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COMMANDING INVERTERS TO ESTABLISH COORDINATED μGrid FUNCTIONALITY AT SANDIA NATIONAL LABORATORIES

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ABSTRACT

Expanded testing capabilities at Sandia National Laboratories Distributed Energy Technologies Lab (DETL) now include a single phase μGrid research test bed platform. This reconfigurable μGrid topology test bed platform is being utilized to evaluate control strategies and communication algorithms and associated issues applicable to high penetration of distributed resources on the grid. To demonstrate coordinated μGrid functionality, battery based Xantrex inverters were integrated in a μGrid configuration along with custom centralized LabVIEW generated virtual Energy Management System (EMS) software to provide system wide control. Enhanced μGrid cooperation was implemented by invoking control schemes based on existing Xantrex inverter command sets issued over a standard communication interface. Inverter cooperation was achieved without additional modifications to embedded software. This paper outlines test configuration and results for cooperative storage management and voltage support scenarios.

INTRODUCTION

Modern μGrids and associated communications and control capabilities add value and will enhance the deployment of large amounts of distributed resources on the grid in a safe, reliable and efficient manner. Several industry efforts are underway to develop μGrid components and control strategies. With support from the US Department of Energy (DOE) Systems Integration program, Sandia National Laboratories has developed a single-phase μGrid at the DETL to demonstrate the effectiveness of μGrids, and to serve as a research and development platform for system components and control algorithms. See Figure 1 for aerial view of the DETL facility. The DETL single-phase μGrid is based on Xantrex XW 6000 Hybrid Inverters integrated with a virtual EMS control system, PV generation, three battery banks, and controllable loads.

This paper outlines test configuration and results for two test scenarios: (i) Inverters Commanded to Manage μGrid Battery Storage where inverters are controlled to cooperatively prevent loss of μGrid flexibility that occurs as battery voltage levels reach unacceptable high/low levels as excessive power in μGrid flows into or out of the utility interfacing inverter battery, and (ii) Inverters Characterized while Supporting μGrid Voltage where the cooperative capability of battery based inverters help support μGrid voltage is characterized. Both test scenarios were accomplished through the application of additional centralized control schemes implemented with virtual EMS software that can issue commands to the inverters and loads without any need to modify inverter functionality. During these scenarios all control originates at the EMS with no direct communications between inverters required. The inverters also adhere to UL1741 [1] standard throughout each test scenario.

Fig. 1 Photo of the DETL facility and surrounding PV resources on 2.5 acre complex at Sandia

TEST METODOLOGY

Present industry efforts are exploring implementation issues regarding utilizing either localized, centralized, or distributed control methodologies that efficiently and safely provide the link between distributed generation in multiple μGrids. Localized μGrid control systems can operate on a peer-to-peer basis with no master control or communications. Instead local control at each generation location is implemented, without the need for awareness of other generation locations, to maintain voltage and frequency stability. An example of this approach is voltage droop control methodology.

Centralized µGrid control systems can be configured to operate from centralized, or master control node, located within proximity of the µGrid to ensure access to essential communications. Individual generation sources are not in direct communications for predefined normal operation but are controllable via communications with the central node. The test scenarios in this report are examples of centralized control. One advantage envisioned with a central control approach is that systems can be setup to mimic conventional electrical grid behaviors such as dispatching bulk power at the µGrid level.

As deployments of µGrids continue, the need for dynamic interconnections among multiple µGrids and back to the conventional electrical grid will require a multitude of decisions be made communally by all the Distributed Energy Resources (DER) and the loads associated to each of the µGrids. This perceived requirement aligns well with the fundamental concept behind distributed agent-based control. A fully distributed control system is appealing since it could be more secure because it has no single point of failure and few if any communication links. Other agent based control initiatives are exploring alternate power systems control schemes whereby distributed load-side control software agents facilitate µGrid stability via load profile management. The test scenarios in this report implement examples of centralized load control, not distributed. However, Sandia is conducting research into investigating these complex agent-based controls concepts.

TEST CONFIGURATION

Both test scenarios documented in this report use the same test setup configuration and components consisting of custom centralized LabVIEW generated virtual Energy Management System (EMS) software controlling the single phase µGrid research test bed platform residing in the DETL facility. These major test configuration components are described below in this section in the following order; DETL facility, test bed platform, and the EMS software.

DETL Facility

Sandia National Laboratories operates DETL for the Department of Energy (DOE). This facility performs development tests with inverter manufacturers, subjecting commercial products to standardized tests to benchmark their performance, and evaluating their operation as system components. This activity has resulted in significant improvements in inverter product reliability and performance.

