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Journey to a Flexible, Reliable Laboratory Platform for Simultaneous Control of Multiple Reactive Power Producing Devices

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Abstract

This paper discusses the instrumentation and control requirements for operating multiple distributed energy (DE) devices in parallel to regulate local voltage. The author and colleagues established a flexible laboratory control and data acquisition system that allows for the integration of multiple DE devices in Oak Ridge National Laboratory (ORNL)'s Distributed Energy Communication and Controls Laboratory (DECC). This paper details the development of the data acquisition and control system, problems encountered and solutions found. Although this paper details one particular example, the lessons learned are applicable to any test or measurement platform that uses real-time measurements.

The objective of the overall project is to develop controls with this flexible laboratory setup that allow DE devices to control local distribution system voltage through dynamic reactive power production. Originally efforts were made to control the reactive power output using data from commercially available meters designed for monitoring and analyzing electric power values. After the evaluation of various unacceptable methods of data acquisition and control, a flexible and capable real-time control system was chosen. This controller is commercially available and is easily programmable through Simulink and MATLAB's Real Time Workshop. The dSPACE controller together with the integration and instrumentation platform provides both the flexibility and expandability needed to integrate and control the reactive-power-producing devices under consideration.

Background

This paper deals primarily with the process of developing the laboratory setup and the lessons learned during that process, but a brief discussion of the overall goals and background of the project is in order. The objective of the overarching project is to develop control methods for regulating local voltages and power factor by supplying varying amounts of reactive power from DE sources. The need for additional reactive power reserves became apparent after the occurrence of blackouts such as the Northeastern Blackout of 2003 (Anderssen, 2005). A case has been made for providing this reactive power reserve from a variety of sources. The overall project intends to demonstrate the capability of DE devices, which are already being installed throughout the country, to provide this ancillary service (Campbell, 2005). The flexible platform detailed in this paper has the ability to test various control strategies for the injection of reactive power and regulation of voltage and power factor by DE devices. Multiple DE devices can be controlled for voltage regulation either working together on the same circuit or on neighboring circuits.

A literature survey did not yield any papers that detail the types of problems encountered in developing a flexible setup such as the one necessary for this project. However, Terwiesch (1999) does give some details about software problems to overcome using a dSPACE controller for real-time operations. A good resource for comparing power monitoring devices is found in Casada & Staunton (1996); however, it contains no information on how to interface these devices with a real-time controller. One purpose of this paper is to bring to light some hardware-related difficulties that are not adequately covered in available literature.

Active and Reactive Power

Understanding voltage control first requires a basic understanding of active and reactive power. Total apparent power is the vector sum of its two components, active power and reactive power. Resistive loads such as light bulbs use active power, while inductive loads such as magnets inside of motors absorb reactive power. When reactive power is supplied from capacitive loads it tends to elevate the voltage, while inductive loads tend to lower voltage. Voltages must be controlled by providing reactive power for system stability and to prevent voltage collapses. Both active and reactive power are necessary in alternating current (AC) systems (Taylor, 1999). This concept can be compared to the flight of an airplane. The distance a plane travels from one point to another is analogous to active power use by a load. Also, the plane must reach a certain altitude to find a smooth path of air to avoid obstructions in the terrain and to minimize turbulence. While the altitude at which the plane flies does not do any useful work to get the passengers to their destination, it is necessary for safe and comfortable airline travel. Therefore, inserting reactive power is similar to increasing the airplane's altitude. As the required voltage increases (or distance to travel for the airplane), reactive power (or the airplane's altitude) must increase. Reactive power is a necessary component in electricity flow just as altitude is necessary for an airplane to fly over obstacles (Li, 2006). A depiction of this relationship is shown in Figure 1.

Figure 1. Power triangle: vector sum of active and reactive power.

