NEW TECHNOLOGIES FOR ELECTRICAL TRANSMISSION AND DISTRIBUTION IN FCC

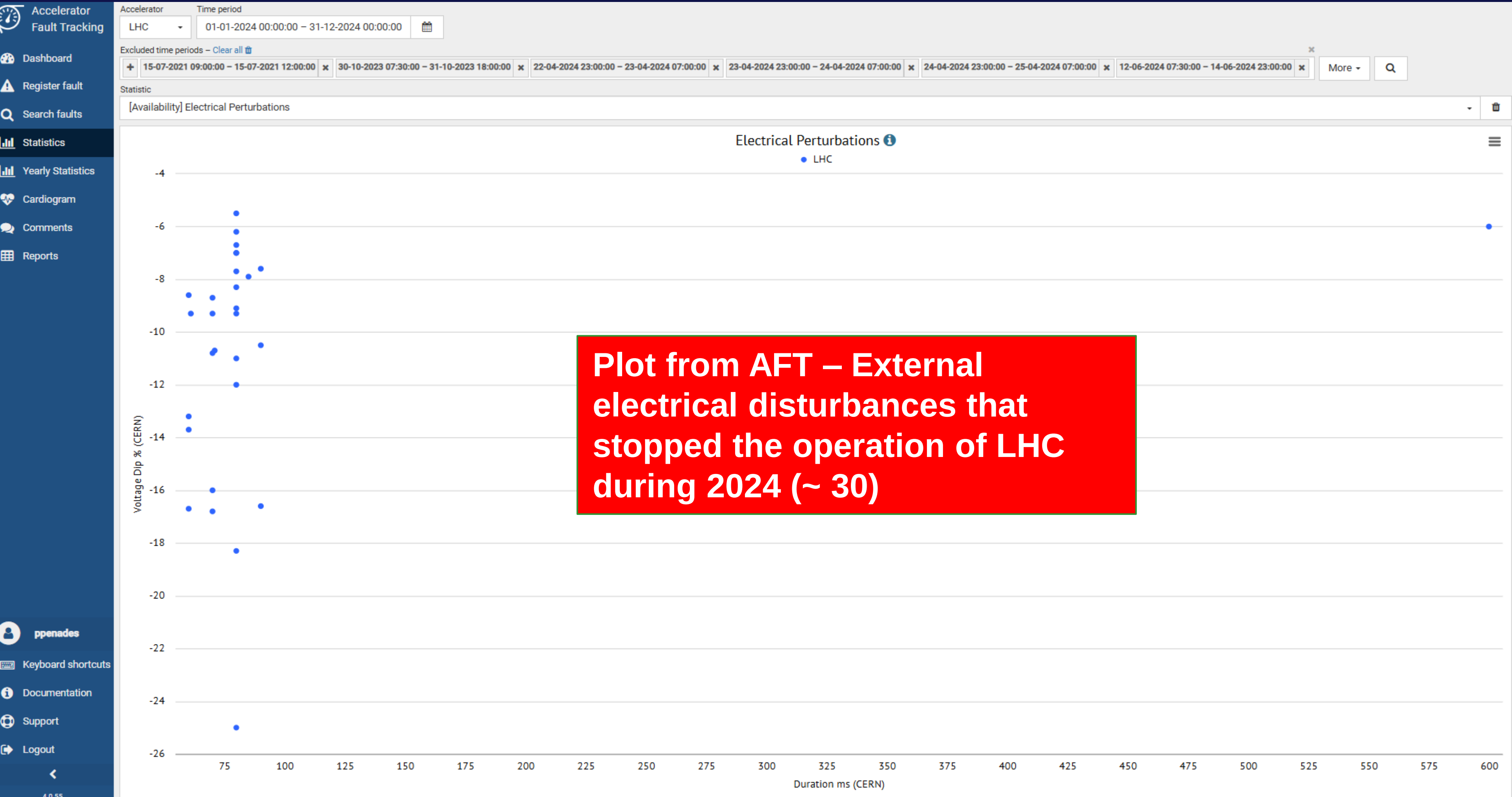
Table of contents

The problem of the power quality

The Power Quality of the electrical grid is an essential factor for the successful operation of the accelerator

- Variations (continuous) or events (sudden)
  - Voltage dips/sags
  - Voltage swells
  - Interruptions
  - Transient overvoltages
  - Voltage unbalance
  - Harmonic distortion
  - Flicker
- Possible causes:
  - Switching
  - Lightning
  - Grid faults
  - Big transformer/capacitor/motor inrush
  - Load transfers
  - Power electronic/non linear loads

- Many devices and systems of an accelerator can be extremely sensitive to these variations and events



Plot from AFT – External electrical disturbances that stopped the operation of LHC during 2024 (~ 30)

Retrieving data from today: RF2.0 and PMUs

Integration of PMUs in the energy control of accelerators:

Develop dashboards to display the recorded data, investigate integration possibilities with CERN's SCADA and the Accelerator's Fault Tracking system.

Power Quality and Harmonic content analysis:

Enhance CERN's understanding on the current power flows of its electrical grid and identify mitigation actions and possible improvements.

Thanks to Isabel Amundarain Arguello (EN-EL) and the RF2.0 project team that helped for this and the following slides

Digital Twins:

Develop real time digital twins for accelerators and green High Power Computing Centers.
Feed the model with the PMUs data.

Retrieving data from today: RF2.0 and PMUs

Perturbation analysis:

Enhance CERN's understanding on the undergoing perturbations on the transmission grid.

Correlation with equipment:

Enhance CERN's understanding on the correlations between disturbances and their impact on connected downstream loads.

Increase of grid resilience:

Develop methods to increase the resilience of existing **and future accelerators** against grid disturbances and thus their availability.

Retrieving data from today: RF2.0 and PMUs

PMUs at LHC

400 kV network
2 substations (BE1 and BE2)
1 PMU/substation

66 kV network
1 substation (SEH9)
2 PMUs

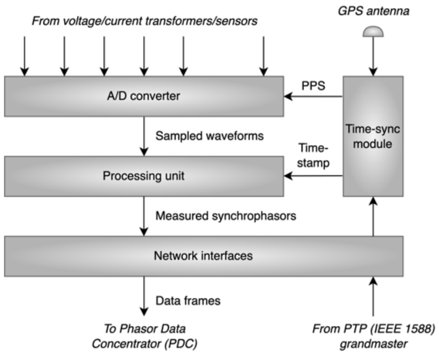
18 kV network
LHC loop + PCC
20 PMUs

Retrieving data from today: RF2.0 and PMUs

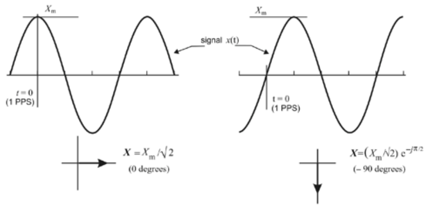
Installation of +20 Phasor Measurement Units (PMUs) in CERN electrical network to retrieve real time data - COMPLETED

