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

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SUMMARY

The increasing penetration of renewable distributed energy resources (DER) is introducing new challenges to the operation and control of the power grid. This is especially true for microgrids which have high penetration of DER typically with less inertia. Previously, a robust droop control (RDC) technology has been designed and developed to overcome this challenge through smart inverter controls. This paper focuses on demonstrating the first implementation of this advanced smart inverter design into large-scale high-power inverter product with grid support applications. Specifically, the factory acceptance test (FAT) process and results for a 100kW smart inverter with robust droop control (RDC) technology are presented. The validation of RDC for solar PV and battery energy storage systems (BESS) applications are demonstrated, which provides the foundation for testing the inverter in advanced microgrid applications.

KEYWORDS

Smart inverters, power hardware in loop (PHIL), droop control, voltage droop, frequency droop, robust droop control, PV inverter, battery inverter

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INTRODUCTION

The increasing penetration of renewable distributed energy resources (DER) is introducing new challenges to the operation and control of the power grid, especially within the context of microgrids which have generally lower levels of inertia [1-2]. Unlike synchronous generators which inherently support the grid via inertia of the rotor and turbine, inverter-based generators do not contribute to system inertia without special control schemes. As a result, the system can become unstable due to high rate of change of frequency in the absence of physical inertia from generation machines, a situation that can be observed in microgrids without enough inertia. One solution is to emulate synchronous machine capabilities as basic frameworks for governing power-electronic based systems [3].

In Chicago, ComEd - an electric utility company - is building the Bronzeville Community Microgrid (BCM), which will interconnect with a microgrid on the campus of Illinois Tech creating the first utility-operated microgrid cluster in the USA. The microgrid is expected to serve more than one thousand customers aggregating to a load of approximately 7MW. The state-of-the-art microgrid cluster will include DERs including solar PV, battery energy storage and dispatchable generation for islanding operation from the utility grid.

As a part of the project, ComEd is developing a microgrid integrated solar-storage technology (MISST[1]) to develop and demonstrate scalable and cost-effective technology for integrated solar PV and energy storage through a hierarchy coordinated control approach[1]. The proposed technology addresses the availability and intermittency inherent in solar PV sources. The first stage involves local control with advanced smart inverter functionalities that are integrated into the central coordinated control using the microgrid master controller.

With a high penetration of DER, inverters need special control for maintaining system stability, power balance and fault ride-throughs in the system. In addition to this, with the proliferation of inverter-based resources, there is a need to effectively operate them in parallel, especially during load sharing. In general, grid connected inverters are expected to perform four quadrant operations by providing active and reactive power as per desired set-points or to respond to changes in grid voltage/frequency through droop control [4].

In the traditional power system, droop control is used by the generators to share load. Following the same philosophy, emulating droop characteristics in inverters operated in parallel can result in sharing load proportional to the inverter ratings. While many methodologies have been proposed, sharing linear and nonlinear loads in proportion to inverter ratings is still challenging. For inverters to share load in proportion to their ratings, two conditions are required: 1) when using conventional droop control, the inverters need to have the same internal per-unit impedance, and 2) the inverters need to have the same root mean square (RMS) voltage set points. In AC microgrids, due to line impedance mismatches, there are imbalances in reactive power sharing. Therefore, several droop techniques have been proposed to overcome challenges associated with power sharing, speed of transient response and dependence on line impedance. These include virtual-impedance loop-based droop, adaptive droop and robust droop [3].

A novel droop control algorithm for proportional load sharing among inverters operating in parallel called robust droop control (RDC) was developed by Q.-C. Zhong, which is independent of disturbances, noises, numerical errors, parameter drifts, component mismatches and feeder impedances [5]. As part of the SHINES-MISST project[1], this technology has been implemented for the first time into a 100 kW level, three-phase bidirectional commercial inverter, and factory tested for both grid forming and grid following applications based on existing grid codes. This paper presents the implementation of the RDC on large scale inverter, and successfully validates the technology with both BESS and PV in grid connected and grid following modes. In the next section the RDC algorithm will be briefly introduced along with the challenges associated with its implementation in the inverter, and steps taken to overcome these challenges. Following the hardware testing setup, the results section will provide validation of the RDC for solar PV and BESS application. This work is an important part of the proposed Microgrid Integrated Solar Storage Technology being developed in ComEd Bronzeville Community Microgrid project.

