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PHIL CAPABILITIES AND EXPERIENCE AT THE POWER NETWORKS DEMONSTRATION CENTRE

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Presentation Overview

1. Triphase Platform Development Project
2. PV Inverter Response During Transients and Disturbances Project
3. Q&A

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PNDC – Unique Testing Capabilities

Power Supplies

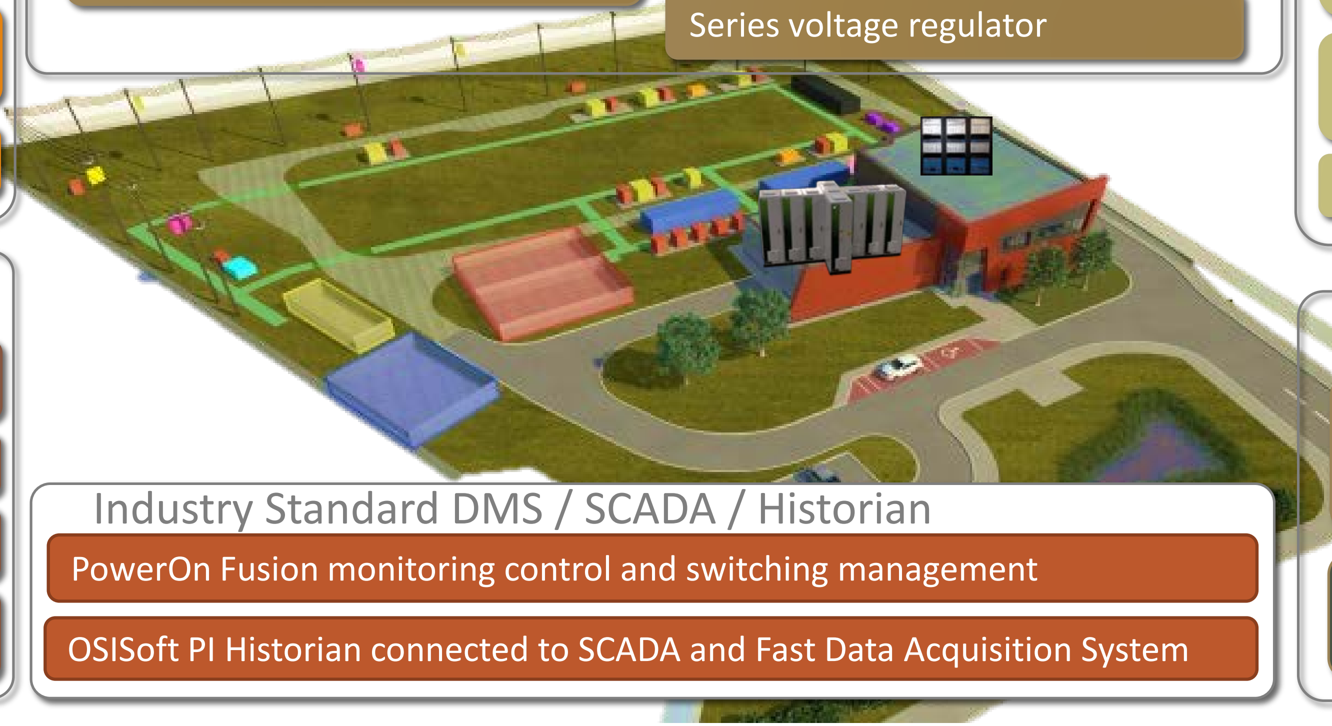
- On Grid : 11kV 2 x 1MVA connections
- 11/11kV 1MVA Isolation Transformer
- TriPhase Convertor: 500KVA ±0-1300V DC
- Off Grid : 1MVA Gen Set

LV Network

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

HV Network (11kV)

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



Industry Standard DMS / SCADA / Historian

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

Power Hardware In the Loop

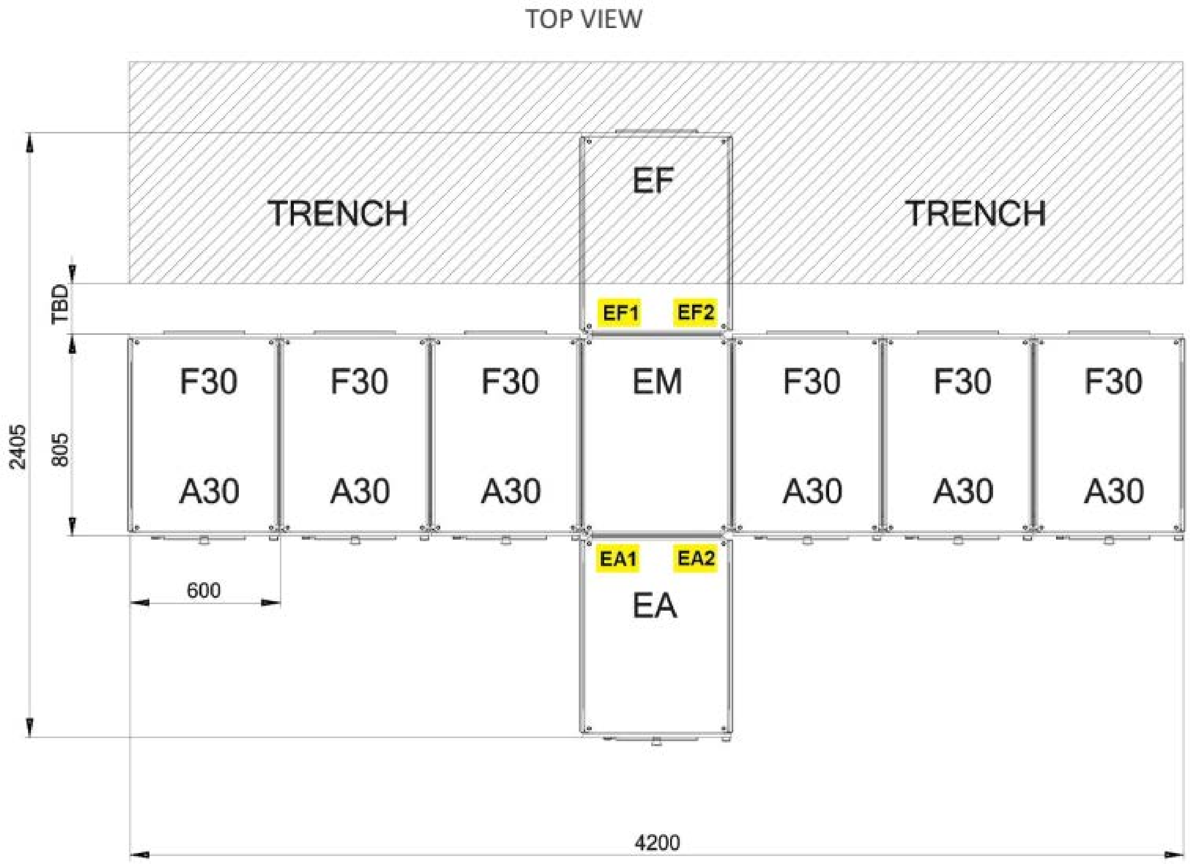
- Hardware in the Loop Simulation with 6 x racks of RTDS hardware
- Optical interface provides 2 way interaction with both Gen Set and TriPhase Convertors.
- 3-50µs simulation time-step … up to 360 x 3 phase busses
- Accurate frequency response up 3kHz