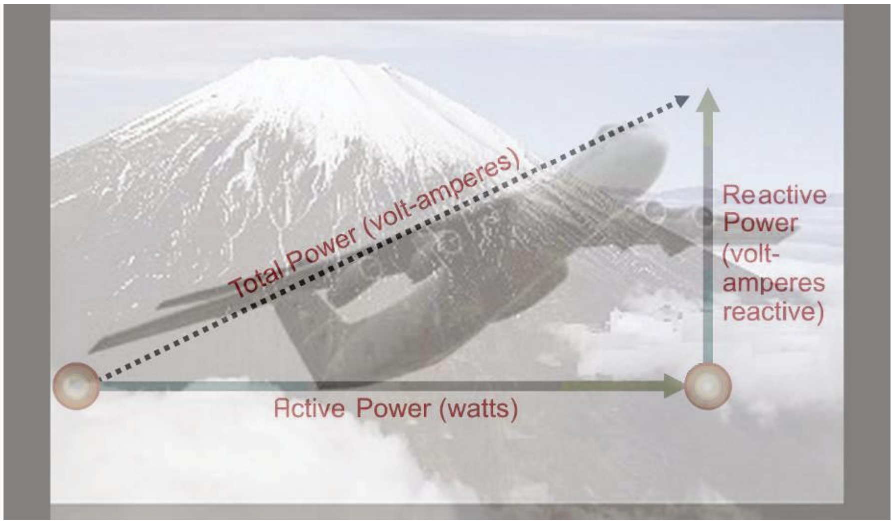
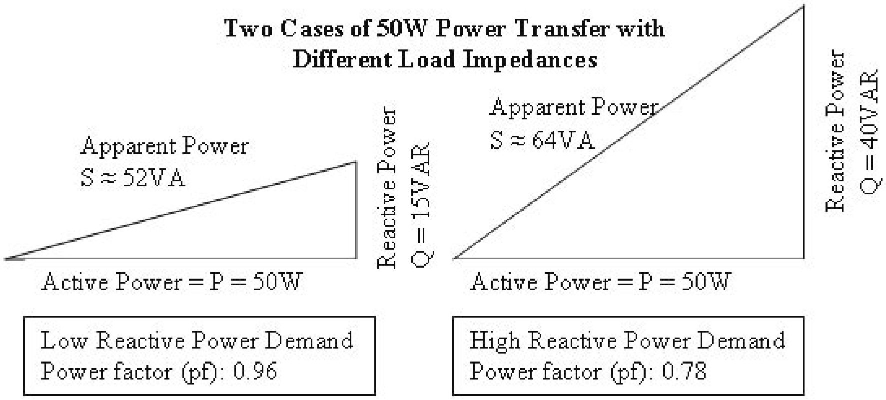


Figure 2. Effect of increased reactive power demand on total (apparent) power.



$$pf = \frac{P}{S} \qquad (1)$$

Reactive power is measured in volt-amperes reactive (VARs) and can be either "lagging," when current lags voltage, (corresponding to inductive loads), or "leading," when current leads voltage (corresponding to capacitive loads). Reactive power flow increases energy losses on power lines since the vector sum (apparent power) of reactive and active power is the instantaneous product of voltage and current. As apparent power increases and voltage remains constant, current must increase. Further, insufficient reactive power can result in excessive voltage sags, leading to potential voltage collapse and ultimately to the blackout of a power system (Li, 2006). In Figure 2 the importance of reactive power is quantified by two power triangles.

Both cases in Figure 2 show an active power (Watt) transfer of 50W. However, the two cases have very different reactive power needs. In the case where 15 VAR is required, the resultant apparent power is about 52 volt-amperes (VA). An additional 12 VA is needed when the reactive power requirement is increased to 40 VAR in the second case. Therefore, in this example, if the root-mean squared (RMS) value of voltage stays constant at 100 V_{AC}, the first case will need an RMS current of 0.52 A, while the second case will need an RMS current of 0.64 A. More than a 23% increase in current flow is needed to supply the same amount of active power to the load for these two different reactive power needs.

There is an enormous benefit from locally produced dynamic reactive power, as detailed by Kueck (2004 and 2006). Some of the benefits include the avoidance of financial penalties for low power factor imposed by utilities, increased capacity on transmission lines due to reduced current flow to provide the same amount of active power, and reducing the danger of voltage collapse through increased voltage support.

Distributed Energy Communication and Controls (DECC) Laboratory

The layout diagram of the DECC laboratory, represented in Figure 3, details the DE devices currently used in this project and the most important instrumentation needed for control. (Details of the power sources and cable routing are eliminated to simplify the figure.) Figure 4 shows photos of the synchronous condenser (SC) and inverter test areas in the laboratory.

Figure 3. Instrumentation and equipment layout of the DECC Laboratory.

