OVERARCHING GOAL

Stability of the power system

Minimum acceptable stability level

Transit zone
System stability is addressed within the existing framework: controllers and grid codes

Inclusion

Improvement of system stability within the existing framework

Technology leap
System stability is addressed with breakthrough methodologies and controllers with modified grid codes

Power electronics penetration L_2\% L_1\% L_3\% 100\%

Hannes Munzel, TenneT TSO GmbH
INTRODUCTION

WP1
Power System stability issues under high penetration of PE

WP2
Real Time Monitoring and Control

WP3
Control and operation of a grid with 100% converter based devices

WP4
Protection schemes in transmission networks with high PE penetration

WP5
Power quality in transmission networks with high PE penetration

WP6 – Exploitation

WP7 – Communication and Dissemination

WP8 – Management

Minimum acceptable stability level

Transit zone
System stability is addressed within the existing framework; controllers and grid codes

Improvement of system stability within the existing framework

Technology leap
System stability is addressed with breakthrough methodologies and controllers with modified grid codes

Power electronics penetration
GET TOGETHER AT 17:00
MITIGATION APPROACHES FOR POWER SYSTEM STABILITY UNDER HIGH PENETRATION

Result Overview from MIGRATE WP1

Dr. Sven Rüberg, TenneT TSO
AGENDA

1. Working Package Overview
2. Result Overview
3. Conclusions / Further Research Needs
WORKING PACKAGE OVERVIEW
WORKING PACKAGE OVERVIEW: MAIN OBJECTIVES

Development of Mitigation Approaches to Address Power System Stability Issues Under High Penetration of Power Electronics

1. To identify and prioritise the **stability-related issues faced by the TSOs** considering different network topologies, geographical locations and penetration levels of PE (generators, HVDC converters, FACTS, loads);

2. To develop **novel approaches and methodologies** able to analyse and mitigate the impacts of PE penetration on power system stability based on simulations, laboratory scale experiments and PMU measurements methods (data supplied by WP2);

3. To propose **control strategies so as to further tune and coordinate existing system controls** in order to maximise the penetration level of PE considering the current operating rules, the existing control and protection devices and the available degrees of freedom in the network codes (RfG and HVDC grid codes as well as the DCC);

4. To validate the use of a **monitoring approach** of the PE penetration **based on-line PMU measurements** methods developed in WP2.
WORKING PACKAGE OVERVIEW: STRUCTURE

WP1 is structured into 8 strategic tasks:
RESULT OVERVIEW
RESULT OVERVIEW: DELIVERABLE D1.1

D1.1: Report on Systemic Issues

– Summary of existing requirements for grid connected PE
– Preliminary assessment for PE capabilities
– Current and arising issues
  + Questionnaire to 33 TSO and literature survey
  + 11 issues identified: low inertia, PE resonance, transient instability, etc.
  + Issue prioritization
– High-level description of the model problems

-> D1.1 is public! <-
www.h2020-migrate.eu
RESULT OVERVIEW: CURRENT AND ARISING SYSTEMIC ISSUES

- MIGRATE TSOs were asked to rate each issue in three dimensions.

- As a result, the issues were ranked:

  1. Decrease of inertia
  2. Resonances due to cables and PE
  3. Reduction of transient stability margins
  4. Missing or wrong participation of PE-connected generators or loads in frequency containment
  5. PE controller interaction with each other and passive AC components
  6. Loss of devices in the context of fault-ride-through capability
  7. Lack of reactive power
  8. Introduction of new power oscillations and/or reduced damping of existing power oscillations
  9. Excess of reactive power
  10. Voltage dip-induced frequency dip
  11. Altered static and dynamic voltage dependence of loads

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<th>Severity</th>
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<th>Timeframe</th>
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<tr>
<td>medium</td>
<td>medium</td>
<td>≤10 years</td>
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<td>slight</td>
<td>low</td>
<td>≤15 years</td>
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RESULT OVERVIEW: GROUPING OF RESEARCH TARGETS

<table>
<thead>
<tr>
<th>Model problem</th>
<th>Stability issue</th>
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<tr>
<td>Frequency stability</td>
<td>Decrease of inertia</td>
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<tr>
<td></td>
<td>Missing or wrong participation of PE-connected generators and PE-connected loads in frequency containment</td>
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<tr>
<td>Transient rotor angle stability</td>
<td>Reduction of transient stability margins</td>
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<tr>
<td>Short-term voltage stability</td>
<td>Loss of devices in the context of fault-ride-through capability</td>
</tr>
<tr>
<td></td>
<td>Lack of reactive power</td>
</tr>
<tr>
<td>Controller interactions</td>
<td>PE controller interaction with each other and passive AC components (low-frequency range)</td>
</tr>
</tbody>
</table>
RESULT OVERVIEW: GRID FOLLOWING VS. GRID FORMING CONTROL

Grid following control:
– dq control of current fed into the system
– decoupled control of P and Q
– needs PLL
– needs voltage at the PCC in order to deliver P and Q
– hence, cannot operate at 100 % PE penetration

Grid forming control:
– control of voltage magnitude and frequency/phase
– slight coupling between P and Q
– does not need a PLL
– can blackstart a power system
– hence, can theoretically operate at 100 % PE penetration
PRELIMINARY RESULTS:
AGGREGATED 29-BUS MODEL OF GB (1/2)

- Case Study with grid following control only

**classifications:** stable, unstable, marginally stable

### Zone 1

<table>
<thead>
<tr>
<th>Fault Node</th>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<td>68% A</td>
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<td>57%</td>
<td>ms</td>
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<td>s</td>
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<td>s</td>
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</tr>
<tr>
<td>68% A</td>
<td>ms</td>
<td>ms</td>
<td>ms</td>
<td>ms</td>
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MIGRATE Project - WP 1 - Final Project Conference Brussels
RESULT OVERVIEW: 
AGGREGATED 29-BUS MODEL OF GB (2/2)

- Case Study with some PE units performing grid **forming** control

<table>
<thead>
<tr>
<th>SG (MVA)</th>
<th>WND (MVA)</th>
<th>Total MVA</th>
<th>PE in % (MVA)</th>
<th>Load (MW)</th>
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<td>Engl</td>
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<td>44925</td>
<td>57174,2</td>
<td>78,58</td>
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<td>GB</td>
<td>12249,2</td>
<td>52285</td>
<td>64534,2</td>
<td>81</td>
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**Grid Forming WND in %** 44,5
**Classic Controlled WND in %** 55,5
CONCLUSIONS / OUTLOOK: KEY TAKE-AWAYS

- With increasing levels of PE penetration, the stability and dynamics of a power system will change significantly
- PE interfaced generators will have to actively take part in power system control
- For the given case study,
  - a maximum PE penetration of 68 % was identified if we continue installing grid following PE units only
  - the maximum PE penetration can be significantly increased if some of the PE units perform grid forming control
- Also, grid forming control
  - can operate at extremely low short-circuit ratios (below 1)
  - can inherently balance active-power mismatch (→ frequency stability)
  - has less tendency towards control interaction with other local PE units
CONCLUSIONS / OUTLOOK

DELIVERABLE D1.6

D1.6: Demonstration of mitigation measures and clarification of unclear grid code requirements

– Key take-aways from WP1

– Case study: How to reach approx. 65 % PE penetration in a realistic test case? How to go further towards approx. 100 %?

