Advanced Power Hardware in Loop Test Setup for Evaluation of Utility Applications of Emerging Power Electronic Apparatus

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Agenda

- Introduction
- Industry challenges with new technologies
- SDG&E Integrated Test Facility (ITF)
- Hardware in Loop (HIL) test setups at ITF
- Power HIL inverter test setup versus Traditional testing
- Smart inverter testing
- Dynamic load balancer testing
- Test cases and results
- Summary

Industry Challenges – Emerging Technologies

Renewable Generation	Energy Storage	Microgrids	PMUs
• High penetration issues (PQ, stability and protection) • Smart inverter controls • Fault Current	• Performance evaluation • Control functions • Integration	• Design & Protection • Safety • Control & Operation	• Application evaluations • Communications infrastructure (especially for Distribution)

Modeling, Analysis, Testing, and Diagnostics is required prior to field deployment of a new technology or wide scale utilization

Integrated Test Facility (ITF)

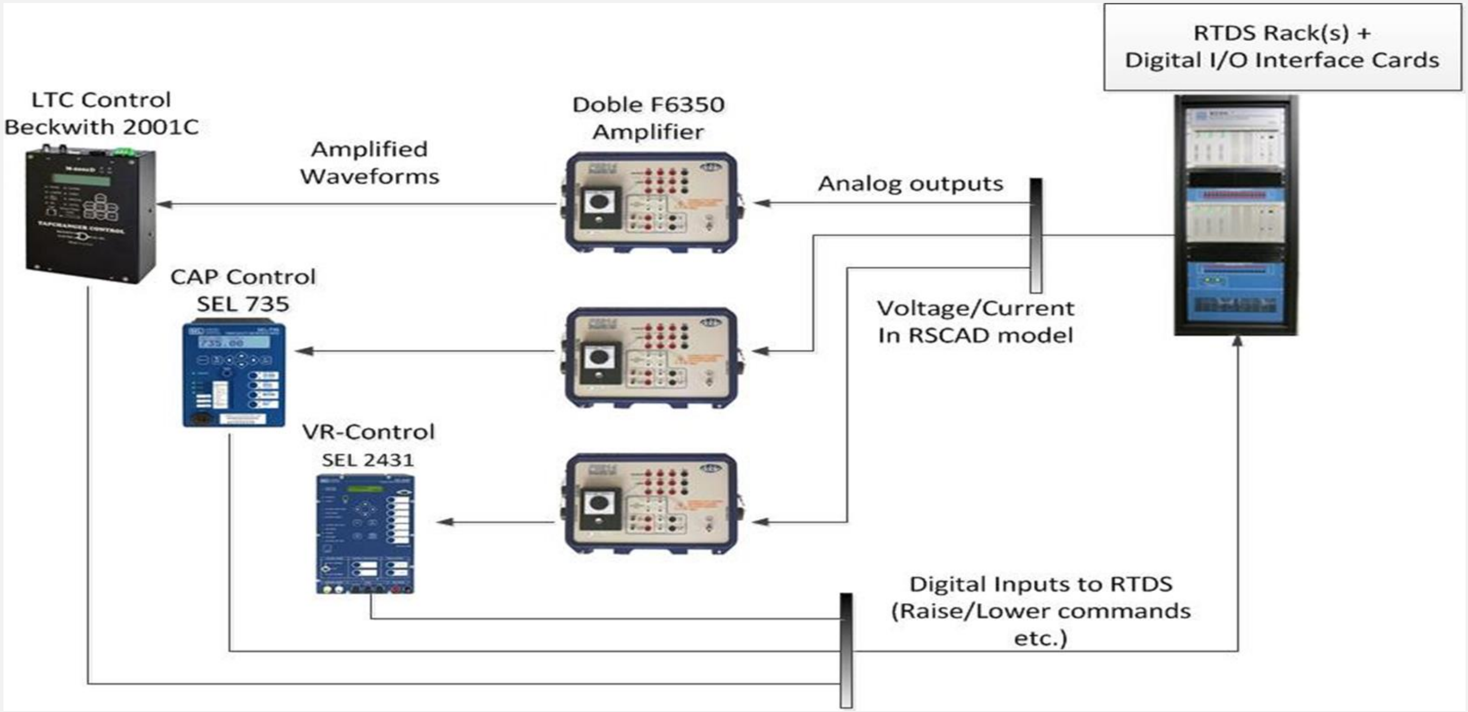
- Opened January 2014
- Seven Labs
  - Power System (10 RTDS racks)
  - DER (various DG and Energy Storage)
  - Smart Garage
  - Home Area Network
  - Information Security
  - Foundational/Communication
  - Situational Awareness

ITF Purpose and Utilization

- Purpose
  - Allows for internal development and retention of institutional knowledge
  - A true cross-functional effort, designed to help projects from different departments at SDG&E coordinate and integrate, increasing SDG&E's knowledge of power system and advanced technologies

- Projects
  - EPIC
  - Borrego/DERMS
  - Energy Storage Integration
  - Volt/VAR Optimization
  - Smart Inverter Pilot
  - Resilient GPS Spoofing
  - Power Your Drive

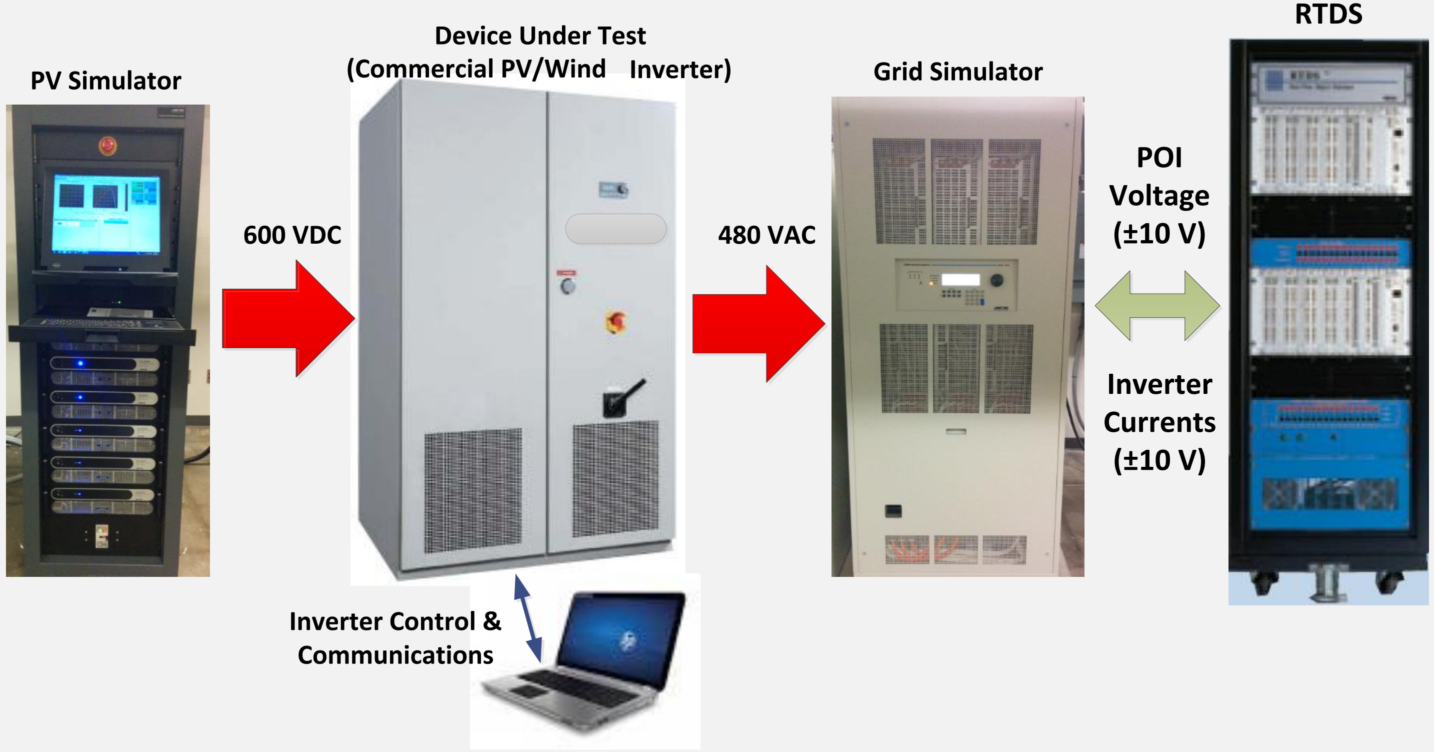
CHIL Test Setup for Integrated Volt/VAR Control



Device under test: Under load tap changer (LTC), Capacitor controllers (SEL 735), Line voltage regulator controller (SEL 2431)

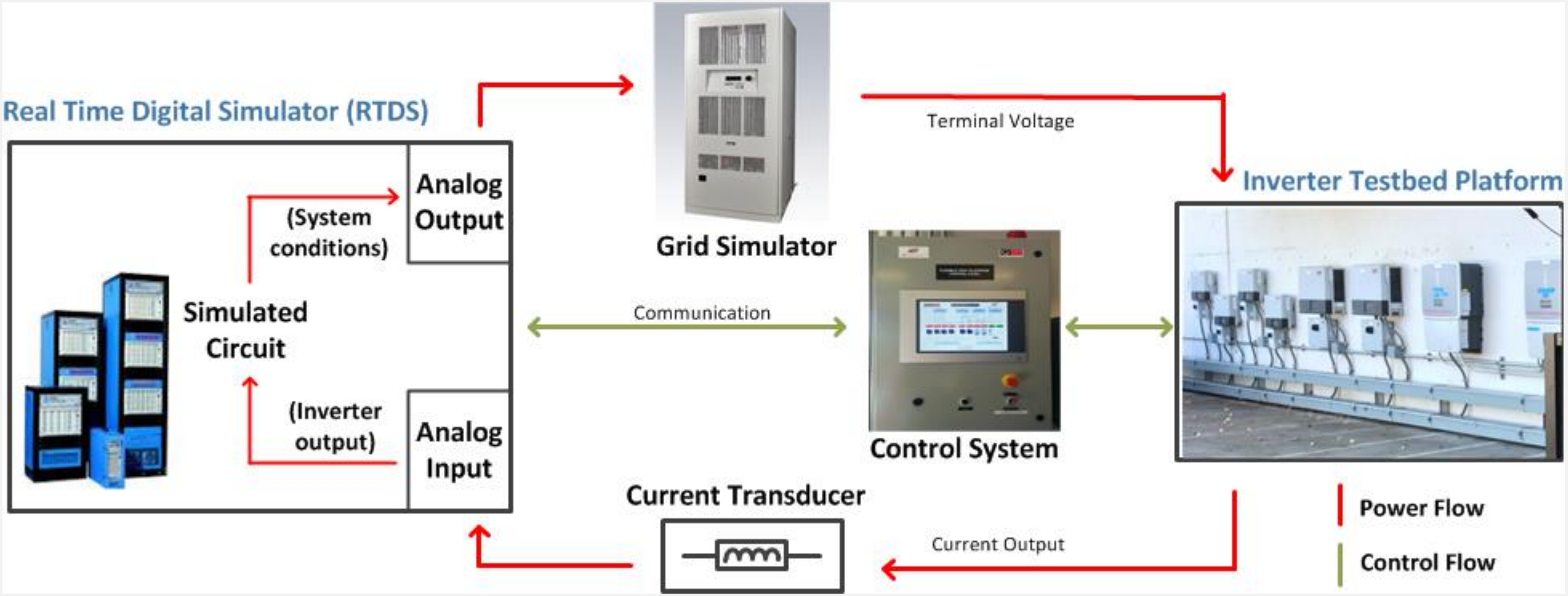
Power Hardware in Loop Testing (PHIL)