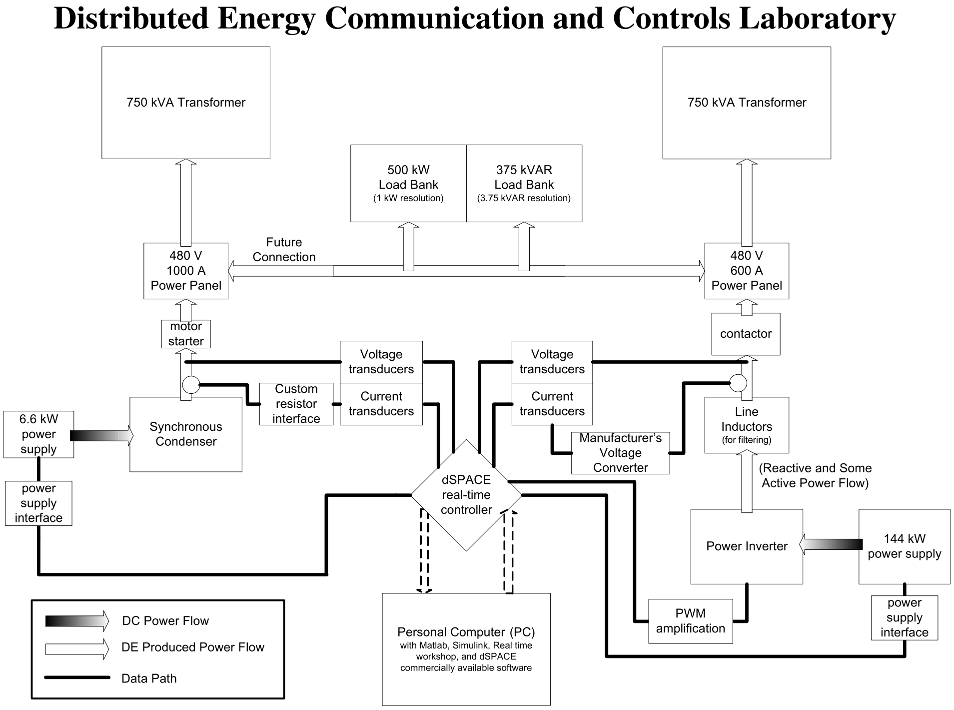


Figure 4. Photos of DE device testing areas in the DECC laboratory: the synchronous condenser test area (left) and the inverter test area (right).

(a) SC Test Area (b) Inverter Test Area

Two 750 KVA (delta-wye connected) transformers which are fed by the Oak Ridge National Laboratory (ORNL) distribution system provide electric service for the DE devices. Physically, the SC is interfaced with circuit 4 of ORNL's 3000 substation and the inverter is interfaced with circuit 2, also of the 3000 substation. The power panel for the SC via circuit 4 is rated at 1000 A and the power panel for the inverter via circuit 2 is rated at 600 A. Both of the power panels are three-phase 480V. The transformer tap settings on both services have been adjusted so that the nominal line-to-line voltage is around 475 to 477 V_{RMS} to provide a sufficient range for voltage regulation testing. This is important since the SC at maximum output is capable of raising its bus voltage to over 500 V_{RMS} even with the lower tap setting. A unique aspect of this laboratory is that ORNL owns and operates its distribution system, which is supplied by Tennessee Valley Authority (TVA). This ownership allows for the staging of unique test scenarios, including starting of large motors, and system reconfiguration to provide different load profiles in conjunction with the tests.

Description of Laboratory Equipment

The laboratory currently has several devices interfaced to the ORNL distribution system. The most important devices are listed in Table 1, which is followed by more detailed information.

A 250-hp synchronous motor (SM) is operated as a synchronous condenser (SC) capable of injecting up to 300 kVAR of reactive power because of the motor's high service factor. A synchronous motor operates as a synchronous condenser when the excitation voltage changes the motor's power factor from unity to leading. A SC is slow to react (tenths of a second), but is an important source of dynamic reactive power.

