PHIL CAPABILITIES AND EXPERIENCE AT THE POWER NETWORKS DEMONSTRATION CENTRE
Presentation Overview

1. Triphase Platform Development Project
2. PV Inverter Response During Transients and Disturbances Project
3. Q&A
PNDC – Unique Testing Capabilities

**Power Supplies**

- **On Grid**: 11kV 2 x 1MVA connections
- **11/11kV 1MVA Isolation Transformer**
- **TriPhase Convertor**: 500KVA ±0-1300V DC
- **Off Grid**: 1MVA Gen Set

**HV Network (11kV)**

- 3 x underground feeders for a total equivalent length of 6km.
- 11kV/400V transformers from 1.2 MVA to 25kVA
- 1 x overhead feeder for a total equivalent length of 60km
- Pole mounted auto reclosers
- Series voltage regulator

**LV Network**

- HV Fed from HV Network
- Mock impedances ~ 0.6 km
- Load banks total ~ 600 kVA
- Indoor and outdoor test connection points

**Power Hardware In the Loop**

- Hardware in the Loop Simulation with 6 x racks of RTDS hardware
- Optical interface provides 2 way interaction with both Gen Set and TriPhase Convertors.
- 3-50μs simulation time-step ... up to 360 x 3 phase busses
- Accurate frequency response up 3kHz

**Fault Throwing**

- High Voltage Fault Throwing Phase to Phase, Phase to Ground, Multiple Injection Points
- Low Voltage Fault Throwing Unit, Flexible Connection

**Industry Standard DMS / SCADA / Historian**

- PowerOn Fusion monitoring control and switching management
- OSISoft PI Historian connected to SCADA and Fast Data Acquisition System

- *Mock impedances ~ 0.6 km*
- *Load banks total ~ 600 kVA*
- *Indoor and outdoor test connection points*
Overview Triphase: Programmable Power Converter

- 6xPM90 modules = 540kVA installed capacity
- Open Simulink model control of power converters
- Fibre optic link to RTDS
- Modular expansion capability
Overview Triphase: Key Components

PM90
- Power Electronics
- Inductors
- Capacitors
- Measurement
- Fuse Protection
- Busbars

Front cabinet
- Target PC 1
- Target PC 2
- Circuit Breakers
- Anti-condensation heater thermostat control
- Triphase output: Powersafe panel mounted source type connectors
- Triphase output: Link between right and left
Overview Network upgrade

- 1 MVA three phase
- 2 secondary winding transformer

New Genie Evo Switchgear

- Triplex cable
- 11kV
- 433V
- HV Earth
- LV Earth 1
- LV Earth 2

- 433 supply 1
- 433 supply 2

- 2x120mm 4 core

Triphase
Overview Triphase: Operation Modes

DC current and voltage source operation
±650V, ±390A, ±270kW

DC voltage source operation (1)
±650V, ±780A, ±540kW

DC voltage source operation (2)
50-1300V, ±600A, ±540kW

3-wire AC current and voltage source operation (1)
0-480V_{RMS}, 0-390A_{RMS}, ±270kW

3-wire AC voltage source operation (2)
0-480V_{RMS}, 0-780A_{RMS}, ±540kW

2x 3-wire AC voltage source operation
2x 0-480V_{RMS}, 0-390A_{RMS}, ±270kW
Overview Triphase Interface: RTDS, Simulink & GUI

- **RTDS**
- **Simulink**
- **GUI**

LC multi-mode communication fibre
Grid Simulator Testing: Triphase Platform

**PNDC Network Development**

- **PNDC Power Supply**
- **Triphase**
- **Device under test**

**RTDS control and measurement logging**

Modelled power system

Digital link

DC or AC

PHIL Testing
Demonstration Project

RTDS control and measurement logging
Modelled Shipboard power system

Triphase (Voltage Source)

Device under test

AC pulse load

1 2 3 4
Overview Triphase: Applications

- Shipboard power system PHIL platform
- Grid-integration of renewables for industrial scale PV
- Energy storage based interface
- Smart Programmable load and source to validate aircraft equipment
- Battery test emulation system
- Testing of battery system for grid stabilizing
- Testing of multiple PV inverters connected to common DC bus (PNDC planned project)
Dynamic Power Systems Laboratory

- **RTDS (Real Time Station)**
- **Campus Supply**
  - 433V
- **Cell 1**
  - 90 kVA Triphase
  - 40 kW (256 steps)
  - 30 kVAR (256 steps)
  - Static load bank
- **Cell 2**
  - 15 kVA Triphase
  - 10 kW (64 steps)
  - 7.5 kVAR (64 steps)
  - Static load bank
  - 2.2 kW & 5.5kW Induction machines (motors or generators)
- **Cell 3**
  - 2 kVA Synchronous
  - 10 kVA 3-phase inverter
  - 10 kW (64 steps)
  - 7.5 kVAR (64 steps)
  - Static load bank
  - Spare for visiting projects
  - 2x 7.5kW Induction machines (motors or generators)

**Microgrid management algorithm** (example of graphical display in real time)
CHARACTERISING LV PV INVERTER RESPONSE DURING FAULT TRANSIENTS AND VOLTAGE DISTURBANCES
Project Overview and Objectives

• Empirical characterisation of LV connected PV inverters.

• DNOs need to understand the impact on switchgear ratings due to inverter fault contribution.

• Low voltage ride-through implications when considering large inverter penetration.

