

“CYBER PHYSICAL SMART GRID”

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Abstract

The Cyber Physical Smart Grid (CPSG) project models a small-scale power distribution system that integrates intelligent metering and distributed generation and allows for improved automation and control via a graphical user interface. Creating a distribution system testbench allows for the testing of implementation of autonomous controls on a physical system. The cyber physical smart grid seeks to develop this testbench by creating variable controllable loads, power factor correction, renewable energy sources, and a graphical user interface to control and monitor the grid. The project achieves these goals by using a phase angle control circuit and static resistor and inductors to create a controllable circuit that can simulate load profiles on the system. Additionally, a controllable capacitor bank allows for power factor correction based on the phase angles determined by the phasor measurement units located at each bus. To emulate renewable energy injection the project utilizes a synchronized DC to AC inverter that can match the voltage of the testbench and allows for control of the power supplied to the grid. Finally the project developed a graphical user interface to allow a human operator to both view the current and historical data collected from the testbench and execute control actions as necessary to operate the grid. The project endstate will be to develop algorithms that will determine and implement the most efficient and economical operating point by turning on and off generation sources, correcting for reactive power and turning on and off transmission lines as needed. The testbench allows for full integration testing of smart metering and distributed generation on a physical system and improves the efficiency of the grid by making autonomous control decisions to correct power factor and transmission line loading.

Keywords: Microgrid, Power System, Phasor Measurement Unit, Smart Grid, Renewable Energy

1. Introduction

The current power grid is aging and often relies on manual control for higher level decisions such as generator scheduling and VAR control. The integration of intelligent metering and distributed generation within the distribution grid allows for improved automation and control. CPSG will create a distribution level smart grid testbed incorporating advanced metering, distributed generation, automated VAR control, and a GUI allowing complete real time and historical analysis. This testbench incorporates physical devices calibrated to model transmission lines from a real world system at 46kV scaled down to run at 46 V (26 V phase). Creating a model of a distribution grid with physical components allows for exploration of autonomous controls designed to improve efficiency a step beyond simulation before actually implementing controls on a real world system. The goal of this project is to first develop a test bed that accurately represents a real world system by designing loads that can mimic various load profiles and provide visibility of that system through a graphical user interface. Then the design and implementation of control algorithms can be thoroughly tested.

2. Methodology

One major concept of the Smart Grid is to allow for integration of more sophisticated, faster acting autonomous control systems that improve the efficiency and reliability of the aging power grid. It integrates multiple generation sources to provide power to the end user; it switches on and off capacitor banks in order to correct the non unity power factor. Additionally, the smart grid takes more detailed measurements from the grid and uses them to enable better analysis and control of the grid. These readings are to allow for future forecasting and scheduling of generation sources. More generally a Smart Grid is an electric power grid that attempts to intelligently respond to all the components with which are interconnected, including suppliers and consumers, in order to deliver electric power services efficiently, reliably, economically and sustainably. A Smart Grid employs intelligent monitoring, control, communication, and self-healing technologies to improve quality and efficiency of the power grid. Figure 1 shows the big picture of a smart grid where advanced communication and measurement systems are deployed from the individual user through the distribution grid and to the generation system. This end-to-end integration enables the grid to more accurately measure and respond to small changes throughout the system.

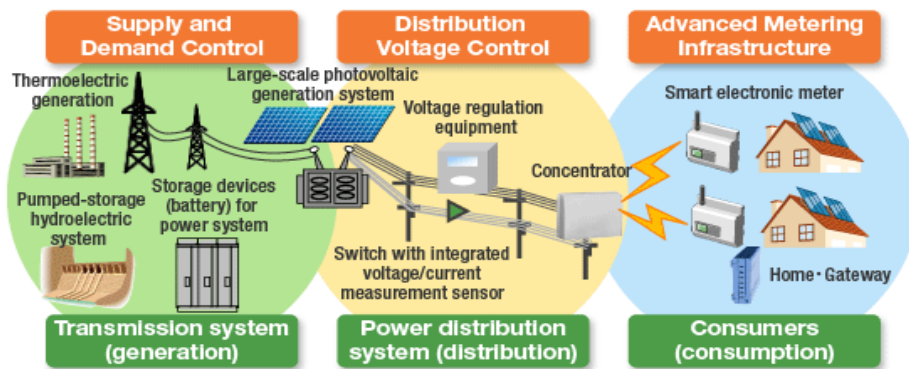


Figure 1. General Idea of a Smart Grid [1]