Fault Throwing

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

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

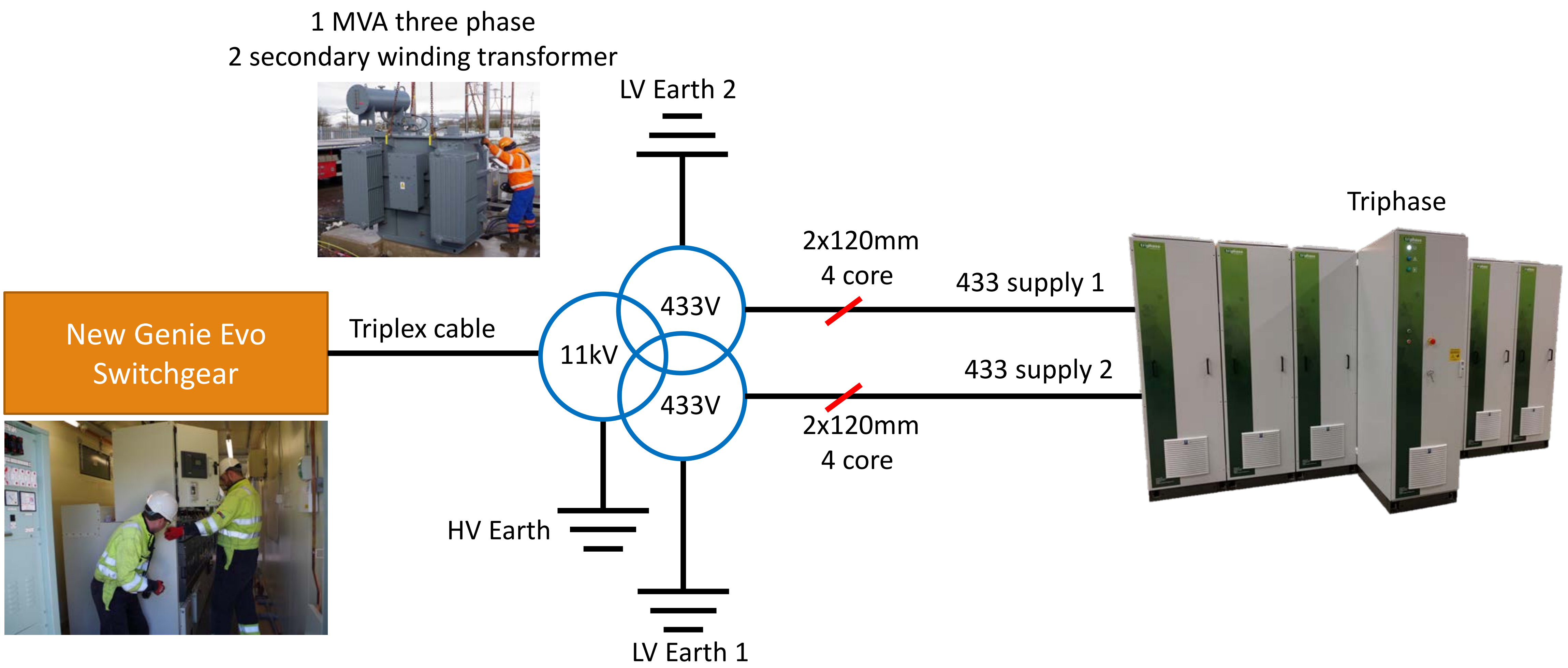
Circuit Breakers

Anti-condensation heater thermostat control

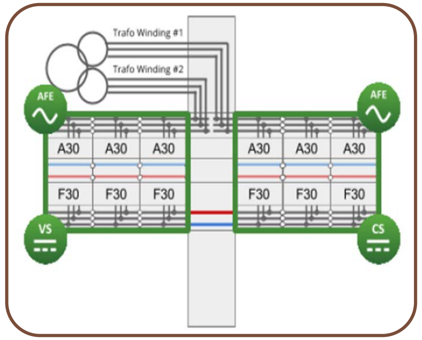
Triphase output: Powersafe panel mounted source type connectors

