent MPPT	4
Independent functional module	390 kVA
Output Voltage	690 Vac
Rated Power ($P_{ac,r}$)	1.400 kW
Maximum Power ($P_{ac,m}$ @ cosφ=1)	1.560 kW
Max. Eff. (η_{max}) / Euro Eff. (η_{EU}) / CEC Eff. (η_{CEC})	98.7%/98.2%/ 98.0%
User Interface	Touch Screen Graphical Display
Communication	RS 485
Ambient Temperature Range	-20/60°C (with derating above 50°C)
Environmental Protection Rating	IP 65 / NEMA 4X
Cooling	Liquid
Size (WxHxD in mm)	4420 x 2920 x 1520
Certification	CE
Safety Standards	EN50178, EN61000-6-2, EN61000-6-4, EN61000-3-11, EN61000-3-12
Grid Standard	Att. A70 Terna, CEI 0-16; BDEW, FERC661

Grid code compliance
A successful case of R&D proactiveness

R&D department overwhelmed by new grid code requirements consequent to market expansion

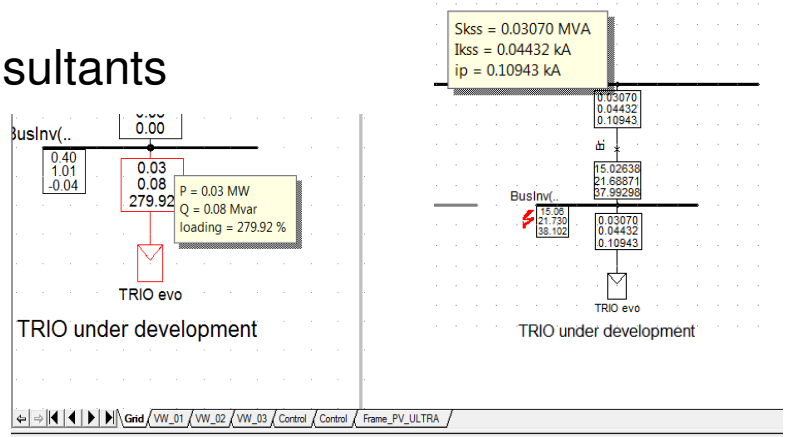
- Task force for Grid Code Monitoring
- Compliance to incoming most stringent grid codes and standards
  - CEI 0-16, CEI 0-17, BDEW, NEPCO, IEC, NERSA, Rule 21 phase 1, HECO, Chilean Grid code
- Fully parameterized PVIs to facilitate the compliance to further grid codes
- Eased by internal testing labs

Grid code compliance
State of the art functionalities

- Reactive power modes
  - PF_{PVI}=const (local / remote via PPC)
  - Q=const (local / remote via PPC)
  - Q(V) (local)
  - P=const=min{P_{av},P_{ref}} (local / remote via PPC)
- Control of positive and negative sequence currents
- Decentralized power ramp-up rate limitation
- *ULTRA:*
  - *Modular inverter: M&S or MultiMaster*
  - *Specifically designed for harsh environments (IP65, liquid cooled)*

PVI models portfolio
Certifications, g.c. compliance and customer needs

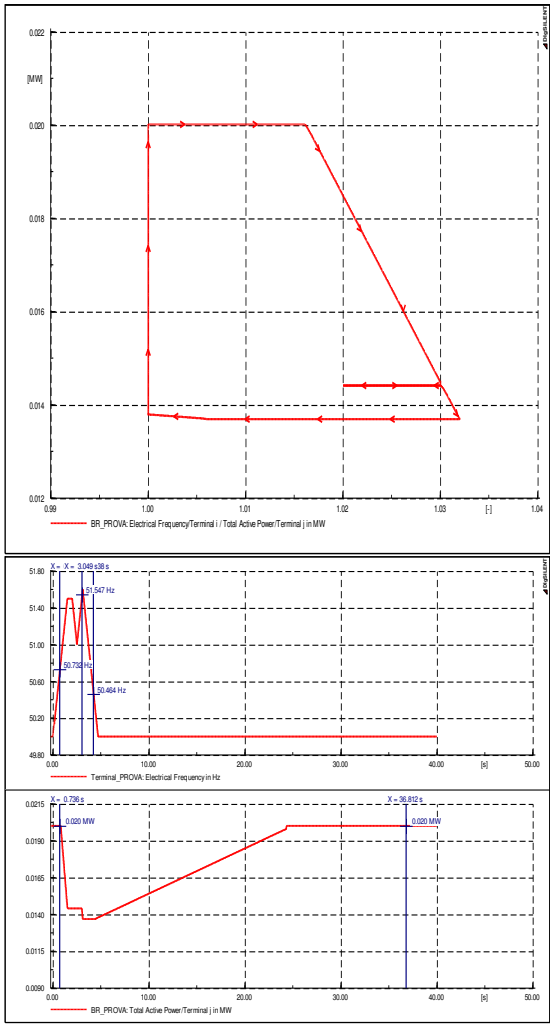
- Design and maintenance of PVI templates portfolio
  - In-House: DIgSILENT PowerFactory, SimPowerSystem
  - Coordination for PSS/E, PSCAD, DSA model designs
- FGW-TR4 certification
- Full models ready for the consultants
  - Fully parameterized
  - Capability
  - Harmonic load flow
  - Short circuit contribution
  - Dynamic VSC response



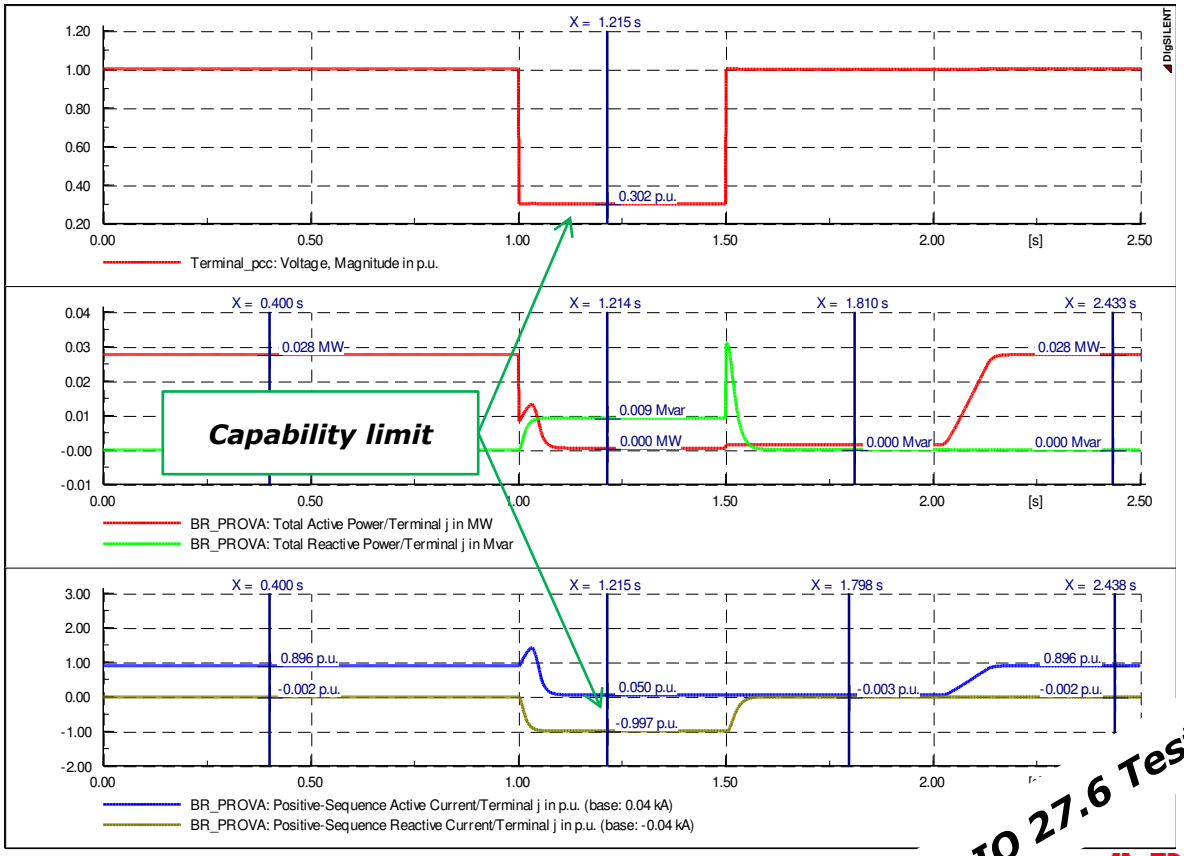

```
DIgSI/wrng - ' C':
DIgSI/wrng - Nominal voltage differs by 72.50 % from bus voltage!
DIgSI/wrng - ' L':
DIgSI/wrng - Nominal voltage differs by 72.50 % from bus voltage!
DIgSI/info - Element 'AC Voltage Source' is local reference in separated
DIgSI/info - Grid split into 3 isolated areas
DIgSI/info - Calculating load flow...
DIgSI/info - ----------------------------------------------------------------
DIgSI/info - Start Newton-Raphson Algorithm...
DIgSI/info - load flow iteration: 1
DIgSI/info - Newton-Raphson converged with 1 iterations.
DIgSI/wrng - 'Grid\TRIO evo.ElmGenstat':
DIgSI/wrng - Maximum Reactive Power Limit Exceeded (0.08 Mvar > 0.01 Mvar)
DIgSI/info - Load flow calculation successful.
```