It is the policy of the United States to support the modernization of the nation's electricity transmission and distribution system to maintain a reliable and secure electricity infrastructure that can meet future demand growth. A smart grid should provide power quality for a range of needs in a digital economy, accommodate all generation and storage options, enable new products, services, and markets, enable active participation by consumers, operate resiliently against physical and cyber attacks and natural disasters, anticipate and respond to system disturbances in a self-healing manner, and optimize asset utilization and operating efficiency. CPSG accomplishes this by creating a testbed to enable full testing of systems prior to full scale implementation on a physical system. The specifications for the CPSG project are:

- Emulate a real world power distribution system
- Remotely control Sweitzer Engineering Laboratory (SEL) Relays
- Develop a controllable RL capable of emulating an hourly load profile
- Provide automatic power factor correction for the grid to a power factor of 0.9 or better
- Emulate a solar input on the grid with a solar profile
- Create a database of all measurements from each of the ten relay phasor measurement units
- Create a GUI capable of interfacing with SEL relays that displays live and searchable historical data
- Create a website that displays live and searchable historical data

The overall block diagram is shown in Figure 2. The solar input, controllable load, and capacitor bank are modular and can be placed at any bus within the testbed. There are SEL relays at every bus that send phasor measurement data

do the phasor data concentrator which feeds the graphical user interface. Figure 3 shows the one-line diagram of the power system modeled within the testbed.