Triphase output: Link between right and left

Overview Network upgrade

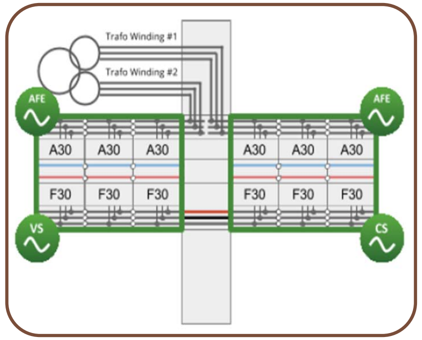


Overview Triphase: Operation Modes



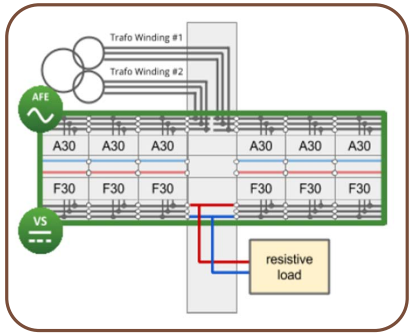
DC current and voltage source operation

±650V, ±390A, ±270kW



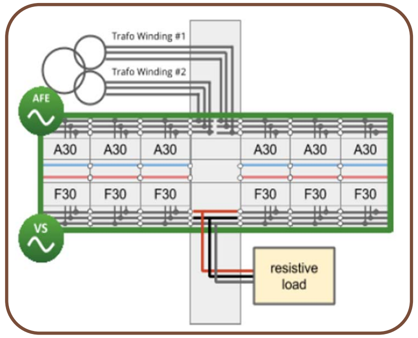
3-wire AC current and voltage source operation (1)

0-480V$_{RMS}$, 0-390A$_{RMS}$, ±270kW



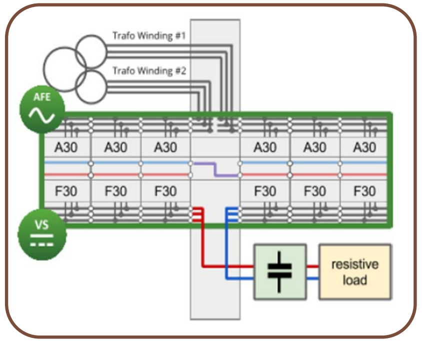
DC voltage source operation (1)

±650V, ±780A, ±540kW



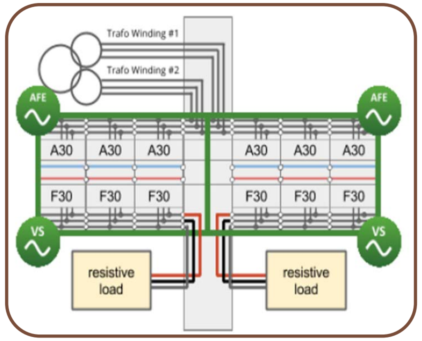
3-wire AC voltage source operation (2)

0-480V$_{RMS}$, 0-780A$_{RMS}$, ±540kW



DC voltage source operation (2)

50-1300V, ±600A, ±540kW

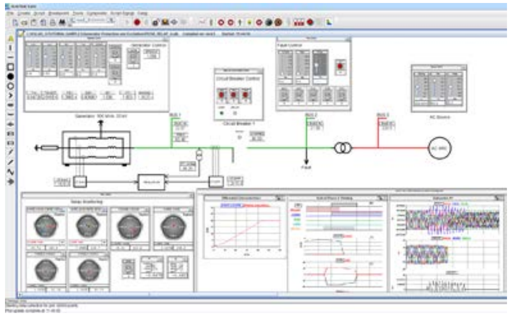


2x 3-wire AC voltage source operation

2x 0-480V$_{RMS}$, 0-390A$_{RMS}$, ±270kW

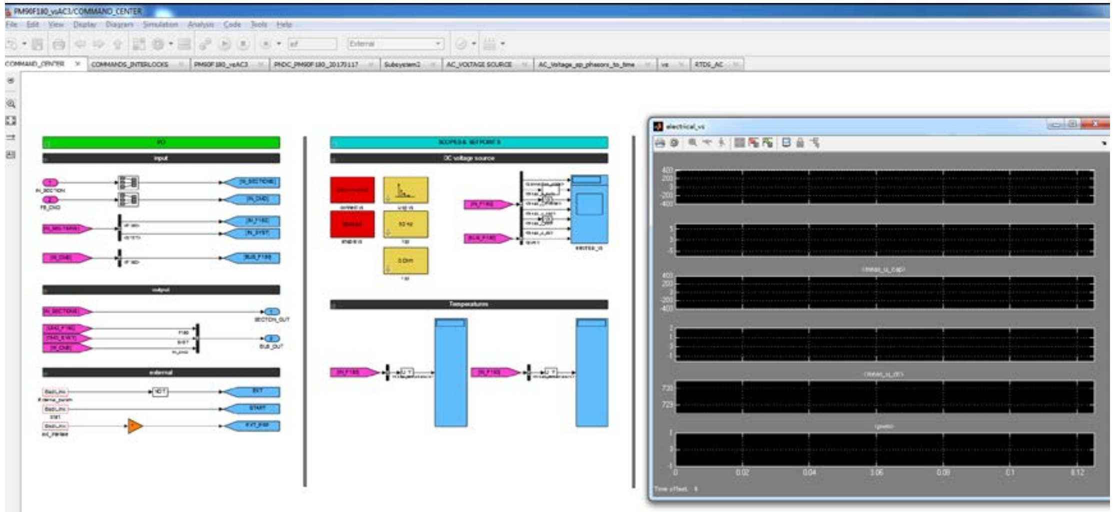
Overview Triphase Interface: RTDS, Simulink & GUI