TRIO 27.6 Tests

PVI models portfolio
Examples of dynamic studies



- HFRT
- DRCS



TRIO 27.6 Tests

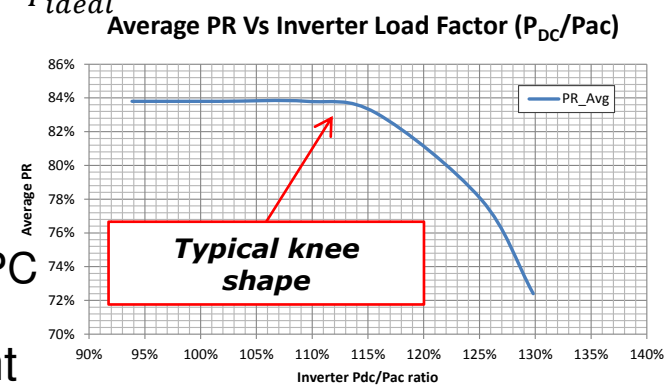
PVI models portfolio
The proper model

- GIS ⇨ Detailed plant model with PVI templates designed for RMS sims, Load Flows, Short Circuit calculations
- Network integration studies ⇨ An equivalent PVI for the overall plant
- R&D PVI debugging or control testing ⇨ An equivalent network-plant connected to a detailed PVI model

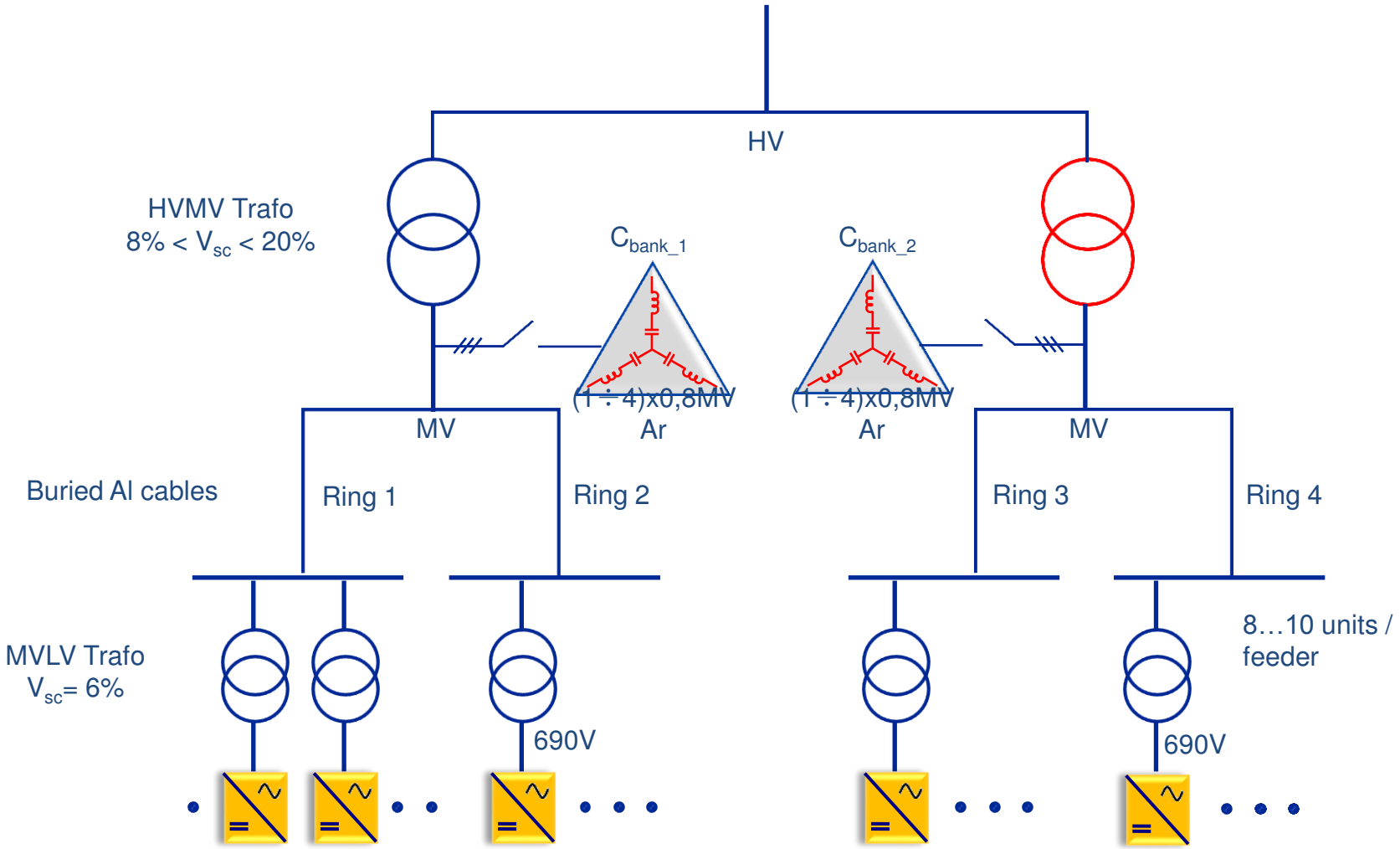
Engineering Support
Beyond a Power Electronics manufacturer

A successful project relies on a solid plant design

- ABB DMPC PG Solar doesn't take over the role of EPC
- Offered services:
  - Preliminary studies
    - Estimations of Performance Ratio $PR = \frac{Y_{real}}{Y_{ideal}}$
    - Plant capacity assessment (P,Q)
  - Grid Impact Studies
    - In-house preparation OR support to EPC
  - Component selection and procurement
    - ABB and trusted suppliers



Engineering Support
Typical utility scale plant layout



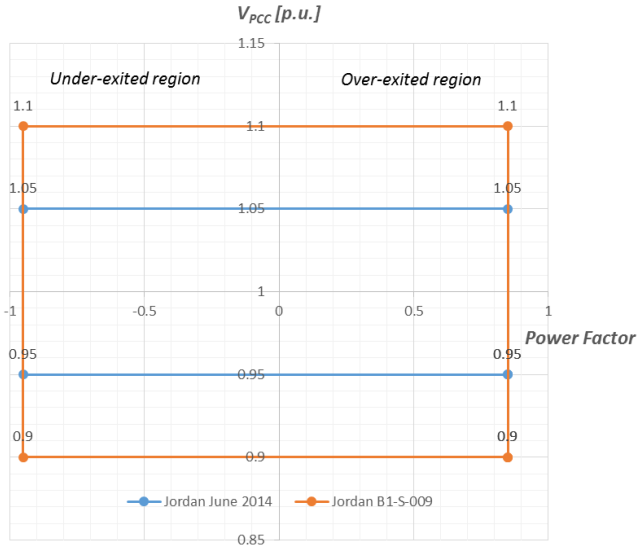
Fulfillment of contractual powers at the PCC
The problem and grid codes capability requirements