Event	Severity	Data source	Conditions and parameters
Rapid voltage change	Info	PMU	Voltage variation >4%
Voltage dip	Warning	PMU	Start: Rapid voltage variation detected (see above) and voltage below 90% of nominal. End: Voltage above 90% of nominal. Hysteresis: 2%.
Voltage dip	Warning	PMU	Start: Rapid voltage variation detected (see above) and voltage below 90% of nominal.
Voltage dip	Info	PMU	End: Voltage above 90% of nominal. Hysteresis: 2%.
Voltage interruption	Alarm	PMU	Start: Rapid voltage variation detected (see above) and voltage below 10% of nominal. End: Voltage above 90% of nominal. Hysteresis: 2%.
Voltage interruption	Alarm	PMU	Start: Rapid voltage variation detected (see above) and voltage below 10% of nominal.
Voltage interruption	Info	PMU	End: Voltage above 90% of nominal. Hysteresis: 2%.
Voltage swell	Warning	PMU	Start: Rapid voltage variation detected (see above) and voltage above 110% of nominal. End: voltage below 110% of nominal. Hysteresis: 2%.
Voltage swell	Warning	PMU	Start: Rapid voltage variation detected (see above) and voltage above 110% of nominal.
Voltage swell	Info	PMU	End: Voltage below 110% of nominal. Hysteresis: 2%.

Phasor Measurement Unit (PMU):



- **Phasor**: compressed representation (complex number) of an AC waveform



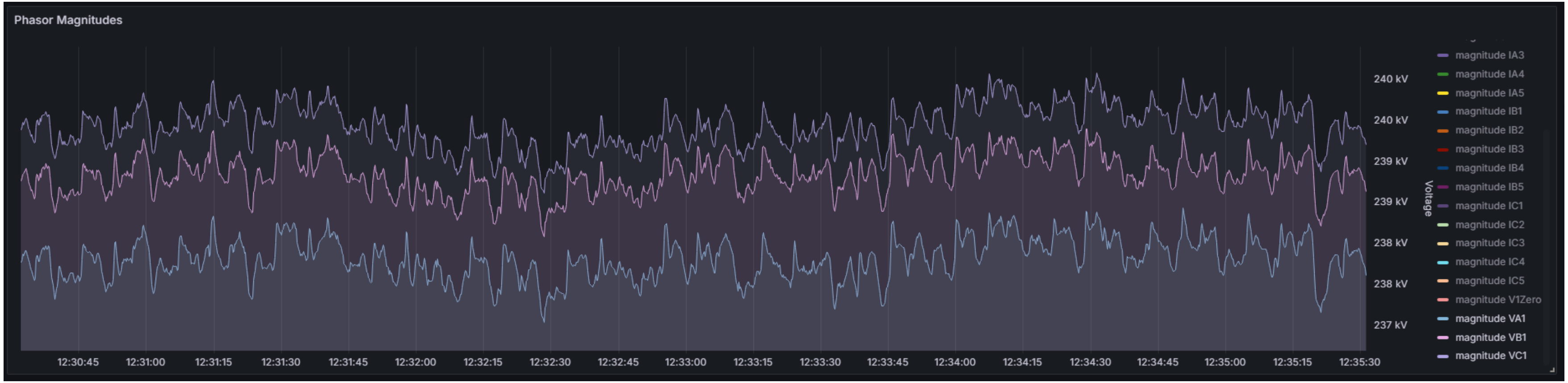
- **Synchrophasor**: phasor measurement synchronized to a common time reference (e.g., GPS) and reported at a very high rate (50/60 Hz)

Main features

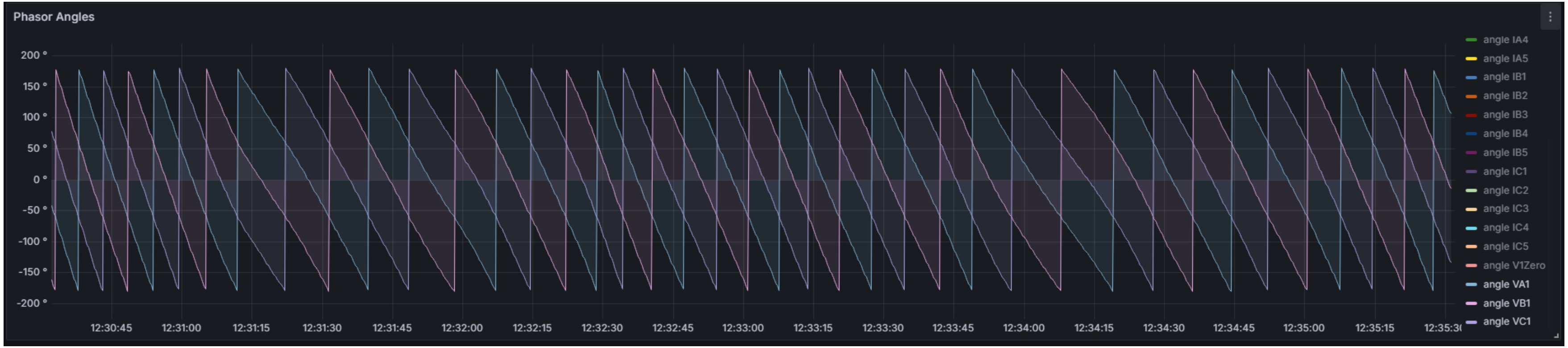
- 10 kHz sampling rate, GNSS time synchronization (accuracy in the order of the nanoseconds)
- Fulfil CERN short-term objective for disturbance monitoring and correlation event-impacted system
- Feed a digital twin for real-time simulations
- Analyse P/Q and harmonics power flows at CERN