RTDS



LC multi-mode communication fibre

Simulink



GUI

Grid Simulator Testing: Triphase Platform

PNDC Network Development

PNDC Power Supply

RTDS control and measurement logging
Modelled power system

Digital link

Triphase

DC or AC

Device under test

PHIL Testing

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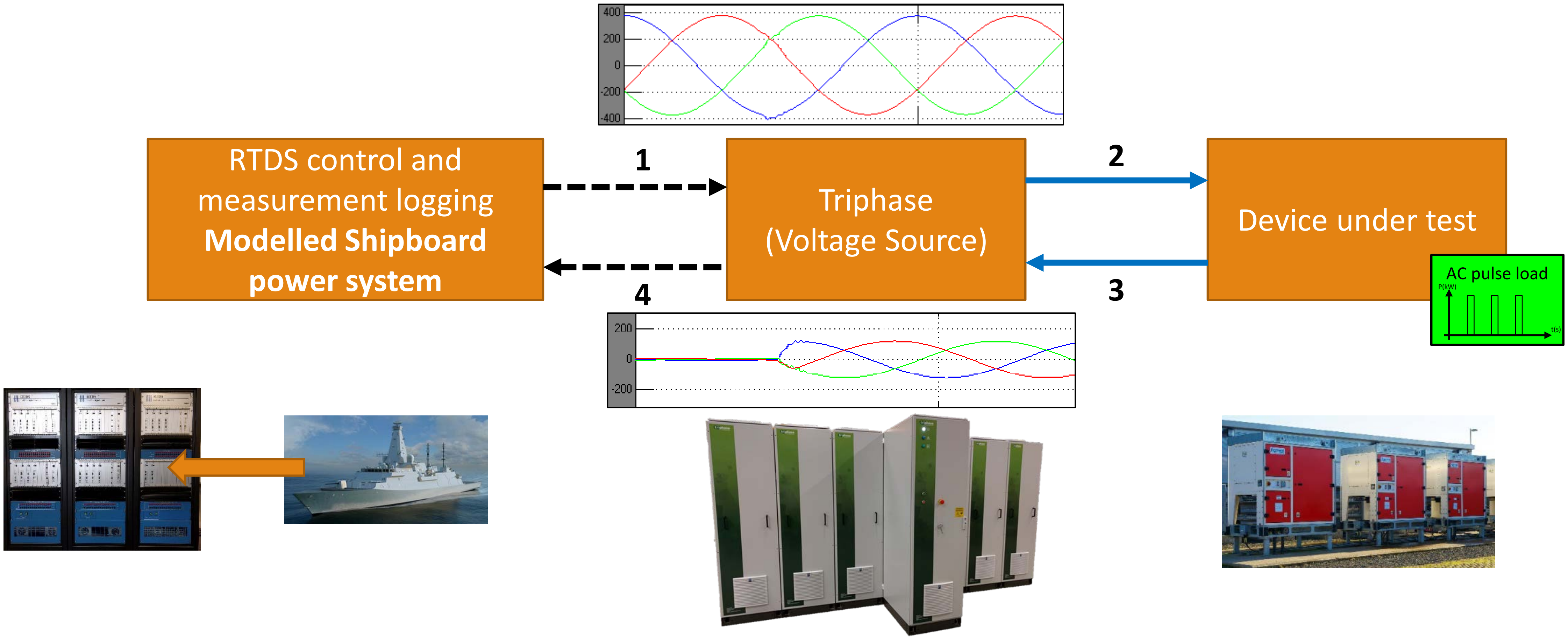
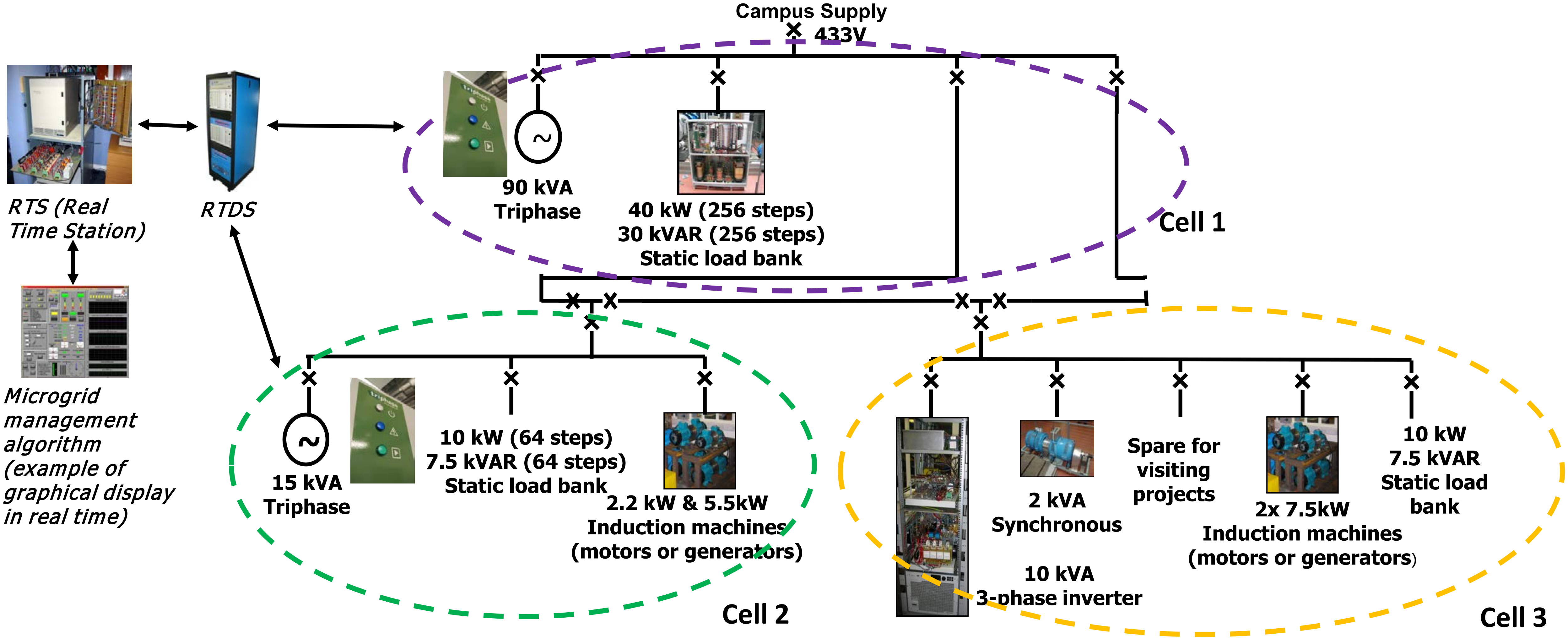
Demonstration Project



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



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CHARACTERISING LV PV INVERTER RESPONSE DURING FAULT TRANSIENTS AND VOLTAGE DISTURBANCES

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Project Overview and Objectives