The lab has a power inverter station that allows a single inverter to be tested as well as allowing quick change-outs for testing various manufactures' inverters. The inverter creates AC voltage by converting it from DC voltage through a pulse-width-modulation-switching algorithm. During this conversion it is beneficial to produce voltage wave-

Table 1. Primary devices in the DECC Laboratory

Device	**Purpose**
Unloaded and Overexcited Synchronous Motor	Operates as a 300 kVAR Synchronous Condenser (SC)
62, 125, and 250 kVAR Programmable Inverters	Provides 75, 150 and 300A rated output and simulates output of inverter-based DE devices
144 kW DC Power Supply	Simulates the DC output of a DE device
6.6 kW DC Power Supply	Operates as an exciter for the SC
500kW & 375kVar Variable Load Banks	Provides manually switched dynamic loads with 1kW or 3.75 kVAR resolution
480 V/600 A Power Panel 480 V/1000 A Power Panel	Provides an interface for inverter output to ORNL distribution system Provides an interface for the SC output to ORNL distribution system

forms that will help to maintain the desired bus voltage and minimize voltage imbalance (Tolbert, 2005).

Two DC power supplies are installed in the laboratory. One serves as a power source for the inverter and the other serves as the adjustable excitation control for the SC.

Two adjustable load banks with remote manual control are connected at the lab to simulate dynamically changing loads and provide the lab with a flexible load profile. They can consume up to 500 kW and 375 kVAR in steps of 1kW and 3.75 kVAR, respectively.

The Journey Begins

As the project started, the controls method for the SC used only off-the-shelf, standard components. Originally, the plan was to test algorithms using simple controls in MATLAB and very intelligent sensors to quickly test possible control options. MATLAB, by The Mathworks, is a widely used software environment that uses a novel “MATrix LABoratory”-based programming language that allows a user to quickly prototype code. MATLAB also has many add-on packages called toolboxes that greatly extend the program’s capabilities. For example, the Real Time Workshop automatically compiles Simulink models into C code. After some viable controls methods were found, the process of integration into a dedicated controller could begin. This dedicated controller would simulate a control board similar to one included in a typical DE device installation.

Minimal Integration with Intelligent Sensors

Due to the desire to use intelligent sensors, a handheld power meter with a serial communication feature was used for data acquisition. A PC served as the controller, outputting the control signal in the form of a serial data stream to the DC power supply. Modulating the DC excitation voltage controls the reactive power output of the SC. Since a SC’s reactive power output changes slowly (tenths of a second), it was expected that some small communication delays would not be a major problem for testing control algorithms. Using a power meter with integrated serial communications was simple and thought to be sufficient for basic analysis of different control methods. The update was by means of an encoded file being written on the PC including all power, voltage, current, and power factor data. All of the data must be sent. The user has no choice in what data is sent to the PC. MATLAB scripts were needed for opening, reading, decoding, and closing the file, which added complexity to the programming. Fortunately, the MATLAB scripts took much less than the 300 ms data update time to execute, so there was no additional delay imposed by program run time. Although simple to implement, serial communication to the PC was far too slow to be used for data acquisition in this control system.

The next data acquisition system used to test controls for the SC was a much faster power-analyzing device. A desktop power analyzer was used with USB communication to the PC. Unfortunately, it was several weeks before the new data acquisition could be used in a test, because software had to be developed for the USB communications integration into MATLAB. Once implemented, an update rate to the PC of slightly less than 60 ms per sample was achieved. This device includes a way to stream only the data of interest to the PC, but it does not give the user the option to stop calculating values that are not needed.

Although the power meter and power analyzer are calibrated to have very little error, they do not provide very much flexibility. For the purposes of control, it is desirable to only measure and calculate the values that are necessary for the implemented control. In the case of the power meter, there was almost no way to access or modify the operation of the meter. In the case of the power analyzer, lots of custom programming needed to be done in order to use the USB data transfer in a control loop. Even with the USB communication, the transfer speed was not quite as fast as needed by the control algorithms. Further, there were no clear guidelines on how to interface many “intelligent” devices including the power meters directly or indirectly to the real-time controller that would model a standard control board on a DE device. Therefore, different sensors would be needed to interface with the real-time controller.

Analysis of Sampling Rates

A comparison of the data sampling rates, in Table 2, shows the benefit of not using intelligent power measurement devices. Internally, these intelligent devices have very fast sampling rates, but they do not export this raw sample data to be used externally. For the purpose of equitable comparison, the definition of sample time for the case of the power meter and power analyzer is the amount of time between data updates sent to the PC. For the dSPACE controller the definition of sample time is the amount of time between samples of the data. Data conversions in the dSPACE system occur on the order of nanoseconds and are negligible in comparison with the 60 Hz waveforms being sampled. Table 2 shows the great increase in measurement speed achieved by using the dSPACE system.