– Scientific discussion of unclear grid code requirements:
  + Virtual inertia?
  + Fast fault current?

– Suggestions for a compliance testing methodology

-> D1.6 will be public! <-

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WORKPACKAGE 2: REAL TIME MONITORING AND CONTROL TO ENABLE TRANSMISSION NETWORK TRANSITION

MIGRATE WP2: Final Result Dissemination Event

WP2 Team with WP leader, James Yu
SP Energy Networks
MIGRATE

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OUTLINE

1. Reminder of our purpose and mission
2. Simulation, Testing and Pilot Trial
3. Collaborations
4. Contributions
5. Conclusions
ON SOME CHALLENGES AND OUR PURPOSES
THE EUROPEAN SUPERGRID

2030: EWEA offshore grid vision
UK CHALLENGES – TOPOLOGY AND GENERATION MIX

- Scotland – 5 GW
- East Coast – 18 GW
- East Anglia – 6 GW
- Bristol Channel – 3 GW
- South Coast – 1.6 GW

Total Capacity ~ 40 GW

Years:
- 2015
- 2014
- 2018

FITNESS Project (2016-2020)
THE IMPACT ON THE TRANSMISSION NETWORK

Reducing System Inertia

More Extreme Variations in Power Flow

New Challenges in Facilitating Access for Maintenance & Construction

+ Transfers between Scotland and England increasingly driven by wind conditions

+ Security required under a wider range of conditions

+ Outages for critical upgrades becomes increasingly difficult to deliver

Implications of reduced system inertia?

Implications of power flow variations?

How to reduce need for outages? Or how to accelerate the return to service?
WHAT DO WE MEAN BY SYSTEM STRENGTH?

Inertia
Spinning mass, stored energy, mostly in large synchronous generators. A single value for the whole system, or area inertia.

Short circuit currents
The current that will flow into a fault
Triggers protection, interrupted by circuit breakers
Specific to location

Stiffness
The ability to keep voltage step changes within limits, survive switching transients, etc.
Specific to location
Complementary approach to other WPs- Under WP1. Real-time monitoring and forecast of:
• PE penetration,
• Area (local) inertia
• Short Circuit Capacity

Software will be developed that can make these solutions available to TSOs and knowledge will be generated regarding the ICT requirements and the issues encountered during deployment and operation.

Pilot testing of Closed Loop Wide Area Control in the Landsnet system (Iceland) as a world premiere.

Lessons learned and knowledge generated by the field trial can be exploited by ENTSO-e.
A REMINDER OF WP2

Key objectives:

- To develop new monitoring and forecasting tools using modern technology, so to provide real-time information on stability KPIs which will more accurately assess the stability limits of a system;
- To assess the infrastructure needs to make the KPI monitoring/forecasting feasible;
- To develop and test a world-first real time wide area control algorithm in the GB and Icelandic networks; and
- To demonstrate the ability of the solutions to be accurate and reliable in a pan-European application with a period of trialling the solutions across various power systems.
SIMULATION, TESTING AND PILOT TRIAL
HIGH FIDELITY MODELS (EMTP)
TESTING OF THE EFCC SCHEME

Region 1
Region 2
Region 3
PMUs

EFCC scheme

Wind farms
DSR
PV
Energy storage
CCGT

Fast, coordinated response closest to the disturbance
Virtual PMU Zone

IEEE C37.118 Communication Infrastructure

RTDS EFCC

User Setting From IEC 61850 Client

IEC 61850 MMS

IEEE C37.118 Communication Infrastructure

Service Providers Models in RTDS

User Setting From IEC 61850 Client

IEC 61850 DOSE Communication Infrastructure

EFCC HARDWARE CONNECTED TO THE RTDS GB MODEL

RTDS

EFCC

Zone

PV

CCGT

DSR

Wind

RA1

RA2

LC1

LC2

LC3

LC4
ICELANDIC TRANSMISSION SYSTEM

Extensive WAMS monitoring & records (~60 PMUs)
Good quality communications network
Landsnet & grid-stakeholders willing to trial innovation
New control is measurable on small system

Location with PMU
GENERAL METHOD FOR LOCATIONAL FAST RESPONSE

The MIGRATE Project - WP2
TEST ENVIRONMENT
TESTING USING PLAYBACK OF REAL EVENTS

Central PhasorPoint Server

Linux Workstation

Export disturbance events

Scripts & c37.118 Simulator

PhasorPoint Instance & PDC

Playback PMU Data

Control output

PhasorController (PhC)
20ms Real-Time PMU-based logic controller with specialist WACS function block library in IEC 61131 PLC logic

Supports:
• IEEE C37.118
• IEC 61850 / GOOSE
• Modbus
• Digitals

22 test events trials, 27 events during pilot test period

<table>
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<tr>
<th>#</th>
<th>Date</th>
<th>Description</th>
<th>Location</th>
<th>freq minimum [Hz]</th>
<th>Warning</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
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<td>3</td>
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<td>E</td>
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<td>Fu-50MW island &amp; oscillation</td>
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<td>East 66 kV break out, following trip of a 132 kV transmission line</td>
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<td>49.6, 50.6</td>
<td>X</td>
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</table>

In 2 ½ years from go-live to present time, around 70 activation triggering events.

"The activations have all been in time and helpful for the stability of the grid.”