• Challenge current modelling and fault calculation assumptions.
Inverters under Test

- Off the shelf inverters.
- Vendors most commonly found in the UK.
- G59 or G83 compliant.

<table>
<thead>
<tr>
<th>Inverter model</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABB PVI-5000-TL-OUTD</td>
<td>5.56 kVA (single-phase)</td>
</tr>
<tr>
<td>SMA Sunny Boy 5000TL</td>
<td>5 kVA (single-phase)</td>
</tr>
<tr>
<td>KACO Powador 6002</td>
<td>5 kVA (single-phase)</td>
</tr>
<tr>
<td>SMA Tripower 10000TL</td>
<td>10 kVA (three-phase)</td>
</tr>
</tbody>
</table>
Test Network Configuration

- Fault test configuration
  - LV short circuit (solid or resistive).
  - Aims to control retained voltage at the inverter output.
  - 0° and 90° point on wave (PoW) fault inception.

- Voltage depression test configuration:
  - MG set controls the network voltage following an RTDS generated profile.
  - Rate and depth of voltage depression is limited by the exciter controls.
# Applied Tests

<table>
<thead>
<tr>
<th>Fault type</th>
<th>Fault resistance (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-E (A phase to earth)</td>
<td>1.5, 0.75, 0.375, 0.1875, 0</td>
</tr>
<tr>
<td>P-P (A-B phase)</td>
<td>1.5, 0.75, 0.375, 0.1875, 0</td>
</tr>
<tr>
<td>P-P-P (three-phases)</td>
<td>1.5, 0.75, 0.375, 0</td>
</tr>
</tbody>
</table>

### Voltage depression

<table>
<thead>
<tr>
<th>Inverter</th>
<th>Pre-event loading (percentage of inverter kW rating)</th>
<th>Fault approximate PoW inception</th>
<th>Event duration (based on RTDS control profile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABB</td>
<td>100%</td>
<td>0°, 90°</td>
<td>0.3s, 5s</td>
</tr>
<tr>
<td>KACO</td>
<td>80%</td>
<td>0°, 90°</td>
<td>0.3s, 5s</td>
</tr>
<tr>
<td>SMA (1ph)</td>
<td>100%</td>
<td>0°, 90°</td>
<td>0.3s, 5s</td>
</tr>
<tr>
<td>SMA (3ph)</td>
<td>30%</td>
<td>0°, 90°</td>
<td>0.3s, 5s</td>
</tr>
</tbody>
</table>
Example Single Phase Inverter Fault Response

- ABB 5kW single phase inverter.
- 0.5pu pre-fault loading, 0Ω earth fault, 0° PoW.
- Current output stops after a few cycles.
Example Three Phase Inverter Fault Response

- SMA 10kW three phase inverter.
- 0.3pu pre-fault loading, 1.5Ω earth fault, 0° PoW.
- Inverter increases current output in a healthy phase to maintain pre-fault power output.
Changes in Reactive Power Output

- KACO 5kW single phase inverter.
- 0.5pu pre-fault loading, 0.75Ω earth fault, 0° PoW.
- Current phase angle jumps correspond to changes in reactive power output.
- Sudden reduction in reactive power may be indicative of reaching internal device limits.
Example Fast Voltage Depression Inverter Response

- ABB 5kW single phase inverter.
- 1pu pre-fault loading
- 0.3s commanded voltage depression duration, 93% retained voltage.
- Inverter current dropped by 29%
Example Slow Voltage Depression Inverter Response

- ABB 5kW single phase inverter.
- 1pu pre-fault loading
- 5s commanded voltage depression duration, 87% retained voltage.
- Maximum inverter current drop of 85%
Common Inverter Behaviour

• Variations based on manufacturer implementation, however:

• The inverters are more likely to provide a sustained current contribution during fault conditions with a higher retained voltage.

• The inverters tend to increase their current output in order to maintain the pre-fault active power output level. A more noticeable increase in current output is observed if the inverter is not fully loaded prior to the fault.

• In most cases, where current output is sustained, the inverters attempt to maintain a level of reactive power output that can reach pre-fault levels if the inverter is not fully loaded.

• There is no evidence that the point on wave at which the fault is introduced has an impact on the sustained inverter current output during a fault.
Comparison with Inverter Behaviour Reported in the Literature

- There are many discrepancies between obtained test results and literature results based on modelling – difficult to compare due to limited information about the models.

- Close agreement of test results with reported model behaviour based on manufacturer input (e.g. modelling work by Quanta Technology).

- Most literature reports a fault current contribution of 1.2-2pu of rated current. This is in contrast to the test results, where in the majority of cases the inverters did not exceed rated current output.
• June 12-15\textsuperscript{th}, summarising the main results.

• SPEN co-authors conducted simple simulation to compare the three phase inverter behaviour using PowerFactory.

• When running an EMT simulation, the faulty phase current increased as opposed to the healthy one as tested.

• When running an unbalanced RMS simulation, all three phase currents increase in tandem.
Next Steps

• Characterise the response of multiple inverters connected simultaneously to the grid.

• Testing of larger three phase units with focus on asymmetrical conditions.

• Testing different X/R ratio faults.

• Development and validation of a “parametrisable” inverter model.

• P-HiL testing using Triphase with focus on grid level voltage and frequency disturbances.

• Ultimately feed into UK distribution codes and engineering recommendations.
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- ELECTRA partner

- European organisation
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- ELECTRA partner
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