The dSPACE system's sampling rate is more than 850 times faster than the power analyzer's and more than 4200 times faster than the power meter's. Clearly the difference is that the dSPACE system allows for the actual waveform to be sampled many times every cycle and the intelligent devices only report RMS data about every 3 to 18 cycles.

Table 2. Sampling rate comparisons

Device	Sample Time	Data Reported
Handheld Power Meter	300 ms	Multiple Cycle RMS Data
Table-Top Power Analyzer	60 ms	Multiple Cycle RMS Data
dSPACE Controller[A]	70 µs	Sampled Waveform Values
[A]The sample time listed for the dSPACE system is the internal update time for variables in the controls algorithm during the independent but simultaneous control of two DE devices.		

Table 3. Transducer characteristics

Transducer	Rating	Response Time	Error	Steady-State Usage
Current	600A RMS	1 µs	< ± 1.5%	0-50% of Rated
Voltage	700V RMS	0.3 µs	± 0.2%	12-70% of Rated

Table 4.
Necessary input/output (I/O) for the control of the SC and power inverter

I/O	Location	Purpose
Three-phase line-to-line voltages	480V/1000A power panel feeding the SC	Used to compute the average RMS voltage and compare with the desired set point voltage in the controller.
Three-phase line-to-line voltages	480V/600A power panel output of the power inverter	Used to compute the average RMS voltage and compare with the desired set point voltage in the controller
Power supply set voltages	Analog input to both power supplies	Used to set the output DC voltage of the power supplies
Three-phase currents	Outgoing conductors connected to the AC output of the SC	Used for calculating power and regulating power factor (to be implemented)
Three-phase currents	Outgoing conductors connected to the AC output of the inverter	Used for calculating power and regulating power factor (to be implemented)
Power supply contactor control	Analog input to both power supplies	Used to remotely open and close the contactors that provide DC power to the DE devices

dSPACE Integration

An alternative to the intelligent meter is a real-time controller. On the surface, it seems that using the dSPACE system would be more complicated. However, the dSPACE controller provides extraordinary scalability and flexibility with a full complement of I/O options. Specifically, the dSPACE DS1005 processor board and the DS2003, DS2103, and DS5101 I/O boards were used. Figure 5 is a photo of the dSPACE system and interface boards. The PC is still used to develop the software for the controller but does not perform any control calculations. Because the control calculations are performed by the dSPACE real-time controller, the delay time to the PC is irrelevant.

Table 3 lists the voltage and current transducers used for measuring the operation of both the inverter and SC. Interfacing the outputs of these devices into the dSPACE system allows for only the necessary information to be sampled.

Table 4 gives an overview of the necessary connections for control purposes. Additional data is collected for diagnostic and data recording purposes, but is not included in the table. The dSPACE controller's analog-to-digital conversion circuitry digitizes the measurement samples far faster than the control program uses the data. Therefore, the data measurements are instantly available for use on every pass through the control logic.

Figure 5. dSPACE processor and interface boards.

Further, using the real-time controller enables the use of analog outputs for control of power supplies. Thus, the time delays experienced with serial communication to the power supplies were also eliminated. Further, the controller can open and close the power supply's output contactor remotely. A custom interface box that connects the 37-pin cable connection of the power supply's analog I/O port to the dSPACE controller (via individual BNC cables) was constructed so that the controller's various I/O modules could communicate with the power supply.

Synchronous Condenser

Upon initial integration of the SC with dSPACE the error in current measurements was far greater than expected. The manufacturer-provided interface box converted a current ranging from 0 to 400 mA (corresponding to a measured current of 0 to 600 A) to a voltage signal. The relative error (ratio of measured voltage minus actual voltage to actual voltage) appeared to fluctuate randomly in all the tests attempted. Table 5 gives the recorded current errors from one of these tests. Eventually, it was found that the output voltage from the manufacturer-provided voltage conversion box was so small that the controller could not record an accurate measurement from the current transducers (CT)s. In general all the voltages output from the manufacture's interface box were low: < 0.5V.