The MIGRATE Project - WP2
LOCATIONAL CONTROL RESOURCES – IMPLEMENTATION

1. Landsnet’s Control Centre
2. East Iceland Fish Factory Load Shed (x6 plants)
3. ISAL Smelter Load Control
4. Sigalda (SIG) Intelligent Split
5. Hrauneyjafoss (HRA) Fast Ramp
6. NAL Smelter Load Control (similar to ISAL control)
7. Geothermal governor control
8. Geothermal governor control

PhasorController
20ms Real-Time PMU-based logic control with specialist WACS function block library

Operational now
Under development
The MIGRATE Project – WP2

LOCATIONAL CONTROL RESOURCES

West - Iceland

- REY Unit: [0-45] MW
- HRA unit 1-3: [0-180] MW
- ISAL load control: 10 MW
- NAL load control: 30 MW

East - Iceland

- THR Units: [0-90] MW
- EILS load shed: [0-100] MW
- Alcoa load control: 60 MW
- ADC load shed: 60 MW

Dimensioning Contingency: 300MW
Result of Wide-Area-Controls

- Fast acting (<0.5s)
- Fault-tolerant distributed control
- Handles complex multi-event sequences
- Frequency containment improved
- Reduced islanding probability
- More connection capacity
- Diverse loads & generators can contribute
- Cost effective
CONTRIBUTIONS
KEY CONTRIBUTIONS

New Concepts and Its Definitions

Effective Area Inertia and Its Measurement


Publication Highlights


• 16 published papers and journals

• 5 conference presentation

New Products
GRID STABILITY PROBLEMS WITH REDUCING INERTIA

1. Under-Frequency Load Shed (UFLS) occurs faster

2. Large **system ROCOF** causes DER loss-of-mains tripping

3. **Regional ROCOF** variations causes DER loss-of-mains for events thought to be “secure”

4. **Islanding** risk increases
CONTINUOUS PASSIVE INERTIA MEASUREMENT & FORECASTING

MIGRATE Area Inertia Measurement from events

Continuous PMU-based Area Inertia Measurement

Machine Learning Area Inertia Model & Forecast

Effective inertia of area

\[ H_{EA} = \frac{\Delta p_b(t)}{2 \frac{df_a(t)}{dt}} \]

Area

Equivalent centre of inertia within a boundary of measured transmission lines

\[ \Delta p_e \]

Electrical power to accel/decel rotating inertia

\[ \Delta p_{ni} \]

Power to non-inertial elements e.g. load

\[ \Delta p_b \]

Net power across area boundary

\[ \Delta p_b = \Delta p_e - \Delta p_{ni} \]

PMU measurements
- Frequency within area
- Sum of P of lines into area

Applicable to control room & automated control schemes.

Average Rate of Change of Frequency in Area

\[ df_a/dt \]
SYSTEM STRENGTH ISSUES RELATE TO OSCILLATION STABILITY

System Strength (Stiffness) must be distinguished from Short Circuit Capacity. A weakened system can result in unstable voltage control oscillations, typically 4-12Hz.

System Strength

Short Circuit Capacity - Fault

Graphic source: Orsted technical report included in Appendix to NGESO Technical Report on the events of 9/8/19
## SYSTEM STRENGTH & FAST OSCILLATION DETECTION

<table>
<thead>
<tr>
<th><strong>Frequency Range</strong></th>
<th>0.0024 to 22.5 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inputs</strong></td>
<td>Any analogue signal within PLC logic</td>
</tr>
<tr>
<td><strong>Outputs</strong></td>
<td>Mode frequency, amplitude &amp; damping ratio</td>
</tr>
<tr>
<td><strong>Frequency bands</strong></td>
<td>12 bands; 0-2 modes per band</td>
</tr>
<tr>
<td><strong>Detection time</strong></td>
<td>Typically &lt; 3 oscillation cycles</td>
</tr>
<tr>
<td><strong>Parameters</strong></td>
<td>Frequency range, amplitude &amp; damping thresholds, hysteresis</td>
</tr>
<tr>
<td></td>
<td><strong>Configurable instances for Near-Instability &amp; Instability cases</strong></td>
</tr>
</tbody>
</table>

**Instability Detector** as Application Function Block (AFB) on PhasorController

![Graph showing Power (MW) vs Time (seconds)](image_url)

- **Power (MW)**
- **Trigger**

Time (seconds)
ADDRESSING SYSTEM STRENGTH WITH WIDE AREA CONTROL

WIDE AREA STUDY
Measurement based System Strength review

WIDE AREA CONTROL
Event-based Triggers (SPS)
Sensing Near-Instability
Fast Instability Detection

ACTUATION
HVDC & Renewables
1. Control mode selection
2. Run-back
3. Trip
CONCLUSIONS

- Through joint efforts, academia and industry are in the position to offer appropriate solutions for enabling economic, reliable, secure and affordable energy to customers

- MIGRATE project was just one excellent example of collaboration, delivery and impacts

- MIGRATE is only a start
COFFEE BREAK UNTIL 11:15 H
MIGRATE WP3: OPERATING A SYSTEM WITH 100% POWER ELECTRONICS DEVICES

Guillaume DENIS, Thibault PREVOST, RTE, 4th December 2019, Brussels
OVERVIEW OF WP3 CHALLENGE

Synchronous machines create voltage waveforms with the same frequency.

Converters measure the grid frequency.

Converters provide active and reactive power at the measured frequency.
OVERVIEW OF WP3 CHALLENGE

MIGRATE: Requirement for systems with high share of PE-interfaced devices:

Acceptable level of stability while keeping costs under control

WP3: Control and operation of large transmission systems with 100% converter-based devices

“to be forced to reset our brain”

The requirement for grid forming inverters
WP3: THE PROBLEM ANALYSIS IN 2016 [D3.1]

**Ideal electrical sources**

- 3ph - Voltage Sources
- Perfectly synchronized at $f_n$
- Infinite power supply
- Infinite energy storage

**Physical constraints of PE-based system**

- Limited Bandwidth and Current of VSC
- No communication
- Limited power and finite energy
- Topology imposed and variable
- Additional constraint of WP3
  - Compatibility with other sources (SG, gf, IM)

[D3.1] « Description of system needs and test cases », TSOs of MIGRATE project, Deliverable 3.1, 2016
WP3: THE PROBLEM ANALYSIS 2018 [D3.2] [D3.3] [D3.4]

**Ideal electrical sources**
- 3ph - Voltage Sources
- Perfectly synchronized at $f_n$
- Infinite power supply
- Infinite energy storage

**VSC Grid-Forming Function:**
- As close as possible from Voltage Source
- Stable synchronization around nominal frequency
- Decentralized Load Sharing services
- New operational rules

**Physical constraints of PE-based system**
- Limited Bandwidth and Current of VSC
- No communication
- Limited power and finite energy
- Topology imposed and variable
- Additional constraint of WP3: Compatibility with other sources (SG, gf, IM)

[D3.2, L2EP 2018], [D3.3, ETH 2018], [D3.4, UCD 2018]
THE GRID-FORMING FUNCTION

Stiff voltage source behavior

$\approx 50 \text{ Hz}$

Synchronizes with other sources (EnR, MS, GF)

Current-limiting strategy

Islanding
THE GF FUNCTION: MULTIPLE WAYS TO REALIZE

3 controls developed within WP3 (D3.2, D3.3) (and made open source)

Theoretical proof of stability can be achieved with basic grid assumptions. (D3.3)

Multiple other controls in the literature...