An optimized design

- Objective Function
  - $k_c \cdot \min\{\Sigma c_{PVI} + \Sigma c_{Qcomp.\ devices}\} + k_{PR} \cdot (1\text{-}PR)$
    - ⇨ define n_{PVI} and Q compensation issue
    - ⇨ Maintain acceptable PR
    - Further OF terms: min losses and equalize plant layout
  - Comply with the requirements
    - NEPCO (HKJ) ⇨$P_{AC\text{-}PCC}^{max}$ + capability

      ⇨ceiling to $P_{AC\text{-}PCC}$⇨ P_{DC}^{n}
    - Israel ⇨capability (PF)

      ⇨plant design starts from P_{DC}^{n}

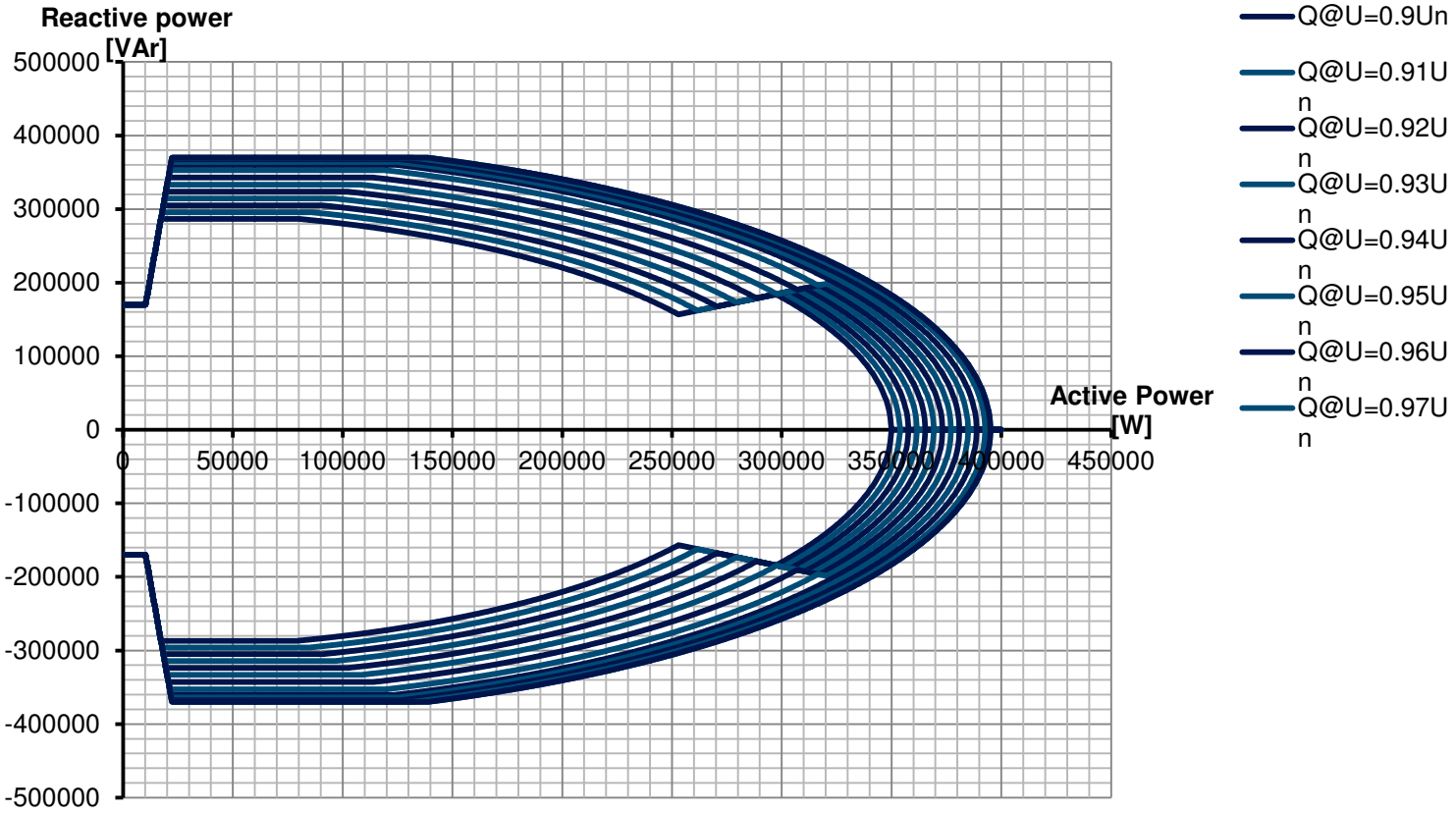


Fulfillment of contractual powers at the PCC
Constraints and possible degrees of freedom

- Constraints
  - PVIs and STATCOM capabilities are V and ϑ_{amb} dependent
    - dependency is lin. vs quadratic of SVC and cap banks
  - V rating of plant devices
    - Typical problem with MV devices when V_{cc}^{HVMV}>>
  - Tap changer position ranges for:
    - HVMV Trafo On-Load-Tap- Changer
    - MVLV Trafo Off-Load-Tap- Changer
- In case of small capability violations the designer could demand modifying transformer ratings:
  - Nominal V
  - Special designs leading to reduced leakage impedance

Fulfillment of contractual powers at the PCC
Reactive power sources: Caps and PVIs

- Capacitor banks normally split in stages
- PVI inverters



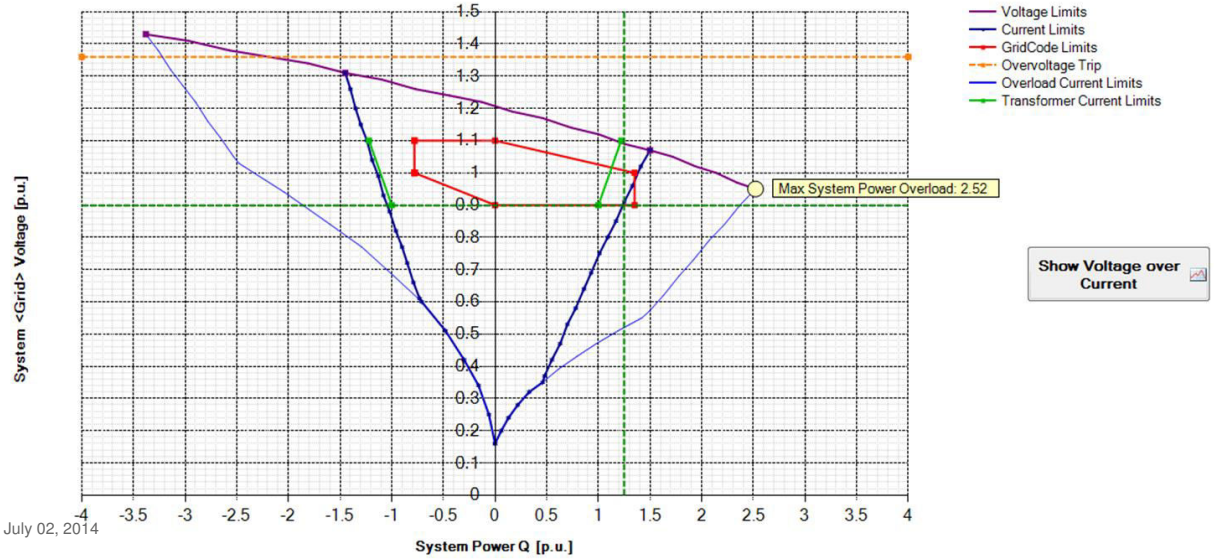
Fulfillment of contractual powers at the PCC
Reactive power sources: STATCOM (ABB PCS 100)

