Abstract

The Distributed Energy Communications & Controls (DECC) Laboratory is a unique first-of-its kind R&D facility for testing reactive power producing distributed energy resources (DE). Reactive power doesn't perform work like real power, but it is necessary for energizing inductive and capacitive loads and for supporting voltage and preventing voltage collapse. Reactive power occurs when reactive loads (capacitors or inductors) are present and voltage and current are out of phase. When reactive power is present, current either lags (when reactive power is being consumed) or leads (when reactive power is being produced) the voltage. Real (or active) power, which does work, is only present when voltage and current are in phase. However, when voltage and current are out of phase, greater overall power capacity (due to the vector sum of real and reactive power) is needed to get the same level of real power and do the same level of work. The laboratory is exploring the use of both rotating (generators, motors) and static-based (inverters) Distributed Energy (DE) technologies for producing reactive power for supporting voltage and correcting power factor both locally and on the campus distribution system.

The goal of the laboratory is to work with the power industry, manufacturers, and universities in developing local control for producing reactive power from reciprocating engines, microturbines and fuel cells using synchronous generators and inverters. The laboratory is fully operational with an area for testing and operation of a 300kVar synchronous condenser (250hp synchronous motor operated unloaded and overexcited) and an inverter testing area. The inverter testing area is capable of testing an inverter either off the grid using resistive and reactive load banks or on the grid by interfacing with the ORNL distribution system via a 480V/600A distribution panel to a 750kVA transformer connected to a circuit from the 3000 substation. Three different ratings of three-phase programmable inverters, 75A (62kVA), 150A (125kVA) and 300A (250kVA) are available for testing and will have already run tests with the two lower rated inverters.

Introduction

Alternating Current (AC) is supplied in a 60Hz (60 cycles per sec) waveform. Reactive power is produced when the current waveform is out of phase with the voltage waveform due to inductive or capacitive loads. Current lags voltage with an inductive load, and leads voltage with a capacitive load. Only the component of current in phase with voltage produces real power which does work. Current is in phase with voltage for a resistive load, like an incandescent light bulb. Reactive Power is necessary for producing the electric and magnetic fields in capacitors and inductors.

The additional current flow associated with reactive power can cause increased losses, excessive voltage sags, and increased power capacity requirements. Transmission system operators have to ensure that reactive reserves are available to handle system contingencies such as the loss of a generator or transmission line because increased current flows after the occurrence of these types of contingencies can produce greatly increased reactive power absorption in transmission lines. Some transmission system operators are now considering new rules for distribution systems which require a minimum allowable power factor. These minimum power factors could reduce the amount of reactive reserves that the system operator would have to provide. Distributed Energy Resources (DE) could be ideally suited for providing reactive reserves in the distribution system.

DE, includes such resources as microturbines, reciprocating engine generators, and fuel cells. DE is often installed at or near electrical loads for local power and to take advantage of CHP (cooling, heating and power) benefits that come from waste heat recovery of DE by thermally-activated technologies. With the right control scheme and algorithms, DE could be controlled to supply local reactive power and to regulate local voltage. Some DE devices utilize synchronous generators, which can be directly connected to the local power system, and some, such as fuel cells or microturbines, must be interfaced to the local power system through an inverter because they produce DC or high-frequency AC that must be converted to 60Hz AC. Similar to a synchronous generator, the inverter can also be designed and controlled to "inject" reactive power locally and regulate voltage. Thus, a DE with a synchronous condenser or inverter could supply reactive power reserves.

The Oak Ridge National Laboratory (ORNL) has established the Distributed Energy Communications & Control (DECC) Laboratory which is a new and unique first-of-its kind laboratory for studying reactive power supplied from DE. ORNL is unique in that it owns and operates its own electric distribution utility for the laboratory campus, and can configure the distribution system to provide opportunities for testing of reactive power injection effects from the laboratory. The ORNL distribution system is directly fed by the TVA 161kV backbone transmission system. The laboratory and project are also unique in that the tests are designed by representatives from the electric utility industry and DE manufacturers to address the actual challenges faced by DE and utilities currently and in the future.

The DECC project has the overall goal of developing methods of incorporating distributed energy (DE) that can produce reactive power locally and for injecting into the distribution system. The objective for this new type of DE is to be able to provide voltage regulation and dynamic reactive power reserves without the use of extensive communication and control systems.