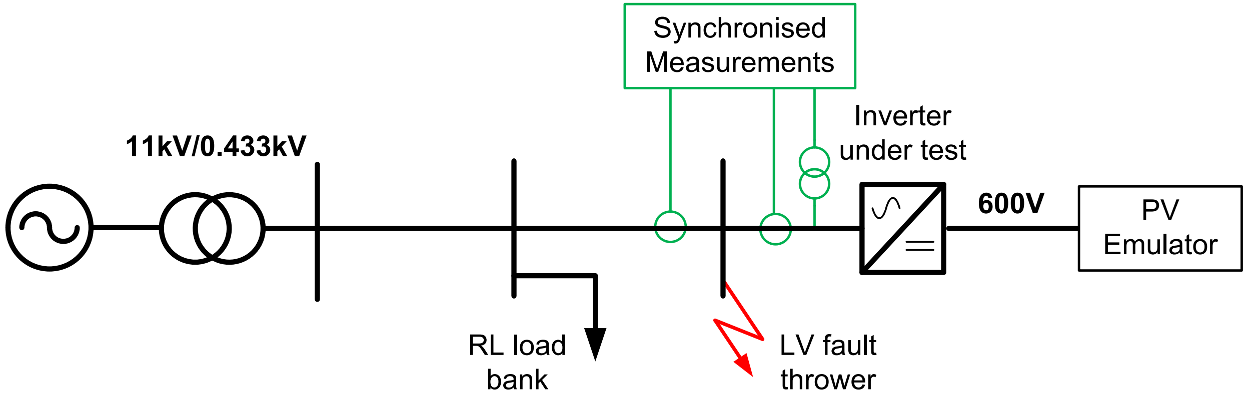
- Empirical characterisation of LV connected PV inverters.
- DNOs need to understand the impact on switchgear ratings due to inverter fault contribution.
- Low voltage ride-through implications when considering large inverter penetration.
- Challenge current modelling and fault calculation assumptions.

Inverters under Test

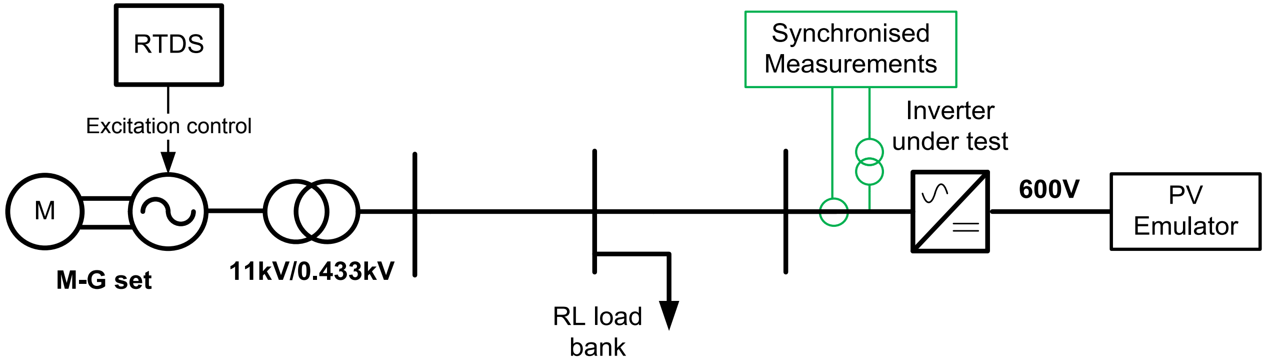
- Off the shelf inverters.
- Vendors most commonly found in the UK.
- G59 or G83 compliant.

Inverter model	Rating
ABB PVI-5000-TL-OUTD	5.56 kVA (single-phase)
SMA Sunny Boy 5000TL	5 kVA (single-phase)
KACO Powador 6002	5 kVA (single-phase)
SMA Tripower 10000TL	10 kVA (three-phase)

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

Faults

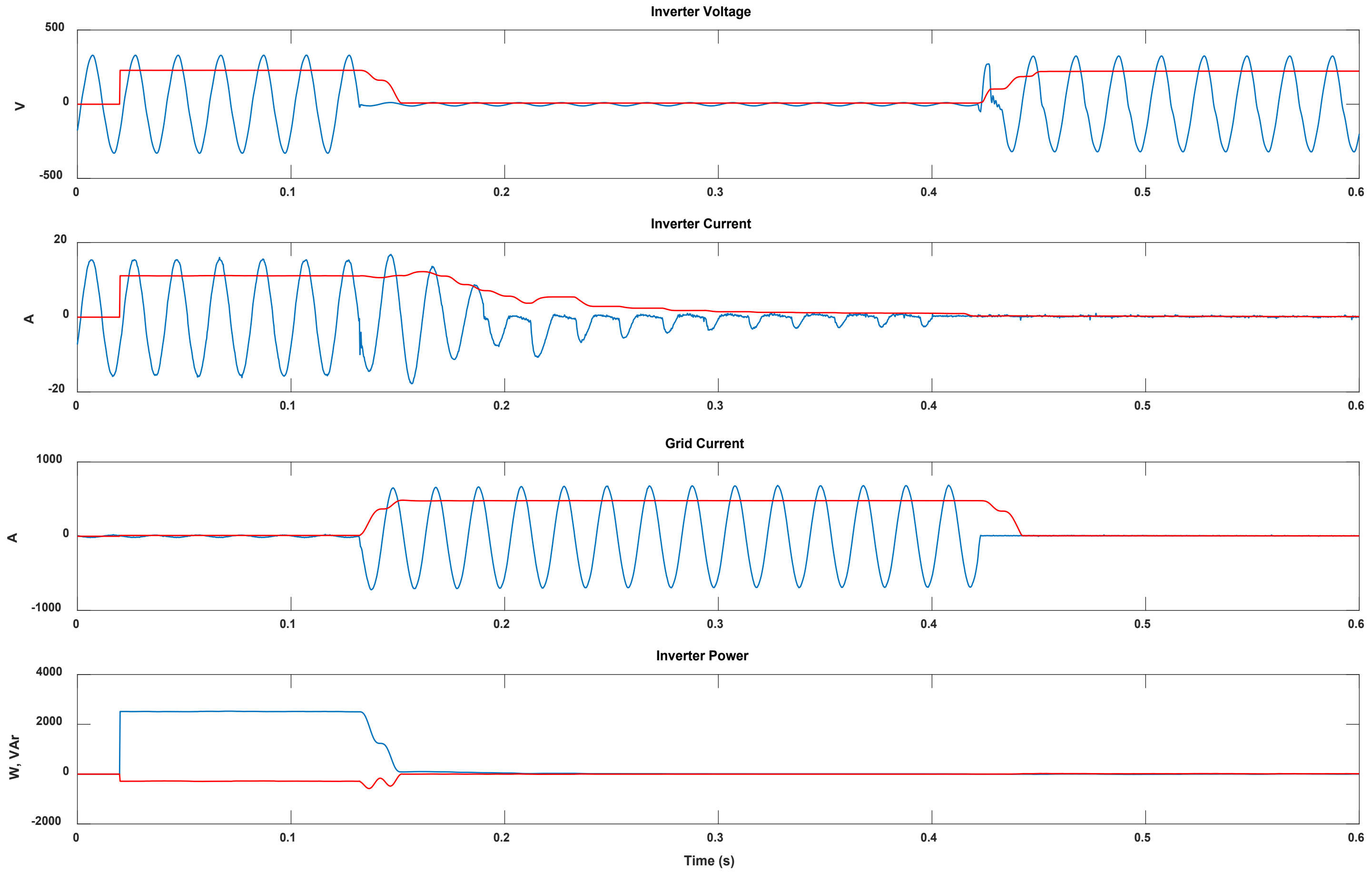
Fault type	Fault resistance (Ω)
P-E (A phase to earth)	1.5, 0.75, 0.375, 0.1875, 0
P-P (A-B phase)	1.5, 0.75, 0.375, 0.1875, 0
P-P-P (three-phases)	1.5, 0.75, 0.375, 0