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ROBUST DROOP CONTROLLER

The robust droop controller [5] is a universal controller which is independent of inverter output impedance or the RMS voltage set points [6]. Due to this, the controller provides accurate proportional load sharing and is robust against disturbances, noises, numerical errors, parameter drifts, component mismatches and feeder impedances. The RDC provides voltage regulation for voltage drop due to load effect and that due to droop effect. RDC implements the frequency droop and voltage droop to regulate system frequency and voltage and can be equipped with an inherent self-synchronization mechanism [6].

RDC Overview

The universal droop controller is applicable to any inverter with an impedance angle in the range $\left(-\frac{\pi}{2},\frac{\pi}{2}\right)$ radians. For systems with predominantly resistive output impedance, a correlation is observed between 1) active power and voltage (positive correlation), and that between 2) reactive power and frequency (negative correlation) (1)-(2) [5].

$$P \approx \frac{E-V_o}{Z_o} V_0 \quad and \quad Q \approx -\frac{EV_o}{Z_o}\delta \tag{1}$$

$$P \sim E \quad and \quad Q \sim -\delta \tag{2}$$

where, P and Q are the active and reactive power transferred from the inverter source, E is the RMS value of reference voltage and V_0 is the RMS output voltage. δ is the phase angle difference between the reference and the output voltage while Z_0 is the output impedance. Using the above, the dynamic representation of the droop principle can be represented as:

$$P-V\ Droop\colon \quad E = K_e(E^* - V_0) - nP \tag{3}$$

$$Q-f\ Droop\colon \quad \omega = w^* + mQ \tag{4}$$

where, E^* is the rates RMS output voltage, ω^* is the rated system frequency, n and m are the droop coefficients, and K_e is the amplifying coefficient. Proportional active power sharing can be ascertained using the same value of K_e for all inverters operating in parallel. According to the P-V droop, the terminal voltage of the inverter decreases when active power is generated and vice-versa. In the Q-f droop, frequency increases if reactive power is being generated (capacitive) and vice-versa. These relationships are counter-intuitive and are applicable to any physical resistive system like the distribution system [6].

Due to the effectiveness of the above algorithm, it was implemented in a 100kW, 480VAC bidirectional inverter originally designed for battery energy storage (BESS) applications. Its functionality was extended to solar PV applications with MPPT control.

Power Stage and Inverter System Topology

For prototyping the RDC algorithm in medium power applications, the firmware of a bidirectional inverter originally designed for grid-connected battery energy storage applications was updated. The firmware was custom designed and built to implement the RDC.

The topology of the three-phase bi-directional 100kW inverter is shown in Figure 1. The device has a built in isolation delta-star transformer. Filter inductance were installed on the delta and star side respectively along with AC capacitor banks. The DC bus voltage ranges between 50Vdc-835Vdc.

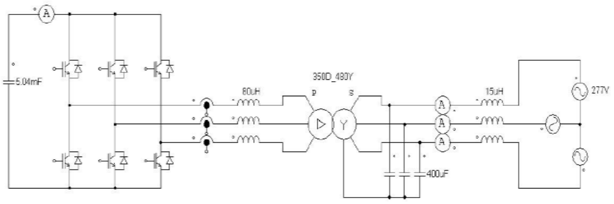


Figure 1.Topology of 100kW bi-directional RDC inverter

Controller stage for RDC

The inverter is controlled using NI Single-Board RIO General Purpose Inverter Controller (GPIC) that offers the flexibility of NI Labview for rapid prototyping. The control stage for the RDC algorithm implemented in this inverter is shown in Figure 2 [6]. The grid following and grid forming modes can be determined by the states of the switches S_p, S_q and S_c. The P_d and Q_d represent the grid-forming modes for the inverter. The control circuit uses advanced digital signal processing (DSP) to operate, monitor and protect the power conversion system (PCS).