A custom resistor box was constructed with known resistor values to scale up the voltages to the range of 0 to 5 volts. The resistors were chosen to operate at a low power output to minimize nonlinearities in the measurements. After system integration using this custom resistor box (Figure 6), the error (approximately 2%) almost fell within the manufacturer's reported tolerances found in Table 3.

Table 5. Relative error In measurements before correction

Average RMS Current (A)	Converted Voltage (V)	Relative Error (With Manufacturer's Interface Box)			
		Phase A	Phase B	Phase C	Average
7.8	0.01	0.74%	21.15%	47.30%	23.06%
36.4	0.06	12.81%	9.84%	9.49%	10.71%
147.9	0.25	16.51%	13.85%	12.63%	14.33%
215.0	0.36	11.82%	9.84%	8.85%	10.17%

Figure 6. Layout for the custom resistor box.

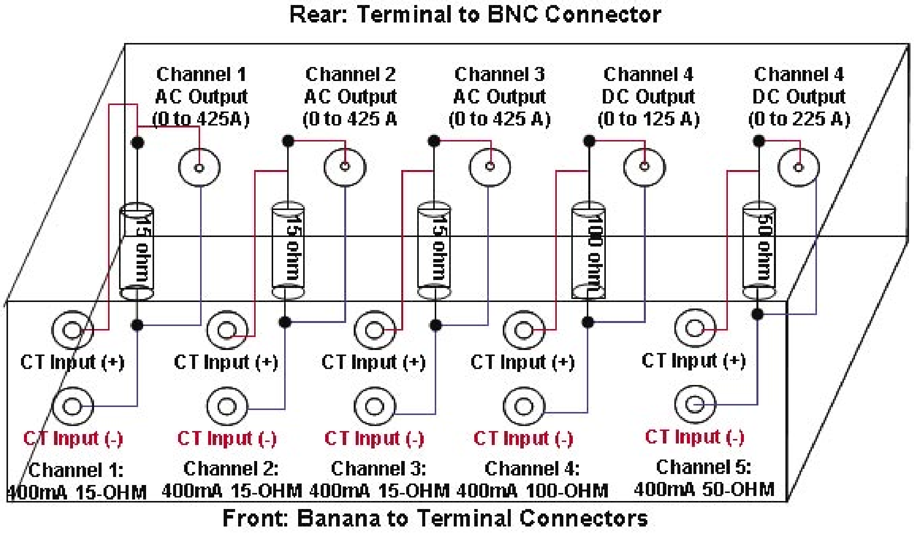
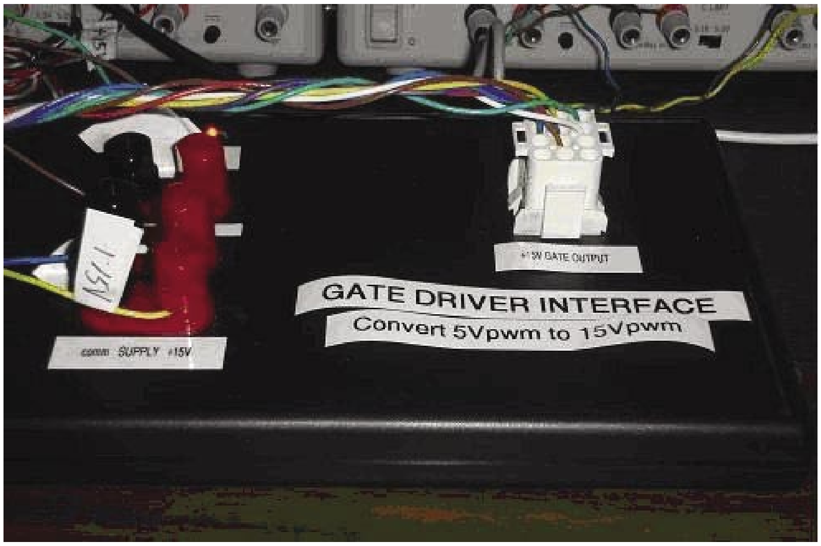