- High power amplifiers (grid simulator): in kVA range (e.g. 90 kVA), and up to 480 V
- Power Electronic device under test (inverter, converter, FATCS device)

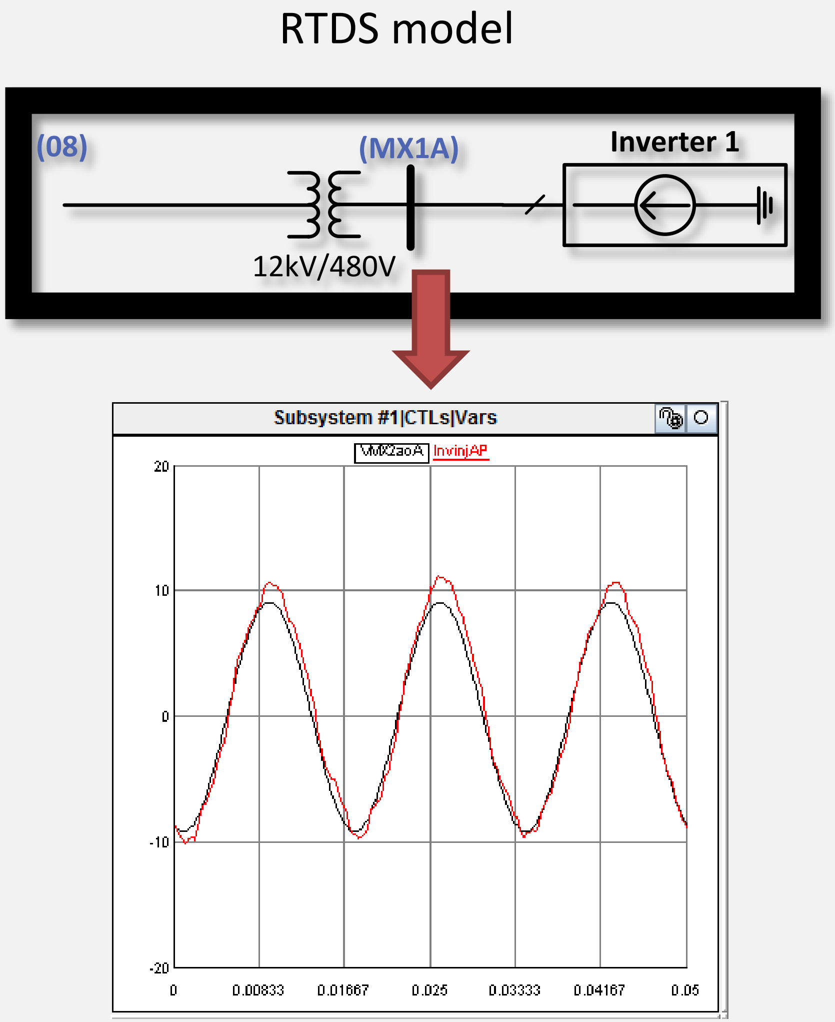


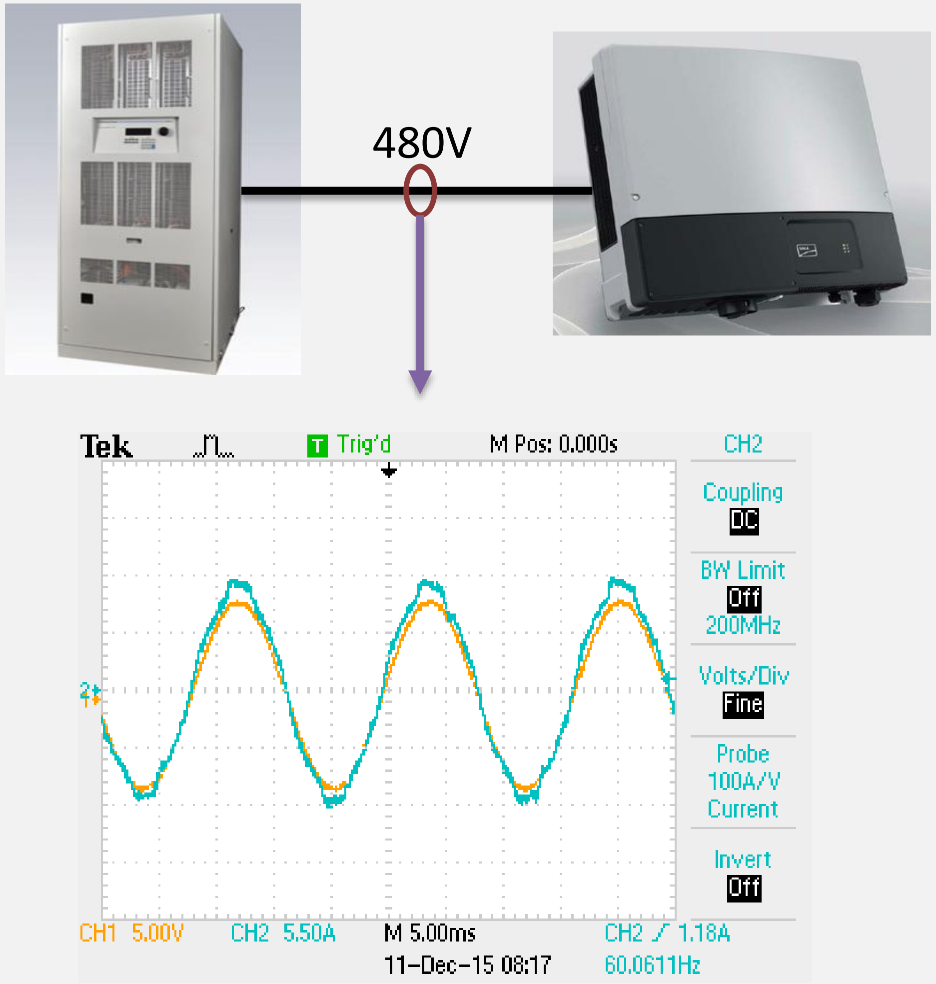
Test Setup for Smart Inverter Testing - PHIL

- Power system (distribution circuit) is represented in Real Time Digital Simulation (RTDS) environment
- Voltage at PCC of inverter is measured and applied to inverter through power amplifiers
- Inverter output (current injection from inverter) is measured and injected to the simulated circuit at PCC
- Inverter output changes the voltage and power flow at PCC and interacts with the circuit