Inverter	Pre-fault loading (percentage of inverter kW rating)	Fault approximate PoW inception
ABB	50, 100%	0°, 90°
KACO	50, 80%	0°, 90°
SMA (1ph)	50, 100%	0°, 90°
SMA (3ph)	30%	0°, 90°

Voltage depression

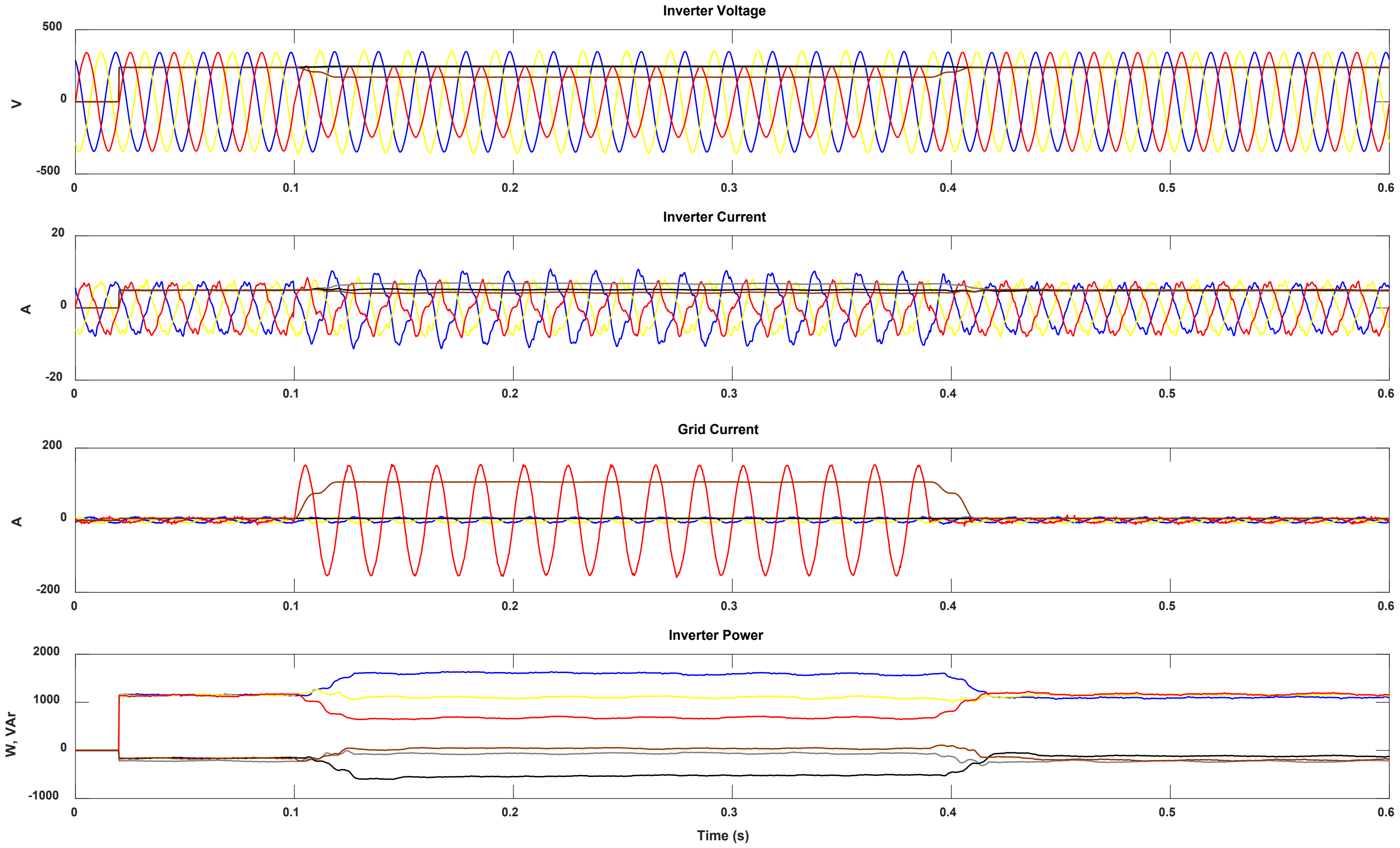
Inverter	Pre-event loading	Event duration (based on RTDS control profile)
ABB	100%	0.3s, 5s
KACO	80%	0.3s, 5s
SMA (1ph)	100%	0.3s, 5s
SMA (3ph)	30%	0.3s, 5s