In MIGRATE, the controls were developed independently, on simple test cases
THE GF FUNCTION: EXAMPLE OF TEST-CASES

Figure 32: DC signals of a single converter during a short circuit fault and subsequent line opening. A short circuit fault occurs on one of the lines at $t = 1.5$ s and is cleared by disconnecting the line after 150 ms.

Figure 33: AC signals of a single converter during a short circuit fault and subsequent line opening. A short circuit fault occurs on one of the lines at $t = 1.5$ s and is cleared by disconnecting the line after 150 ms.
THE GF FUNCTION: EXAMPLE OF TEST-CASES

Interoperability on 3-bus Benchmark

$K_3$ opens, $K_{sc}$ closes, $K_{line}$ open 150 ms after,
**Key finding:**

1. Stability and robustness are achieved if, after grid disturbance, the response of the imposed voltage magnitude and frequency is « slow enough » (D3.3)

2. In small-signal, all the grid-forming control behave similarly, as seen from their output. (D3.2, D3.3)

3. Interoperability of independently designed controllers (D3.2, D3.3)
PROBLEM OF GRID-SENSITIVITY OF GRID-FORMING

Slow voltage source are subject to overcurrent during stressing events

Problem:

Proposed solution: Current loop saturation during first peak and virtual impedance afterwards (D3.2)
⇒ Validated concept in simulation, and on lab scale hardware. (D3.5)

Another solution have been proposed, integrating the current limitation constraints in the voltage control loop. (D3.6)
CURRENT-LIMITING STRATEGY AND EXPERIMENTAL RESULTS

Extensive description of the hardware and the lab test results are available in D3.5

1- 2-Level voltage source converter
2- Controller dSPACE 1005
3- Transformer
4- DC supply
5- PCU-3X5000-BC amplifier

Bolted fault for 400ms
IRISH SYSTEM SIMULATION WITH 100% POWER ELECTRONICS

Assessing the findings on a real case benchmark

Stability assessment for 100 ms, 3-phase faults for various distributed grid-forming / grid-following configuration

Ireland (GF %)

<table>
<thead>
<tr>
<th>Ireland (GF %)</th>
<th>Ballylumf (near converter) North</th>
<th>Tamnam (far) North</th>
<th>Inchicore (near converter) Dublin</th>
<th>Shannonb (far) Dublin</th>
<th>Aghada (near converter) South</th>
<th>Ballyvoul (far) South</th>
</tr>
</thead>
<tbody>
<tr>
<td>31.0</td>
<td>LG</td>
<td>LG</td>
<td>LG</td>
<td>G</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>30.1</td>
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<td>G</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>29.5</td>
<td>R</td>
<td>LG</td>
<td>LG</td>
<td>G</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>28.9</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>LG</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>29.9</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>LG</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>28.8</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>LG</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>27.9</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>G</td>
<td>LG</td>
</tr>
<tr>
<td>26.3</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
</tr>
</tbody>
</table>

Key finding:

Following an **optimal placement procedure**, the level of designed grid-forming controlled PE capacity have been found to be **satisfying above 30 %** on the Irish System (D3.4).

Latest work showed that with inverters providing Ancillary Services, this share can be reduced to almost 20% (D3.4).
1. Grid forming control will release the stress put on the remaining synchronous machine.  \( \text{D3.6} \)

2. Grid forming controls are more efficient than grid following inverters providing “similar” services.  \( \text{D3.3} \)

3. Digital control of inverters can be seamlessly updated to have optimal allocation of new services.  \( \text{D3.3} \)

4. When the share of inverter will be very high, (80-99%), some controls of remaining synchronous machines will need to be adapted.  \( \text{D3.6} \)
Specific simulation methods and model reduction methods have been tested and developed. (D3.2)

- to allow to have an accurate simulation result
- to avoid complex and timely full EMT models, that would require data that are hard to obtain.
WP3 CONCLUSIONS

1. Operating a grid with only Power Electronics is possible with Grid Forming inverters. (D3.2, D3.3, D3.4)

2. Grid-forming function performances have been unified and defined from a system level perspective (techno-agnostic). The Grid-forming function gather the necessary conditions of a source to ensure proper and stable definition of voltage waveform that resist to small-disturbance, throughout a multi-sources grid. (D3.2, D3.3, D3.6)

3. Suitable current-limiting strategy can protect sensitive power-electronics devices during stressful event without compromising their grid-forming function and without requiring costly oversizing. (D3.2, D3.6)
WP3 CONCLUSIONS

4. Some ancillary services will need to be adapted to the new system dynamics. \textsuperscript{D3.3}

5. The Grid Forming inverters are technologically feasible, and \textbf{might be cost-effective}. \textsuperscript{D6.3}

6. It cannot be expected from Grid forming to have the same level of maturity than Synchronous Machine, first grid code must be open, and TSO will learn from experience.

7. The transition at very high penetration need specific attention and will require change in SM controllers. \textsuperscript{D3.5}
Questions?
POWER SYSTEM PROTECTION SOLUTIONS FOR FUTURE TRANSMISSION NETWORKS

WP4- MIGRATE PROJECT
4th December, Brussels
INDEX

1. PEIG: IMPACT ON PROTECTION ALGORITHMS
2. PRESENT PROTECTION SCHEMES IN TRANSITION AND HIGH PEIG PENETRATION SCENARIOS
1. PEIG: IMPACT ON PROTECTION ALGORITHMS

- Short circuit current contribution from Power Electronic Interfaced Generation systems (PEIG) differs from classical Synchronous Generation:
  - The Short Circuit Current contribution is fixed by Power Electronic Control Strategies and the type of converter.
  - Grid Codes establish the requirements to PEIG to be connected to the Grid:

**Capability of PE-based components to stay connected in short periods after a fault inception in the grid**

**Capability of injection/consume of reactive power to reduce voltage dip**
1. PEIG: IMPACT ON PROTECTION ALGORITHMS

TYPE IV, PV, AND HVDC: Short Circuit Current Contribution fully fixed by Power Electronic control.

Source: “Negative sequence current injection by power electronics based generators and its impact on faulted phase selection algorithms of distance protection” presented in Western Protective Relay Conference October 2018, Spokane, US.
1. PEIG: IMPACT ON PROTECTION ALGORITHMS

- **Distance protection (21)** is the most affected protection function in transition and high penetration scenarios:
  - **Current are distorted during transition period** and differs from classical synchronous generator shortcircuit current contribution.
  - Control strategies which suppress **negative sequence current injection** (I2) makes that PEIG fed any type of fault in a balanced way during the short circuit steady state.
  - Consequences:
    - Negative impact on **direcionality** algorithms
    - Negative impact on **faulty phase selection** algorithms:
      - Superimposed currents
      - Angular difference I2/I0
      - Unstable source impedance during transient periods
    - Negative impact on the **impedance calculation** during transient periods due to an unstable source impedance
  - Better performance, **after the initial transients**, has been observed when negative sequence current injection is included in the control strategy.
1. PEIG: IMPACT ON PROTECTION ALGORITHMS

Short circuit contribution affected by Power Electronics Control:

- Great influence of crowbar/ DC chopper control strategy: (Example of Phase to Phase Fault)

- Consequences on Distance Protection Function (21):
  - Negative impact on fault detection
  - Negative impact on directionality
  - Negative impact on impedance calculation
2. PRESENT PROTECTION SCHEMES IN TRANSITION AND HIGH PENETRATION SCENARIOS

○ SUMMARIZING THE PROBLEMS.....