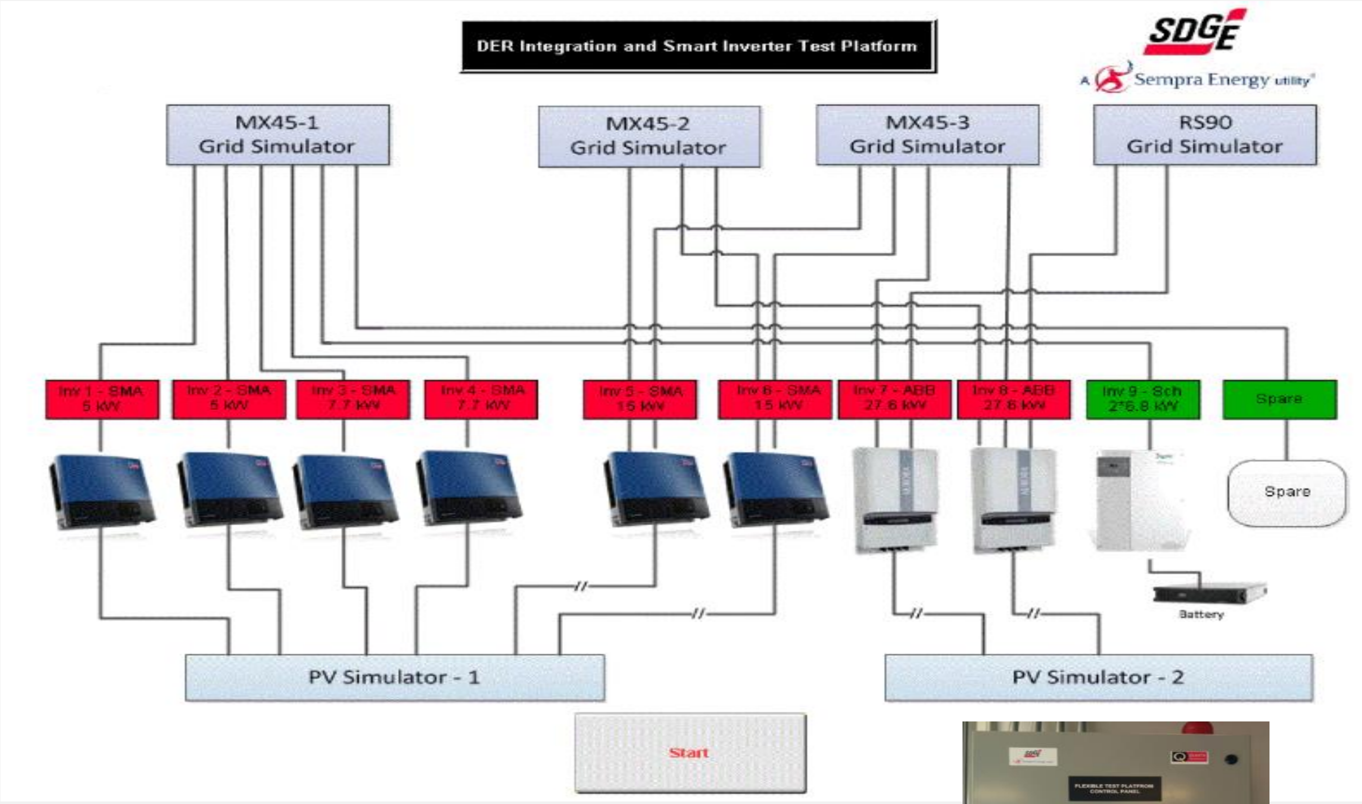
Waveform Comparison: RTDS & Real World





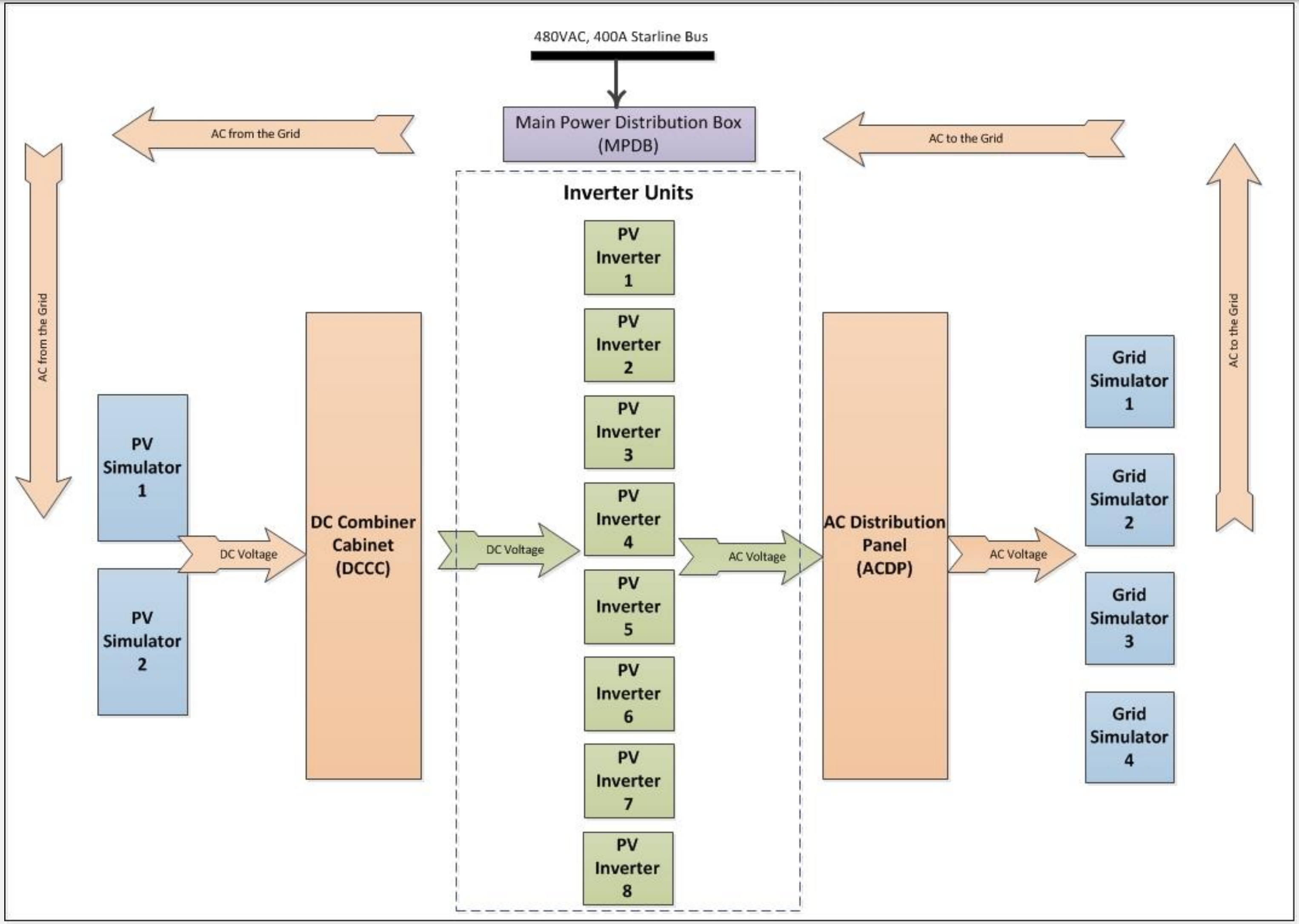
Smart Inverter Test Bed – Example Project

Control and DC feed



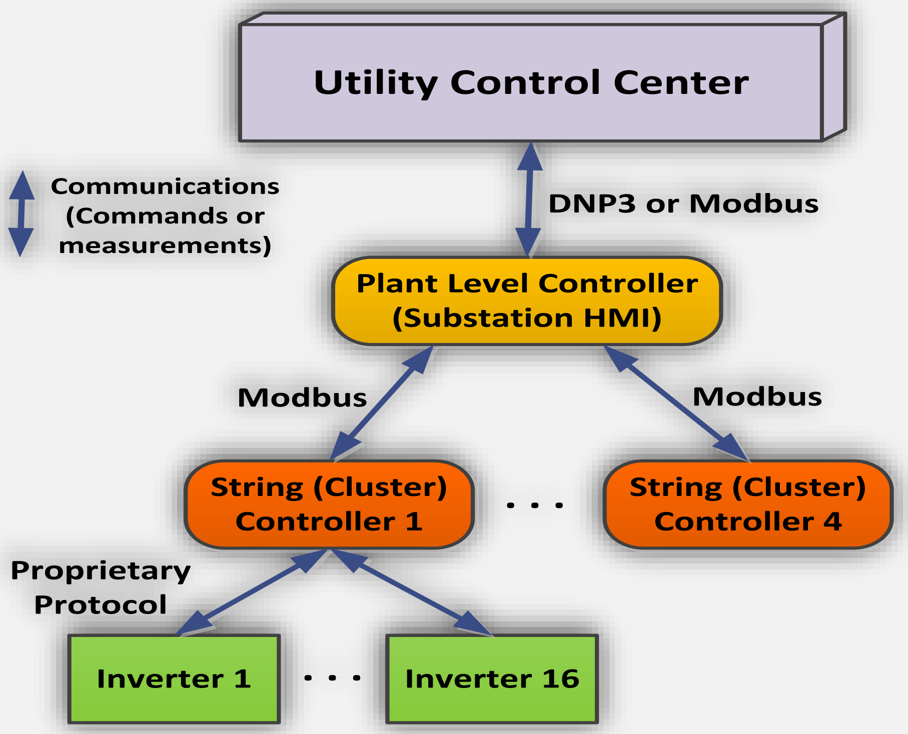
Smart Inverter Test Bed – ITF Setup

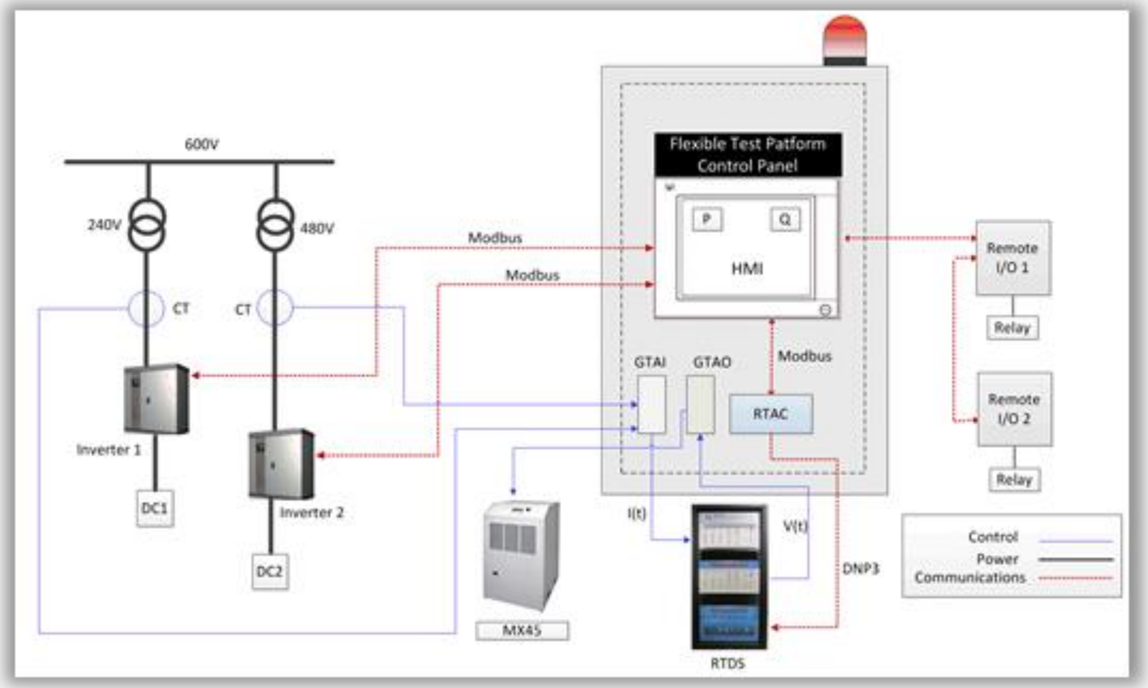
- **Multiple inverters from various vendors**
  - Three phase & single phase inverters
  - Grid-tie & grid forming inverters
- **Flexibility in changing the setup configurations**
  - Two or four inverters in parallel
  - Groups of two inverters at one location
  - Mix of 1Ph and 3Ph
- **Control through various communication schemes (Modbus, DNP3, IEC 61850)**



DG Dispatch: Inverter Controls & Communications

- Representing Utility approach in communications and controls of PV inverters (Dispatch)





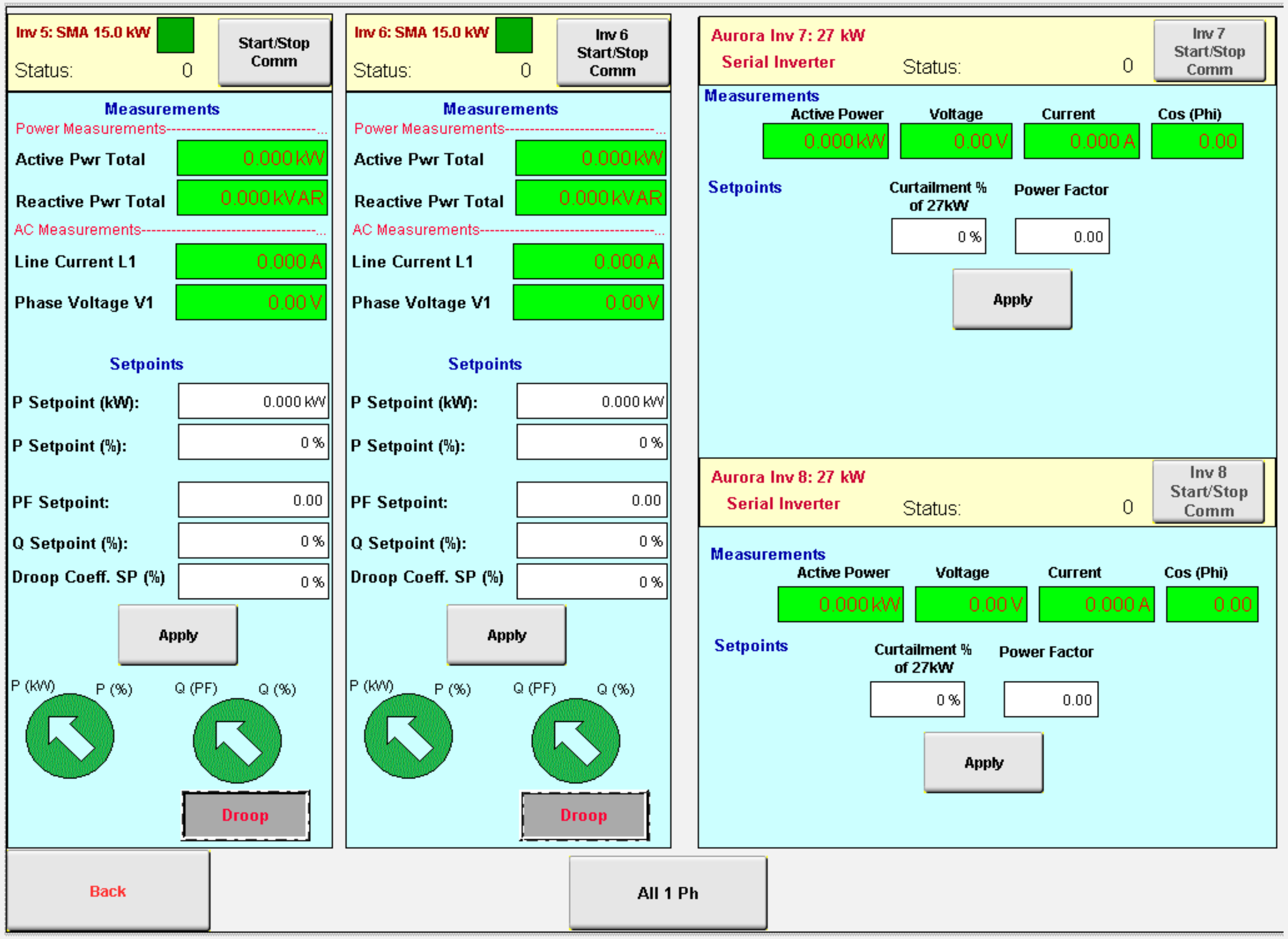
Integrated RTDS I/O cards in an Automation Panel