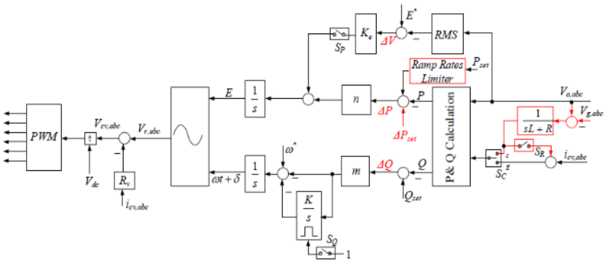


Figure 2. Control stage of the robust droop controller (RDC)

The unit could be operated remotely from a remote controller/HMI interface through a TCP/IP communication link using the Modbus protocol.

IMPLEMENTED SMART METER FUNCTIONALITIES

The RDC smart inverter is designed to operate in grid-connected or grid-forming modes of operation with solar PV or BESS, which is applicable to microgrids. The modes of operation are shown in Table 1. For application with solar PV, MPPT (Maximum Power Point Tracking) function was added to the inverter.

Grid-forming or Stand-Alone Mode

In the grid forming mode, the inverter (along with DER) forms the grid. The unit operates as an AC voltage-controlled voltage source inverter. During this mode the voltage droops as a function of active power and the frequency droops as a function of reactive power, which is uniquely inhenrited by the RDC design [5].

Grid-following or Grid-Tied Mode

In the grid-following mode, the system synchronizes with the grid (AC line). The unit operates as a current controlled voltage source inverter. Several smart inverter functions like Volt-Watt, Volt-VAR, frequency-Watt, fixed power factor, normal and soft ramp rates, anti-islanding and auto-reconnection have been made available in this mode. It is worth noting that the droop functionalities may be activated in grid-forming mode but this would entail disabling all other grid-following smart inverter functions. In droop mode, voltage and frequency dictate the operating point. Therefore, other grid-following modes cannot be activated.

The PCS is designed to operate between 88%-110% of the nominal line voltage. The AC output meets the requirements of IEEE Std. 519-1992 for voltage and current power quality [7].

Table 1. 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

Therefore, in the grid-connected mode, the control inputs are active and reactive power. In the stand-alone mode, the operator controls the voltage and frequency set-point. In the MPPT mode, the inverter runs perturb-and-observe type MPPT algorithm on its DC bus tied to PV. The active rectifier function needed to regulate the DC bus was built by adding a PI controller that takes the DC bus voltage command from the MPPT algorithm and measures the DC bus voltage that is used as a feedback. The output of the PI controller is then fed to the RDC controller as the P_{set} command (Figure 3).

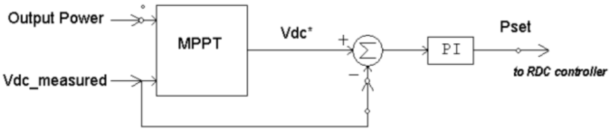


Figure 3.Outer loop for PV-MPPT mode Controller with RDC

FACTORY ACCEPTANCE TEST SET-UP

The inverter was tested using a grid simulator in power hardware in loop to conform with UL-1741 SA [9] as well as other functions beyond. For example, the droop functionalities are beyond existing standards, they were also tested. Data including frequency, voltage and current, active and reactive power, and power factor was recorded using a power analyzer. The test set-up is shown in Figure 4. A unique thing about this set-up is that power is circulated in the circuit such that the grid supplies only the losses in the system.