→**Provide inputs for FCC studies**

Voltage Phasor Magnitude



Voltage Phasor Angle



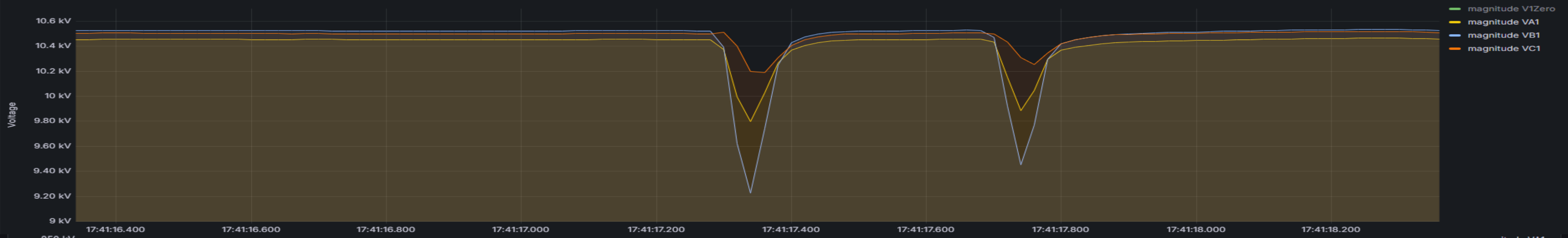
Event journal

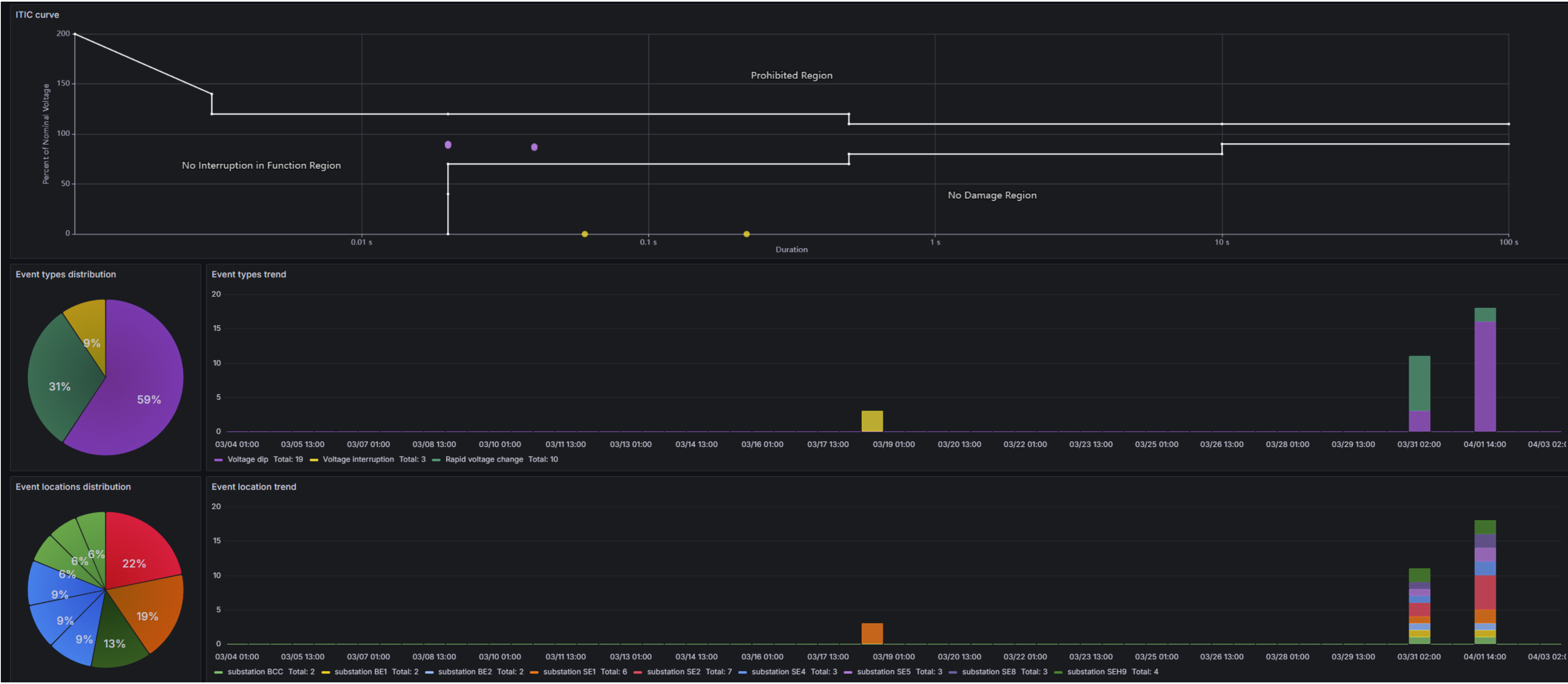
Details	Event type	Status	Start time	Duration	Message	Percentage	Value	Reference
	Voltage dip	Completed	2025-04-01 17:41:17.340	20 ms	Voltage dip detected by PMU 13, in substation SE1 on channel VB1. Residual voltage: 9225 V (89% of nominal voltage). Duration: 20 ms.	88.8%	9.22 kV	10.4 kV
	Voltage dip	Completed	2025-04-01 17:41:17.340	20 ms	Voltage dip detected by PMU 2, in substation BCC on channel VB1. Residual voltage: 9286 V (89% of nominal voltage). Duration: 20 ms.	89.4%	9.29 kV	10.4 kV
	Voltage dip	Completed	2025-04-01 17:41:17.340	20 ms	Voltage dip detected by PMU 15, in substation SE2 on channel VB1. Residual voltage: 9346 V (90% of nominal voltage). Duration: 20 ms.	89.9%	9.35 kV	10.4 kV
	Voltage dip	Completed	2025-04-01 17:41:17.340	20 ms	Voltage dip detected by PMU 23, in substation SEH9 on channel VB1. Residual voltage: 33661 V (88% of nominal voltage). Duration: 20 ms.	88.3%	33.7 kV	38.1 kV
	Voltage dip	Completed	2025-04-01 17:41:17.340	20 ms	Voltage dip detected by PMU 6, in substation SE4 on channel VB1. Residual voltage: 9319 V (90% of nominal voltage). Duration: 20 ms.	89.7%	9.32 kV	10.4 kV
	Voltage dip	Completed	2025-04-01 17:41:17.340	20 ms	Voltage dip detected by PMU 17, in substation SE2 on channel VB1. Residual voltage: 9346 V (90% of nominal voltage). Duration: 20 ms.	89.9%	9.35 kV	10.4 kV
	Voltage dip	Completed	2025-04-01 17:41:17.340	20 ms	Voltage dip detected by PMU 12, in substation SE8 on channel VB1. Residual voltage: 9316 V (90% of nominal voltage). Duration: 20 ms.	89.6%	9.32 kV	10.4 kV

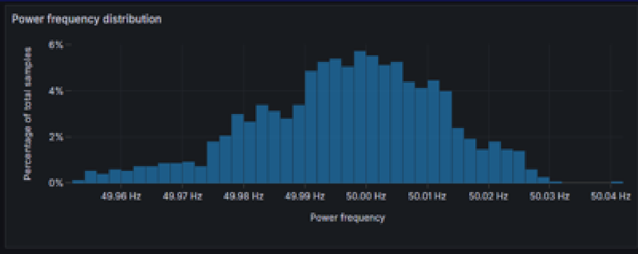
Event journal

Event type	Status	Start time	Duration	Phases	Message
Voltage dip	Completed	2025-04-01 17:41:17.340	20 ms	B	Voltage dip detected by PMU 13, in substation SE1 on channel VB1. Residual voltage: 9225 V (89% of nominal voltage). Duration: 20 ms.