Site Controller and HMI for Inverter Controls

Inverter Measurement

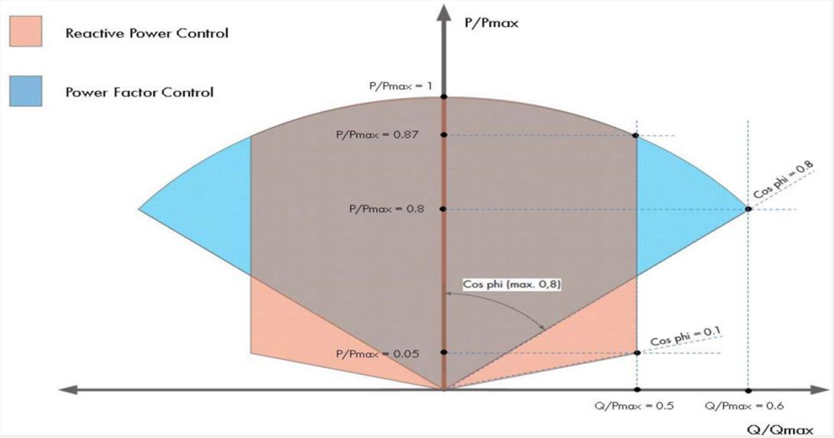
Inverter Setpoint

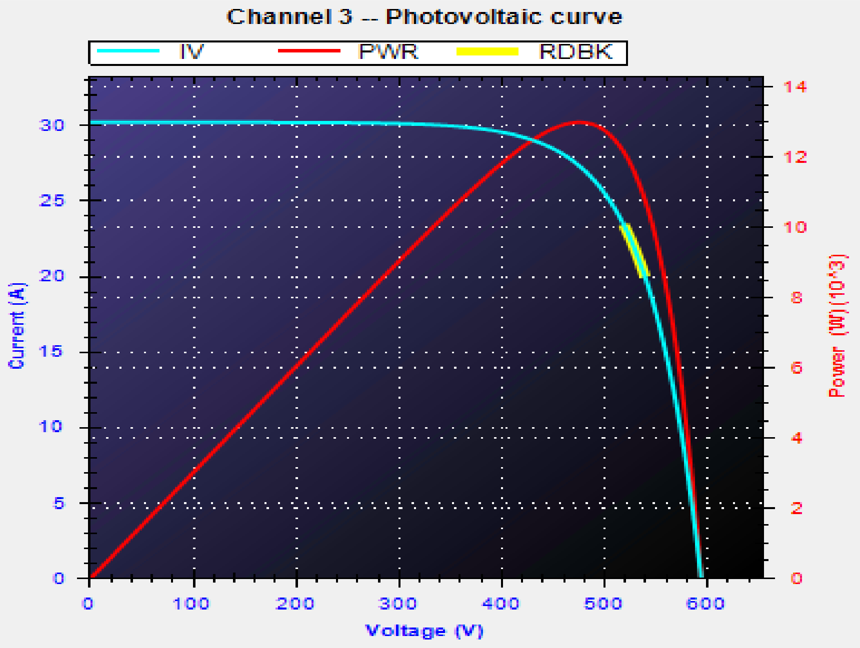
Command Type



Typical Smart Inverter Test Cases

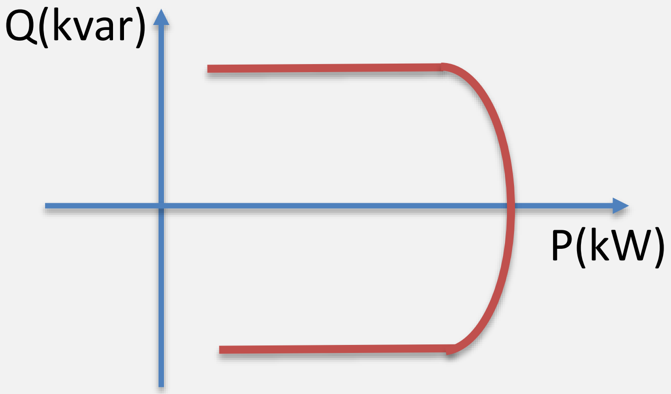
- Voltage and Frequency Variations (Ride-through)
- Fault Current and Protection Analysis (e.g. anti-islanding, faults on adjacent circuits)
- Inverter Dynamic Response to change in DC resources (intermittency) and P/Q setpoints
- Power Conversion Analysis (Efficiency, Waveform Quality, Harmonics)
- Advanced Communications and Controls
- Inverter Characteristics (P & Q Curves)
- Load Rejection
- MPPT Accuracy



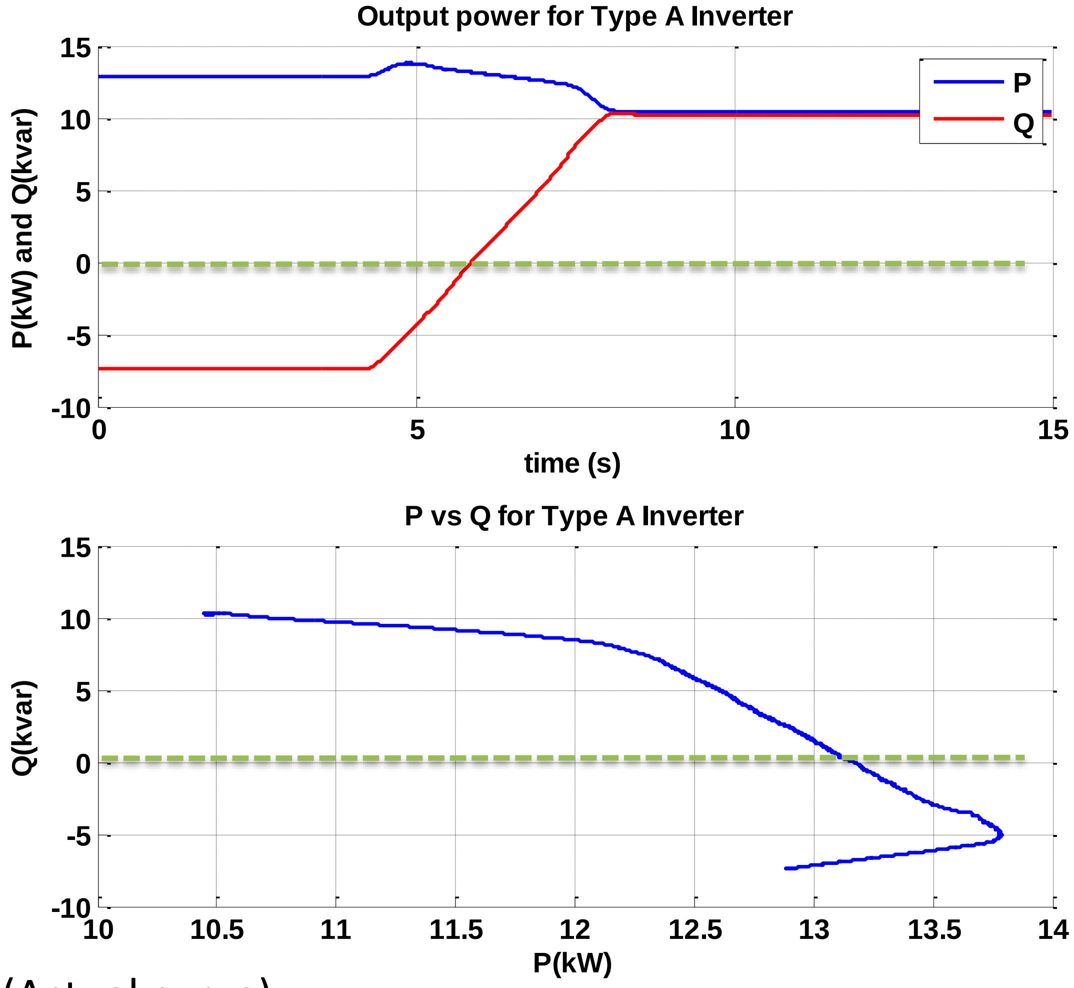


P-Q Characteristics of PV Inverters

- Testing the reactive power capability curve of the inverter
  - P = about rated kW
  - Changing Q from -5 kvar to +10 kvar
  - ➔ P has dropped (priority on Q)

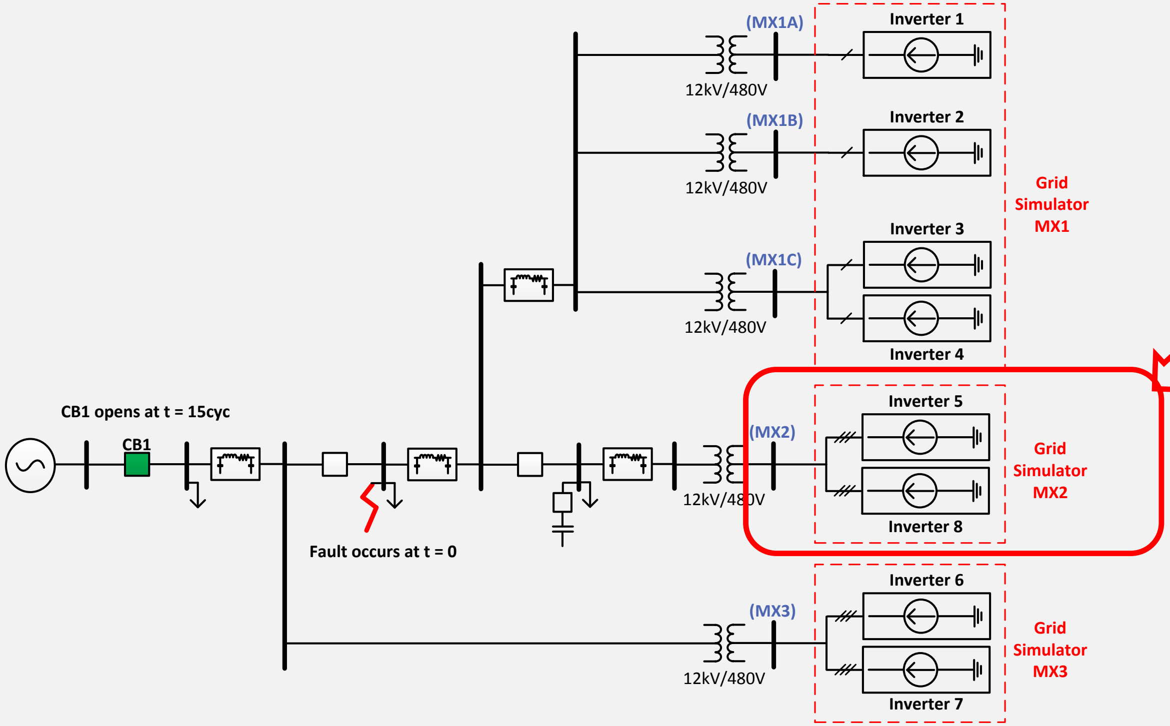


(Theoretical curve)