DECC Laboratory

The DECC Laboratory has been established for studying reactive power supplied from both rotating and power electronic-based DE. The electrical design and layout of the Reactive Power Laboratory is shown in Figures 1 and 2. Figure 1 shows the laboratory's interface with the ORNL distribution system while figure 2 shows the layout at the laboratory itself. The laboratory is located at the north end of the Oak Ridge National Laboratory campus at building 3114. The test areas of the laboratory are in the building while the transformers and load banks are just to the east of the building. The laboratory equipment interfaces to the ORNL distribution system through two different distribution circuits (#4 and #2 fed from ORNL's 13.8/2.4kV Distribution Substation 3000). The rotating-based DE of the laboratory consists of a 300kVar synchronous condenser (l250hp synchronous motor unloaded and overexcited) which is fed from circuit #4. The power electronic-based DE of the laboratory consists of an inverter test area which is fed from circuit #2. The test area currently has a 150A inverter for testing and previous tested a 75A inverter. Both areas of the laboratory are fully functional as of February 2006.

The laboratory includes the following equipment:

- 250hp synchronous motor for use as a synchronous condenser
- 75A, 150A, and 300A programmable inverters
- Two 750kVA 2.4kV/480V pad-mount transformers for interfacing to circuits #4 and circuit #2 of the ORNL 13.8/2.4kV distribution network at the 3000 Substation
- 480V/900A three-phase electrical panel configuration for the 250HP synchronous condenser interface (via a 450A motor starter) to the ORNL 2.4kV distribution circuit #4
- 480V/600A three-phase electrical panel configuration for the inverter interface to ORNL 2.4kV distribution circuit #2

- Dranetz/BMI PowerGuide 4400 Meters; one located at the motor/starter and the second at the electrical panel.
- Yokogawa WT3000 Digital Power Meter
- Danfysik Ultrastab 866 Current Transducer Systems, one for measuring the synchronous condenser output currents, a second for measuring the inverter output currents and a third for measuring the load bank currents.
- Matlab/Simulink and Real-Time Workshop software for design voltage regulation and power correction control algorithms for the synchronous condenser and inverters
- dSpace real-time control hardware and software for implementing autonomous feedback control for the synchronous condenser and inverter
- 150kW dc power supply for the providing DC voltage to the programmable inverters
- 6.6kW dc power supply for providing excitation to the synchronous condenser
- Resistive (0 to 500kW in 1kW steps) and Reactive (0 to 300kVar in 3.75kVar steps) load banks with remote control
- Portable resistive load bank (0 to 100kW in 1kW steps) for use on either power panel
- 75HP Induction Motor for use as a dynamic load

Important capabilities of the laboratory include:

<u>Testing Areas:</u> The laboratory provides testing capability of rotating (generator or motor) and power electronic or static (inverter) based DE. Also, the laboratory has the capability to test vendor provided reactive power producing DE, such as a microturbine or reciprocating engine.

<u>Distribution Interface:</u> The laboratory interfaces at two different electrical locations on the ORNL distribution system. This provides the capability to test single or multiple reactive power producing DE and also their interaction. The DE devices can be connected in parallel (by using both power panels) or in series (by using only one power panel).

<u>Substation:</u> The reactive power compensation at the substation can be relaxed to provide a more severe testing scenario for the laboratory. Shunt capacitor banks at the substation provide power factor correction for the ORNL distribution system. The reactive power compensation can be relaxed by switching out some of these capacitor banks. Presently, the substation has 900kVar of reactive power compensation in capacitor banks in units of 150kVar.