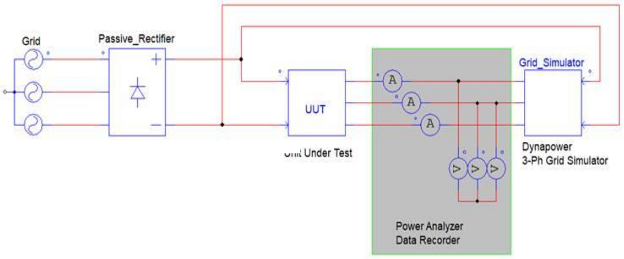


Figure 4. Factory acceptance test set-up

FACTORY ACCEPTANCE TEST RESULTS

Grid Forming Mode

In the grid forming mode, the voltage and frequency droops are tested. As more active loads come online, the output voltage drifts away from nominal. The slope of the droop curve is set to

$10\%\ V/rated\ P$, meaning a 100% change in active power will cause a 10% change in output voltage. User can set the slope ranging between 1%-100%. Voltage droop test for 5% voltage regulation was performed and the results are shown in Figure 5.

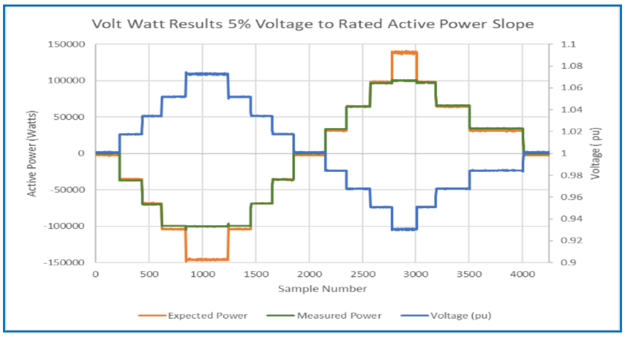


Figure 5. Voltage droop for 5% rated voltage to rated active power slope

Similarly, as more reactive loads come online the output frequency drifts away from nominal. The slope of the droop curve is set to $1\%\ Freq/rated\ Q$, meaning a 100% change in reacactive power will cause a 1% change in output frequency. The user can change this slope in the range 0.25% to 10%. Frequency droop test for 0.83% frequency regulation was performed and the results are shown in Figure 6.

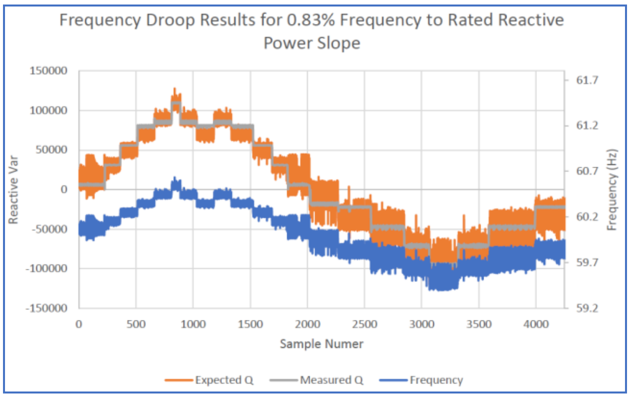


Figure 6. Frequency droop results for 0.83% frequency to rated reactive power slope

Grid Following Mode

Smart inverters have the capability of supporting the grid by providing active and reactive power through different functionalities. By activating a certain functionality the inverter is capable of alleviating a voltage or frequency issue. A comprehensive test plan was followed to fulfill the UL-1741 SA requirements [8]. Some of the results of the factory acceptance test follow.

Volt-Watt Mode

In this mode, the inverter limits its maximum output power (charge/discharge) as a function of measured voltage at its output terminals. The user can set a deadband in % of rated voltage defined around the nominal, and the gradients on the high/low sides to define the slope of power curtailment in % rates kW/% rated Volts. An example of these settings is shown in Figure 7. While several tests were performed for conformance, the results for one of the settings (displayed on the graph) have been shown in Figure 8.