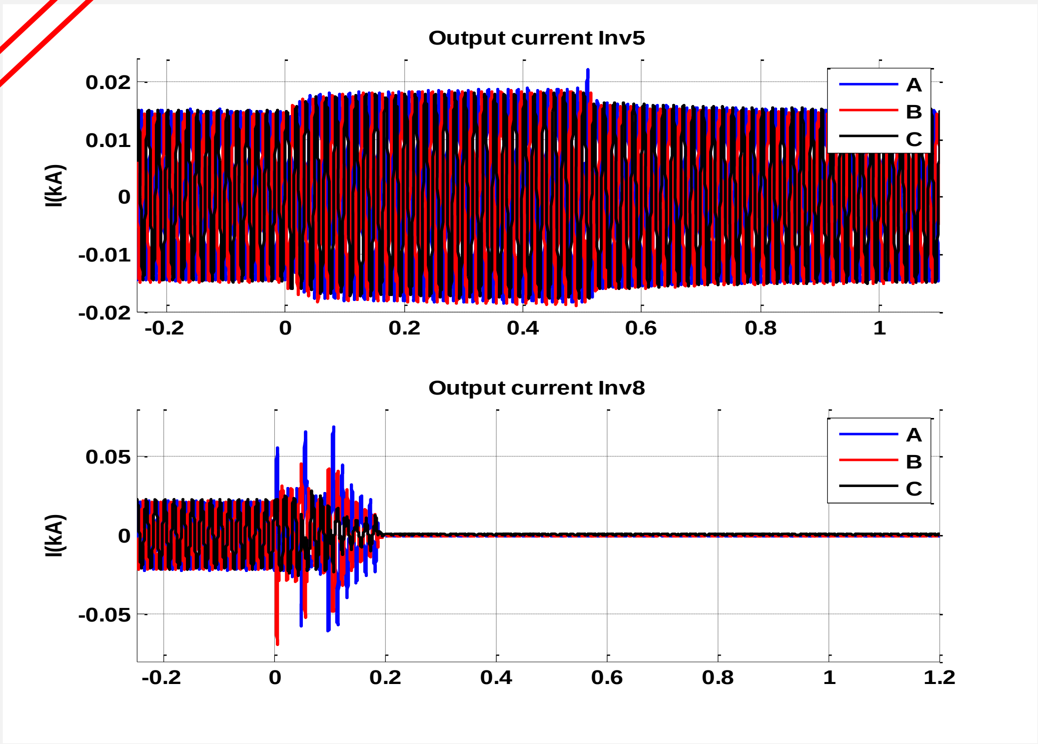
(Actual curve)

