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Designing, Implementing and Testing Advanced Inverter with Robust Droop Control for Microgrid Integrated Solar Storage Technology

cigre
United States

2019 Grid of the Future

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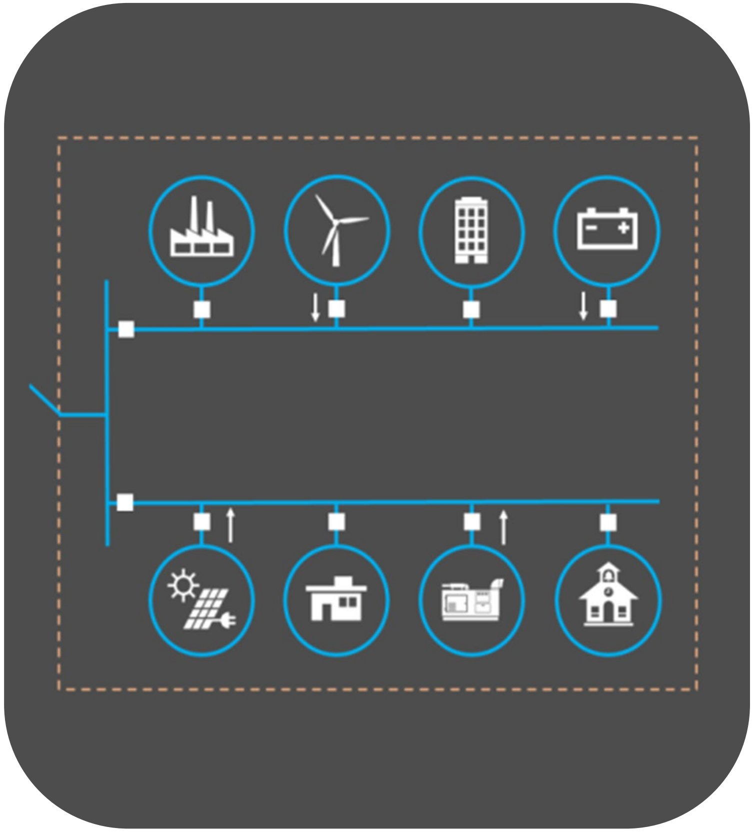
Outline

- Introduction
- Background
- Robust Droop Controller Algorithm
  - Inverter Test Schematic
  - Inverter Control Architecture
- Smart Inverter Functions
- Smart Inverter : Factory Acceptance Testing
  - Factory Acceptance Test Results – Grid Forming
  - Factory Acceptance Test Results – Grid Following
- Conclusion

Introduction

- Increasing amount of Inverter based DER penetration can reduce system inertia
- Reduced inertia may lead to instability due to high rate of change of frequency (RoCoF)
- One solution is to create synthetic inertia which will emulate synchronous machine by creating special control schemes:
  - Robust Droop Control (RDC) is one such technology
- RDC enables proportional load sharing in parallelly-operated inverters



Background

- Sharing load proportional to inverter settings requires:

Inverters to have same internal per-unit impedance when using conventional droop	Inverters need to have the same root mean square voltage set-point

- Robust droop control, proposed by Dr. Q.-C. Zhong introduces parallel operation of inverters with proportional load sharing
  - Independent of disturbances, noises, numerical errors, parameter drifts, component mismatches and feeder impedances
  - Universal controller independent of inverter output impedance or the RMS voltage set-points
  - Provides voltage regulation for voltage drop due to load effect and droop effect
  - Implements frequency droop and voltage droop to regulate system frequency and voltage, and may be equipped with a self-synchronizing mechanism

- This technology has been prototyped in a 100 kW, 480 VAC three-phase bi-directional inverter as part of the DOE SHINES – Microgrid Integrated Solar Storage Technology (MISST) grant[1]

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[1]SHINES: Sustainable and Holistic Integration of Solar and Energy Storage (DE-EE000716)

Robust Droop Control Algorithm

- For a predominantly resistive system, droop correlations are:

$$P \approx \frac{E-V_0}{Z_0} V_0 \quad and \quad Q \approx -\frac{EV_0}{Z_0}\delta$$

$$P \sim E \quad and \quad Q \sim -\delta$$

- Dynamic representation of the droop principle:
  - Terminal voltage decreases when active power is generated by the inverter
  - Frequency increases if reactive power is generated (capacitive) by the inverter