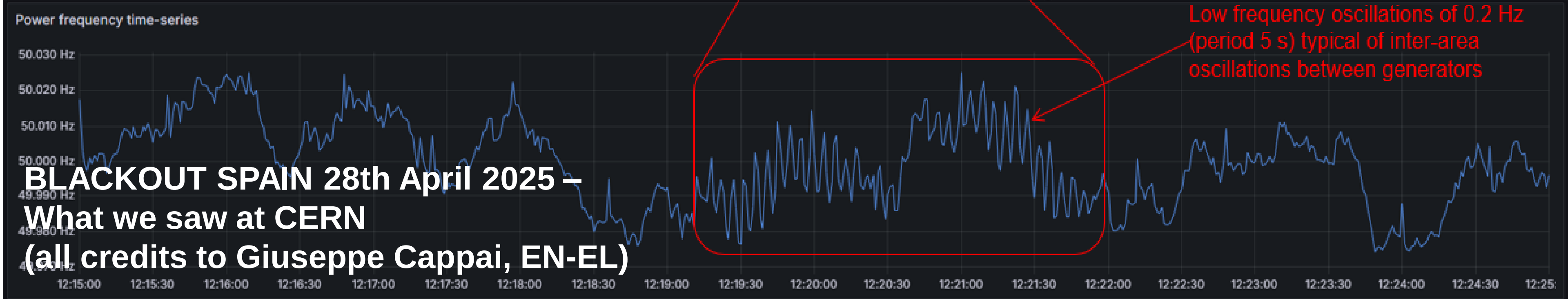
Phasor Magnitudes

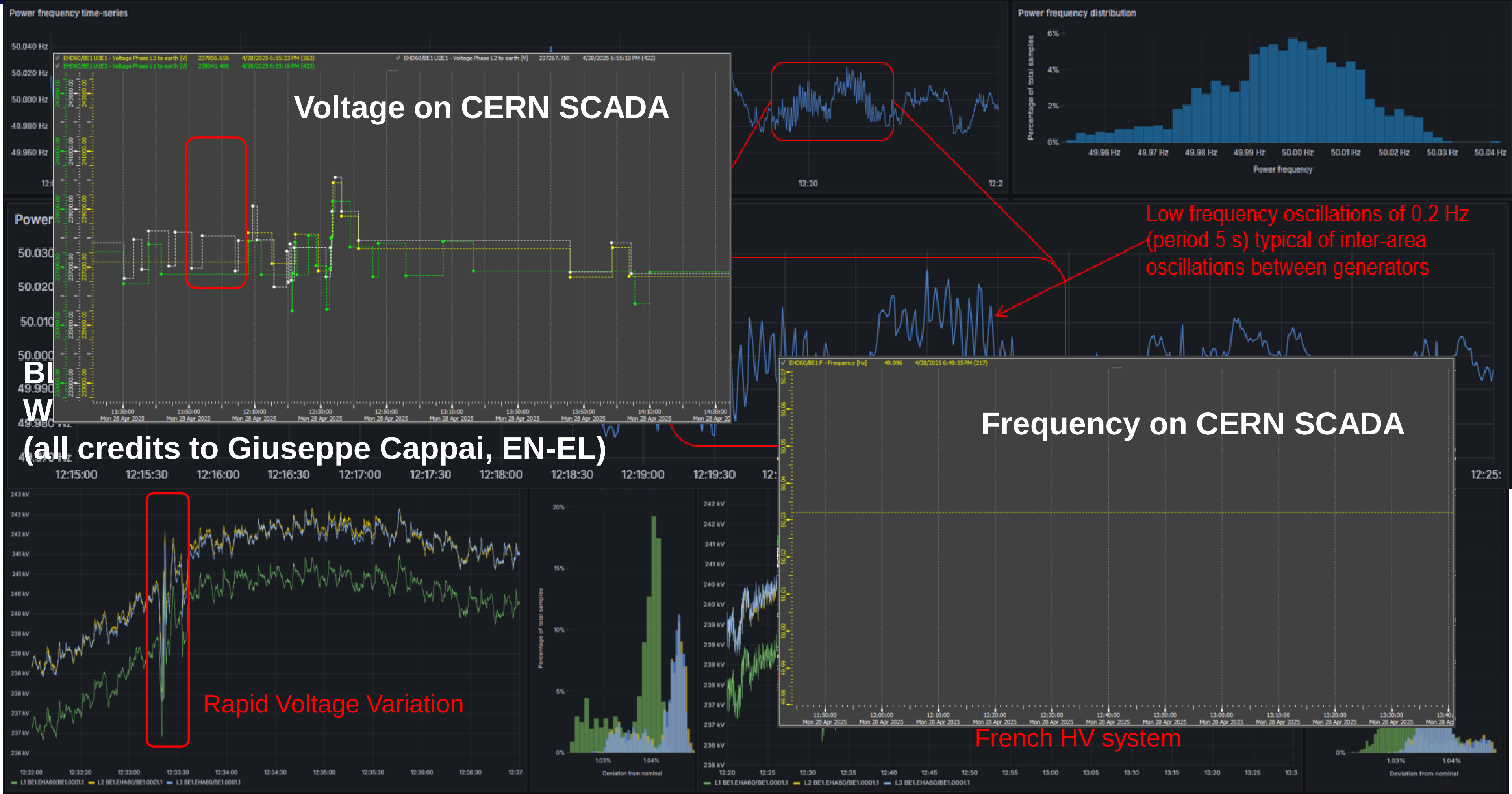



ITIC curve
Prohibited Region
No Interruption in Function Region
No Damage Region
Percent of Nominal Voltage
Duration
0.01 s
0.1 s
1 s
10 s
100 s
Event types distribution
9%
31%
59%
Event types trend
Voltage dip Total: 19
Voltage interruption Total: 3
Rapid voltage change Total: 10
Event locations distribution
22%
19%
13%
9%
9%
9%
6%
6%
6%
Event location trend
substation BCC Total: 2
substation BE1 Total: 2
substation BE2 Total: 2
substation SE1 Total: 6
substation SE2 Total: 7
substation SE4 Total: 3
substation SE5 Total: 3
substation SE8 Total: 3
substation SEH9 Total: 4



BLACKOUT SPAIN 28th April 2025 – What we saw at CERN
(all credits to Giuseppe Cappai, EN-EL)




Power frequency time-series
Power frequency distribution
Power frequency
Percentage of total samples
Voltage on CERN SCADA
Low frequency oscillations of 0.2 Hz (period 5 s) typical of inter-area oscillations between generators
(all credits to Giuseppe Cappai, EN-EL)
Frequency on CERN SCADA
Rapid Voltage Variation
French HV system
Deviation from nominal