➤ DISTANCE PROTECTION IS THE MOST AFFECTED PROTECTION FUNCTIONS IN TRANSITION AND HIGH PEIG PENETRATION SCENARIO.

➤ FREQUENCY ISSUES RUNNING LOW INERTIA SYSTEMS ARE ALSO EXPECTED

- PROBLEMS EXPECTED WITH DIRECTIONALITY DECLARATION AS PHASOR FREQUENCY DIFFERENCE OF POLARIZING MEMORY VOLTAGE AND CURRENT PHASORS CAN LEAD WRONG DIRECTIONALITY DECLARATION
- UNDERFREQUENCY LOAD SHEDDING SCHEMES MUST BE REVISITED

○ SCENARIOS:

TRANSITION SCENARIO

HIGH PEIG PENETRATION SCENARIO
2. PRESENT PROTECTION SCHEMES IN TRANSITION AND HIGH PENETRATION SCENARIOS

TRANSITION SCENARIO

PRESENT PROTECTION SYSTEM SCHEMES:

- **OPTION 1:**
  2x PROTECTION (PRIMARY AND BACKUP)
  2x OPTICAL FIBER COMMUNICATION

- **OPTION 2:**
  2x PROTECTION (PRIMARY AND BACKUP)
  1x OPTICAL FIBER COMMUNICATION
  1x CARRIER WAVE COMMUNICATION

<table>
<thead>
<tr>
<th>FAULT</th>
<th>PERFORMANCE OPTION 1 IN N-1</th>
<th>COMMENT OPTION 1</th>
<th>PERFORMANCE OPTION 2 IN N-1</th>
<th>COMMENT OPTION 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>LINE FAULT (N-1 = 1 x OPTICAL FIBER FAILURE)</td>
<td>GOOD</td>
<td>87L EXPECTED TO WORK PROPERLY</td>
<td>GOOD</td>
<td>21 – TP EXPECTED TO WORK PROPERLY IMPLEMENTING WEAK INFED SCHEME.</td>
</tr>
<tr>
<td>SGB NODE BB FAULT (N-1 = SGB NODE BBP FAILURE)</td>
<td>GOOD PROTECTION SYSTEM OF FEEDERS CONNECTED TO SG GRID</td>
<td>Z2 PROTECTION SYSTEM OF SG GRIDS EXPECTED TO WORK PROPERLY</td>
<td>GOOD PROTECTION SYSTEM OF FEEDERS CONNECTED TO SG GRID</td>
<td>Z2 FEEDERS SG GRIDS EXPECTED TO WORK PROPERLY</td>
</tr>
<tr>
<td>PHASE PEIG BB FAULT (N-1 = PEIG NODE BBP FAILURE)</td>
<td>GOOD</td>
<td>Z2/Z_REV PROTECTION SYSTEM PEIG EXPECTED TO WORK PROPERLY</td>
<td>GOOD</td>
<td>Z2/Z_REV PROTECTION SYSTEM PEIG EXPECTED TO WORK PROPERLY</td>
</tr>
</tbody>
</table>

WP4- MIGRATE project final conference 81
2. PRESENT PROTECTION SCHEMES IN TRANSITION AND HIGH PENETRATION SCENARIOS

HIGH PEIG PENETRATION SCENARIO

PRESENT PROTECTION SYSTEM SCHEMES:

OPTION 1:
2x PROTECTION (PRIMARY AND BACKUP)
2x OPTICAL FIBER COMMUNICATION

OPTION 2:
2x PROTECTION (PRIMARY AND BACKUP)
1x OPTICAL FIBER COMMUNICATION
1x CARRIER WAVE COMMUNICATION

FAULT | PERFORMANCE OPTION 1 IN N-1 | COMMENT OPTION 1 | PERFORMANCE OPTION 2 IN N-1 | COMMENT OPTION 2
---|---|---|---|---
PHASE LINE FAULT
(N-1 = 1 x OPTICAL FIBER FAILLURE) | GOOD | 87L EXPECTED TO WORK PROPERLY | POTENTIAL FAIL | 21–TP COULD MALOPERATE, BOTH ENDS POTENTIAL WEAK INFEED AND HIGH PEIG FEEDED

PHASE SG BB FAULT
(N-1 = SGB NODE BBP FAILLURE) | POTENTIAL FAIL PROTECTION SYSTEM FEEDERS CONNECTED TO PEIG + SGB NODE FAIL PEIG PROTECTION SYSTEM | PERFORMANCE DEPENDING ON GENERATION MIX OF SG AND PEIG Z2/Z_REV PEIG DELAYED TRIPS OR MISSED TRIPS | POTENTIAL FAIL FEEDERS CONNECTED TO PEIG + SGB NODE FAIL PEIG PROTECTION SYSTEM | PERFORMANCE DEPENDING ON GENERATION MIX OF SG AND PEIG Z2/Z_REV PEIG DELAYED TRIPS OR MISSED TRIPS

PHASE PEIG BB FAULT
(N-1 = PEIG NODE BBP FAILLURE ) | POTENTIAL FAIL PROTECTION SYSTEM FEEDERS CONNECTED TO PEIG + SGB NODE FAIL PEIG PROTECTION SYSTEM | PERFORMANCE DEPENDING ON GENERATION MIX OF SG AND PEIG Z2/Z_REV PEIG DELAYED TRIPS OR MISSED TRIPS | POTENTIAL FAIL FEEDERS CONNECTED TO PEIG + SGB NODE FAIL PEIG PROTECTION SYSTEM | PERFORMANCE DEPENDING ON GENERATION MIX OF SG AND PEIG Z2/Z_REV PEIG DELAYED TRIPS OR MISSED TRIPS
2. PRESENT PROTECTION SCHEMES IN TRANSITION AND HIGH PEIG PENETRATION SCENARIOS

• CONCLUSIONS:

- IN TRANSITION SCENARIO, PRESENT PROTECTION SCHEMES ARE STILL RELIABLE:

  - PROBLEMS TO DETECT BUSBAR FAULTS IN N-1 FROM PEIG PROTECTION SYSTEMS, BUT DOES NOT REPRESENT TRANSMISSION SYSTEM STABILITY RISKS.
  