Fault Response Tests



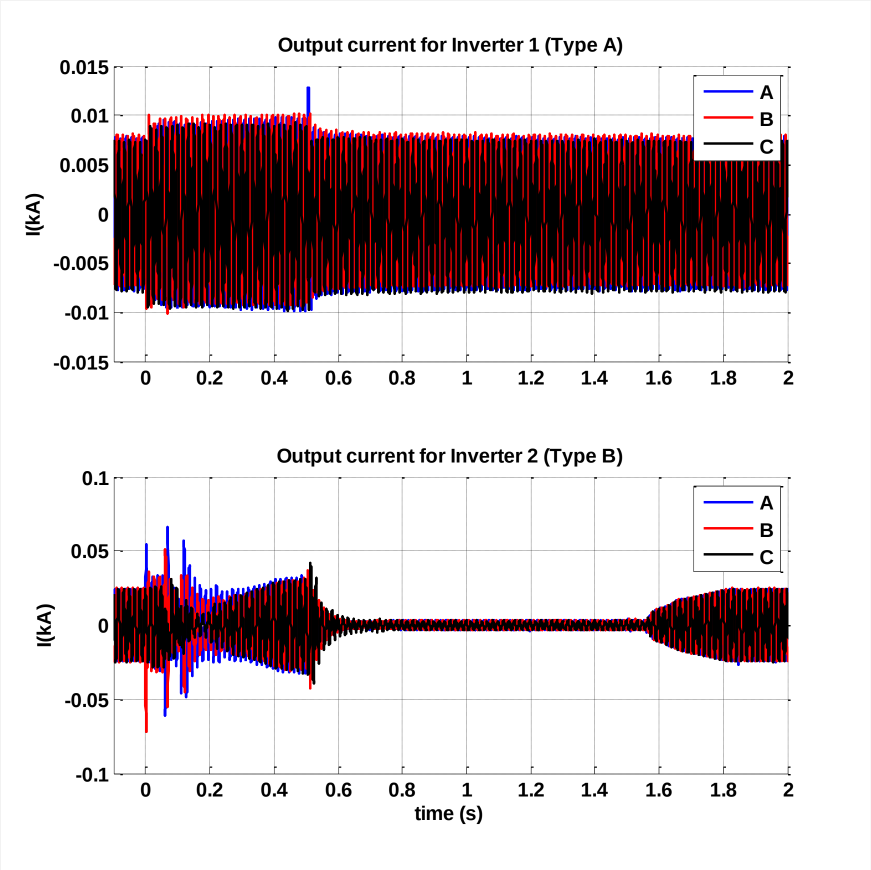
Circuit Model in RTDS

Three-phase inverter (Inverter A & B) response to fault and breaker operation

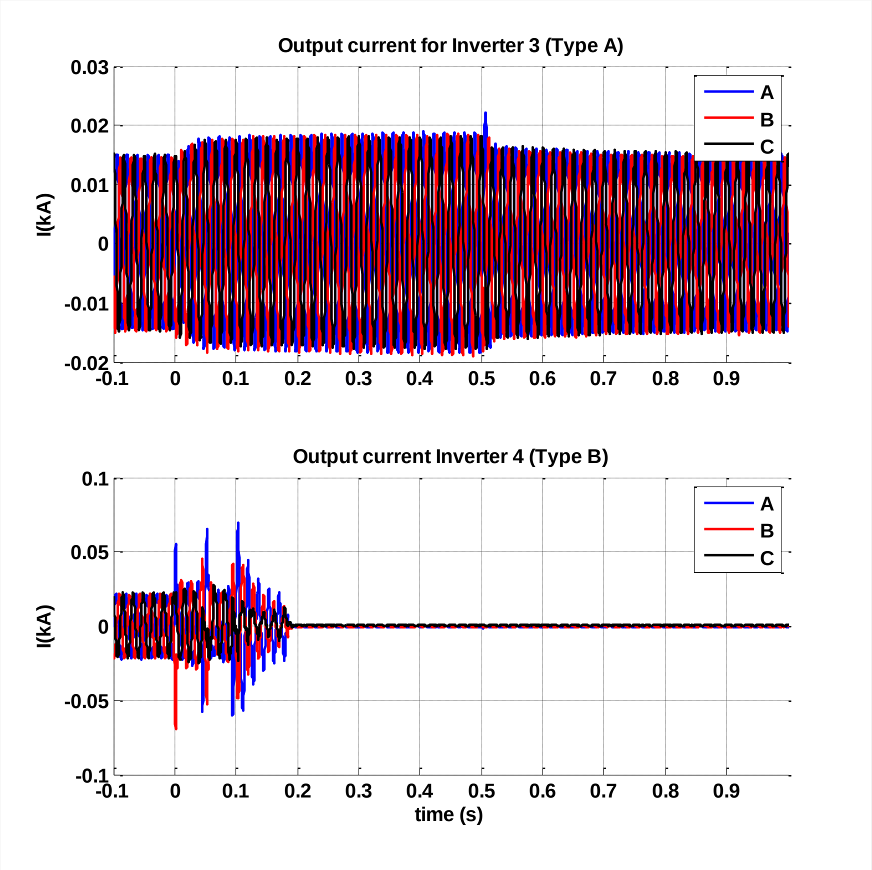


Fault Ride Through Tests

Fault further away from the Inverter



Fault Close to the Inverter



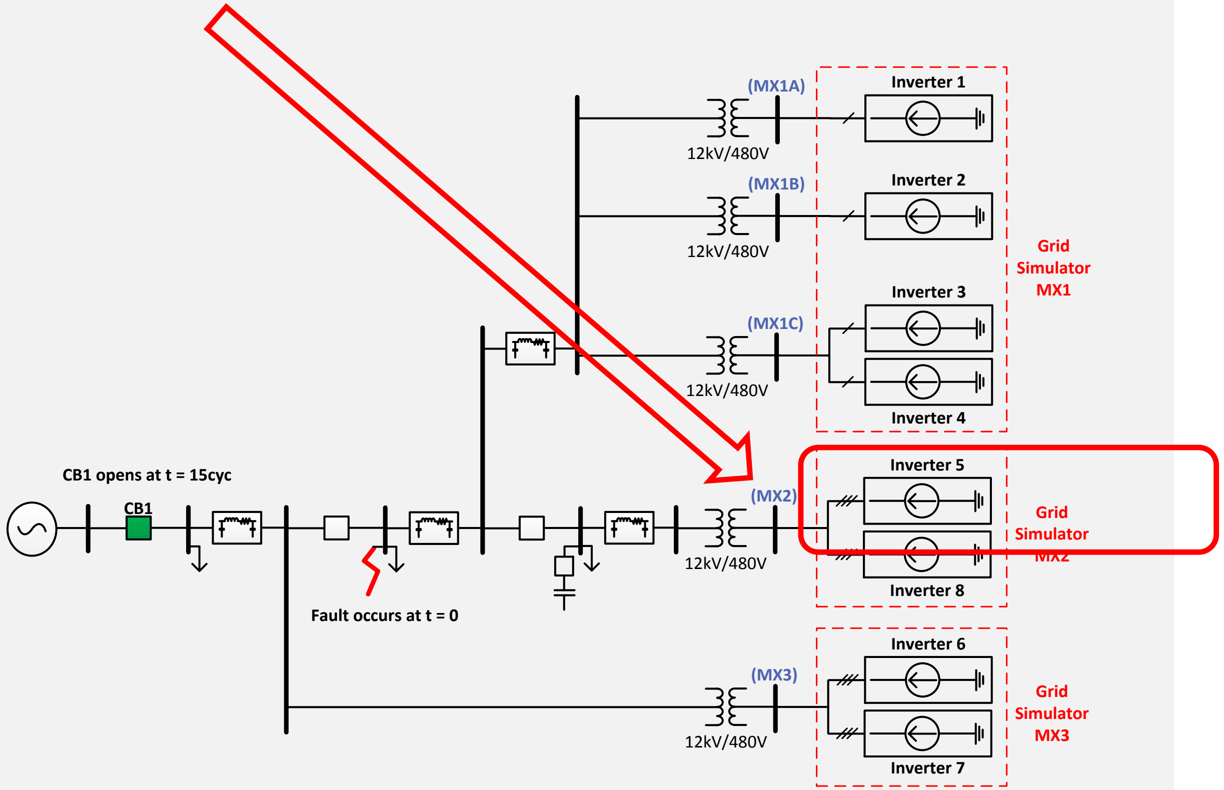
SLG Fault, 30 cycles

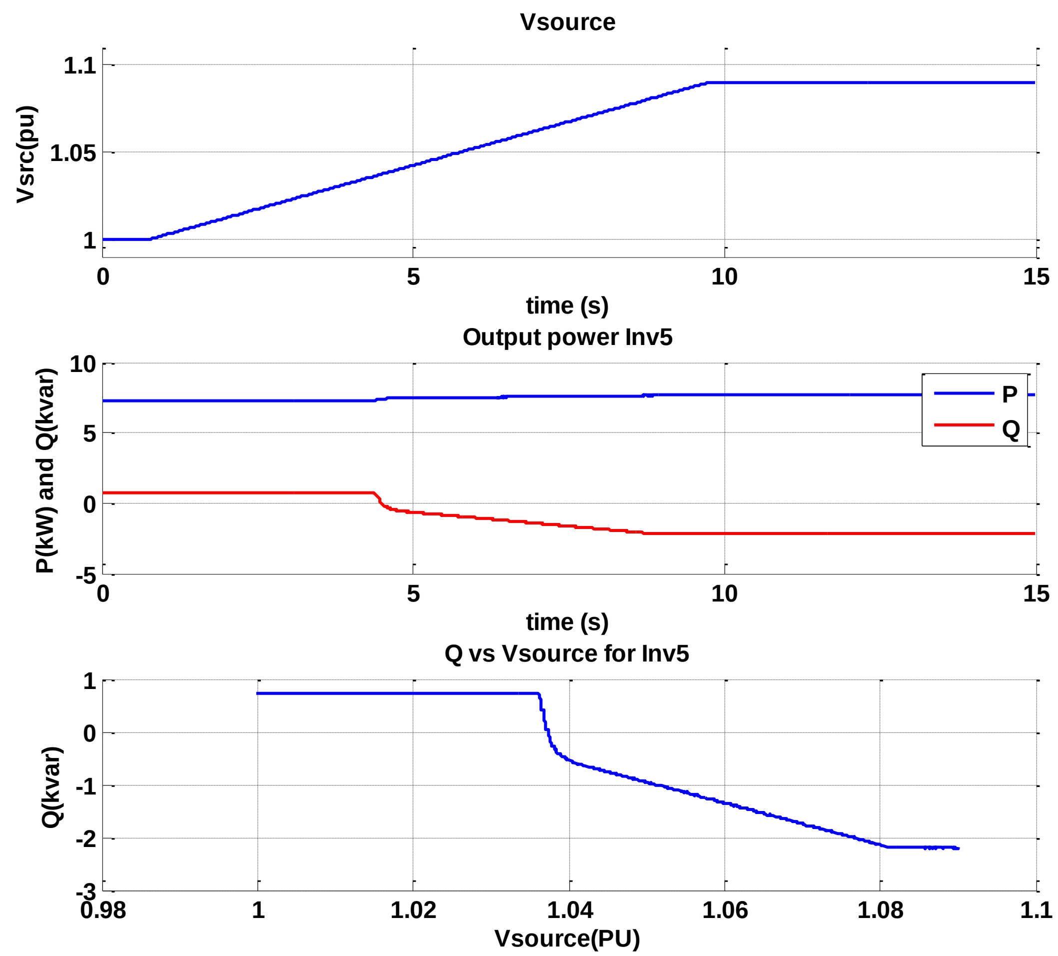
Q-V Droop Characteristic Tests

Droop test, Inverter 5, Voltage Increase from 1 to 1.09 pu in 9 Seconds (increase rate 0.01 pu /sec)

Active power = 50% max

Droop Coefficient =10%

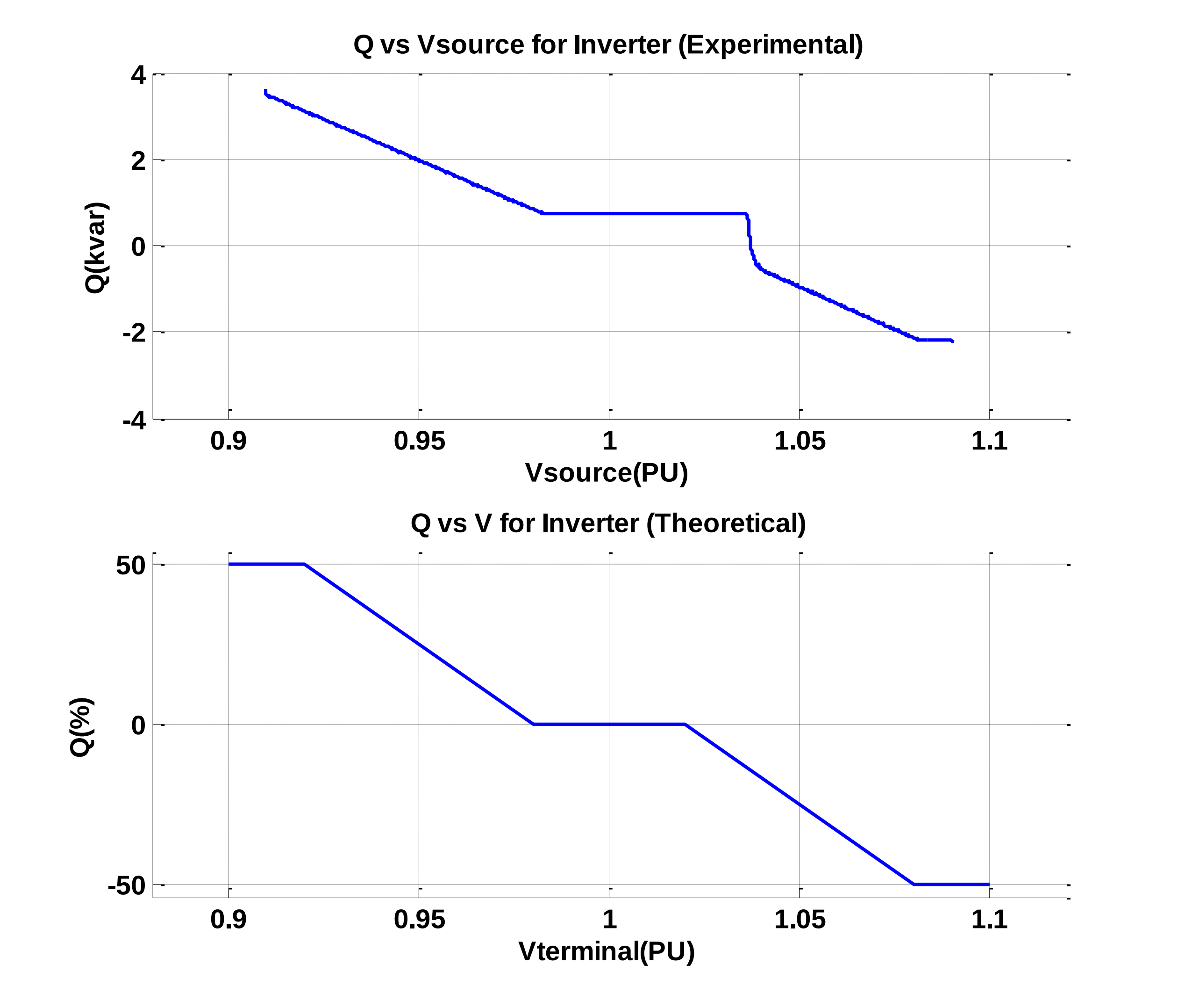




Q-V Droop Characteristics – Comparison

Experimental

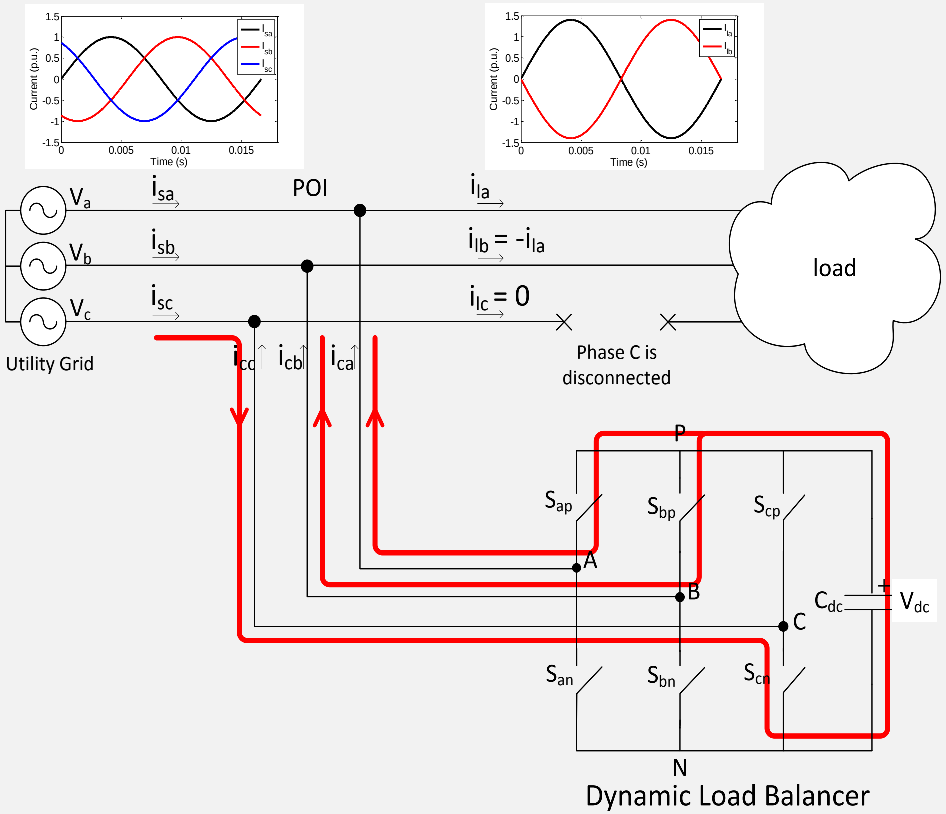
Theoretical



New Technology Evaluation with PHIL

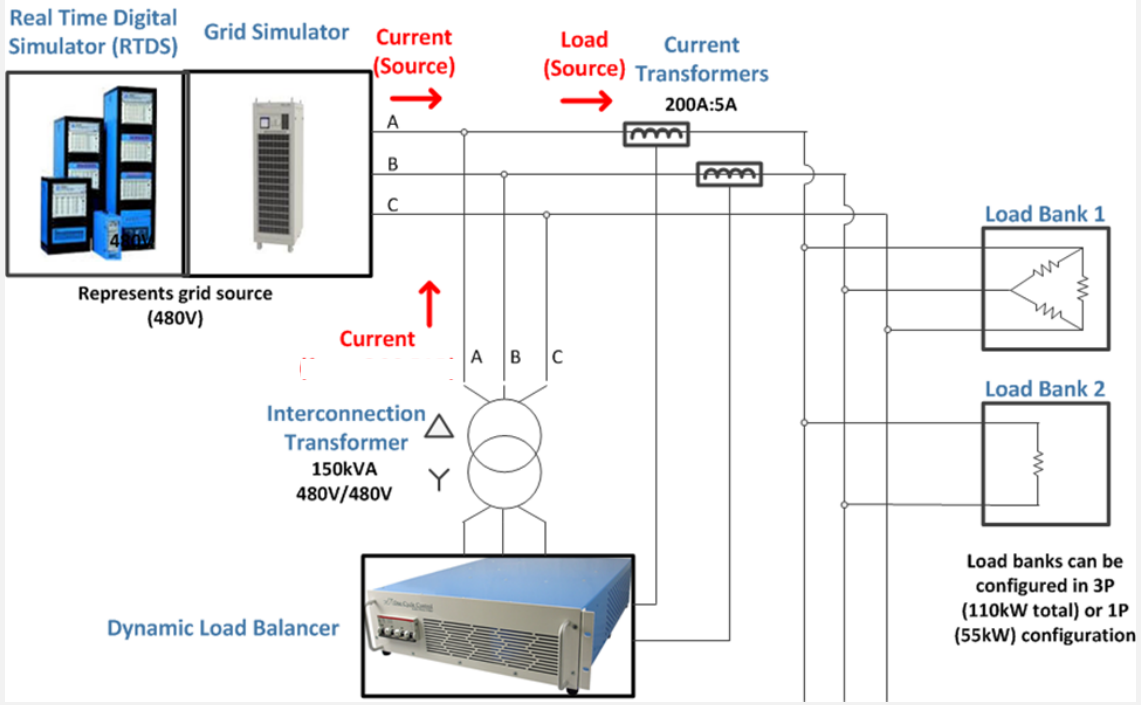
- Dynamic load balancing concept (DLB)
  - Using power electronic converters to balance the load on distribution circuits from upstream view