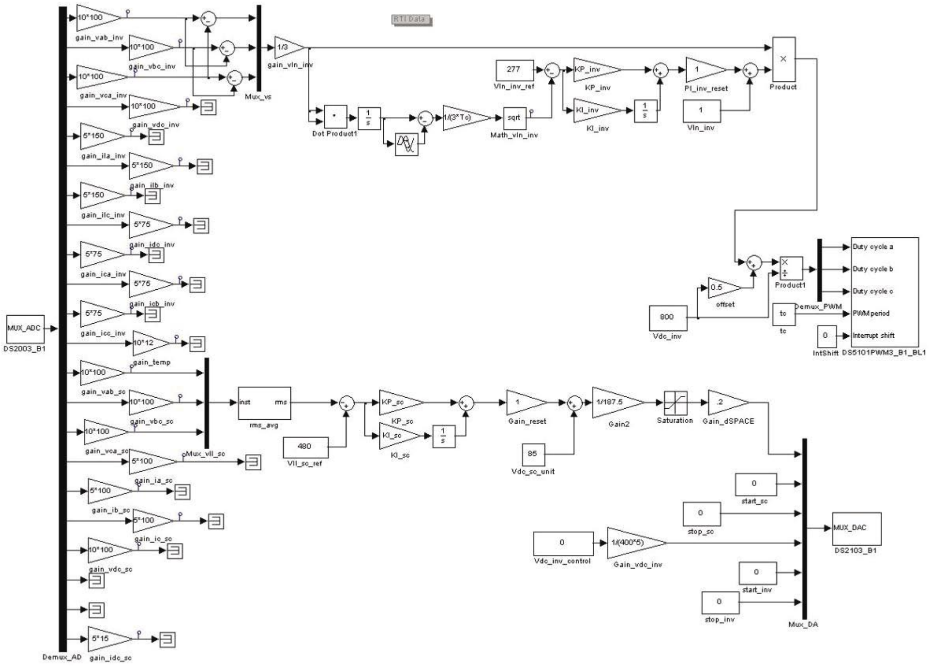
Figure 7. Gate driver interface for the power inverter.



Power Inverter

Although the inverter came equipped with on-board voltage and current transducers, the ones shown in Table 3 were used for the data acquisition in this project. The need for external transducers for inverter measurements was primarily motivated by extreme electromagnetic interference from high-speed switching of the power inverter's Insulated Gate Bipolar Transistors (IGBT)s. Electromagnetic interference, a characteristic of power electronic devices (EPRI, 1992), was amplified because of the lack of sufficient shielding on the programmable inverter. An additional custom interface seen in Figure 7 was necessary to interface the inverter with the real-time controller's pulse-width-modulation (PWM) outputs. The real-time controller can create an arbitrary 5-volt PWM output sequence. However, the power inverter's IGBTs require a 15-volt PWM signal and its complementary signal for proper switching. Therefore, the special conversion box shown in Figure 7 was constructed to produce the complementary signal from the 5-volt PWM signal and perform the amplification to 15 volts.

Figure 8. Independent functional control for two DE devices operated simultaneously.



SC and Inverter in Parallel

The goal for the flexible platform was the capability to operate multiple DE devices at the same time. The developed control process for these DE devices uses no communication with the substation or other DE devices. Each DE device is controlled independently to maintain a specific voltage or power factor at its output terminals using only information about its own local voltage.

A controller for each of the devices was created separately in Simulink (a graphical programming environment that is a standard add-on to MATLAB). More information about the controls follows in the next section. Once the controls for the two devices were running correctly individually, the two devices could be operated simultaneously with separate controls. The next step was to integrate two separate control schemes and all the associated I/O into a single dSPACE controller (because of the lack of a second dSPACE system). Fortunately, the only issue that needed special care was verification that all the appropriate I/O data connections were mapped to the correct controller channel in the new combined Simulink model. Figure 8 is a Simulink model including two separate proportional integral controllers in the same model file. This control diagram is one viable control method for the parallel operation of the SC and power inverter.

Control

This paper does not emphasize the specific control algorithms currently used because the purpose of the project is to evaluate a number of control methods. Ultimately the aim of the laboratory setup is to provide a test bed that allows multiple synchronous machines and/or power electronics-based devices to be tested with various control methods in a variety of system configurations. Further, these tests will be used to develop reliable rules of thumb to alleviate the need for expensive engineering analysis every time a new DE device is added or retrofitted to a utility distribution system for reactive power regulation.