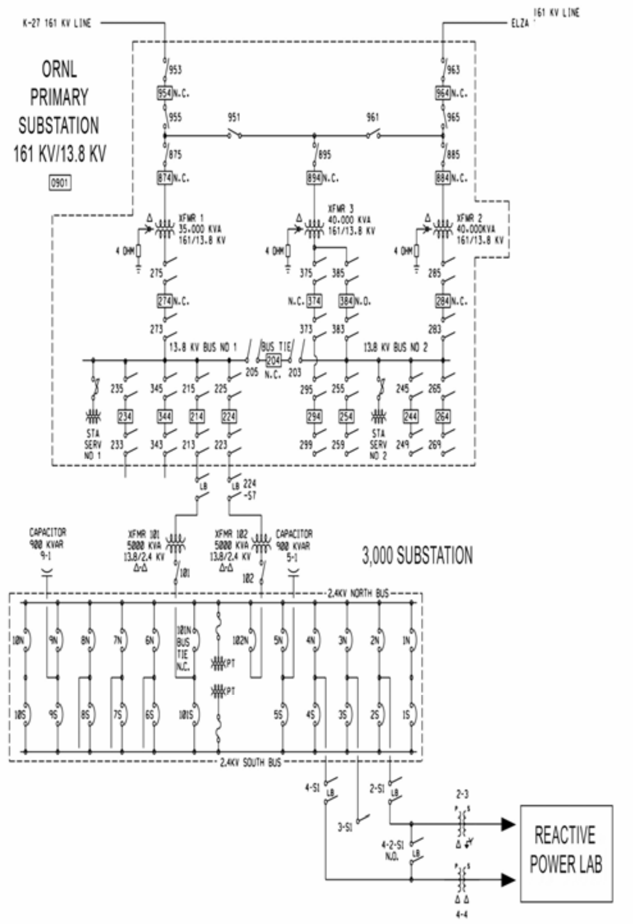


Figure 1. DECC Laboratory Interface with the ORNL Distribution System.

Distribution and Power System: The laboratory interfaces with the TVA grid through the ORNL distribution system. The TVA transmission lines provide power to ORNL at 161kV and it is stepped down to 13.8kV at ORNL's substation. Secondary substations, such as the 3000 substation, which provides the electrical interface for the laboratory, steps it down further to 2.4kV. Our ownership of the distribution system allows the capability to vary loading and reconfigure the distribution feeder circuits for testing different operating scenarios at the DECC Laboratory.

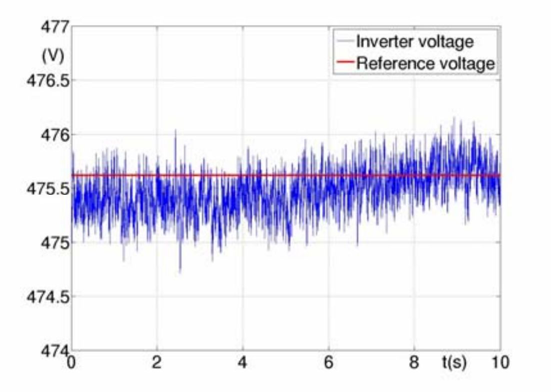
Figure 2. Reactive Power Laboratory Layout

Test Results - Simultaneous Operation

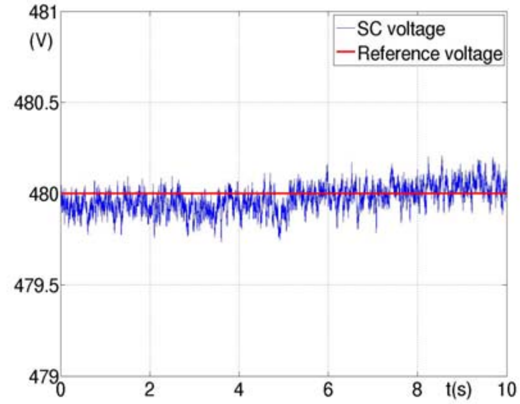
On Wednesday, September 6th 2006, the final FY06 milestone for the reactive power producing Distributed Resources (DR) effort was met more than three-weeks ahead of schedule with the simultaneous operation of the 150A (125kVar) PowerEx Inverter and 300kVar Synchronous Condenser (a large synchronous motor operating unloaded and overexcited). Both the Inverter and Synchronous Condenser (SC) were controlled by the dSpace real-time control hardware and software system to regulate line voltage locally at their respective power panels. Each device regulated their local voltage independent of the other. The real-time controller used control algorithms that ORNL designed using the Matlab/Simulink environment.