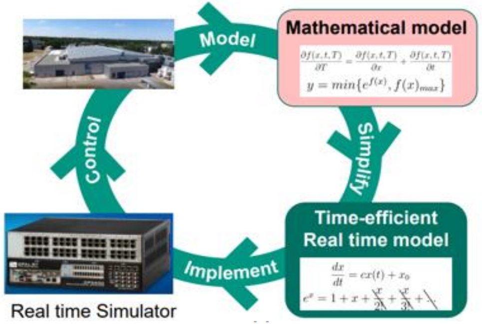
Possible benefits for FCC

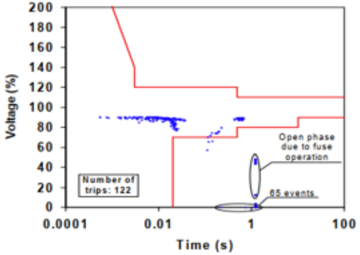
Precise statistics on the events happening in the grid

- Comprehensive record of the external events with curves and main parameters
  - Creation of the “immunity curve” of an existing accelerator
  - Enhance the understanding of the correlation between events and impact on a specific system
- Fundamental and harmonic power flow of the existing network
  - Extensive view that will allow to identify the axis of improvement
- The results will **“size” the requirements** that we want to consider for FCC, and **give the inputs** to a precise study for the optimal solutions

Deployment of new technologies

- Thanks to the digital twin of LHC network and a real-time framework, simulate the application of new technologies: DC distribution, DC back-to-back, STATCOM, energy storage, UPFC
- Assess new features for the future grid: state estimation, fault location, wide area adaptive protective relaying, distributed voltage regulation, losses reduction, harmonic flows estimation

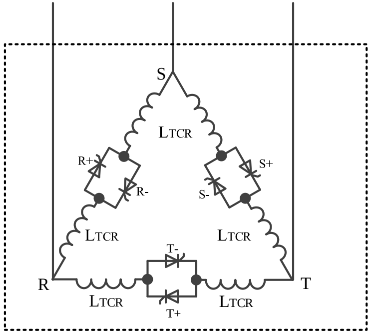




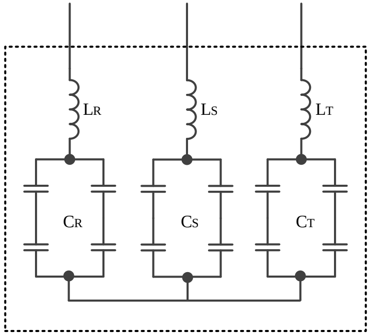
Power Quality at Today's CERN Network

Nowadays, CERN network power quality is managed by Static Var compensators

- Popular technology until 2010s
- Combination of thyristor-controlled reactor and harmonic filters



TCR: Thyristor-Controlled Reactor



Harmonic Filters

Why are important for CERN operation?

- Many magnets are powered by thyristor rectifiers
- Thyristor rectifiers are consumers of reactive power and producers of harmonics

Without Static Var Compensators, we would observe:

- Severe voltage fluctuations → SPS Network
- Significant harmonic content in LHC and SPS machine networks

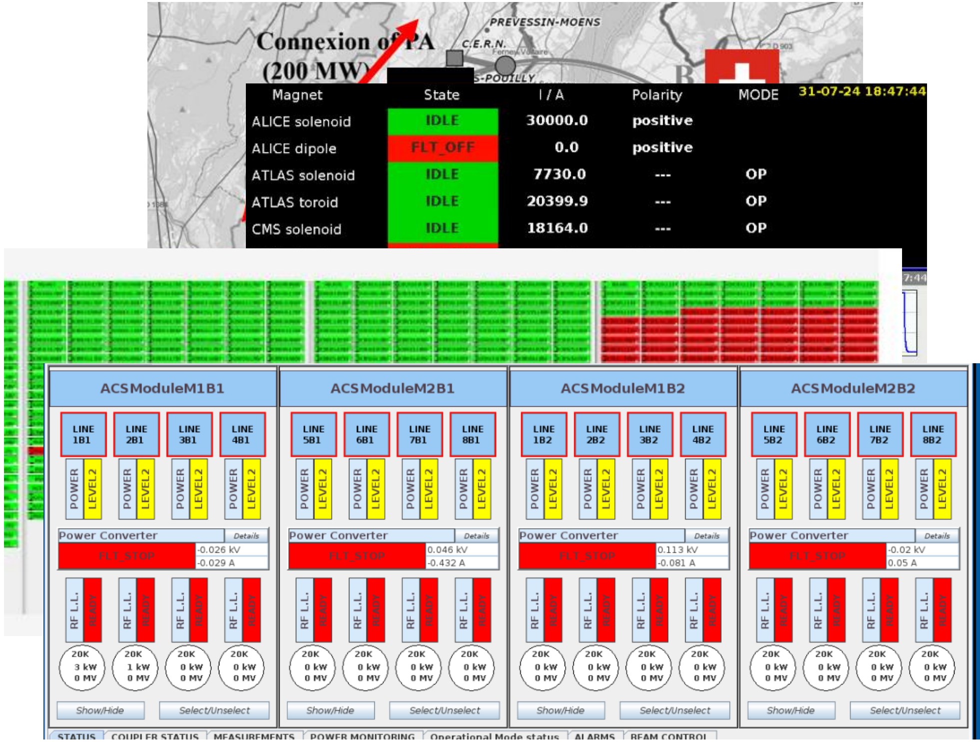
Power Quality Requirements for FCC

Can we use the existing concept based on Static Var Compensators for the FCC?

➡ **We expect significant differences in the operation of the FCC network**

Main differences between FCC and LHC:

- Thyristor converters replaced by switch-mode power supplies
  - ➢ Harmonic filtering requirements are lower
  - ➢ Significantly lower reactive power consumption
- FCC network is supplied from three connection points
  - ➢ Possibility of undesired active and reactive power flows through FCC
  - ➢ Undesired impacts on RTE surrounding networks
- Number of external perturbations (i.e. voltage glitches)
  - ➢ Expected to be higher due to higher interconnection of the machine



Power Quality Controllers

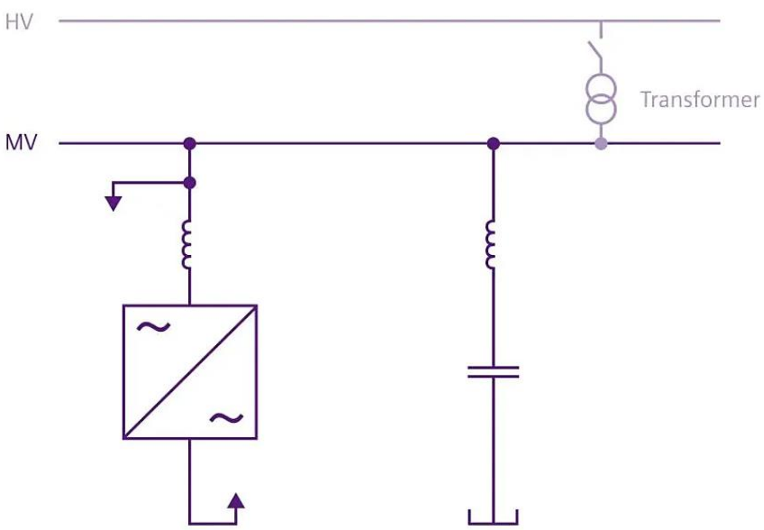
Things Static Var compensators can do:
- Compensate reactive power
- Filter harmonics