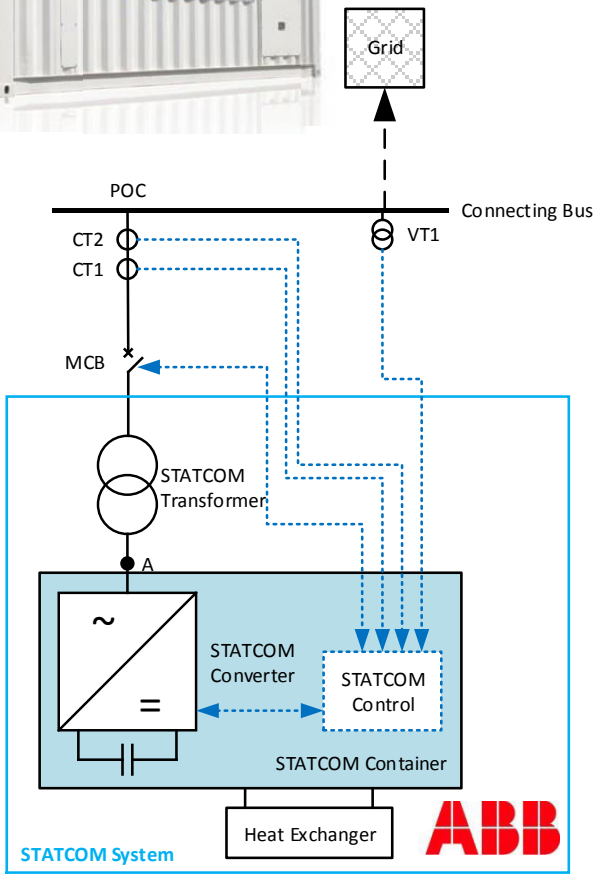
Rack mountable module

2.0 MVAr STATCOM line-up with all 24 modules

Containerized solution

ABB tool for preliminary design (STATCOM and plant capability at the MV PCC)



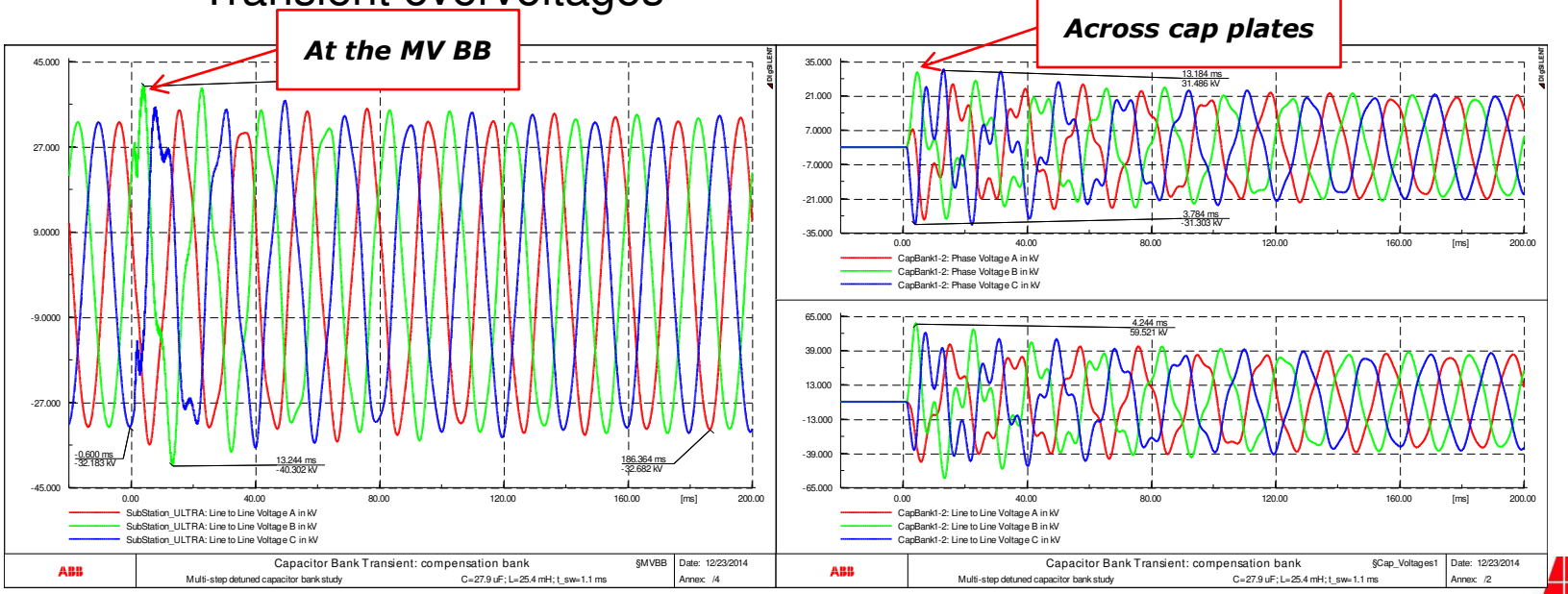


Fulfillment of contractual powers at the PCC
Comparison between Q sources

	Pros	***Cons***	***Design challenges***
Caps	Low cost Simplicity	Prone to harmonic and energization issues	Granularity definition Insertion strategy definition Design of inrush bank impedance Carefully evaluation of: Harmonics and eventual harmonic traps, inrush and energization scenarios
PVIs	High Q granularity Limited cost Expected lower loading of the inverter for most of the time (extended lifetime)	V dependent capability Efficiency reduction (<0.2%)	Possibility to find optimal solution taking into account plant PR
STATCOM	High Q granularity Harmonic compensation Enhanced fault support	High cost Large footprint on the plant substation	Damping harmonics capability must be properly verified Coordination with PVIs control in case Q capability is shared with the same

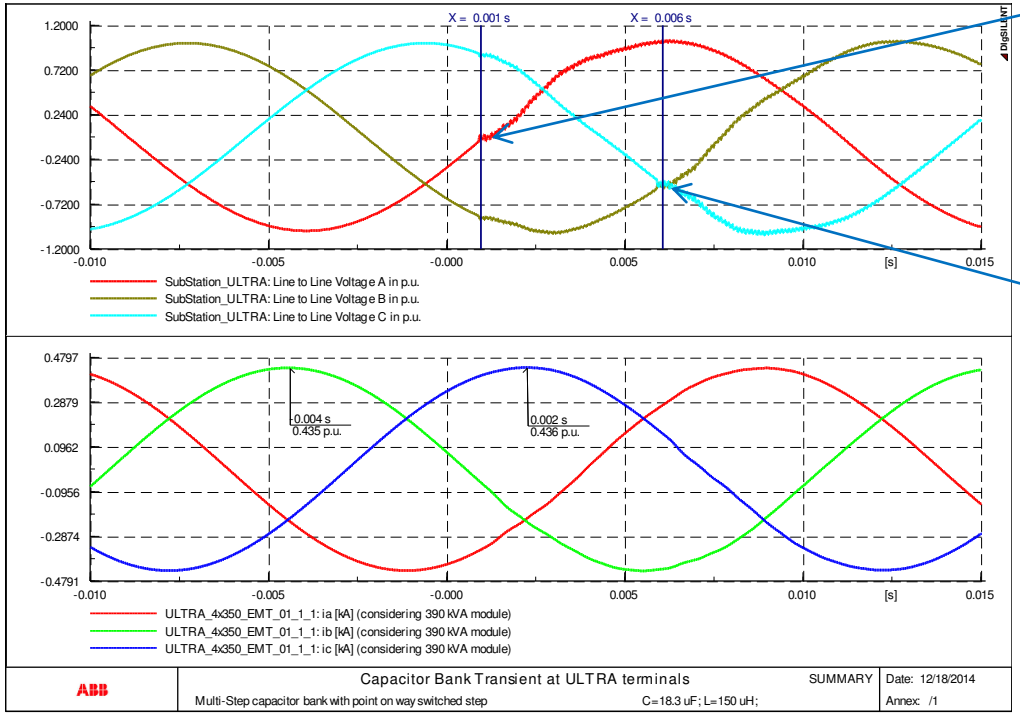
Cap compensation bank design
The objective function

- ULTRA is a 4 level inverter
  - Smaller output filter ⇨ Prone to inrush current phenomenon during capacitor insertions in case of weak networks
- Harmonics
- Transient overvoltages