  - Some delay should be applied to instantaneous distance protection in order to ensure a secure operation during control transitions. This time delay should be set according to grid codes (Voltage Support and I2 injection) and typically will be between 30 to 50 ms.
  
  - Underfrequency load shedding schemes might be readjusted.

- IN HIGH PEIG PENETRATION SCENARIO, NEED FOR HIGHER LEVEL OF PROTECTION EQUIPMENT REQUIREMENTS:

  - PROBLEMS TO DETECT LINE FAULTS IN N-1
  
  - PROBLEMS TO DETECT BUSBAR FAULTS IN N-1, REPRESENTING TRANSMISSION SYSTEM STABILITY RISKS FOR REMAINING SYNCHRONOUS GENERATION CONNECTED TO THE GRID RECOMMENDED 2 X 87B.
  
  - New underfrequency load shedding schemes must be defined: adaptive and centralized.
2. PRESENT PROTECTION SCHEMES IN TRANSITION AND HIGH PEIG PENETRATION SCENARIOS

• CONCLUSIONS:

- FURTHER STUDIES MUST BE CARRIED OUT TO CHECK THE PERFORMANCE OF HIGH PEIG PENETRATION GRIDS:
  - NON HOMOGENEOUS GRID CODE IMPLEMENTATION ON PEIG \(\rightarrow\) I2 SHORT CIRCUIT CURRENTS LEVEL AND IT’S IMPACT ON ALGORITHM ELEMENTS BASED ON I2
  - LOWER SHORTCIRCUIT CURRENTS EXPECTED \(\rightarrow\) IMPACT ON PROTECTION ALGORITHMS
  - Impact of grid forming controls on power system protection
  - Wide area protection schemes as backup protection systems \(\rightarrow\) Time synchronization and time distribution becomes critical
THANK YOU

slopez@ree.es
LUNCH BREAK UNTIL 14:00 H

TIME FOR LUNCH
POWER QUALITY IN TRANSMISSION NETWORKS WITH HIGH PE PENETRATION

MIGRATE – FINAL PROJECT CONFERENCE
Brussels, 4th December 2019

Name: Dr. Blaž Kirn
Company: ELES
E-Mail: Blaz.Kirn@Eles.si
WHY IS POWER QUALITY A CENTRAL ISSUE TO SUCCEED IN MASSIVE POWER ELECTRONIC INTEGRATION?

EU Energy policy & goals

Integration of RES (PE)

Costumers to have same quality of supply

Reliability of the system shouldn’t be endangered

Developing PQ mitigation options

MIGRATE WP5
WP5 – OBJECTIVES AND STRUCTURE

WP5 – Power quality in transmission networks with high PE penetration

T5.1
• Evaluation of PQ related to PE dominated grid

T5.2
• Developing numerical simulation models of PE devices for PQ studies

T5.3
• Propagation of PQ disturbances through power networks

T5.4
• Evaluation of PQ level in future PE rich power networks

T5.5
• Mitigation options for keeping PQ levels within affordable levels

Partners: UNIMAN, TUB, UL, EIMV, TalTech, ELES, TenneT, EIRGRID, SPEN, ELERING

All Publically available: https://www.h2020-migrate.eu/downloads.html
POWER QUALITY PHENOMENA RELATED TO PE DEVICES

- Voltage dips and Temporary Over-Voltage
- Harmonic distortion (PE harmonic injections, device susceptibility to voltage harmonics, grid resonance, poor controllers performance causing excessive harmonic distortion)
- Supraharmonics
- Flicker and voltage fluctuation
- Harmonic resonance
- Voltage Unbalance
- Voltage variation
- Frequency variation
- Frequency fluctuations

Main focus of WP5
FIRST STEP OF PQ RESEARCH - PE DEVICE EMT MODELS

Models developed for:

+ High voltage direct current system (HVDC),
+ Static compensator (STATCOM),
+ Static-var compensator (SVC),
+ Wind-turbine generators (WTG type 3 and 4),
+ Solar photovoltaics (PV) and
+ Battery storages (BS).

– For each device, three types of models with different levels of detail and complexity have been developed: the electromagnetic transient (EMT) model, the average RMS model and the harmonic load-flow model (frequency domain).
A representative topology for each PE device (amongst a wide variety of different topologies and implementations currently available) has been selected. This approach has been adopted in order to provide a generic, yet representative, model and more importantly, to propose a methodology for EMT modelling of PE devices for PQ studies.

Harmonic loadflow models developed by “scanning” the EMT models in various operating points.
PROPAGATION OF PQ DISTURBANCES IN THE GRID

TYPE: Frequency variations
Harmonic distortion

DEVICE MODEL: Average RMS model
Harmonic Load Flow model

TESTING NETWORK:
MERRA wind data
Irish grid
IEEE 68 bus network

METHOD:
10 minutes simulation with wind data in DlgSILENT PowerFactory
Harmonic load flow based on probabilistic simulation of harmonic emissions

Varying SNSP from 60% to 90%
POWER QUALITY PHENOMENA RELATED TO PE DEVICES

- Voltage dips and Temporary Over-Voltage
- Harmonic distortion (PE harmonic injections, device susceptibility to voltage harmonics, grid resonance, poor controllers performance causing excessive harmonic distortion)
- Supraharmonics
- Flicker and voltage fluctuation
- Harmonic resonance
- Voltage Unbalance
- Voltage variation
- Frequency variation
- Frequency fluctuations

Main focus of WP5
FREQUENCY VARIATIONS – MODIFIED IRISH GRID

Frequency:

Balancing power of synchronous generators:

Voltage:
**FREQUENCY VARIATIONS RESEARCH**

- Fourier analysis of frequency variations due to intermittent supply of wind farms indicates that the main impact is on primary regulation, not inertia of the system.
- Primary regulation balancing energy almost doubles going from 60% to 90% SNSP.
- Voltage variations minimum due to voltage control functionality in PE converters.