The successful parallel operation of the two reactive power producing DR devices in our testing is an important first step towards using multiple DRs to provide dynamic voltage regulation. The operation of multiple DRs under local control for voltage regulation on the same distribution system/circuit is vital for its use on distribution circuits of the future. These future circuits will depend on DR devices to provide most if not all of the reactive power needs of a circuit, such as 6 MVars of a 10MVA feeder. The DR devices must operate so that they don't interfere with each other or with the current protection practices and hardware of the distribution system. Our testing is laying the groundwork for "Rules of Thumb" for this new DR paradigm which gives DRs another added value both in utility system support and cost benefit.

The voltage regulation results are shown in Figure 1. During the simultaneous operation, the inverter was operated at a reactive power output level of around 36.5kVar while the SC was operated at an output level of around 45kVar as shown in Table 1. Both devices were set to regulate their local line voltage, and they did this independent of the other. The inverter was set to regulate its average ac line voltage (average of the three phase-to-phase voltages, Vab, Vbc and Vca) at 475.6 or 2 volts above the unregulated line voltage as shown in Figure 1a and indicated in Table 1. The synchronous condenser was set to regulate its average ac line voltage at 480V or approximately 2 volts above the unregulated line voltage as shown in Figure 1b and indicated in Table 1. In the case of the inverter, regulation was achieved by setting the inverter's DC voltage to 790Vdc via the 144kW power supply and then using our feedback control to regulate the output of the inverter to increase/decrease voltage to maintain the reference set point of 475.6V. The inverter was operating at 12.5kHz and so could respond in microseconds to any voltage changes. In the case of the synchronous condenser, our feedback control increased/decreased DC from the 6.6kW power supply to adjust the SC's excitation appropriately to regulate the SC's output to maintain the reference set-point voltage of 480V. The SC is obviously much slower than the inverter due to its large inertia but could respond in milliseconds to voltage changes.



(a) Voltage regulation by the inverter at power panel PP3 of the laboratory.



(b) Voltage regulation by the SC at power panel PP2 of the laboratory.

Figure 3. Local voltage regulation by the inverter and SC on September 6th.

Table 1. Key parameters for the simultaneous DE operation on September 6th.

Parameter	Inverter (125kVar)	Synchronous Condenser (300kVar)
AC Distribution System Interface	ORNL Circuit #2 Power Panel PP3	ORNL Circuit #4 Power Panel PP2
Voltage without regulation (V)[1]	473.7	478.2
Voltage with regulation (V)[1]	475.6	480.0
Current Output (A)[2]	44.5	54.0
Reactive power output (kVar)	36.5	45.0
% of Device Rating[3]	29.2	15.0
Losses (kW)[4]	3.0[5]	5.5[5]
% losses[6]	8.2	12.1

[1] *Average of the three phase-to-phase RMS (root-mean-square) voltages before and after the inverter and SC are controlled to regulate their local voltage.*

[2] *Average of the three line RMS currents from the device.*

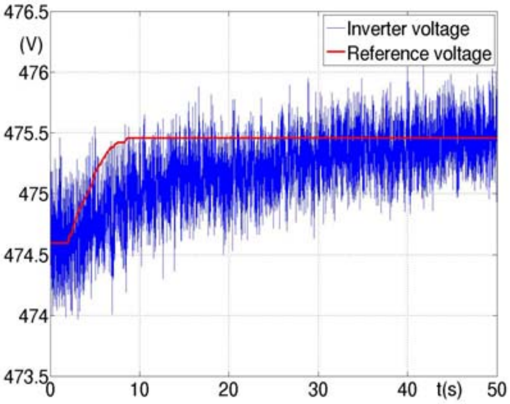
[3] *kVar output divided by the device's rated kVar in percentage. The150A rated inverter ideally could provide around 125kVar if all of its thermal cooling (for the IGBTs) is satisfied. From previous testing, the SC (synchronous motor overexcited and unloaded) was found to be capable of producing just over 300kVar.*

[4] *The DR's losses for producing the needed reactive power output. The losses include the DC power needed by either inverter or SC along with the active power consumed from the ac distribution system.*