Cap compensation bank design
Possible solutions

- Increase number of stages
- Inrush resistor (US Solution)
- Point-On-Wave reclosure



v_{k-l}=0 V
⇨ closure of phases k and l

⇩ After ¼ period

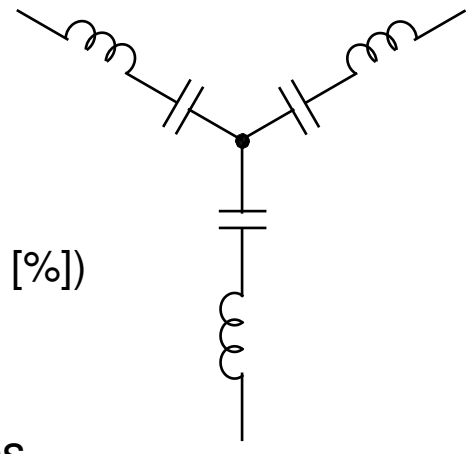
⇨ closure of phase m

Seamless insertion

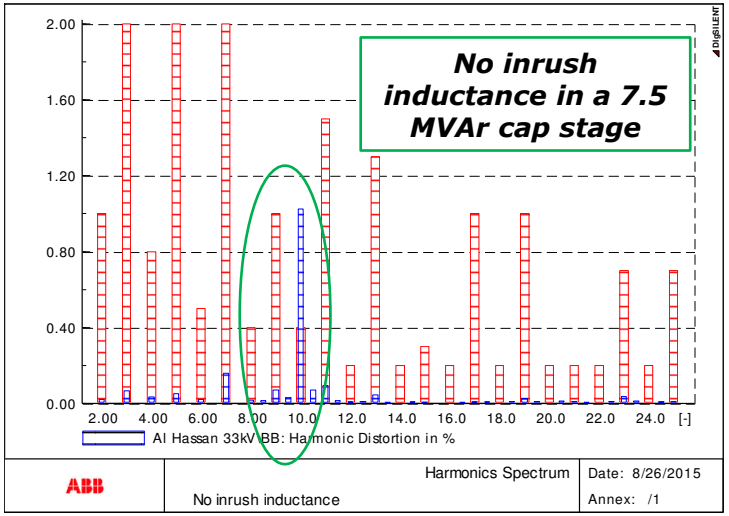
- No contribution to harmonics damping

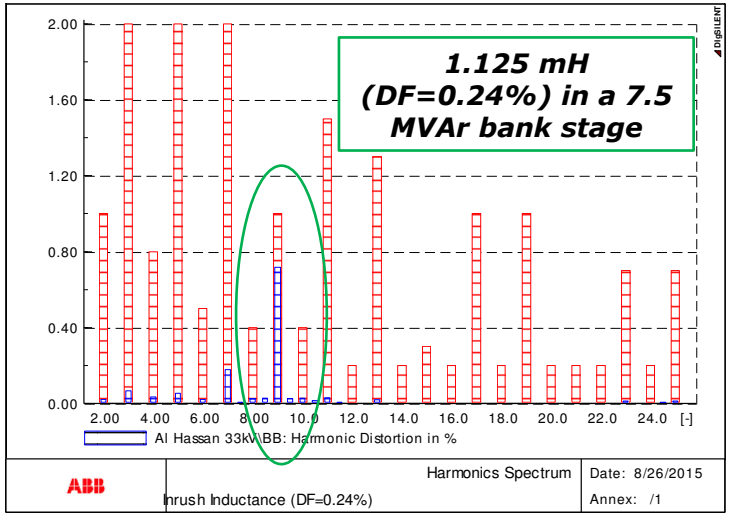
Cap compensation bank design
Possible solutions: inrush inductors and detuned filters

- Detuned filter design guidelines
  - Detuning factor DF = x_L/x_C
  - Given Q_{stage}:
    - DF ↑ ⇨ C↓ and L↑ (typical DF= 5-6-7-14 [%])
    - Tuned at an interharmonic
- Outstanding benefits on the harmonics studies



The case of an external bank connected at the plant PCC node





Insertion strategies of compensation bank stages

Ensure an hysteretical mechanism

Method	***Insert a stage if …***	***Disconnect a stage if …***
A	$\Sigma Q_{PVI} > \%_{insert}\ Q_n^{stage}$	$\Sigma Q_{PVI} > \%_{disc}\ Q_n^{stage}$
B	$PF_{PVI} < PF_{PVI}(p_{PVI})$	$PFeq = \frac{\sum P_{inv}}{\sqrt{\sum P_{inv}{}^2 + \left(\sum Q_{inv} + Q_{stage}\right)^2}}$ $PFeq < PF_{PVI}(p_{PVI}) - 0.1$
C	$\Sigma Q_{PVI} > 0$ (no over-ex if possible)	$PFeq = \frac{\sum P_{inv}}{\sqrt{\sum P_{inv}{}^2 + \left(\sum Q_{inv} + Q_{stage}\right)^2}}$ $PFeq < 0.99$

Risk of overvoltages at PVI terminals

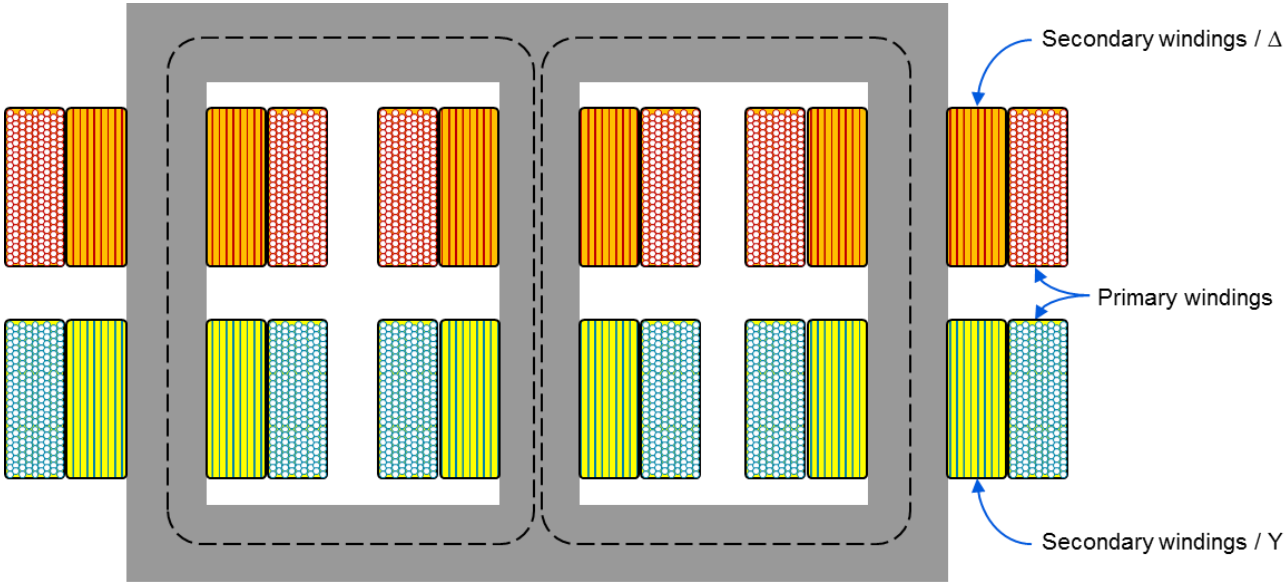
Linked to a predefined $PF_{PVI} < PF_{PVI}(p_{PVI})$ ***curve***