---

**Diagram:**

- **Primary regulation**
  - Fourier analysis of system frequency deviation
  - SNSP increase
  - System inertia
  - Region A
  - Region B

**Graph:**

- **$|\Delta f_{sys}|$ [Hz]**
- $f_{FFT}$ [Hz]
- **$E/S$ [Ws/MVA]**

- **Reference Case**
- **Case 3**
- **Case 3.2**

- **60 % SNSP**
- **90 % SNSP**

**Primary regulation balancing energy needed:**

- 149 % increase
- 194 % increase
FREQUENCY VARIATIONS MITIGATION

- Frequency supportive power signal modifier
- Power losses are taken into account
FREQUENCY VARIATIONS MITIGATION

• The frequency standard deviation is reduced from 46 mHz to 21 mHz
• The Fourier transform confirms that the frequency oscillation was damped significantly
POWER QUALITY PHENOMENA RELATED TO PE DEVICES

- Voltage dips and Temporary Over-Voltage
- Harmonic distortion (PE harmonic injections, device susceptibility to voltage harmonics, grid resonance, poor controllers performance causing excessive harmonic distortion)
- Supraharmonics
- Flicker and voltage fluctuation
- Harmonic resonance
- Voltage Unbalance
- Voltage variation
- Frequency variation
- Frequency fluctuations

Main focus of WP5
HARMONICS DISTORTION: MODIFIED IRISH GRID

- Approximately three time increase of average THD from 60% to 90% PE.
- 110 kV is affected the most – in 90% PE, almost 5% of busses exceeds 3% 95th THD
- Load (non)linearity has great impact on harmonics – for the case of 70% SNSP, increasing the share for non-linear load of distribution networks from 20% to 50% leads to doubling the average THD.

Cases: Ref., 1,2,3 -> 60%, 70%, 80%, 90% SNSP
95th percentile of voltage THD 60% - 90% SNSP

Available for download: https://odinpq.eimv.si
95th percentile of voltage harmonics (5th, 7th, 11th, 13th) 60% - 90% SNSP

Available for download: https://odinpq.eimv.si
HARMONIC DISTORTION MITIGATION

- Optimisation based approach – technical and economical assessment
- Mitigation options: Passive filters or lowering emissions at PE devices

Harmonic Gap Index (HGI) – zonal approach

\[
HGI = \sum_{i=1}^{N} \left( \sum_{j=1}^{B_i} |THD_{i,j} - THD_{TH,i}|_{BPI_{i,j} > BPI_{TH,i}} \right)
\]
HARMONIC DISTORTION MITIGATION

- Identify harmonic phenomena – how?
- Probabilistic approach: clustering of 8760 OP and 20 RES generation profiles into 18 classes
- K-means clustering approach
- Instead of 8760 load flows, 18 load flows are performed
- Below is an example on how one cluster can represent 119 operating points
HARMONIC DISTORTION MITIGATION

- Pool of potential solutions:
  - Option one: passive filters of various sizes & tuning frequency
  - Option two: PE device mitigation – lowering harmonic emissions up to 50%
- Search for optimal based solution: greedy algorithm

\[ X = U; \quad \Gamma = \Phi; \]

1. Install covered solutions \( \Gamma \);
2. Update \( X \) by reselect rating randomly within its associated interval
3. Select \( s \in X \) that minimizes objective function \( F \);
4. \( X = X - \{ \text{all elements in } X \text{ which have the same location and type of solutions as } s \}; \quad \Gamma = \Gamma \cup \{s\}; \)
5. Reach stop criteria?
   - Yes: End
   - No: Install covered solutions \( \Gamma \);

\[ X = U; \quad \Gamma = \Phi; \]
HARMONIC DISTORTION MITIGATION - RESULTS

- Optimisation based probabilistic approach
- Tested on IEEE 68 bus network
- Zonal and global approach evaluated
HARMONIC DISTORTION MITIGATION - RESULTS

- Optimisation based probabilistic approach
- Tested on IEEE 68 bus network
- Zonal and global approach evaluated
HARMONIC DISTORTION MITIGATION - RESULTS

- Economical assessment added into research – new objective function $F$
- Cost of mitigation
- Cost of higher harmonic distortion
- Global harmonic gap index GHGI expressed in a financial matter
- 40 year period evaluated

\[
F = C_m - C_b + \beta \times GHGI
\]

\[
C_m = C_{ICI} + \sum_{t=0}^{n} \left( C_{AnnOpemai}^t \times (1+e)^t \right) \left( \frac{1}{(1+r)(1+i)} \right)^t
\]

\[
C_b = \sum_{t=0}^{n} \left( C_{PQ}^{1t} - C_{PQ}^{2t} \right) \times (1+e)^t \left( \frac{1}{(1+r)(1+i)} \right)^t
\]
HARMONIC DISTORTION MITIGATION - RESULTS

- Economical assessment added into research – new objective function $F$
- Cost of mitigation
- Cost of higher harmonic distortion
- Global harmonic gap index GHGI expressed in a financial matter
- 40 year period evaluated

![Graph showing THD with and without mitigation](image-url)
MIGRATE WP5 RECOMMENDATIONS

– We propose to use probabilistic approach to harmonics mitigation since taking into account the uncertainty of harmonic emission as well as future scenarios enables more future-proof solutions. The operating point clustering can significantly decrease calculation effort and thus enable the optimization algorithm to find an optimum solution for large transmission networks.

– Further research work is recommended to identify in a holistic manner the most robust and cost-effective global harmonic mitigation approach for transmission systems. This should take into account a wide set of scenarios including ancillary aspects such as regulatory, cost recovery mechanisms, risk assessment, responsibility/accountability for data accuracy, as well as additional system impacts associated with multiple filter deployment. For robust results of such research a careful identification and full engagement of stakeholders will be required.

– We propose the use of new wind turbines control algorithm, which significantly reduces the frequency variations, is easy to implement in (existing) wind turbines and only minimally reduces total energy output.

– We propose to create new or modify the existing balancing service, focusing on frequency variations mitigation using wind turbines in order to significantly reduce the stress on existing primary and secondary regulation sources by greatly reducing the frequency variations.

– It is recommended to develop a common power quality legislation between neighbouring countries/systems. This will enable balanced allocation of power quality headroom for all customers, minimize possible future costs related to power quality mitigation and guarantee optimal system development.
THANK YOU FOR YOUR ATTENTION!
THE IMPACT OF MIGRATE
A CONCLUSION ON THE MAIN RESULTS

December 4th 2019, Brussels

Clémentine COUJARD
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WHAT IS THE PROJECT’S ADDED-VALUE IN BRIEF?

*MIGRATE* developed solutions to increase the share of power electronics into the grid from around 30% in 2016 to a potential 90% and proposed new concepts to enable a 100% RES network.
WHAT IS THE PROJECT’S ADDED-VALUE IN BRIEF?