Software

The dSPACE software includes a versatile block set for use with Simulink and MATLAB's Real-time Workshop for rapid code development. The real-time-integration block set seamlessly interfaces the individual dSPACE data acquisition and output units. Further, dSPACE includes software that allows a user to view in real time the measured values being input to dSPACE. An additional benefit of the Simulink environment is the user's ability to simulate the control methods so that a good assessment of the validity of the control algorithms can be made before an actual test is conducted. One essential thing to note about the control is that devices can be controlled separately even in the same controller. Figure 8 shows that there is no sharing of information or I/O between the two controllers, which ensures completely independent control.

Proportional Integral Feedback Control

Proportional integral (PI) feedback control has been used for some tests because it is a well known control method and is adequate for basic control of the DE devices. Fortunately, PI control is quite suitable for the SC control due to its physical characteristics. Inherent delays due to the electromechanical properties prevent the SC from changing its reactive power output as quickly as the power electronics inverter. Conversely, the inverter is capable of making almost instantaneous adjustments as the controller varies the PWM signal. Additional optimization of the inverter's control method would likely result in significant performance improvements. In both cases the flexible laboratory platform provides sufficient flexibility to test multiple control methods. Figure 9 shows how PI control is used to regulate the bus voltage to a desired set point. The controller determines the control signal by using the difference in the actual bus voltage and the desired voltage set point. Either the average RMS voltage for the three phases or a single-phase RMS voltage is compared to the set point voltage to find the error signal.

Figure 9. Diagram of PI control of one DE device.

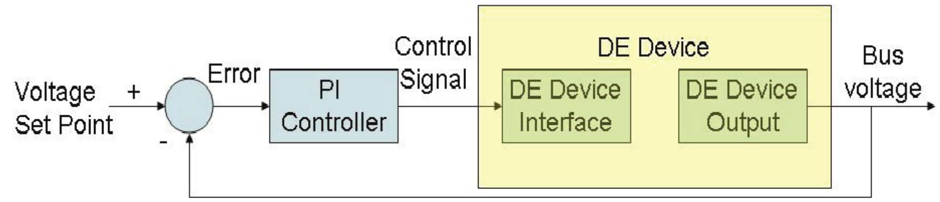
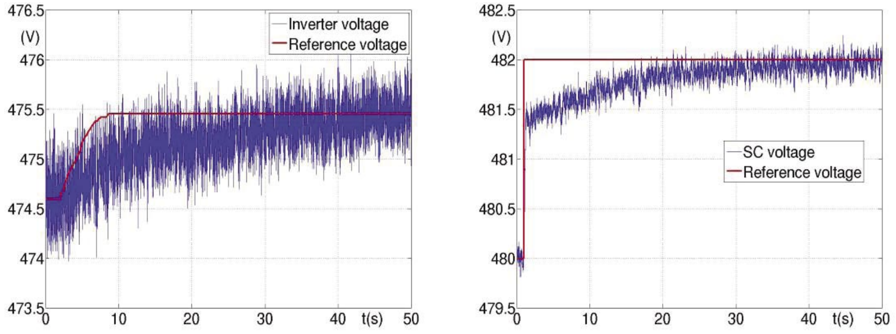


Figure 10. DE devices' dynamic regulation to a voltage set point step change.



The experimental results for the SC and inverter operated on separate distribution circuits using separate PI controllers for voltage regulation can be seen in Figure 10. The inverter response is not typical. During the test the gains on the PI controller were intentionally set very low so that the output would have no overshoot. Certainly the gains could be set higher, allowing the inverter to react much faster but with some overshoot.

Conclusions

A flexible test platform for testing reactive-power-producing DE devices for local dynamic voltage regulation with no communications with the substation or other DE devices has been developed. The overall project goal is to develop control algorithms to later be used in the firmware of DE devices to provide the ancillary service of dynamic voltage regulation. New control logic for reactive power regulation developed in this way could potentially be integrated into DE devices by means of a software update and a few, simple hardware modifications.

Project goals and requirements prevented the use of intelligent power meters with limited I/O communications options and proprietary software interfaces. Although off-the-shelf instruments were used as much as possible, there was a need to construct some special interface boxes to complete the integration. The flexible system described in this paper allows for the testing of various DE devices and combinations of DE devices for voltage regulation with only software changes needed when the control strategy is modified.

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