Applied algorithm

Multiwindings MVLV tranformers
Plant cost reduction

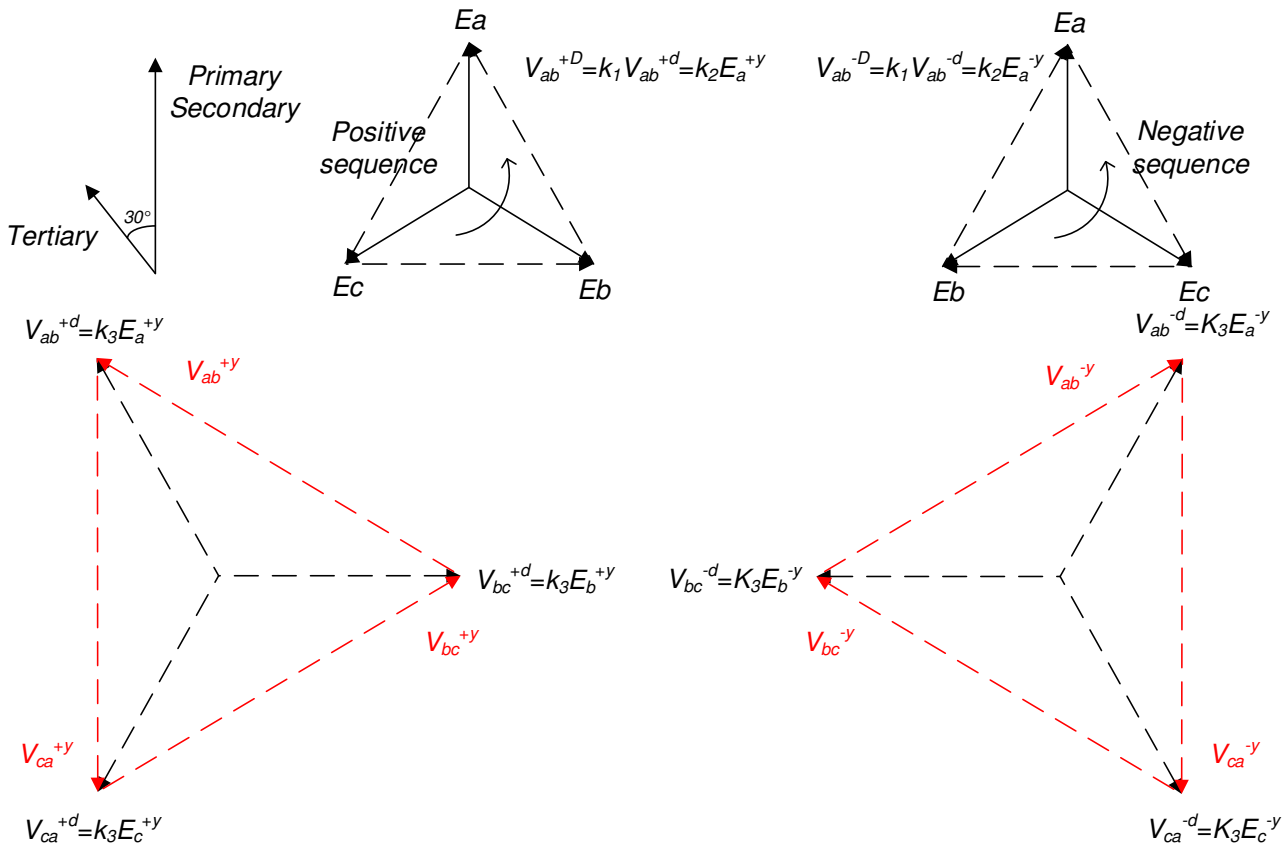
Transformer cost is almost proportional to the weight

- ULTRA doesn't inject common mode currents -> no shielded transformer
- Typical ABB proposal: Dd0y11 connection
  - Stacked construction
  - $z_{cc}^{23}=0.9(z_{cc}^{12}+z_{cc}^{13})$



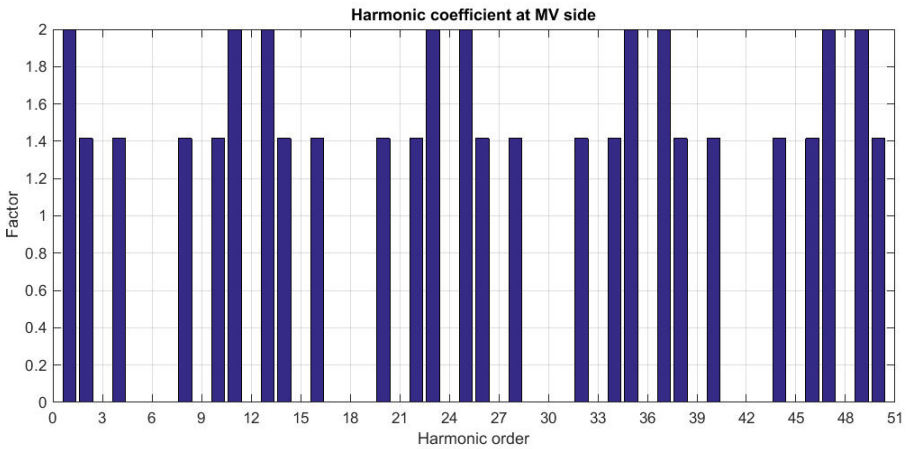
Multiwindings MVLV tranformers
Windings connection choice Dd0y11

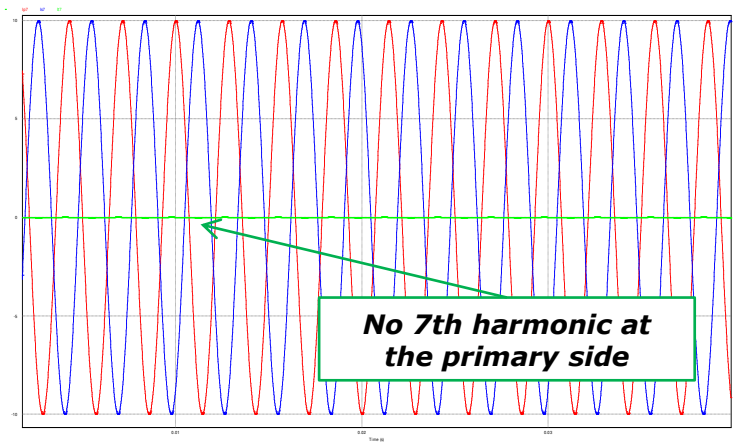
- No homopolar sequence from the secondaries to the primary (recommended ungrounded star conn. secs)
- Sequence circuits of Dd0y11



Multiwindings MVLV tranformers
Windings connection Dd0y11 (contd) OLTC choices

- Dd0y11 effects
  - Harmonic cancellation under the assumption of homogeneous PVI spectrums (3n and 6+12k±1)



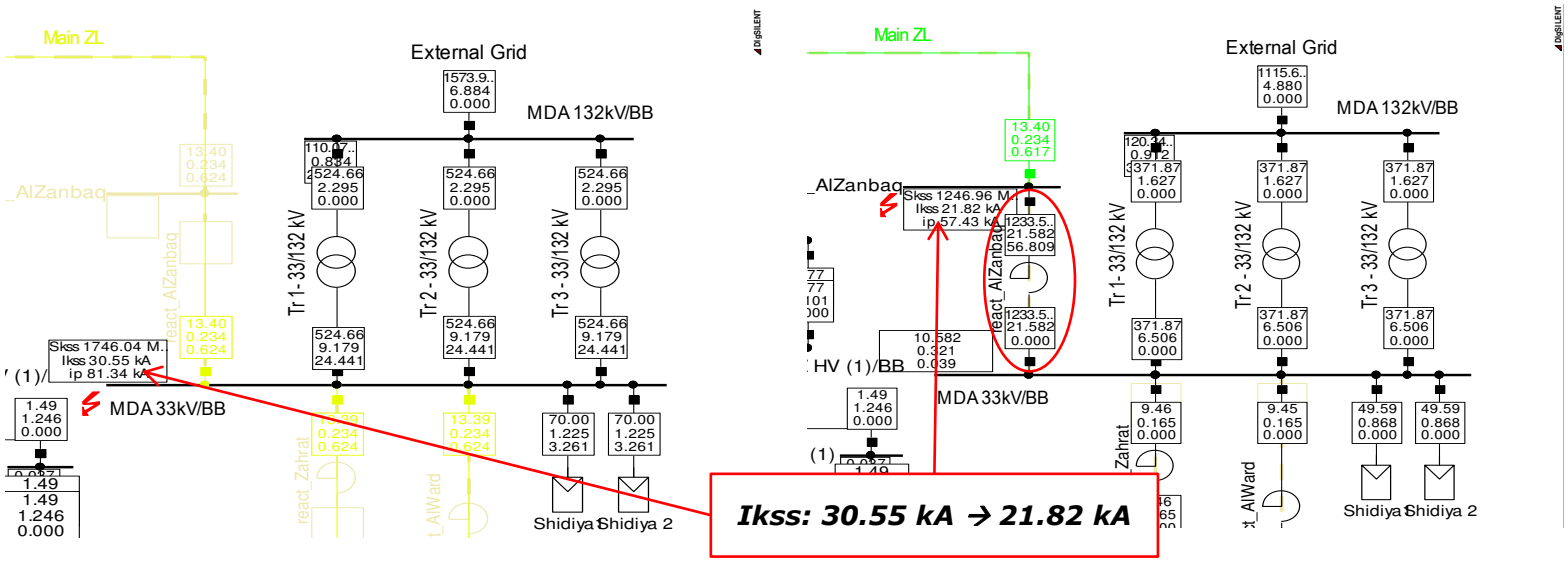


  - Awareness about the effect of asymmetrical faults on the inverters connected at the same transformer