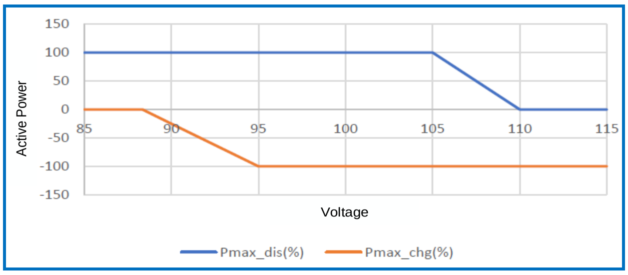
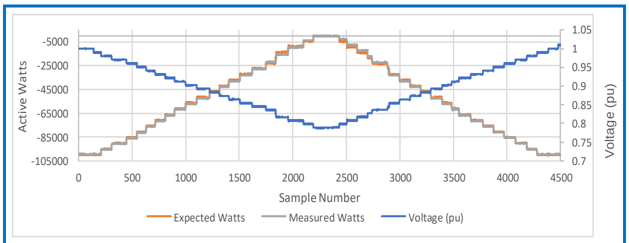


Figure 7. Example of Volt-Watt mode power envelope



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

Figure 8. Volt-Watt test result for full discharge operation

Volt-VAR Mode

In this mode the reactive power reference is generated as a function of grid voltage at inverter terminals. If fixed power factor mode is enabled, the inverter ignored the reference generated by this command. The user needs to set the deadband (% of rated Volts) by defining four voltage and corresponding reactive power set points as shown in Figure 9. The results for one of the settings (shown below the graph) are shown in Figure 10.

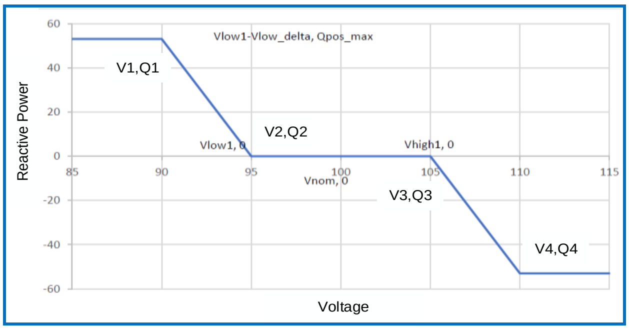
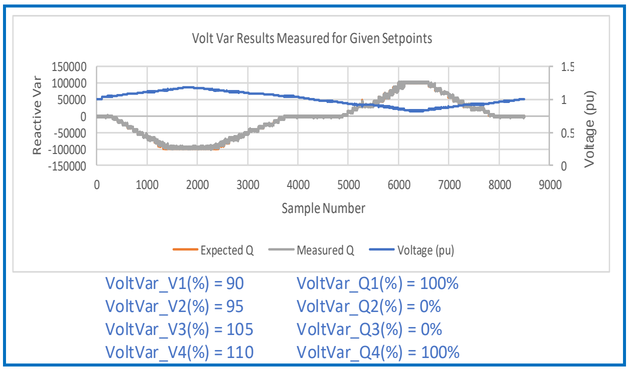


Figure 9. Example settings for Volt-VAR mode



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

Figure 10. Volt-Var test results for the given setpoints

Frequency-Watt Mode

The inverter limits its output power as a function of grid frequency. The output power is curtailed based on a user input in % of Prated per Hz, where Prated is the rated active power level at the PCS. Very similar to the Volt-Watt case, the user needs to define a deadband (Hz) and gradients on low/high side which defines the power curtailment in % of rated kW per Hz. The results for a sample setpoint is shown in Figure 11.