$$P - V\ Droop: \quad E = K_e(E^* - V_0) - nP$$

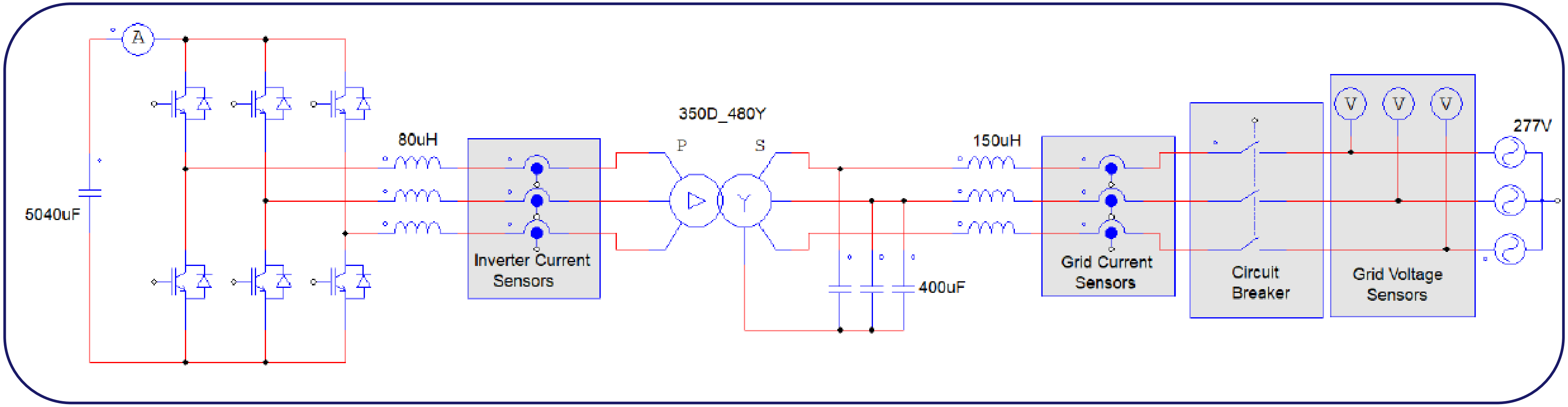
$$Q - f\ Droop: \quad \omega = w^* + mQ$$

- Proportional active load sharing with same value of K_e for parallelly operating inverters

- Q.C.Zhong “Robust droop controller for accurate proportional load sharing among inverters operated in parallel” (IEEE Transactions on Industrial Electronics, vol.60, no.4, 2013, pages 1281-1290)
- Q.C.Zhong, W.-L.Ming, Y.Zeng “Self-Synchronized Universal Droop Controller” (IEEE Access, vol. 4, 2016, pages 7145-7153)

Inverter Test Schematic

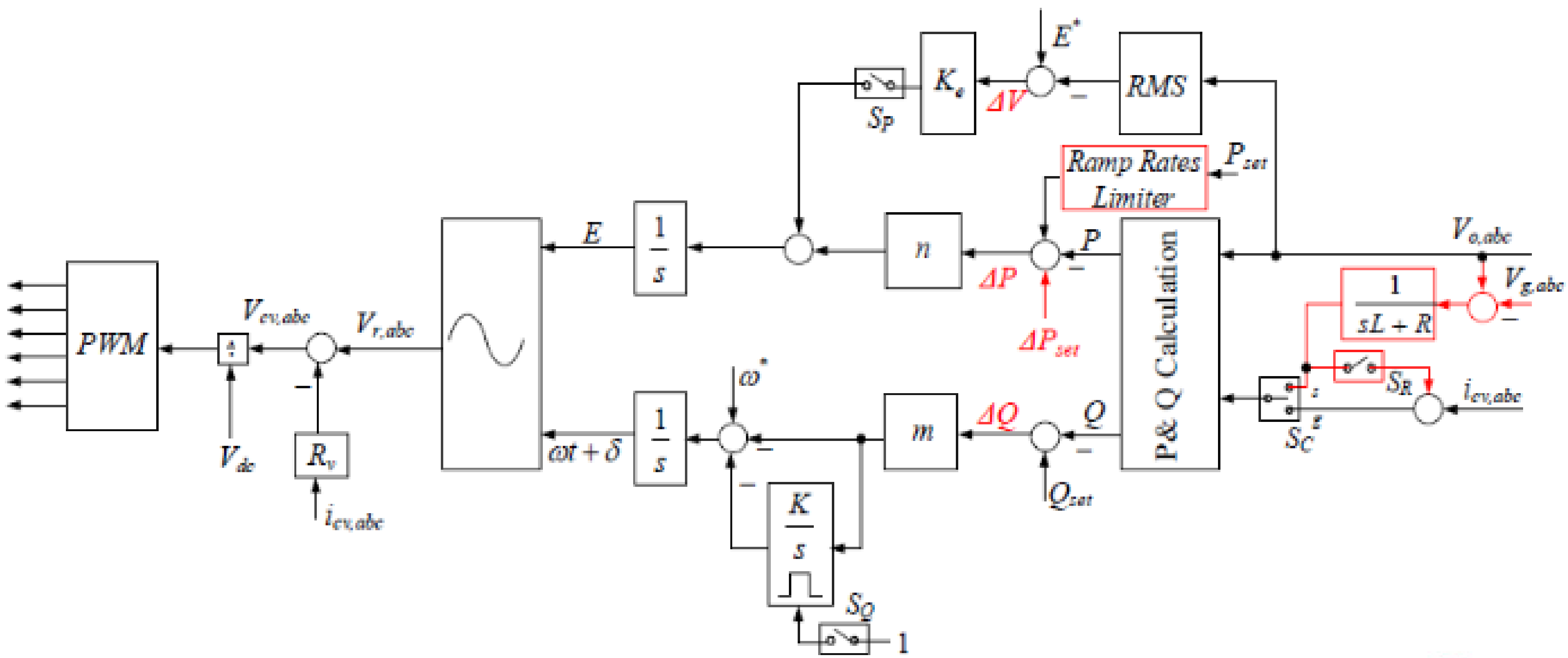
- Custom designed firmware designed and built to implement RDC
- Two-level three-phase bidirectional inverter with built-in delta-star transformer