- Off Load Tap changer
  - Typically ±2·2.5%

Short circuit current limitation
Limiting reactors

I_{SC}^{PCC}>> ⇨ $I_n^{plant\ switchgears}$>> ⇨ Costly solutions

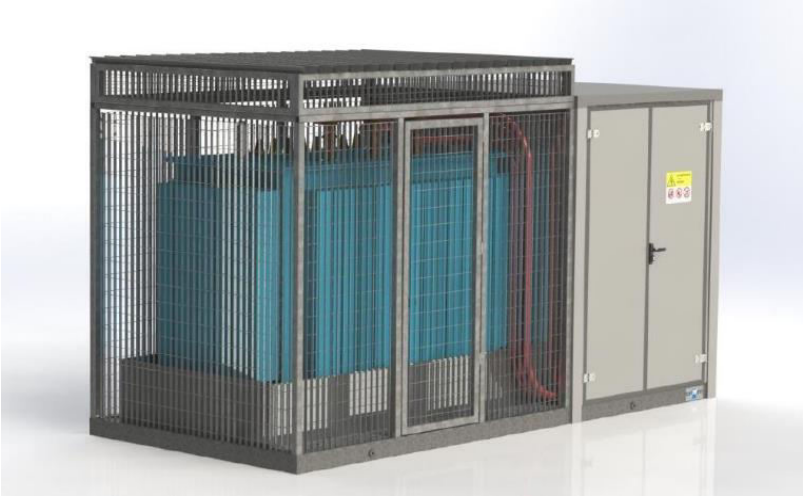


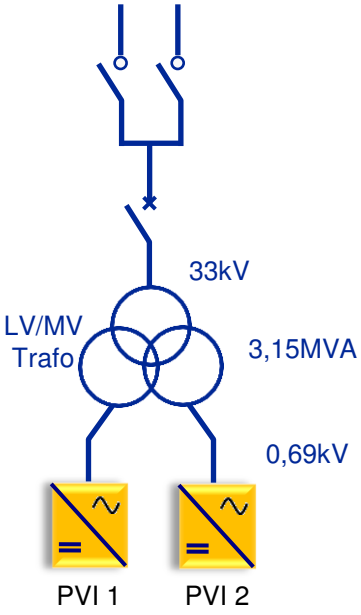
- Limiting reactors
  - Installed at the substation side of the plant feeder
  - Side effect:
    - parasitic power consumption

Complete skid
ULTRA outdoor station

- Our turn key solution
  - MV Switchger with RMU
  - 3w transformer
    - ONAN
  - AUX services
  - PLC for PPC, monitoring and Plant Automation

ABB SafePlus	
Un [kV]	33
Isc, 1s [kA]	25
Isc, 3s [kA]	20
Uimp [kV]	170 / 70





Centralized Vs Decentralized functions
Time decoupling

Fast control must be performed from the PVI

Decentralized Functions PVI

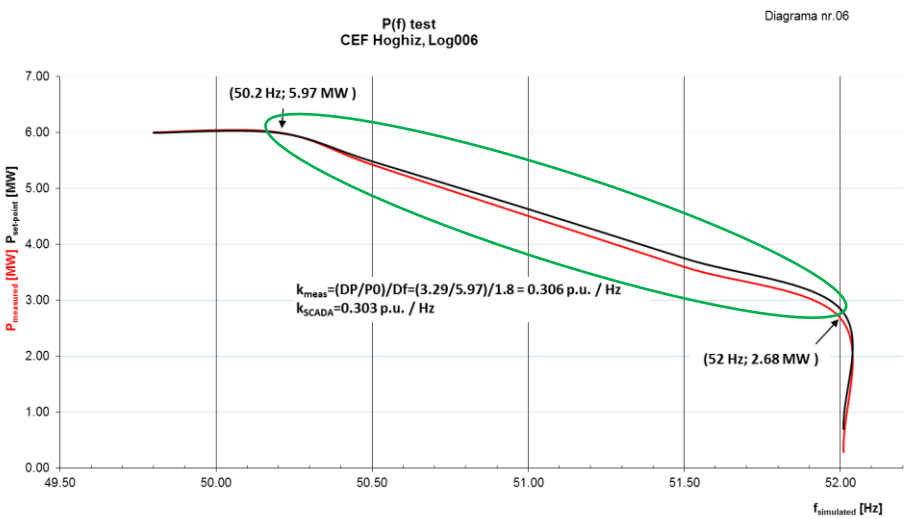
- Dynamic Reactive Current Support
- Anti-Islanding
- Local PQ control (PF=const, Q(V), P(V))
- Over Frequency Power Curtailment
- PCC PQ control (PF=const, Q(V), Qext, Pext)
- Damping clouding effects
- Data storage

Centralized Functions SCADA

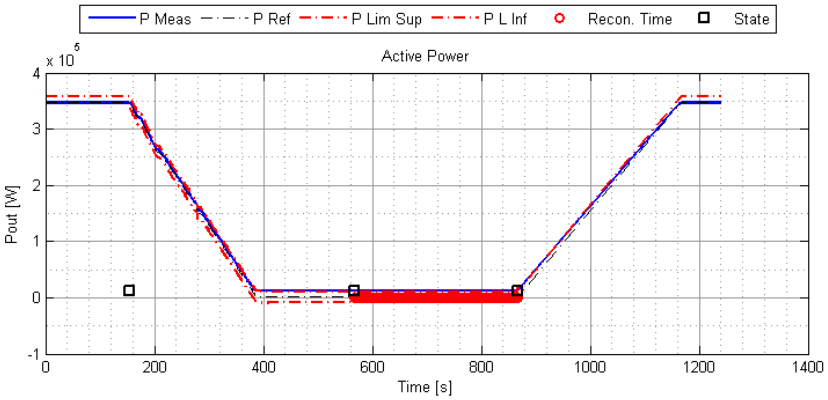
- Closed Loop schemes are recommended for decentralized controls

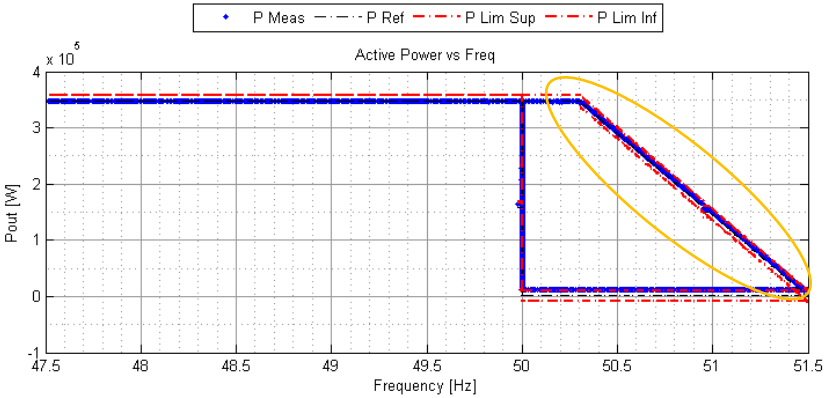
Centralized Vs Decentralized functions
The case of Over Frequency Power Curtailment

Central OFPC
Plant commissioning test through variation of the frequency signal at the SCADA



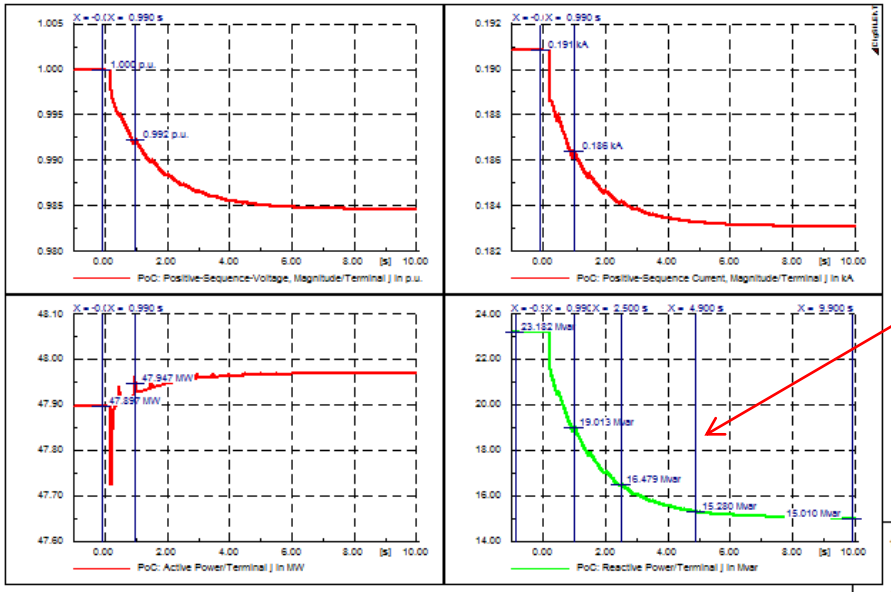
Decentralized OFPC
Lab test using a variable f grid simulator