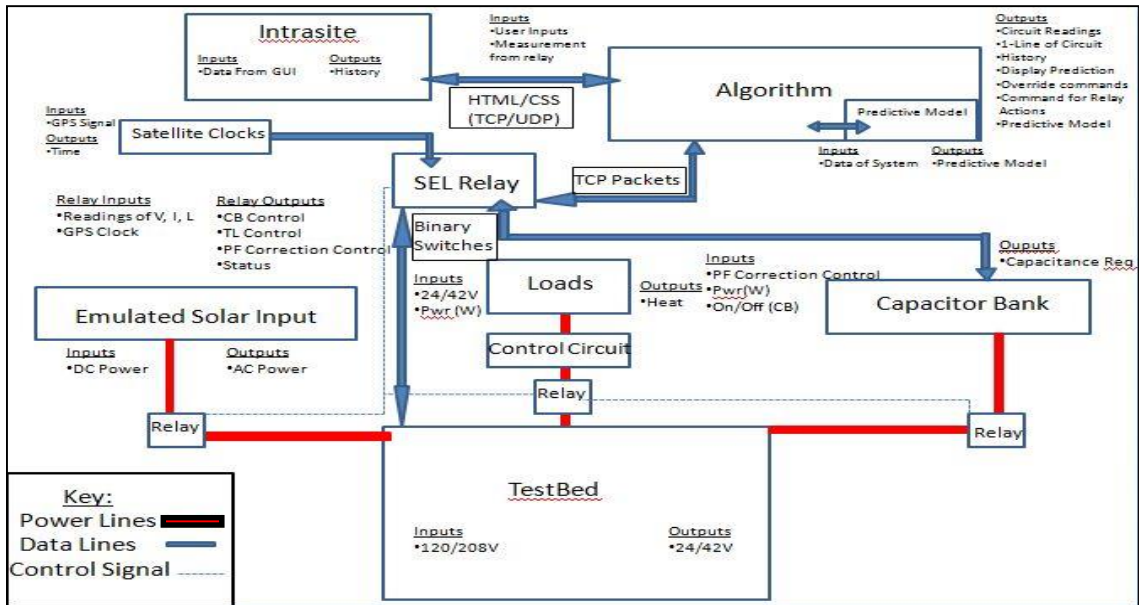


Figure 2. Block Diagram

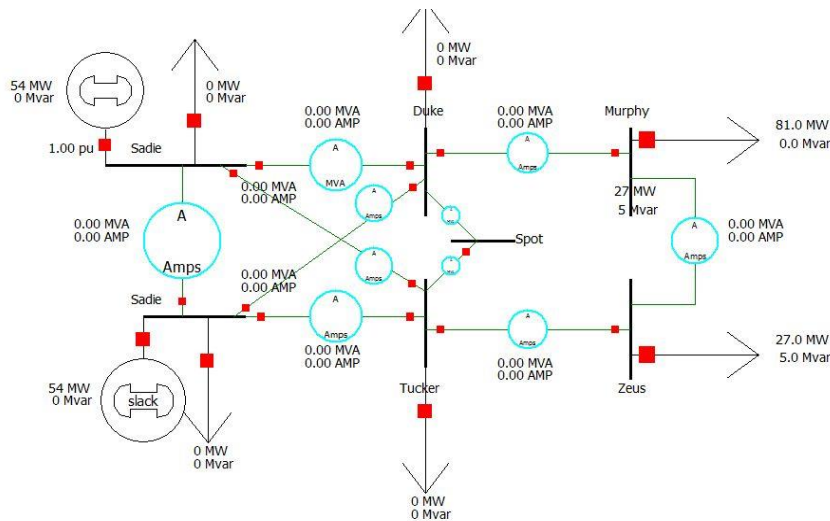


Figure 3. One Line Diagram (TestBed Component of Block Diagram)

4. Data and Discussion of Results

For the overall testbed CPSG has a power distribution test bed that contains 7 busses, with 26V (per phase) primary generation source drawn from a 220V three phase wall outlet which is then reduced with transformers (Figure 4). The busses are interconnected with transmission lines which can be turned on and off via breakers. The transmission lines are modeled with resistive and inductive components. The 10 SEL relays receive information from the grid via current and voltage transformers and creating synchrophasor data comparing to the GPS time which enables the relays to utilize fault detection and provide detailed information for the grid. The max current through each line is $2A_{RMS}$. The

grid is scaled by a factor of 1000, which means that the readings display as 26000V and a max of 2000A. This enables the grid to emulate a real world grid.



Figure 4. The physical testbed in the lab

CPSG has developed an RL load with 100ohms resistance and 28mH inductance which is controlled by a phase angle control circuit (Figure 5). These values were chosen for their ability to maximize the current draw from the load within the system specifications. The phase angle control circuit changes the firing angle of the voltage on the load which then varies from 0V to 26V (Figure 6). This changes the amount of power the load demands from the system. At full 26V the load draws 32 watts and 34 vars. With the 1:1000 scaling this is 32MW and 34 MVA respectively. At full load the power factor decreases from 1 to 0.69. CPSG also uses a capacitor bank to improve the power factor and lower the amount of power drawn from the load. CPSG uses a 66uF capacitor on each phase to correct for the RL load which corrects power factor up to 0.9.

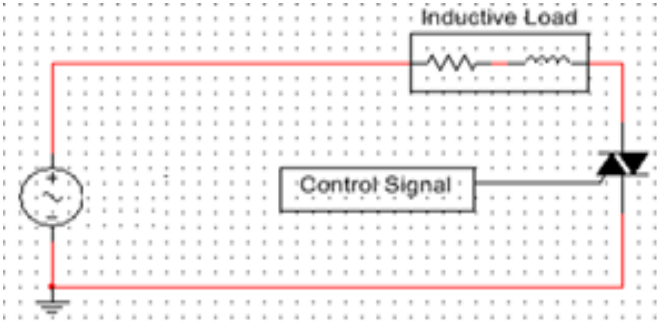


Figure 5. Load with Thyristor Control Circuit



Figure 6. Phase Angle Control Circuit Set at 50% (left) and 100% (right)