The configuration of the DETL facility is an intentionally flexible topology that can be reconfigured as required for different customers and applications. This adaptable resource is also being applied to address a variety of issues related to the more general field of distributed energy resources. Independent test stations have been established for single-phase standalone, single-phase grid-connected, three-phase standalone, and three-phase grid-connected DER. All battery banks are wired so that they can be used for different tests as required and the surrounding PV arrays are configured so that they can either be aggregated or segmented depending on test requirements.

Single-Phase Grid Test Bed

The single-phase µGrid test bed developed to support general µGrid studies served as the platform to conduct the cooperative storage management and voltage support scenarios. See Figure 2 for the single-phase µGrid test bed one-line electrical diagram and Figure 3 for a photo of the main part of the test bed. The test bed interconnects the local utility grid with independent fuses and relays for loss of utility simulation with three Xantrex XW 6000 Hybrid Inverters with independent fuses and relays for isolation and independent batteries, two solar array inputs, and three load branches also with independent fuses and relays for isolation. See Table 1 for a list of the equipment comprising single-phase µGrid test bed.

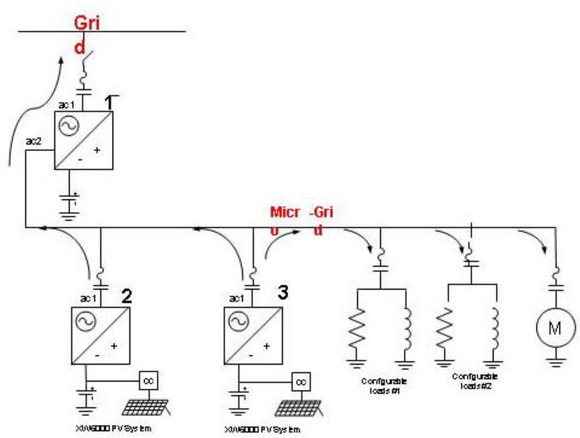

Fig. 2 Electrical one-line diagram of Single-Phase µGrid Test Bed

The single-phase µGrid test bed is wired to enable distributed generation sources to satisfy load requirements while diverting any excess power to the utility through the utility interconnected Inverter 1. Inverters 2 and 3 are commanded to sell a pre-determined amount of PV power to the interconnected bus, labeled Micro-Grid, after their local batteries have been charged to a desired maximum safe voltage level. During testing Inverter 1 interfaces with the utility grid, while Inverters 2 and 3 cooperate to supply the load connected to the µGrid bus. Inverter 1 exports power to the utility through the utility interconnect if excess power is generated. The inverters are able to share load equally or turn on-and-off in a staggered fashion as commanded to increase efficiency. In this test bed configuration, the pre-selected utility-interactive Inverter 1 acts as a master to the other two only for islanding detection and voltage regulation of the µGrid bus and not for any storage management functionality.

Table 1: Single-Phase µGrid Test Bed equipment characteristics description

Component	*Capacity/Rating*	*Description*
Inverters	**3 each 6 kW Inverters**	**Xantrex XW 6000**
PV Arrays	**3.5 kW Inverter #2** **3.5 kW Inverter #3**	**Xantrex Charge Controller 3kW** **Xantrex Charge Controller 3kW**
Batteries	**50 kWh VRLA for Inverter #1** **6 kWh VRLA for Inverter #2** **6 kWh VRLA for Inverter #3**	**Absolyte IIP battery 100A-25** **Absolyte IIP battery 50A-075** **Absolyte IIP battery 50A-075**
Controllable Load	**50 kW R adjustable** **50 kVar L adjustable** **50 kVar C adjustable 1Hp motor with dynamometer load**	**Avtron Resistive load Bank** **Avtron Inductive load Bank** **Simplex Capacitive load Bank** **Dynamometer load system**
Utility Interface	**60 amp, 120/240 V**	**Dedicated 50kVA transformer**

Fig. 3 Photo of the main part of the Single-Phase µGrid Test Bed

Fig. 4 Screen copy of EMS µGrid Display module

Virtual Energy Management System (EMS)

Custom LabVIEW generated virtual Energy Management System (EMS) software was developed to provide a centralized control node to issue system wide commands. See Figure 4 for a copy of the main EMS control screen. The EMS program consists of four modules; the µGrid Display, System Control, Sequencer, and Diagnostic modules. The µGrid Display module function replicates the electrical 1-line diagram with interactive operator control features, the System Control module function exposes all Inverter operating parameters, normally manually entered on a keypad, for automated setup, the Sequencer module function provides means of creating a sequence of steps with defined actions occurring at prescribed times, and finally the Diagnostic module function offers system status information.