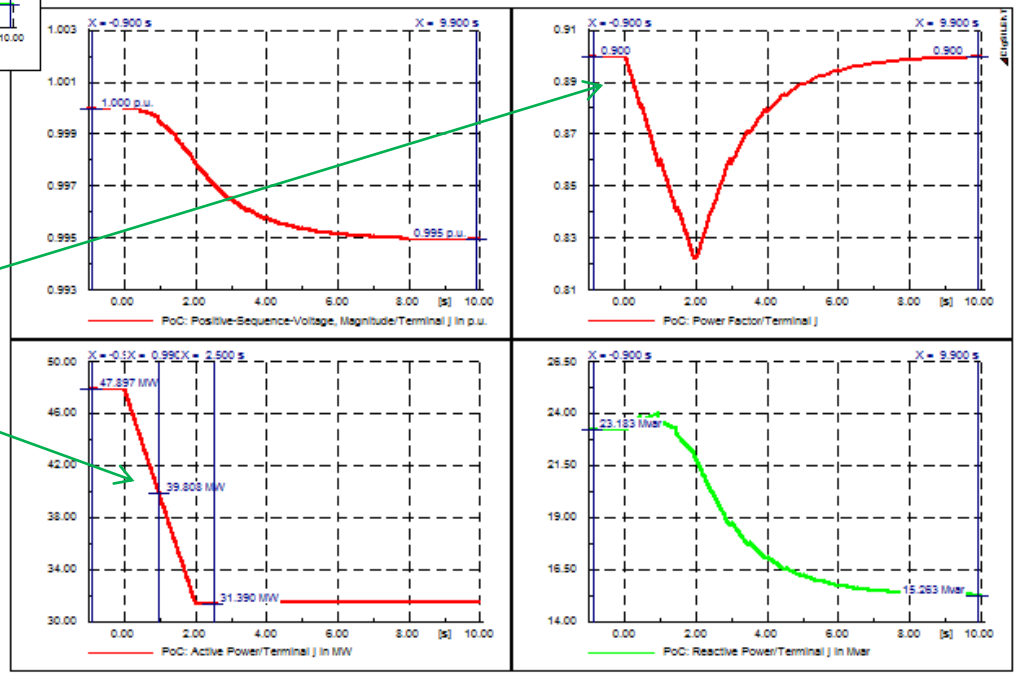
© ABB

Centralized Vs Decentralized
Centralized Q control



Step ΔQ_{PCC}^{ref}=-8.2 Mvar

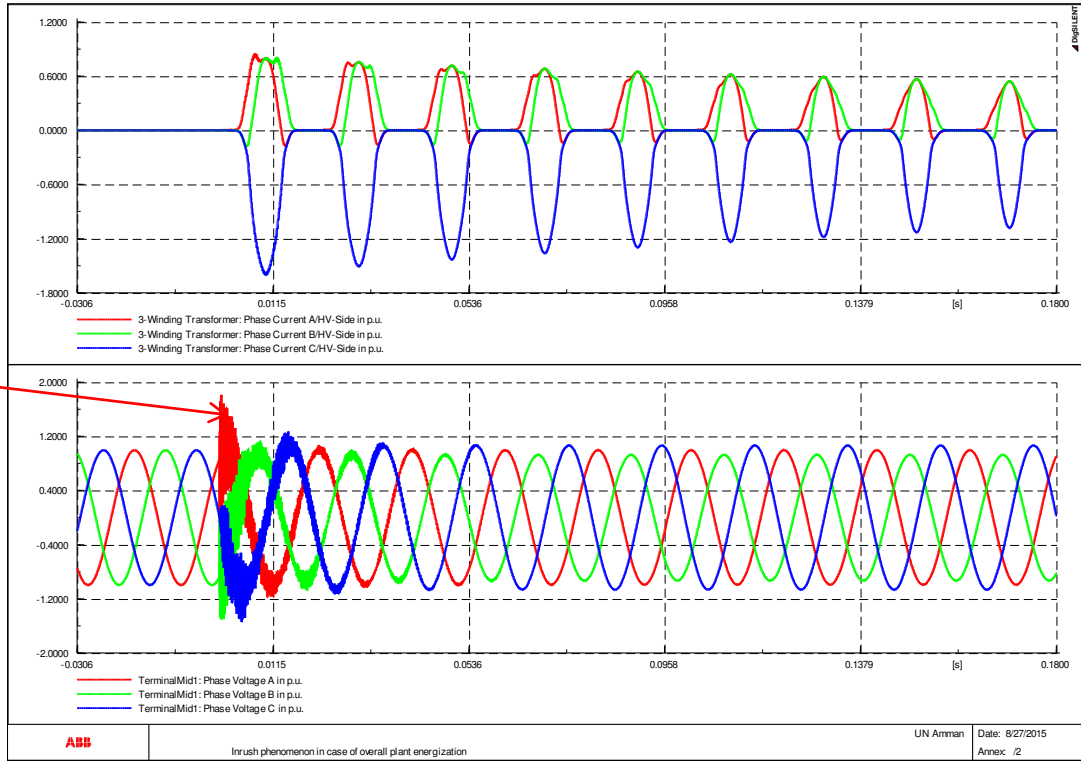
P_{PVI} ramp-down with centralized PF_{PCC} control (constant)



Energization
Mitigation methods

- Energizing transformers or lines (OHL>10 km or shorter cable lines) implies inrush phenomenon

Example case of overall plant energization (long OHL and step-up trafos)
⇨ Δv_{MV}=70% !



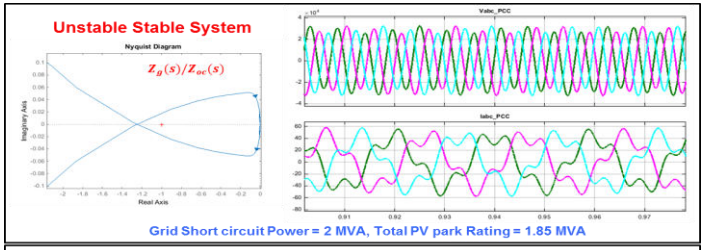
- Sequencing of plant trafos
- Adoption of inrush resistance mainstream to the line

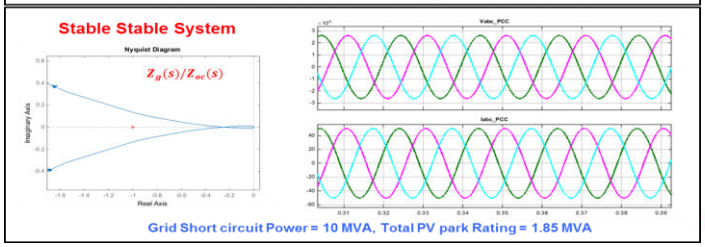
Inter/Harmonics studies
Risks and recommendations

- Need of detailed network data
- Harmonic load flows
  - PVI ⇨ Indipendent current sources
  - IEC 61000-3-6 $I_\mu = \sqrt[\alpha]{\sum_{i=1}^{\alpha} I_{\mu-i}^{\alpha}}$ ⇨ $I_\mu = \sqrt[\alpha]{\alpha} I_{\mu-i}$
  - BDEW $I_\mu = \sqrt{\sum_{i=1}^{n} I_{\mu-i}^{2}}$ where n is the number of PVI ⇨ $I_\mu = \sqrt{n} I_{\mu-i}$

IEC 61000-3-6	
Harmonic order h	α
<5	1
5≤h≤10	1.4
10<h	2

- Stability concerns if S_{PCC}<5S_{plant}
  - Detailed EMT studies
  - s-domain analyses





Conclusions

- Important factors for the successful integration of utility scale PV plants in the modern power systems are:
  - Grid Codes study, PVI and plant compliances
  - Accuracy of PVI templates and overall plant model
  - Professional Grid Impact Study
  - Awareness about pros and cons of alternative plant solutions

In this sense ABB offers one of the broadest solar inverter portfolio combined with a proved integration experience

Thank you for your attention

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