Topology of 100kW bi-directional RDC inverter

Inverter Control Architecture

- NI Single-Board RIO General Purpose Inverter Controller (GPIC) used for controller design
- This powerful controller offers the flexibility of the National Instruments LabVIEW and very useful with rapid prototyping



Control stage of the robust droop controller (RDC)

Smart Inverter Functions

Grid-following mode

- ☐ System synchronizes with grid
- ☐ Current Controlled Voltage Source
- ☐ Several inverter functions like Volt/Watt, Volt/var, etc active

Grid-forming mode

- ☐ Inverter forms the grid
- ☐ Voltage Controlled Voltage Source
- ☐ Droop functionalities active

Smart inverter modes of operation and functional mapping

Function	Grid Forming	Grid-Following Mode	
	Battery-Mode	Battery-Mode	PV-Mode
Anti-islanding		X	X
Frequency-Watt		X	X
Volt-Watt	X	X	X
Frequency-VAR	X		
Volt-VAR		X	X
Constant power factor		X	X
High/Low Voltage Ride-Through	X	X	X
High/Low Frequency Ride-Through	X	X	X
Soft and Normal Ramp Rate		X	X
MPPT Mode			X

Smart Inverter : Factory Acceptance Testing

- Smart inverter technology has been validated for high-power PV application and high-power BESS applications in grid-forming and grid-following modes of operation
- Inverter has been tested in accordance with UL 1741 SA and passed the factory acceptance tests.

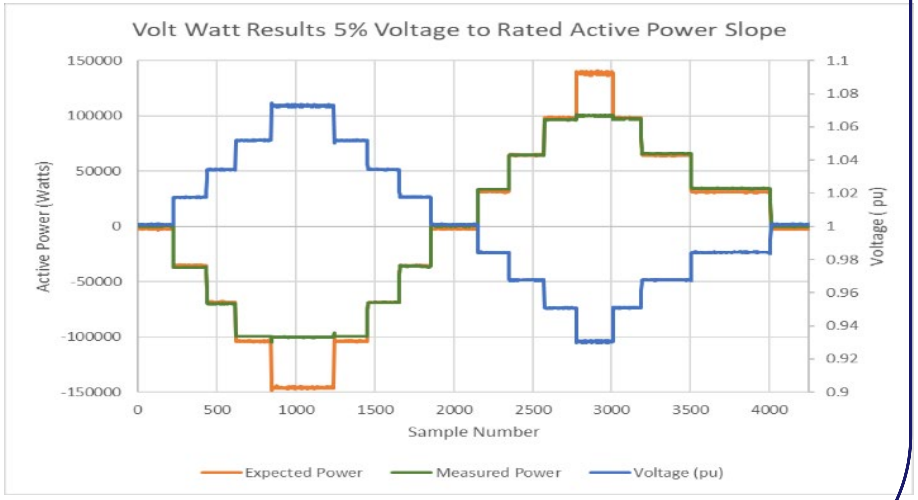
Smart Inverter FAT Tests

Test	Comments
Anti-Islanding	Tested at 100%, 66% and 33% Load
High Voltage Ride-through	Ride-through and trip settings confirmed for low and high voltage
High Frequency Ride-through	Ride-through and trip settings confirmed for low and high frequency
Fixed Power Factor	Tested at 0.85 and 0.91 capacitive and inductive power factor
Volt VAR	Tested for aggressive dead-band for charging and discharging modes
Frequency-Watt	Tested at minimum and maximum dead-band at 33%, 66% and 100% charging and discharging modes
Volt-Watt	Tested for minimum and maximum dead-band for 100% charging and discharging
Ramp Rate and Reconnection	Soft ramp-rate tested for max active and reactive power
Voltage and Frequency Droop	The droop function was tested at various droop slopes
MPPT	MPPT was tested for the PV connection