Eliminating negative sequence

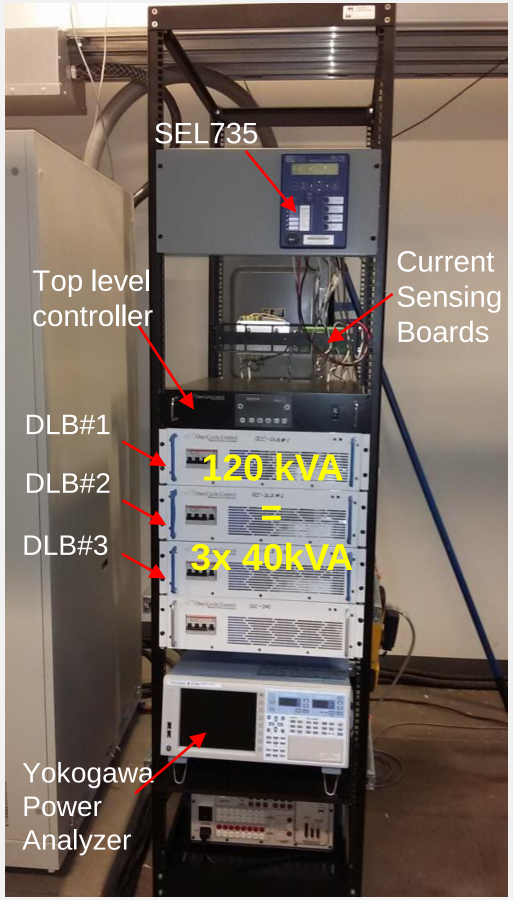


150 kVA Hardware Testbed and DLB rack

RTDS is used to reflect the changes in the voltage at the point of connection to the device under test