The grid utilizes three Texas Instruments Solar Inverter Microcontrollers [2] which act as a secondary source for the grid. The inverters synchronize to the voltage of the grid (26V) on the AC side. Initially these inverters were designed to synchronize to a standard 120V grid. For this project the inverter had to be programmed to work with our lab equipment and at the lower 26V. On the DC side we were using a smaller DC power supply and had to lower the DC bus voltage to 200V from 250V. We also had to make changes to the code that sensed the AC grid so that it did not detect our 26V grid as an undervoltage and switch off the inverter. On the PV or DC side, the inverters take DC voltage (25V) and change the amount of current drawn to change the amount of power it receives from the “solar” side. Normally this is accomplished using maximum power point tracking (MPPT). However, for this project we want to control the power input to the grid and disabled MPPT. We can use the code to set the current demand from the DC source thus controlling the amount of power supplied. This power is then inverted to AC and injected into the grid at the voltage level it is synchronized to. The amount of power injected to the grid varies from a minimum 5 watts to 18 watts (or a scaled 18MW). The amount of power into the board controls the amount out. The power in is controlled by a computer which is linked to the microcontroller. The power out is set by the current we command input into the board, we disable Max power point tracking to set the voltage and current allowing the user to program a solar power profile to provide power to the grid. Figure 6 demonstrates injection of solar energy into the testbed on a near balanced operating point. It can be seen that on phase A the current draw from the primary bus is lower due to the solar inverter providing power.

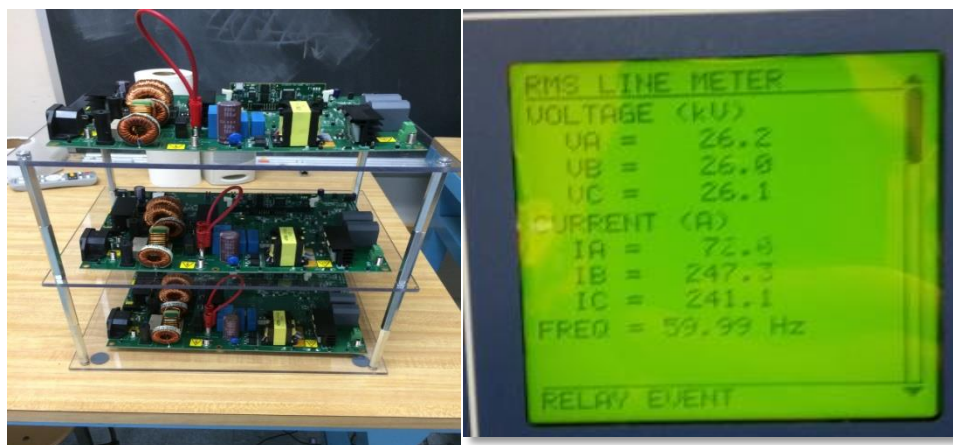


Figure 6. Solar inverter array and an image of the readings at one bus with single phase solar injection

CPSG utilizes OpenPDC [3] to compile readings sent from the grid. OpenPDC provides the user with live graphical representations of phasor readings and also enables the creation of a database in which to store these readings over time (Figure 7). OpenPDC was used during the CPSG project to create a SQL Server database, which was then linked to a user interface created in Visual Studio 2010 C#. The graphical user interface (GUI) seen in Figure 8 draws historical data (such as voltage magnitude, voltage phase angle, current magnitude and current phase angle) from the

SQL Server database and outputs it to the user. The GUI also provides the user with the means to search through the SQL Server data, making it much easier to find and display data that the user requires. This search is based on user input that creates a database query containing elements such as type of reading, date, and time. Finally, in addition to displaying historical data and providing a query builder, the GUI also features a oneline model of the Smart Grid and the basic infrastructure for future expansion into live readings and graphs.