Things Static Var compensators can not do:
- Control active power flows (reactive power flow can be partially controlled)
- Compensation of voltage glitches

Study of new technologies able to performed the required tasks

- STATCOMS
- DC Networks
- UPFCs and Dynamic Voltage restorers

STATCOM
Parallel connected switch-mode converter controlling reactive power
Difficult compensation of voltage dips
Difficult power flow control



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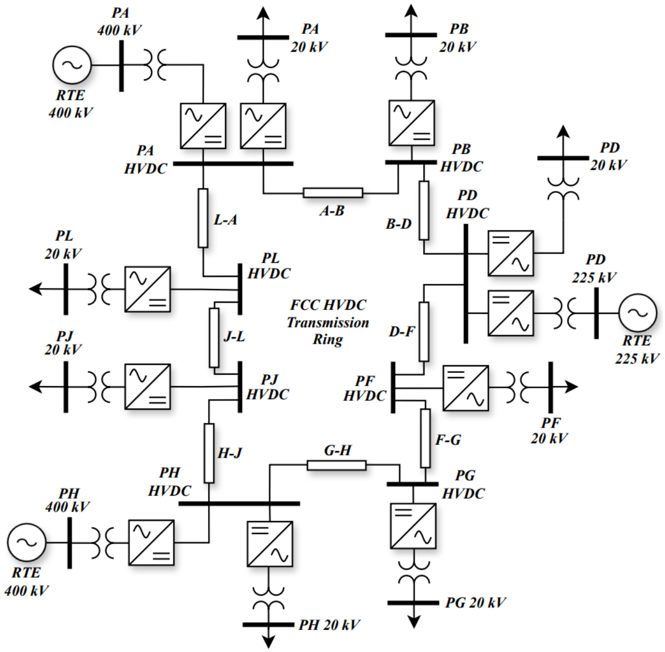
DC Networks

Power flow control

Provides immunity to network perturbations

Expensive and complex implementation



Power Quality Controllers

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Study of new technologies able to performed the required tasks

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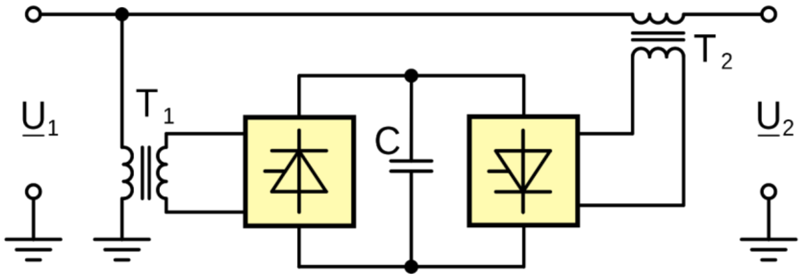
Unified Power Flow Controllers

Power flow control
Provides immunity to network perturbations
Only manages a fraction of the transmitted power

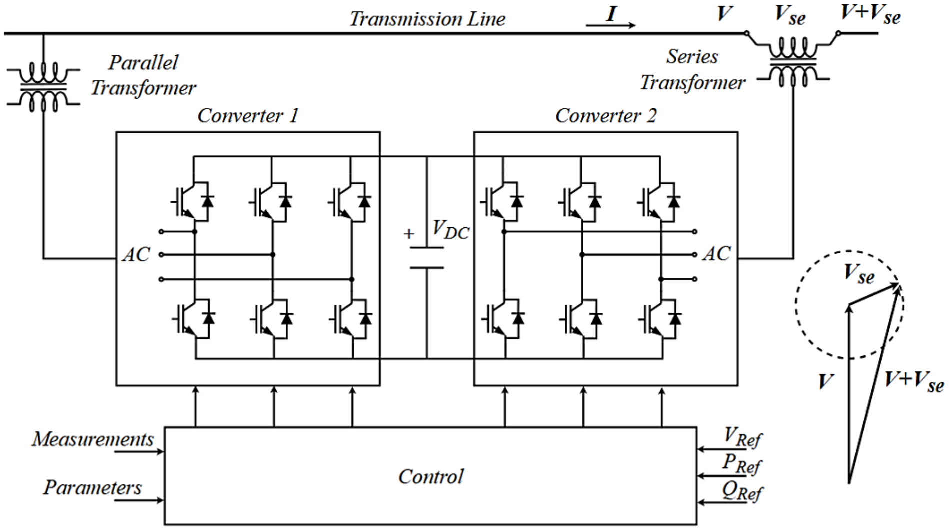


Unified Power Flow Controllers

Theoretically, it can provide all control functions

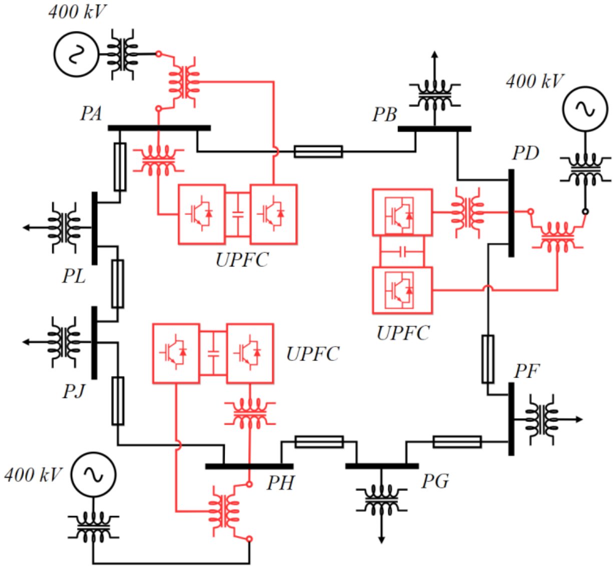
Series converter: Power flow control and dip mitigation