Example Single Phase Inverter Fault Response



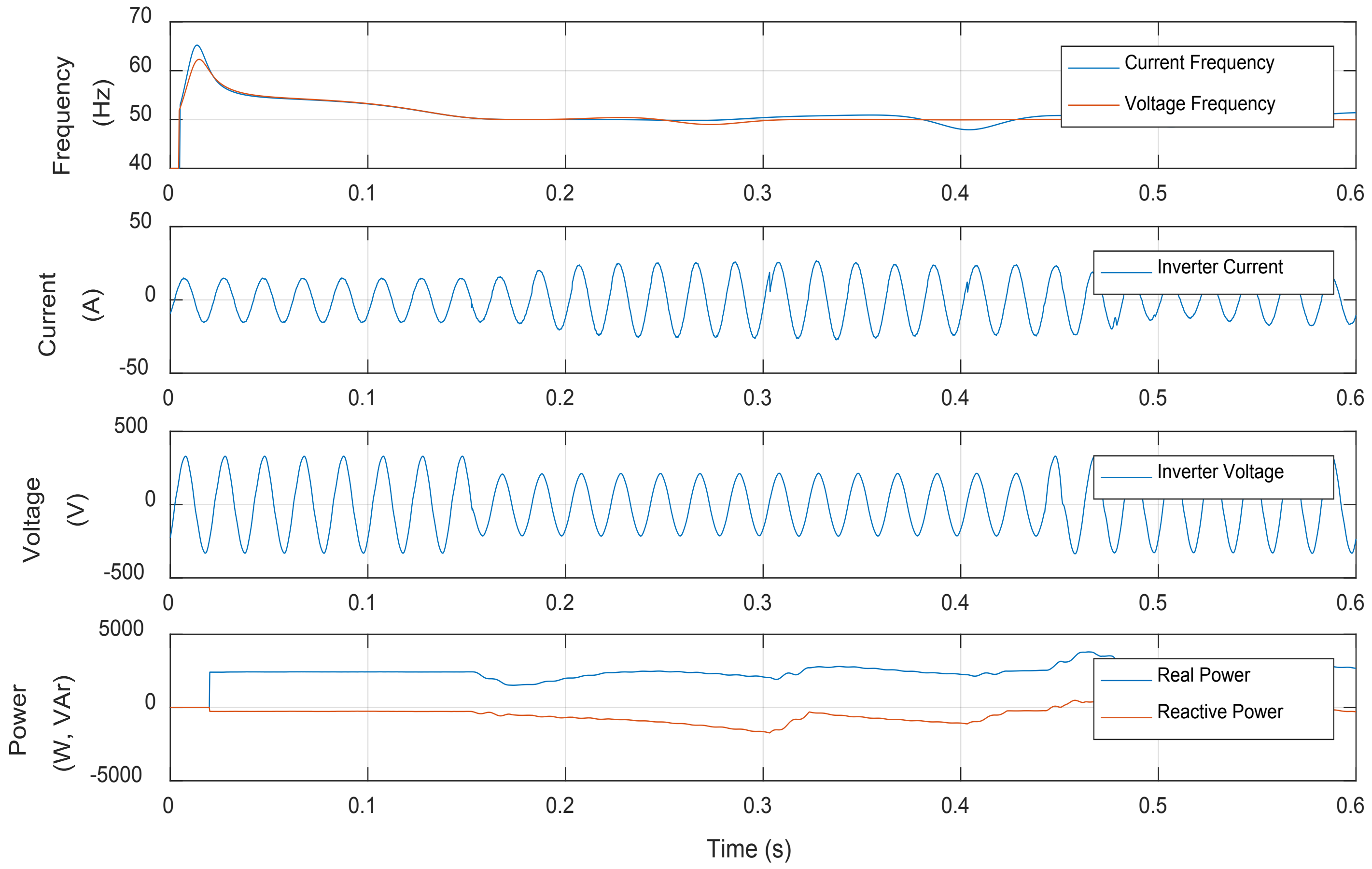
- ABB 5kW single phase inverter.
- 0.5pu pre-fault loading, 0Ω earth fault, 0° PoW.
- Current output stops after a few cycles.

Example Three Phase Inverter Fault Response



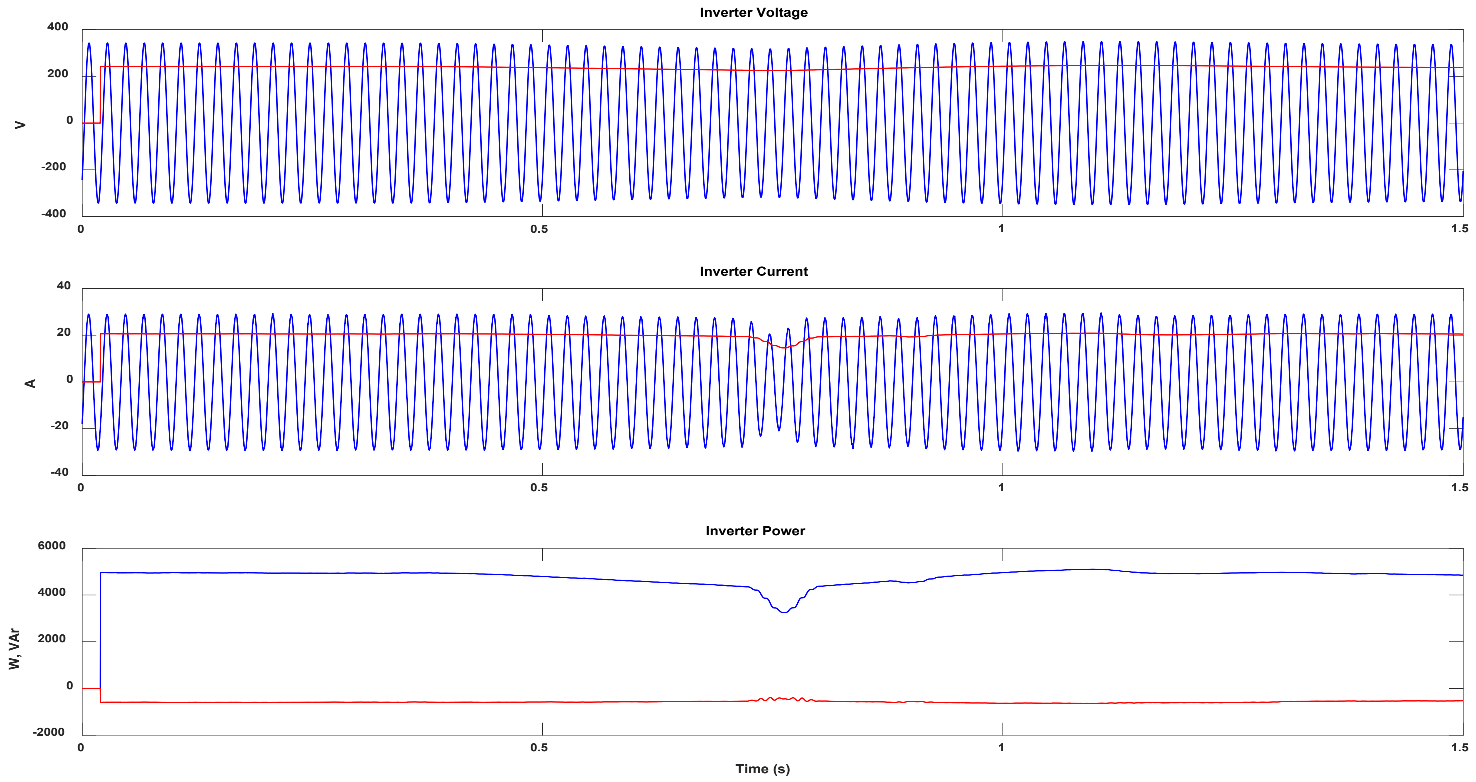
- SMA 10kW three phase inverter.
- 0.3pu pre-fault loading, 1.5Ω earth fault, 0° PoW.
- Inverter increases current output in a healthy phase to maintain pre-fault power output.