Basic embedded control capabilities of the Xantrex inverters allow for connection of up to 6 inverters to a local bus in several configurations and control modes. However, only 3 inverters were used to demonstrate the cooperative storage management and voltage support scenarios. Control commands to inverters are issued through a dedicated, proprietary Xantrex data and control bus (XANBUS). The EMS issued µGrid controls through DETL's Ethernet-based communications infrastructure which were then converted by a Communication Gatewy to the required XANBUS protocol for delivery.

A use case is a sequence of events that describes one way to use a system and how a system user reaches a goal. There may be several different scenario variations within each use case, all directed towards reaching the same goal. Use case scenarios were developed for the cooperative storage management and voltage support demonstrations. See Figure 5 for the use case scenario detailing what sequence is required to maintain safe Inverter 1 battery operation. The use cases were used to guide development of the EMS system control flow. The ten actors depicted in the use case and their representative roles are listed below the diagram.

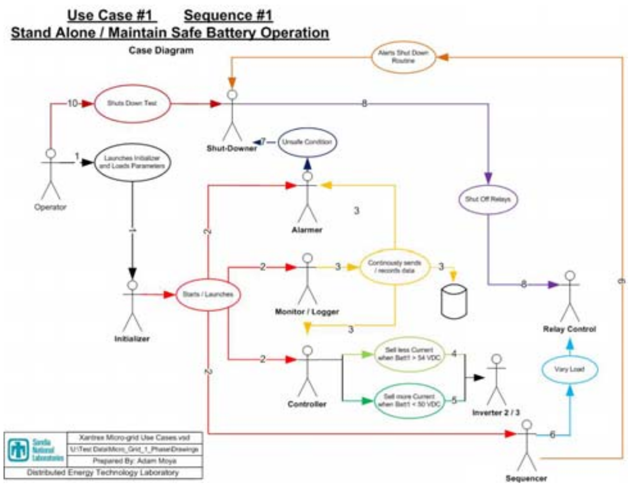

Fig. 5 Use Case scenario detailing sequence to maintain safe battery operation

EMS Actor List

1. μGrid test operator (Operator) Performs Initialization and Shutdown procedures and post data analysis
2. μ-DAQ automated control system stimulus (Controller) Control routines that perform the logic to maintain the safe μGrid operation.
3. μ-DAQ monitoring (Monitor\Logger) Software to constantly monitor the μGrid and provide data to the Controllers and Watchdog. Logs Data to file.
4. Alarm watchdog (Alarmer) Software routine to watch for detrimental μGrid events and perform an automated shutdown if necessary.
5. μ-DAQ device sequencer (Sequencer) Software routine that injects a stimulus at defined times. This is typically switching loads or utility connection to determine how the μGrid reacts.
6. Initializer with checklist (Initializer) Software and manual setup routines to get the system ready for normal operation.
7. Test completer (Shut-Downer). Software routine that will shut off the μGrid to be followed by a checklist for the operator to verify the shutdown and turn off any equipment that requires physical operation.
8. Inverters 2\3: Control power from the PV to the μGrid.
9. Inverter 1: Controls large battery storage, μGrid power, and μGrid to Utility Control
10. Relay Control: Initiates relays to engage the loads, Inverters, and utility connection

TEST SCENARIOS

Inverters Commanded to Manage μGrid Battery Storage

In this scenario inverters were controlled to cooperatively prevent loss of μGrid flexibility that occurs as battery voltage levels reach unacceptable high levels. The unconsumed energy in this specific topology charges the battery. If the μGrid lacks system level management a transition to an undesired state in which μGrid regulation is lost and unrecoverable battery damage occurs. However, initial results show the virtual EMS successfully managing the μGrid during varying PV generation cycles and loading conditions. Continuous μGrid operation independent of state of charge and the amount of unconsumed energy was achieved. EMS sequence steps issued during this scenario are listed below.

1 Operator Launches the Initializer and Loads parameters for the scenario.
2 Initializer starts and launches the monitor, Sequencer, Controller, and Alarmer.
3 Monitor Systems continuously sends data to Controller and Alarmer. Logs Data to file.
4 When Battery 1 > 54 VDC Inverter 2 and 3 are instructed to sell less current.
5 If Batt1 < 50 Inverters 2 and 3 are instructed to sell more current.
6 Sequencer tells the Relay Control Utility to set relays to Vary Load. This can be based on time of day, sequence time, or by a conditional. This simulates varying load conditions which may or may not correspond to PV generation.
7 Alarmer Senses an Unsafe Condition and Calls the shutdown routine.
8 Shutdown routine tells the Relay Control Utility to shut off all relays.
9 Sequencer Alerts Shutdown routine that the test has expired.
10 Operator Commands the shut down routine to stop the test.