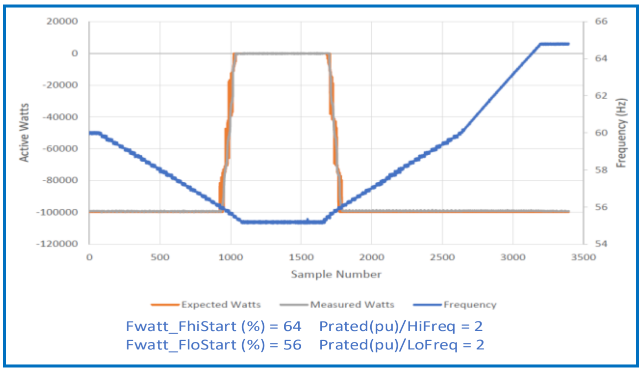


Figure 111. Frequency-Watt results for the given setpoints

Fixed Power Factor

In this mode generates the internal reactive power command as a function of active power output to operate the unit at a specified power factor (pf) measured at the inverter output terminals. The power factor can be set as either inductive (negative) or capacitive (positive) in the range 0.85-1.0. Figure 12 shows the results of changing set-point of the power factor between 1 and 0.85 capacitive with inverter set to discharge at 100%. The active power dispatch is reduced to make room for the reactive power when *Q-priority* is enabled. This is specifically noticeable when operating in non-unity power factor.

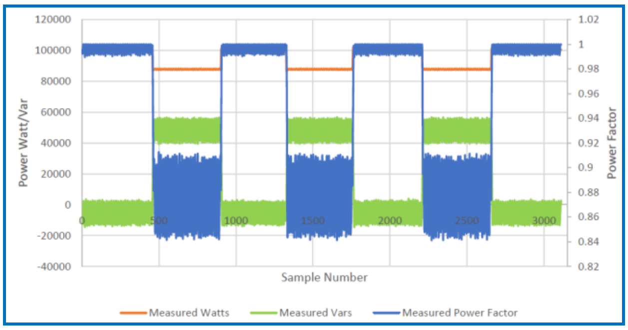


Figure 122. Results of 0.85 capacitive power factor commanded at 100kW discharge case

Soft Ramp Rate and Auto-Reconnect

The auto reconnect feature ensures that the PCS will enter a 'Reconnect' state instead of a 'Faulted' state in the event of a grid fault. The PCS will stay in this state until the grid comes back to the nominal voltage and frequency at which time the internal timer starts counting down. Upon expiration, the PCS automatically resynchronizes to the grid, reconnects and resumes operation at the pre-fault set-point (Figure 1313). Additionally, there is additional function called soft ramp rate that limits the

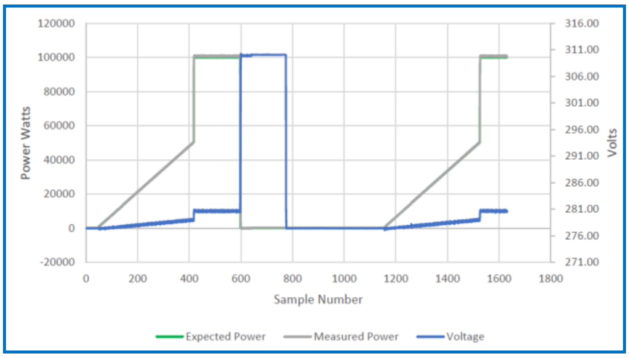


Figure 133. Results of ramp rate and reconnection

ramp rate of the inverter during initial connect or reconnect events as can be seen in Figure 13. This helps in reducing the stress on the grid in the events when large amount of the inverter-based generator come online at the same time.

CONCLUSION AND FUTURE WORKS

This paper presented the first implementation of RDC control algorithm on large scale commercial inverter and successfully validated the control technologies for BESS and PV in both grid connected and islanded mode respectively. The smart inverter functionalities were tested in conformance with UL1741-SA as applied, with additional functions specicially provided by RDC technology.

Having successfully tested in the factory environment, this work will be extended to test the inverter in power hardware in loop (PHIL) environment with a simulated microgrid model in RTDS (Real Time Digital Simulator) using a test setup. The RTDS simulates a grid or a part of the grid such as microgrid in real-time, and the node in the microgrid where inverter connects is emulated using a four-quadrant grid simulator that is connected to the inverter under test. This will allow us to monitor and understand the response of the inverter in various real grid scenarios such as voltage disturbance events and so on. It facilitates study of impact of such inverters and their control on operation and control of distribution system and microgrids, and also demonstrate the benefits of having such inverters.

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