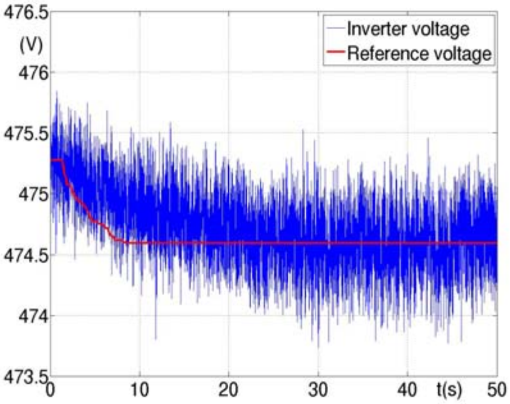
[5] *The inverter consumes 5 kW of active power from the DC power supply while injecting 2 kW to the distribution system. The SC consumes 1 kW from the DC power supply and 4.5 kW of active power from the ac distribution system.*

[6] *Ratio of losses divided by the kVA (square root of kW squared plus kVar squared) in percentage. The % losses for the SC fall to around 6% when the unit is operating at 36% or higher output. The losses for the inverter should fall as well and reach lower than 5% when the unit is operating above 50% of rating and lower than 3% when the unit is operating above 75% of rating.*

The dynamic response of the inverter and SC to a step change in the voltage reference during the parallel operation was also tested. Figure 2 shows the inverter's response to a 1-volt increase and then a 1-volt decrease from the original reference point. Figure 3 shows the SC's response to a 2-volt increase and a 5 volt decrease. Even though, the response is for a voltage step change, a similar response would be expected for a step change in load requiring the SC or inverter to increase/decrease their output in similar fashion.



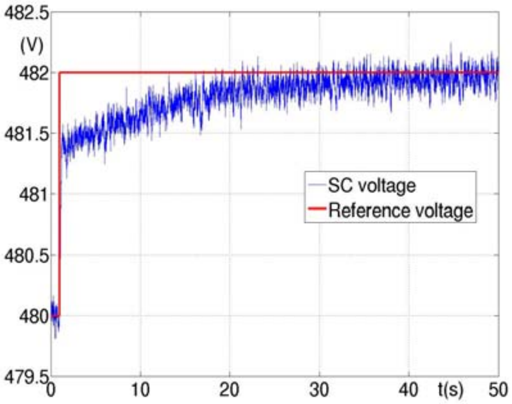
(a) Dynamic response of inverter to a 1V increase in voltage reference setting.



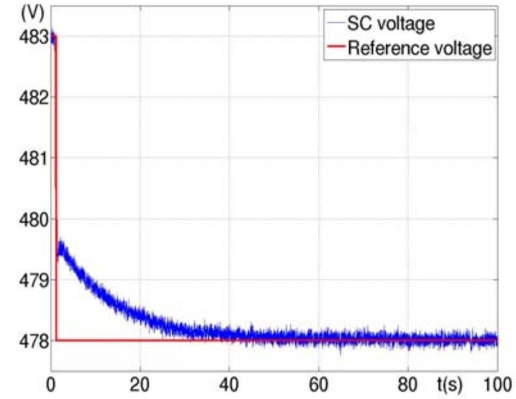
(b) Dynamic response of inverter to a 1V decrease in voltage reference setting.

Figure 2. Dynamic response of inverter to a step change in the voltage reference.

The control variables are the gains of the PID (proportional, integral, differential) feedback controller for the two devices. The objective is for the two devices to dynamically output reactive power to regulate voltage to closely match the reference voltage. The tradeoff is that the gains of the controller need to be adjusted to achieve a fast response but with minimal over/under-shoot of the inverter/SC voltage regulation when the reference voltage changes (either due to load changes or because of a change in regulation setting). The feedback control that was used for the simultaneous operation of the inverter and SC on September 6th used a PI controller and the gains were adjusted as indicated earlier. As shown in Figures 2a and 2b, it took about 30s for the inverter voltage to reach a steady operating point around the reference setting after a 1 volt step change with the gains that were used for the inverter controller. As shown in Figures 2c and 2d, it took longer, around 40 to 60s, for the SC voltage to reach a steady operating point around the reference setting after a 2 to 5 volt step change with the gains that we used for the SC controller. The gains could be set higher to shorten the response time of either the inverter or SC however the tradeoff is an increase in the over/under-shoot of the controls.



(a) Dynamic response of SC to a 2V increase in voltage reference setting.



(b) Dynamic response of SC to a 5V decrease in voltage reference setting

Figure 3. Dynamic response of the SC to a step change in the voltage reference.

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