Parallel converter: Voltage control and Q compensation



Optimal placement on FCC network is under study

Use at the high-voltage level



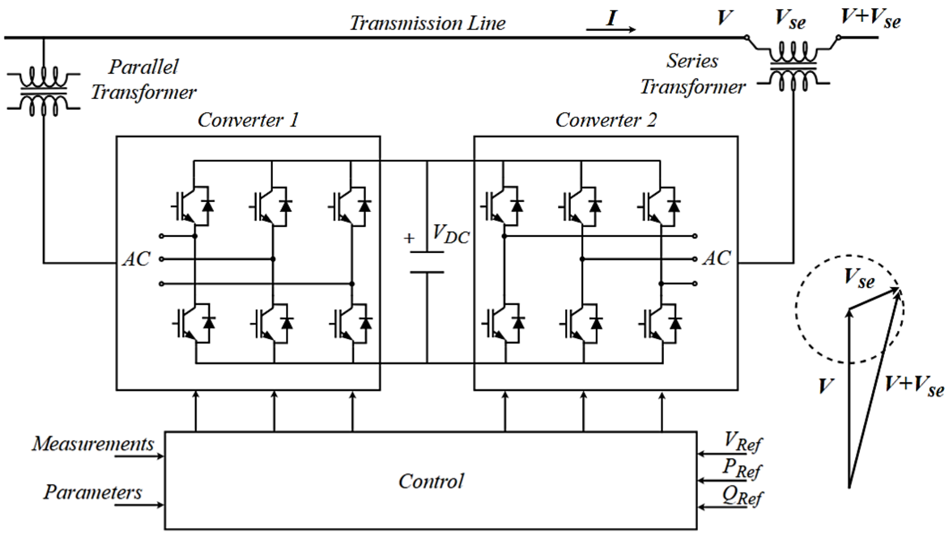
- ➢ Might enable a close-loop operation (not in the baseline)

Unified Power Flow Controllers

Theoretically, it can provide all control functions

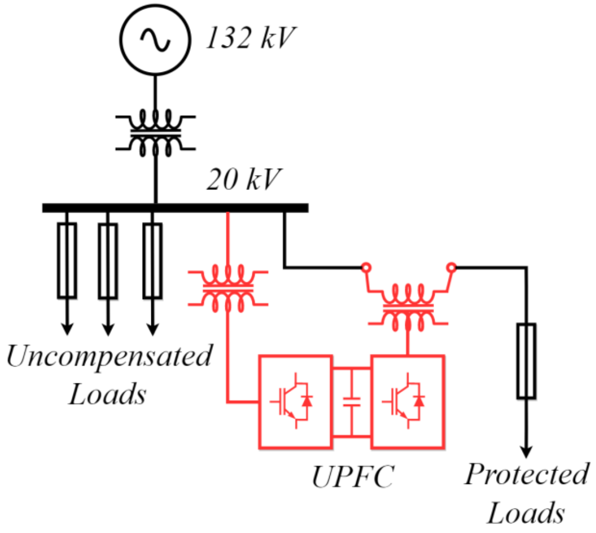
Series converter: Power flow control and dip mitigation

Parallel converter: Voltage control and Q compensation



Optimal placement on FCC network is under study

Use at the medium-voltage level



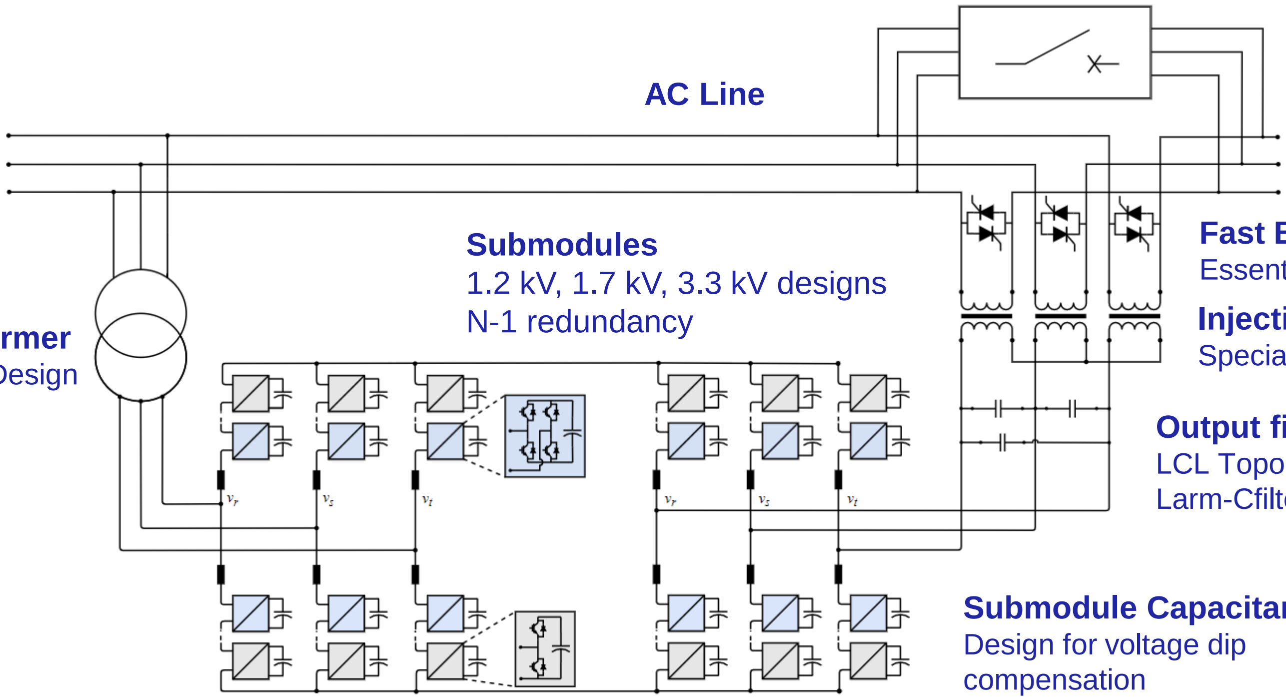
- Creation of a secured network for sensitive equipment connection