Factory Acceptance Test Results – Grid Forming

Voltage Droop

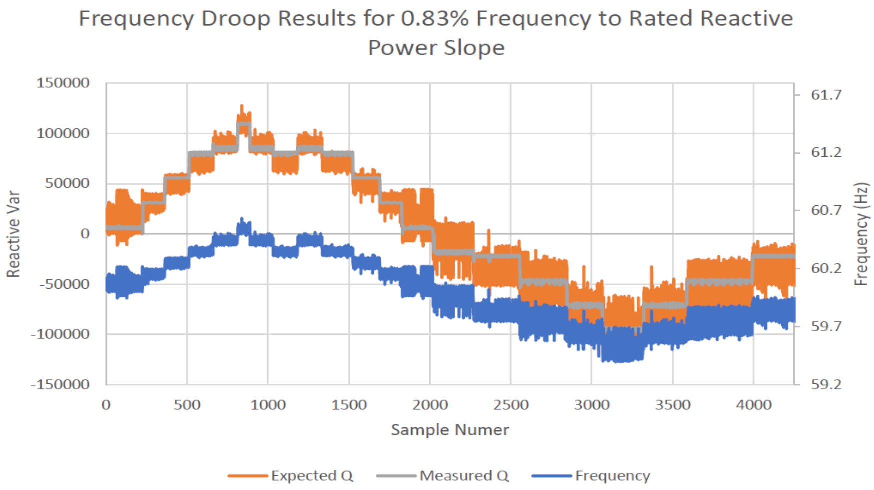
- ❑ As more active loads come on, output voltage drifts away from nominal
- ❑ Slope of droop curve set as $\%\, V / P_{rated}$



Voltage droop for 5% rated voltage to rated active power slope

Frequency Droop

- ❑ As more reactive loads come on, frequency drifts away from nominal
- ❑ Slope of droop curve set as $\%\, Freq / Q_{rated}$

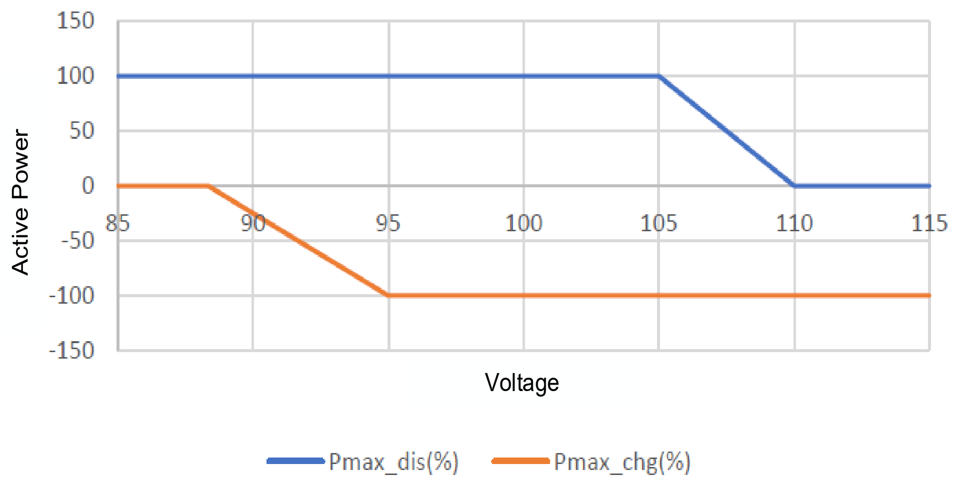


Frequency droop results for 0.83% frequency to rated reactive power slope

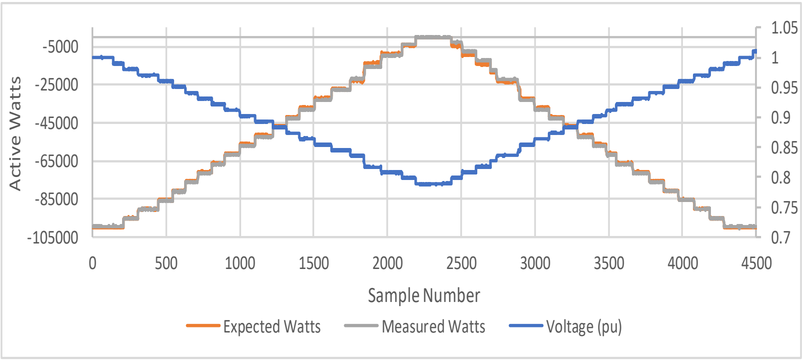
Factory Acceptance Test Results - Grid Following