Figure 7. A screenshot of OpenPDC collecting data in real time

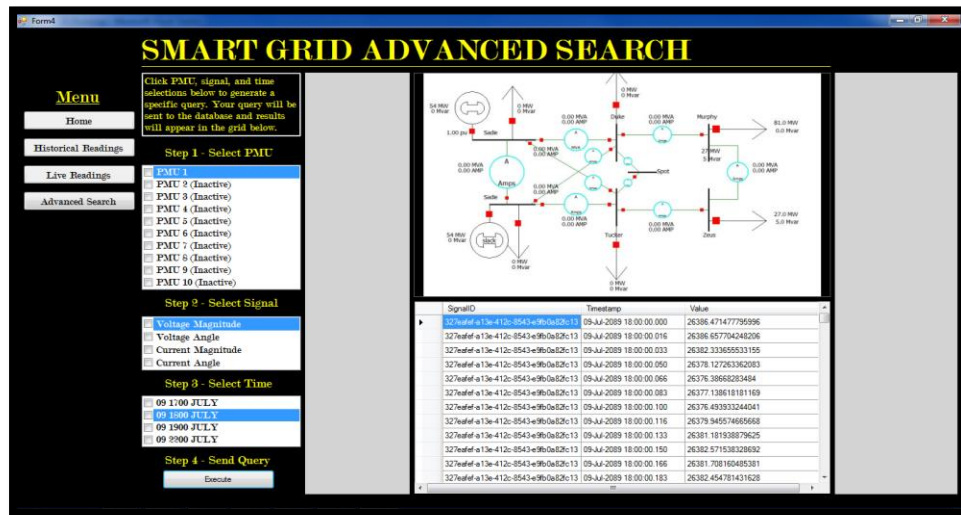


Figure 8. A screenshot of the GUI showing voltage readings staying constant

CPSG also has a website that can access a CSV file with readings from the grid which can then be displayed from all devices connected to the network. This website is remotely accessible and displays only historical data as of now. The website updates from the Open PDC database both historical and live data to display to the user [4]. The website is not accessible from outside of the internal department network.

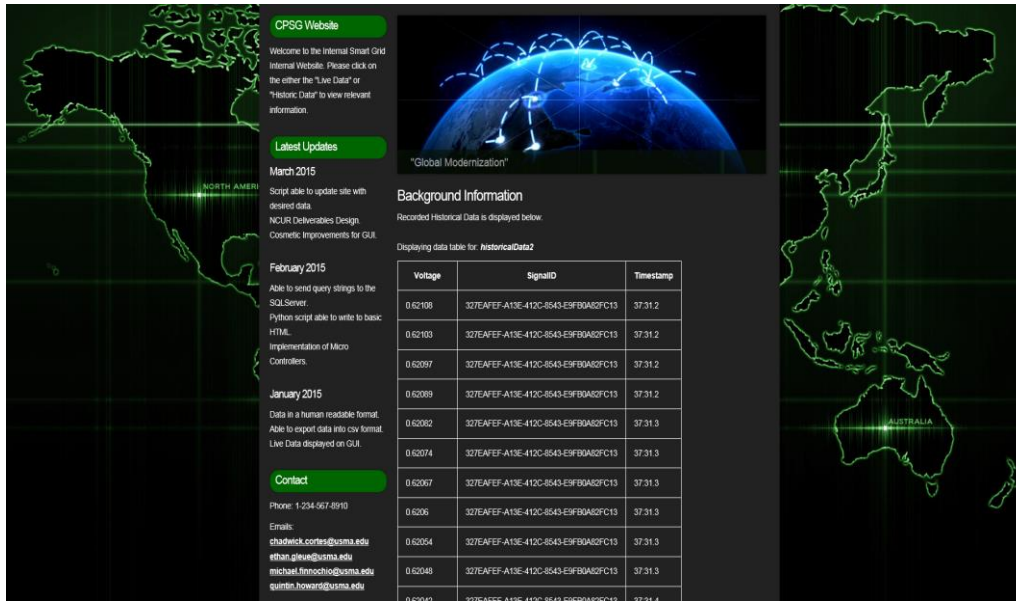


Figure 9. A screenshot of the website showing voltage readings staying constant over time

5. Conclusion and Future Work

The goal of CPSG was to create a distribution level test bed that accurately modeled a real world grid and incorporated smart-grid technology. In order to do this loads, secondary generation sources, and communication backbones needed to be developed and our specifications were built around these goals. Over the course of this project the testbed was assembled and now includes emulated solar inputs, a controllable inductive load, and manual capacitor banks within the physical grid. A graphical user interface now allows a user to view historical data and live information from the grid. The intranet website displays historical data acquired from the OpenPDC database. This testbench now accurately represents a distribution system and allows for implementation of control systems to determine and implement the most efficient and economical operating point by turning on and off generation sources, correcting for reactive power, and turning on and off transmission lines as needed. Future work includes developing these autonomous algorithms, providing fully integrative control from the GUI, and delivering live data to the intranet website for remote monitoring purposes.

6. References

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