Unified Power Flow Controllers

- **Studies conducted on MMC-based UPFCs**

Slow Bypass
Long-term bypassing

AC Line



Parallel Transformer
Normal Design

Submodules
1.2 kV, 1.7 kV, 3.3 kV designs
N-1 redundancy

Fast Bypass Switch
Essential for protection

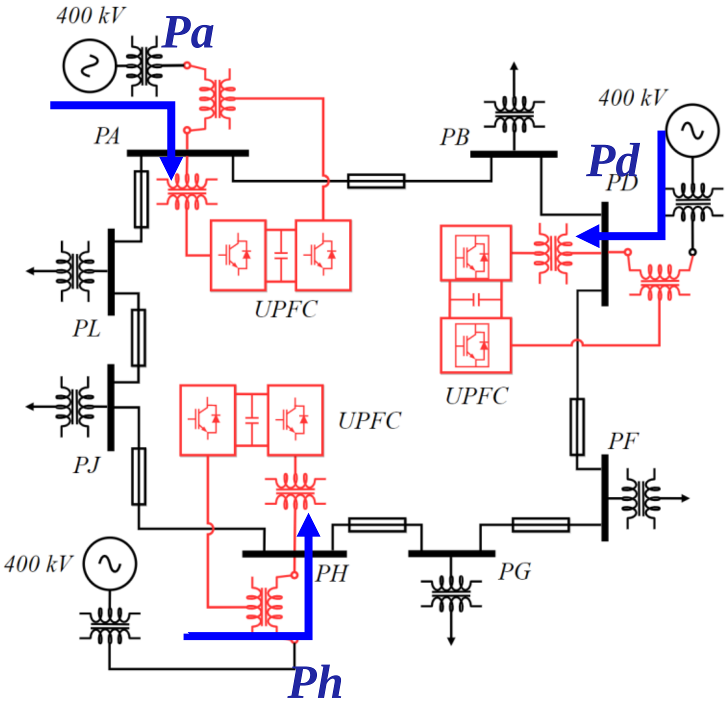
Injection Transformer
Special Design

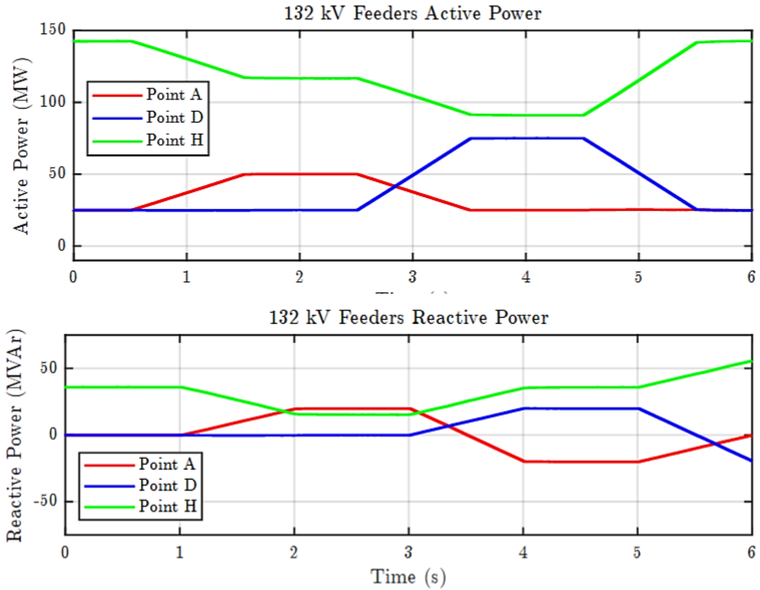
Output filter
LCL Topology
Larm-Cfilter-Ltransfo

Submodule Capacitance
Design for voltage dip compensation

Unified Power Flow Controllers

On-demand control of Active and Reactive power flows on FCC Transmission network





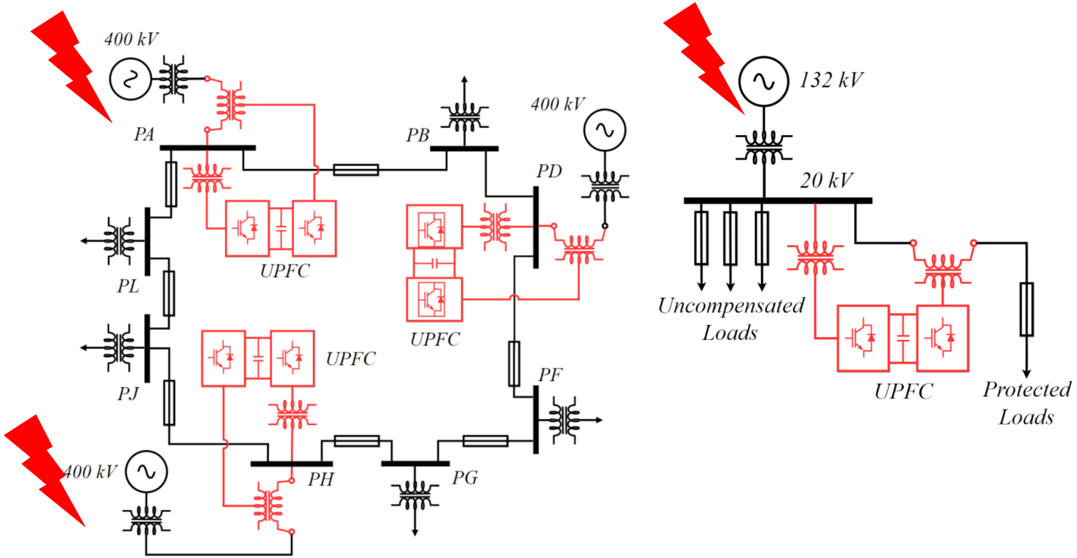
Optimal power flow dispatching → higher efficiency

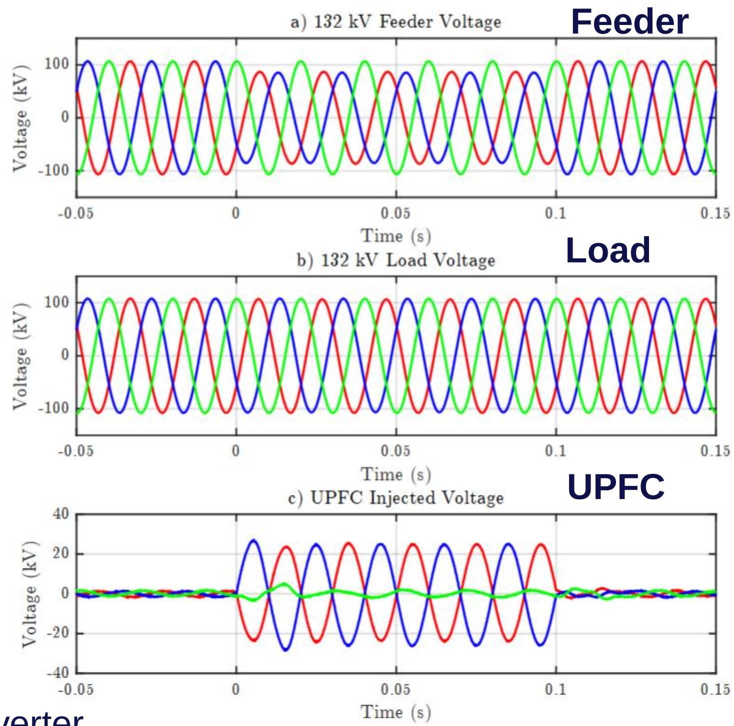
Load balancing between connection points

Currently, this scenario is not the baseline

Unified Power Flow Controllers

Reactive power control and Voltage dip mitigation at HV and MV voltage levels





- ➢ Voltage dips and swells can be easily compensated by the UPFC
- ➢ Voltage control of main busbars is provided by parallel converter

Conclusions

- Power quality is an important factor for the operation of FCC
- We have the great opportunity to retrieve structured and added-value data from CERN existing grid, thanks to RF 2.0 and PMUs
- The first results are already available
- The results will be the inputs to determine the requirements for the systems aiming to guarantee the power quality requirements of FCC
- **All groups shall be informed of the power quality requirements and limitations**

→ **Important input of the design for their system**

- For the moment, at the HV network level we are exploring the use of Unified Power Flow Controllers (UPFC) as preferred choice to improve the power quality
- This is an important study to be completed in the next years to determine the reliability and resilience of the FCC electrical grid

Thank you for your attention.