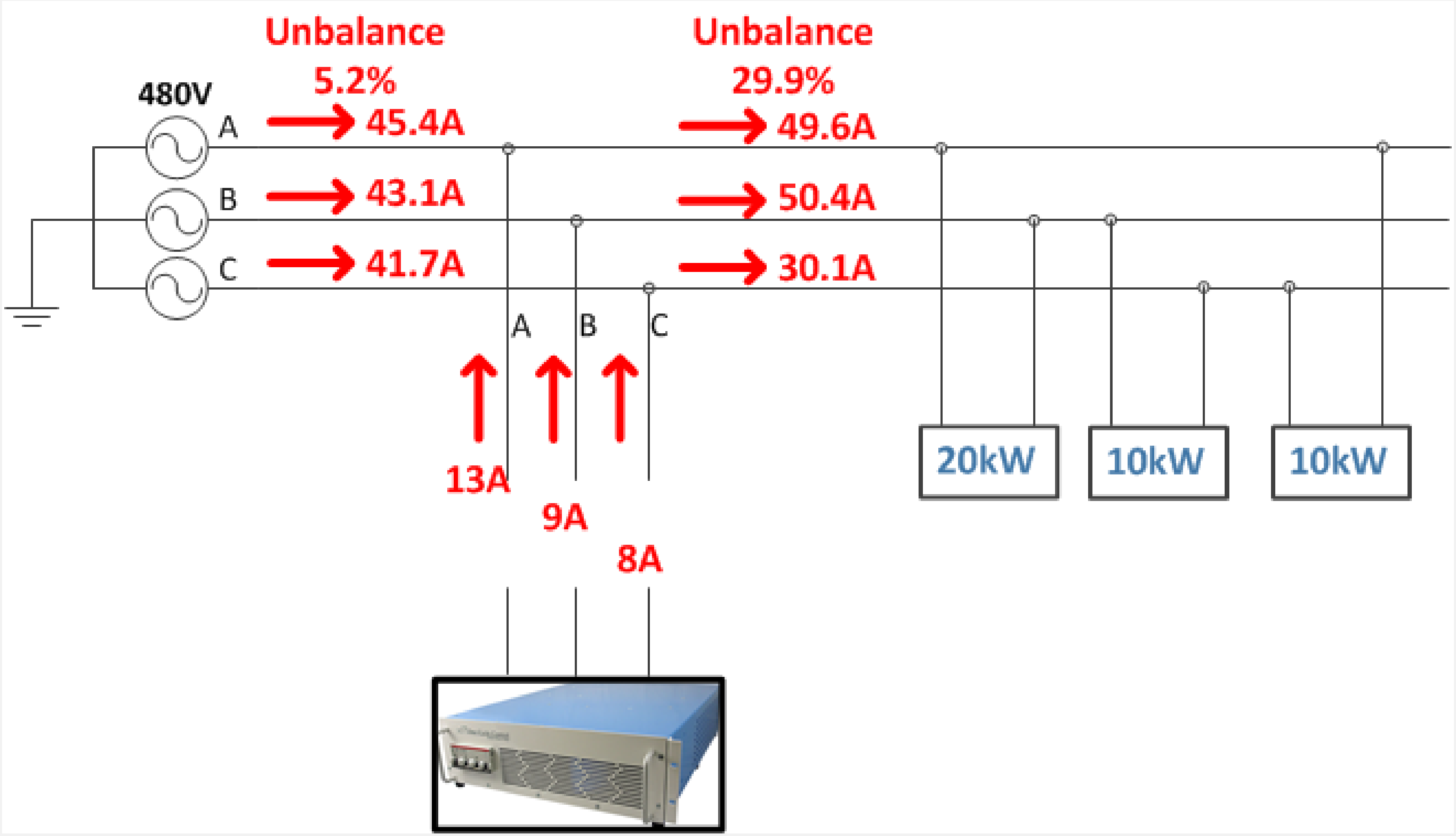


120 kVA Power Hardware in loop Testbed



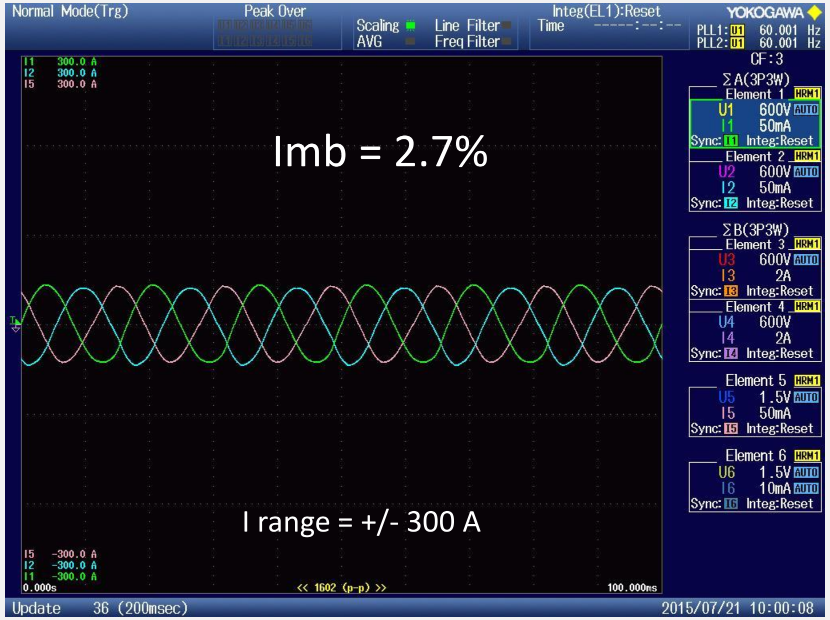
DLB rack

Example 480V – Resistive Load Test

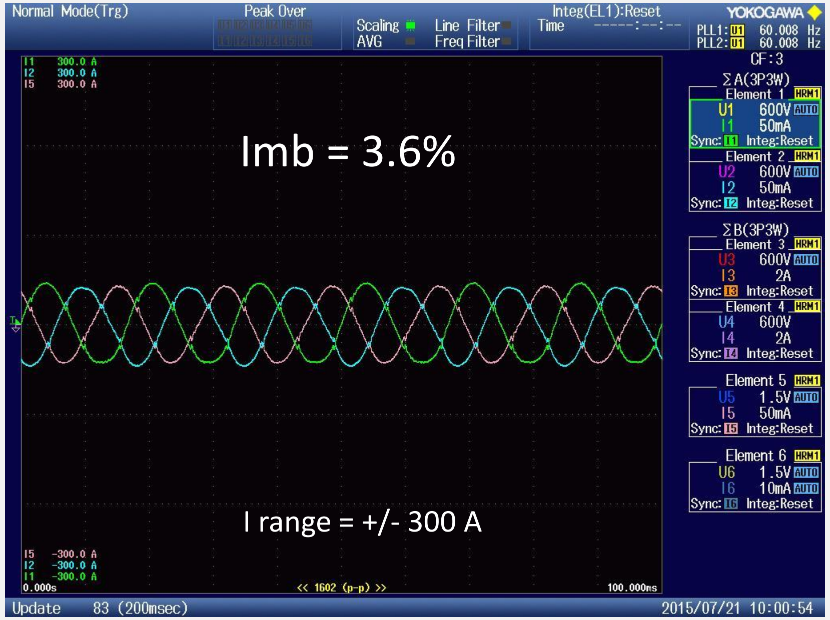


25 kW 3-Ph Balanced Load

DLB is OFF



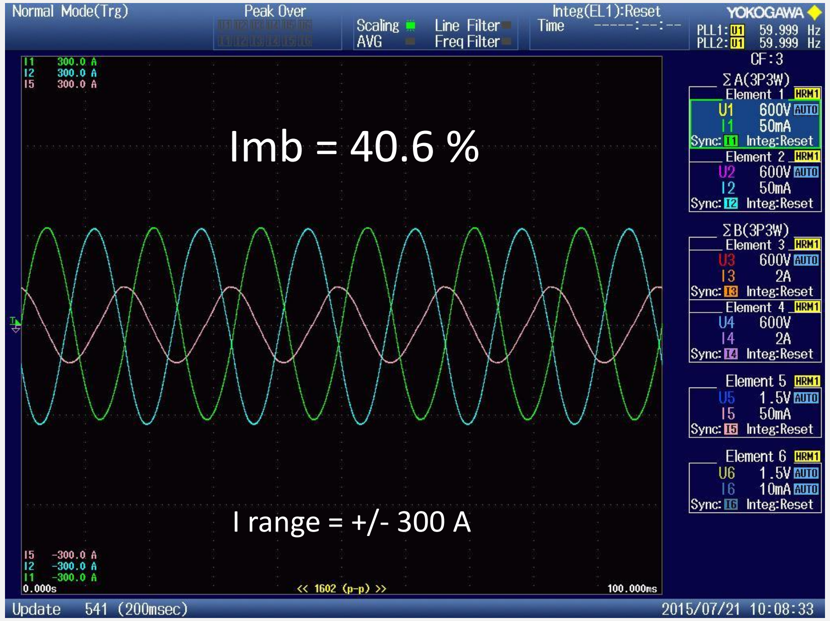
DLB is ON



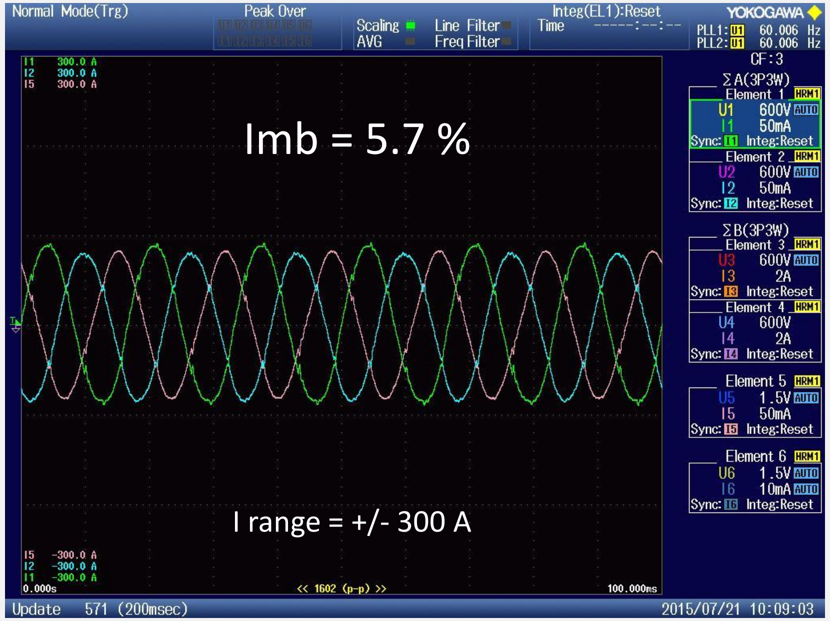
		IS (A)				IS THD (%)			IDLB (A)		
Test #	DLB	ISA	ISB	ISC	% Imb	ISA THD	ISB THD	ISC THD	IDLBA	IDLBB	IDLBC
A	OFF	31.1	30.5	30.1	2.7	5.5	4.7	4.3	x	x	x
	ON	32.2	31.0	30.5	3.6	7.8	7.3	5.4	3.0	2.0	3.0

25 kW 3-Ph Balanced Load and 25 kW 1-Ph Load Between Phase A and B

DLB is OFF



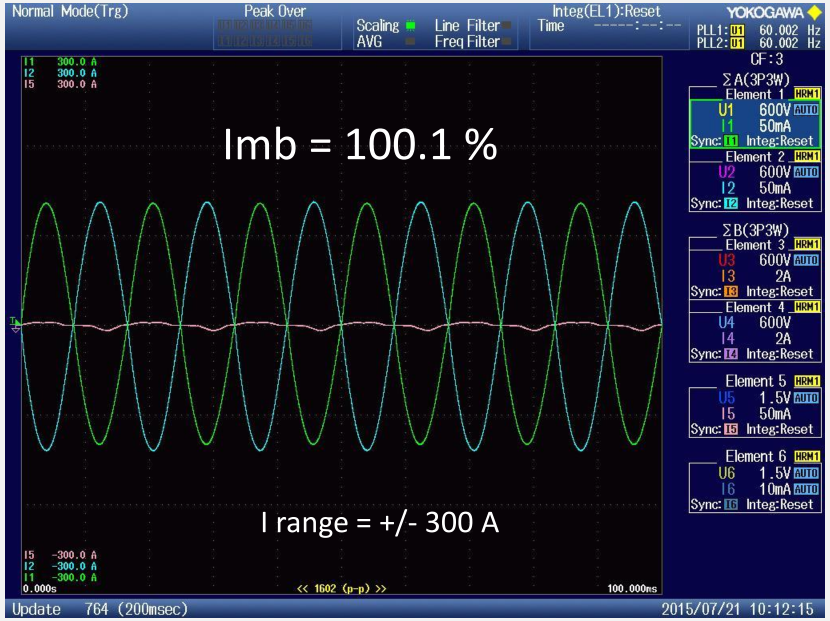
DLB is ON



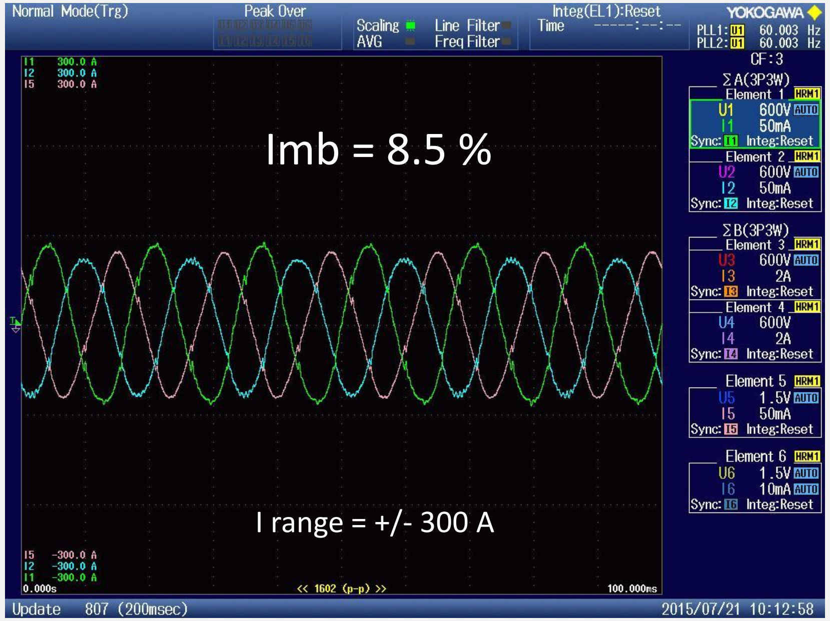
		IS (A)				IS THD (%)			IDLB (A)		
Test #	DLB	ISA	ISB	ISC	% Imb	ISA THD	ISB THD	ISC THD	IDLBA	IDLBB	IDLBC
F	OFF	62.4	63.5	30.1	40.6	2.8	2.2	4.4	x	x	x
	ON	54.2	50.6	49.4	5.7	5.4	4.9	4.2	21.0	16.0	15.0

45 kW 1-Ph Load Between Phase A and B

DLB is OFF



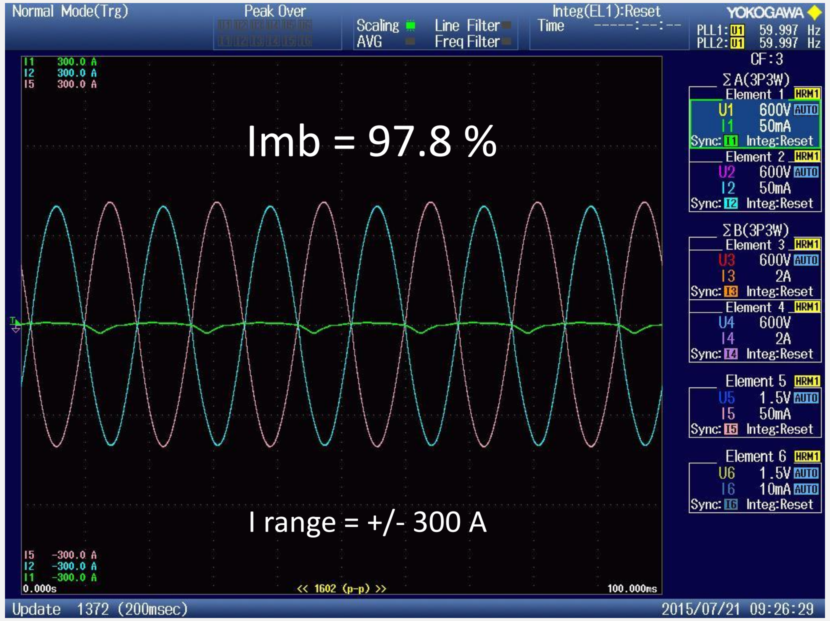
DLB is ON



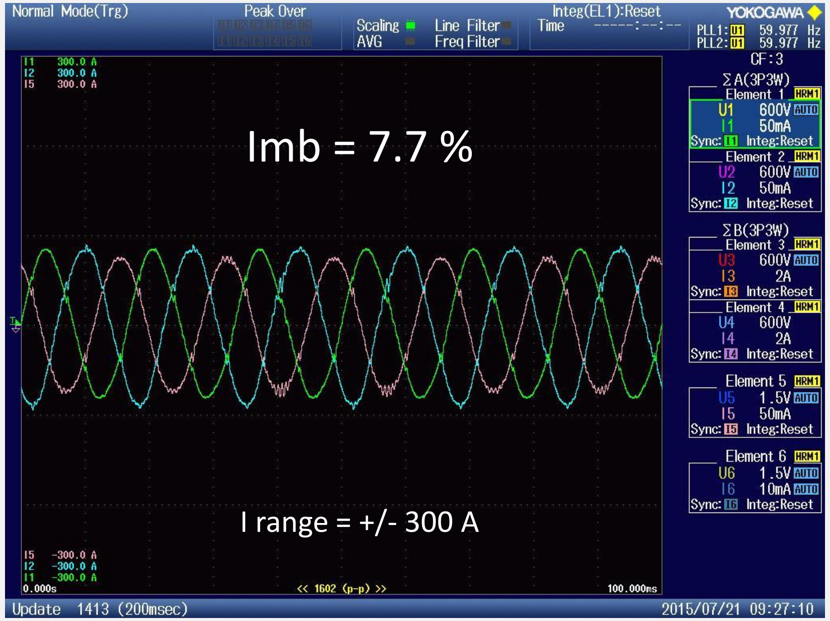
		IS (A)				IS THD (%)			IDLB (A)		
Test #	DLB	ISA	ISB	ISC	% Imb	ISA THD	ISB THD	ISC THD	IDLBA	IDLBB	IDLBC
H	OFF	94.4	97.3	3.1	100.1	1.9	1.5	48.3	x	x	x
	ON	62.6	54.6	56.1	8.5	6.3	5.4	5.6	57.0	50.0	51.0

45 kW 1-Ph Load Between Phase B and C

DLB is OFF



DLB is ON



		IS (A)				IS THD (%)			IDLB (A)		
Test #	DLB	ISA	ISB	ISC	% Imb	ISA THD	ISB THD	ISC THD	IDLBA	IDLBB	IDLBC
G	OFF	3.7	93.1	97.6	97.8	57.4	1.9	1.5	x	x	x
	ON	57.6	61.2	54.1	7.7	5.0	5.7	3.9	51.0	51.0	57.0

Summary and Conclusions

- Growing introduction of Power Electronics and New Technologies in distribution systems as advanced mitigation solutions require in-depth testing and evaluations
- Traditional methods of testing approaches with the use of load bank and controlled sources may not be sufficient enough for comprehensive evaluation of technologies and integrated control/communication functionalities
  - Need to incorporate realistic system conditions and transient events
  - Flexibility in changing power system parameters and using validated circuit models
  - Applying large number of test cases involving contingencies and ability to repeat the tests
- PHIL & CHIL tests have been successfully utilized with superior results to alternative testing approaches and have been able to avoid high cost of experimenting in the field

Thank YOU

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