Volt-Watt Mode

- Inverter limits maximum power output (charge/discharge) as a function of measured voltage at the output terminals
- Deadband - set by user in % of rated voltage



Example of Volt-Watt mode power envelope



Vwatt_VhiStart (%) = 101 Prated/HiVolt = 5
Vwatt_VloStart (%) = 99 Prated/LoVolt = 5

Volt-Watt test result for full discharge operation

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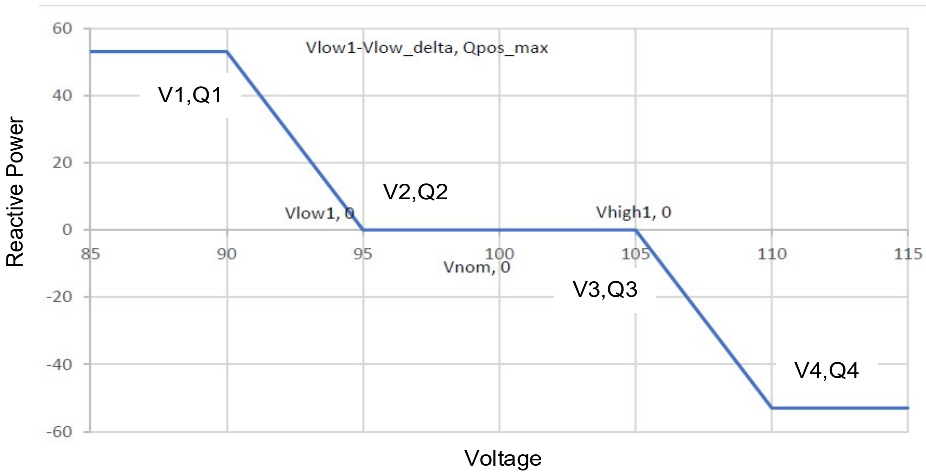
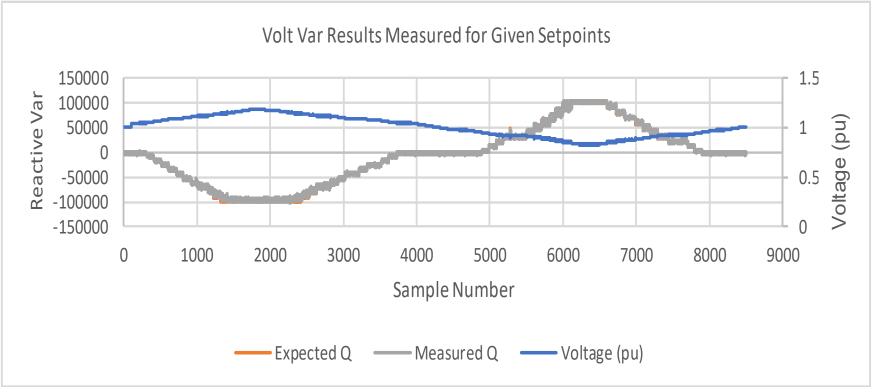
Factory Acceptance Test Results - Grid Following

Volt-var Mode

- ❑ Reactive power reference generated as a function of measured voltage at the output terminals
- ❑ Deadband - set by user in % of rated voltage by defining four voltage and corresponding reactive power set points



Example of setting for Volt-var mode



VoltVar_V1(%) = 90	VoltVar_Q1(%) = 100%
VoltVar_V2(%) = 95	VoltVar_Q2(%) = 0%
VoltVar_V3(%) = 105	VoltVar_Q3(%) = 0%
VoltVar_V4(%) = 110	VoltVar_Q4(%) = 100%

Volt-var results for given setpoints

Conclusion

- Results of the first implementation of RDC control algorithm on large-scale commercial inverter have been successfully validated for BESS and PV
- Inverter functionalities in both stand-alone and grid-tied mode tested in conformance with UL1741-SA and beyond
- The inverter has since been tested in PHIL mode with a simulated microgrid model in RTDS
- This project helped provide insight into the response of the inverter to grid scenarios
- Further investigation is needed to demonstrate the impact and benefits of multiple inverters connected to the grid

Questions …

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