- Improved grid following controls
- Mix of grid following and grid forming controls
- Extended stability boundaries

**Power Electronics Penetration level**

- 2016 level
- 30%
- 65%
- 90%
- 100%

**Control Design framework conditions**

**New Grid Forming controls**
WHAT IS THE PROJECT’S ADDED-VALUE IN BRIEF?

- **Improved grid following controls**
- **New grid forming controls**
- **New power quality mitigation measures**
- **New protection algorithms**
- **Real-time monitoring & forecasting of KPIs**
- **Wide-Area-Controls**
- **Extended stability boundaries**

**Power Electronics Penetration level**

- **30%**
- **65%**
- **70%**
- **90%**
- **100%**

**Control Design framework conditions**

**New Grid Forming controls**
**MIGRATE results**

- Identification & ranking of stability issues under high PE penetration
- Methods & tools to assess power system stability under high PE
- Mitigation measures using existing controls to reach 65-70% PE penetration
- Mitigation measures combing grid-forming and existing grid-following controls to reach 90% PE
- Assessment and mitigation of certain controllers’ interactions

*Examples of Results take* up

**Grid forming ability of converters included in specifications of two major onshore HVDC transmission projects**

*HPoPEIPS Implementation guidelines doc 2017*
*High Penetration Technical Group Report, due Dec. 2019*
MIGRATE results

Identification & ranking of stability issues under high PE penetration

Methods & tools to assess power system stability under high PE

Mitigation measures using existing controls to reach 65-70% PE penetration

Mitigation measures combining grid-forming and existing grid-following controls to reach 90% PE penetration

Assessment and mitigation of certain controllers’ interactions

Recommendations For implementation

Clarify specific requirements in grid codes for national implementations

Consider requirements for grid forming control in the specification of future PE projects

Analyse further how applying KPI techniques in grid planning and operation can facilitate massive PE integration

Next R&D required

Complete knowledge on individual PE-interfaced generators with a grid perspective (interactions & best coordination of PE-interfaced components)

Further explore options to monitor PE penetration using real-time online measurements

More detailed modeling of power systems and PE units to analyse SSCI and PQ issues in future high PE systems
MONITORING & CONTROL

MIGRATE results

Local dimension of inertia and related low-inertia mitigation measures

Tools for monitoring and forecast of KPIs: effective area inertia, short circuit capacity, network strength

World-first full scale demonstration of WAMPAC in Icelandic grid

Examples of Results take

Pilot WAMPAC operational, + 3 other schemes under development; planned project to built related ancillary services

Coordinated investment in PMUs with NG and SSE, plans to deploy MIGRATE approach in a coordinated programme 2021-2026

Project to adapt and deploy WP2 inertia monitoring approach
**MONITORING & CONTROL**

**MIGRATE results**

- Local dimension of inertia and related low-inertia mitigation measures
- Tools for monitoring and forecast of KPIs: effective area inertia, short circuit capacity, network strength
- World-first full scale demonstration of WAMPAC in Icelandic grid

**Recommendations For implementation**

- Systematize the use of PMU data
- Design FFR schemes with locational responses
- Disseminate more evidence of WAMPAC benefits
- Treat System strength and short circuit capacity as two distinct issues
- Standardize practices in network architectures, communication and data collection for synchronized measurements

**Next R&D required**

- Develop adaptive control of power electronic converters for varying levels of system strength.
- Design and pilot test to optimize WACS communication architecture, minimize latency and increase robustness and backup-control
100% PE GRID

MIGRATE results

- Feasibility of a stable 100% PE grid
- Interoperable grid-forming controls
- Min. 30% share of grid-forming required in a 100% PE grid
- Current limitation strategy to protect converters from over-currents
- Optimal location of grid-forming controls for new ancillary services
- Economic feasibility of grid-forming approach

Examples of Results take

**Inclusion of 100% PE grid concepts and controls to the Northsea Windpower Hub project development**

**Design system services aimed to enhancing the system resilience to cope with very high levels of PE converters**

**Demo: 1 MVA grid forming inverter with hybrid DC storage connected to RTE’s Grid in summer 2020**

**Grid Forming permanent working group further to “low inertia grid workshop” at Washington University**
### MIGRATE results

- Feasibility of a stable 100% PE grid
- Interoperable grid-forming controls
- Min. 30% share of grid-forming required in a 100% PE grid
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### Recommendations For implementation

- Prefer “technology agnostic” requirements for grid forming (i.e. Also applicable to synchronous condensers / loads / generation)
- Include grid forming requirements in grid codes, with limited constraints at first in order to foster manufacturers developments
- Perform cost/benefit analysis of grid forming controls at RES plants vs at TSO substations

### Next R&D required

- Optimal location and sizing of grid forming capabilities on very large transmission system
- Regulation of synchronous generators in systems dominated by Grid-forming inverters dynamics
- Testing methods to validate GF capabilities of voltage sources

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**100% PE GRID**

**MIGRATE**
New protection algorithms for high PE penetration scenarios

Assessment of PE impact on protections

Assessment of protections’ impact on PE

Schneider Electrics is currently testing the industrial feasibility of the developed algorithms, for integration into their commercial offer.
**PROTECTIONS**

**MIGRATE results**
- Assessment of PE impact on protections
- Assessment of protections’ impact on PE
- New protection algorithms for high PE penetration scenarios

**Recommendations For implementation**
- Clearly define, and possibly harmonise at EU level the requirements for PE behavior during balanced and unbalanced faults
- Assess new protection technologies’ applicability to specific power systems
- Review and upgrade protection study tools to fully integrate power electronics expertise

**Next R&D required**
- Assess impact of grid forming controls on protection schemes
- Assess impact of PE based generator in distribution systems
- Tools and models for further protection studies with high PE penetration scenarios
POWER QUALITY

MIGRATE results

- Harmonics propagation assessment, visualisation and mitigation
- Evaluation of PQ mitigation measures
- Wind turbine control algorithm to reduce frequency variation

Integration of Visualisation tool in control center

Use of Visualisation tool in planning stages of new customer connections

Harmonics studies as a prerequisite to planned STATCOM installation

Development of national legal requirements on PQ, Use of models and tools for PQ studies
**POWER QUALITY**

**MIGRATE results**

- Harmonics propagation assessment, visualisation and mitigation
- Evaluation of PQ mitigation measures
- Wind turbine control algorithm to reduce frequency variation

**Recommendations For implementation**

- Systematise *probabilistic* approach to harmonics mitigation for more future-proof solutions
- Create ENTSO-E or CIGRE working group to PQ management
- Agree on unified approaches to determine system planning and customer compliance levels
- Include power quality requirements in Grid Codes
- Include in legislative documents procedures to define limits for different PQ phenomena; and monitoring & compliance

**Next R&D required**

- Design and assessment of enhanced FACTS devices to support power quality
- Definition of *unified* harmonic distortion limits for EU transmission grid
- Assessment of harmonic distortion sources and propagation paths *at pan European scale*
- Investigate new balancing services, focusing on mitigating the intermittent nature of RES

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CONCLUSIONS

- A consolidated, collective vision of MIGRATE contribution to the challenges of massive RES integration
- Soon to be released in a synthetic public document (January 2020)
- Will help shape a possible MIGRATE 2?
QUESTIONS?

Clémence COUJARD
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COFFEE BREAK UNTIL 16:00 H
DISCUSSION WITH THE AUDIENCE

Prof. Lothar Fickert,
TU Graz, Austria
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