Changes in Reactive Power Output



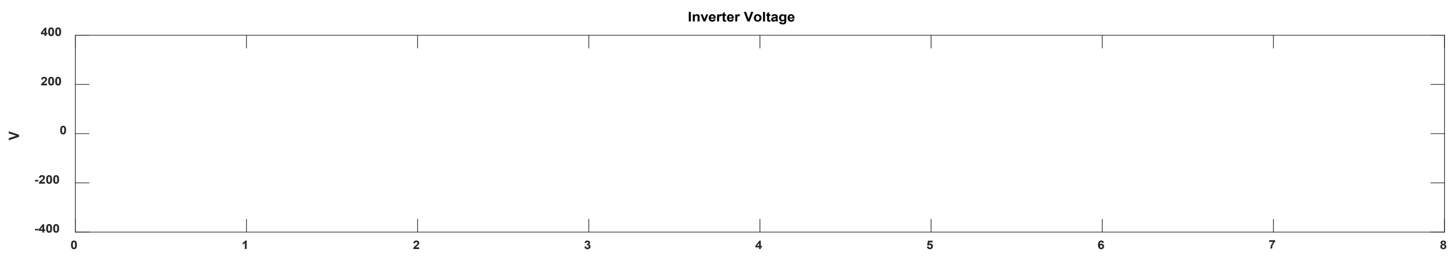
- KACO 5kW single phase inverter.
- 0.5pu pre-fault loading, 0.75Ω earth fault, 0° PoW.
- Current phase angle jumps correspond to changes in reactive power output.
- Sudden reduction in reactive power may be indicative of reaching internal device limits.

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

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- 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.

CIRED 2017 Paper

CIRED 24th International Conference on Electricity Distribution Glasgow, 12-15 June 2017

Paper 0330

HARDWARE BASED CHARACTERISATION OF LV INVERTER FAULT RESPONSE

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ABSTRACT

This paper presents the experimental testing of commercial LV-connected PV inverters to characterise their behaviour during fault conditions. Understanding this behaviour is critical for the proper design and operation of distribution networks with a large amount of inverter-connected generation. Hardware test results for a number of different inverters are discussed and compared. The challenges for modelling, particularly with respect to fault conditions, are discussed with an example simulation.

guidelines for connecting inverter interfaced generating plant connected to the Medium Voltage (MV) network in Germany assume 100% rated current during fault. Where this is expected to be exceeded and would have an impact on the network, an agreement must be reached between the generator and network operator [4]. The Western Electricity Coordinating Council (WECC) provides guidelines and a specification for developing generic dynamic simulation models for transmission connected PV inverters or aggregated distribution connected PV inverters [5, 6].

- June 12-15th, 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.

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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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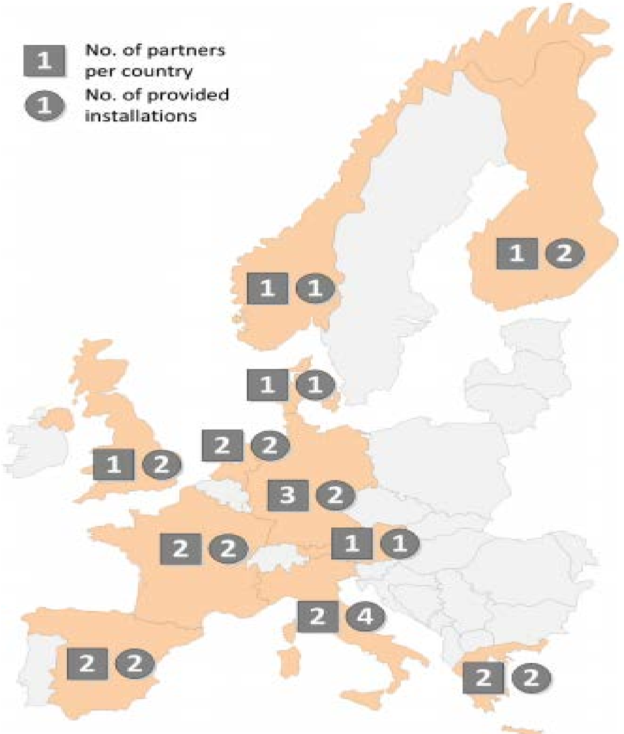

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