Figure 6 shows μGrid stability resulting from successful battery charging cycle control when excess energy from sources is available. Virtual EMS control is exercised with excessive power flowing into battery 1 that caused battery 1 voltage to approach and exceed a preset level of 54 volts. As shown, the EMS decreases the output power of inverter 2 and 3 to maintain a safe battery 1 voltage, which allows the μGrid to remain on and stable.

Inverters Characterized while Supporting µGrid Voltage

In this scenario the cooperative capability of battery based inverters to support µGrid voltage was characterized. The goal was to depict how current control mode inverters respond to the typical µGrid bus voltage sags resulting from varying block load conditions. The virtual EMS controlled application of various resistive and inductive load ramping profiles while recording µGrid transition conditions. Initial results indicate that limited voltage support was exhibited by a series of battery based inverters configured for current support mode. A similar sequence of EMS steps were issued to accomplish this scenario but are not listed here for brevity.

Figure 7 details the limits of inverter support of the µGrid voltage during varying load conditions. The virtual EMS could be programmed to limit load rate of change to maintain µGrid stability.

SUMMARY

Sandia National Laboratories has successfully demonstrated using virtual EMS system commands to safely manage µGrid battery storage and characterize inverter response to varying load profiles. An approach of invoking control schemes implemented with existing commands issued over standard communication interfaces without modifications to embedded software can enhance µGrid operation.

ACKNOWLEDGEMENTS

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REFERENCES

[1] UL1741, UL Standard for Safety for Static Converters and Charge Controllers for Use in Photovoltaic Power Systems, Underwriters Laboratories, First Edition, May 7, 1999, Revised Jan 2001.

Fig. 6: Plot of voltage and power signals of Inverters commanded to manage µGrid battery storage

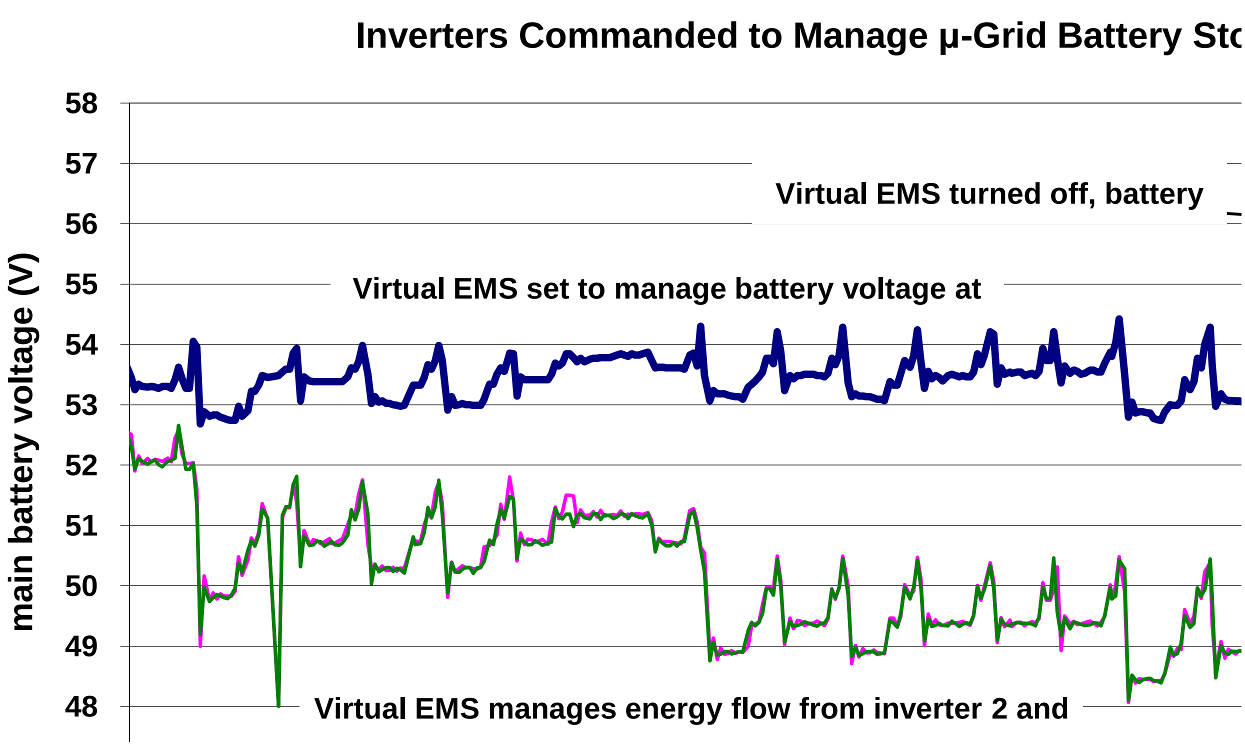

Fig. 7: Plot of power signals during characterization of Inverters supporting μGrid Voltage