AC 2011-1718: IMPLEMENTATION OF LABORATORY-BASED SMART POWER SYSTEM

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Design and Implementation of Laboratory-Based Smart Power System

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Abstract:
Modern power system grid incorporates controllers, communications and information technology infrastructures into the electrical power system to create a smart grid in terms of operation. In this paper, the concept of real time control of a smart grid will be discussed by developing a micro grid test-bed at the Energy System Research Laboratory at Florida International University. This hardware/software based system includes implementation of control strategies for generating stations, as well as power transfer to loads in a laboratory scale reaching to 35 kilowatts, monitoring all system parameters and controlling various components developed in this setup. Laboratory experiments and their analysis give the students a high level of knowledge to understand the concepts of power system engineering fundamentals and the required demonstrations needed for smart grid implementation in the real world. Educational application of this laboratory-based smart grid and its real-time operation analysis capability provide a platform for investigation of the most challenging aspects of actual real world power system and its operation in real time.

Introduction:
Power System planners need to operate the power system under increasingly complex conditions. The utilization of renewable generation, energy storage systems, and plug in hybrid electric vehicles will introduce new complexities to system operation. With these challenging conditions being introduced into the current system operation, the overall scheme requires new and innovative operation methodologies in a distributed manner [1].

Modern power network incorporates communications and information technology infrastructures into the electrical power system to create a smart grid in terms of operation. The smart grid will utilize digital information technology to create a more efficient, reliable and responsive networks that are flexible [2]. With faster and new technologies in communication and computer incorporated into the system operation, a new attitude has been created in the power industry, especially in the field of power system control and demand side management. Communication capability is one of the potential benefits for digital relays, which communicate not only with a control center, but with each other in a two-way format. This in turn will facilitate the overall system-wide protection and control philosophy. The self-managing and reliable smart grid is seen as the future of protection and control systems [3]. This philosophy requires finding a way to implement in the laboratory.

The Smart Grid design aims are to provide overall power system monitoring, create control strategies to maintain system performance and security and to reduce cost of operation, maintenance, and system availability planning. The Smart Grid Control gives us capabilities such as: predicting system behavior, anticipatory operation and adaptation to new environment, handling distributed resource, stochastic demand and optimal response to the smart appliances.

The smart grid is considered to have observability with all interconnected nodes with data integration and analysis to support advances in system operation and control.

The objective of this paper is to apply the concept of real time analysis of a smart grid and implementation it on a smart grid test-bed in the Energy System Research Laboratories at Florida International University. Implementation of control strategies for generating stations as well as power transfer to the loads by monitoring all system parameters in a laboratory scale were developed in this setup. Laboratory experiments and their analysis will give the students a high level of knowledge to achieve confidence when they are involved in smart grid implementation in the real world. Educational application of laboratory-based smart grid and its real-time analysis capability provide a platform for investigation of most challenging aspects of real power system and its operation. This is a unique facility of its kind in an educational institution.

Smart Grid Implementation and Practical Issues

The smart grid is a power system that enables real-time communication and control between the consumer and utility allowing suppliers to optimize a consumer's energy usage based on environmental and price preferences. The business of the Smart Grid has begun in earnest since the mid-2000s. The previous studies, therefore, largely focused on the industrial developments and realization plans. Recently, the Smart Grid operation issues are significant and most reports are focused on the trends of the present [4]. Smart Grid fundamentals include definitions, architecture, formulation of performance requirements, discussion of development of analytical and decision support tools, as well as renewable energy resources. The development of educational schemes will require skills and technologies outside of the power engineering. The design of such grid will be based on cross boundaries of knowledge in communication theory, optimization, control, social and environmental constraints as well as dynamic optimization techniques [5].

International standards such as IEC 61850 and 61968, define the overall architecture of a Smart Grid and its characteristics can be summarized as follows [6]:

- Self-healing by detecting and instantly responding to system problems and restoring
- Provision of high power quality to all consumers and industrial customers
- Accommodating a wide variety of generation options in local and regional scale
- Empowerment of the customer by allowing energy management
- Tolerance of attack by standing resilient to physical and cyber attacks
- Optimizing assets and operating efficiency

The advancement of the curriculum is necessary for preparing future engineering students to advance their skills in the new highly technical environment. This will require increased focus on coupling of power systems with communication systems, information technology, control technologies and embedded system. While many smart grid topics have been identified in the literature, the following are some illustrations of the topics that have not received adequate attention in the education so far and yet they are essential in understanding and implementing the smart grid developments [7]:

- Phasor measurements units and their application in power systems for improved monitoring, protection, and control

- Integration of distributed sources including renewable resources (wind, solar, geothermal, etc) in power generation and their fully control structure
- The concept of digital protection in new protective digital relaying, monitoring, control, power quality and asset management applications
- Intelligent protection schemes and their application in detecting, mitigating and preventing cascading outages, islanding situation and total grid blackout occurrences
- Impact of Plug-In Hybrid Electric Vehicles (PHEVs) and Electric Battery vehicles (EBVs) on electricity and transportation infrastructure
- Multifunctional uses of smart meters for revenue metering, demand side management, outage management, and load control
- Integration of Hybrid AC-DC systems in creating new micro grid solutions for residential and industrial applications
- Enhancement of energy efficiency by the technologies that allow implementation of highly efficient and economical affordable solutions for the Smart Grid
- Green House Gas (GHG) emissions and means of lowering carbon footprint of the Smart grid solutions

Many countries have been trying to develop the Smart Grid technologies by performing some projects as test-beds with different points of view. The United States has some projects such as GridWise, GridWorks [8] and is trying to expand their results focusing on improving the efficiency of its old transmission and distribution networks. The European Union has SmartGrids projects [9], while focusing mainly on stably adopting renewable energy resources. Canada is running Integration of Decentralized Energy Resources Program [10], and in Korea, a project called K-Grid has been launched to design a highly integrated Korean Smart Grid System [11].

The Energy System Research Laboratory at Florida International University is working on constructing and implementing of a small-scale power system test-bed which has different capabilities for experimental research and educational purposes. This setup uses laboratory scale of power system components in order to model the realistic behavior of a large power system. By having this type of power system, engineers and researchers are capable to implement their own idea about power system phenomenon in a practical way. It would be an excellent base not only for innovative research ideas, but also for teaching power system engineering concepts to students who are interested to get an overall idea of power system operation and the continual insertion of renewable resources.

Overview of Power System Components Employed in the laboratory Smart Grid Test-bed

The Test-bed power system grid in the Energy Systems Research Laboratory at Florida International University is being developed for different applications, as well as Smart Grid operation study of a power system. Most of the power system laboratories have some power system elements available for education and experimental tests and they don't provide the integrated power system test-bed for studying on interconnection, control and protection issues. Mostly, they use software emulation through Real-Time Digital Power System Simulators (RTDS). To our knowledge this is the first effort of its kind of involving both hardware and software interactions. The objective of this work is to integrate all power system components together for architecture more realistic laboratory scale power system for research and education purpose. In order to achieve this aim the lab director involved a group of graduate and undergraduate students to design, implement and connect to test-bed setup. All the equipment used for this test-bed setup will be discussed and illustrated in the following sections with their control and communication capabilities.

A. Generation Station Model

The generators are 13.8-kVA and 10.4 KVA, at 60-Hz, 230-V and 1800-RPM synchronous machine. The prime mover of these generators is coupled to one of available motors which are derived by different frequency drives. All the generators are equipped with an Automatic Voltage Regulator (AVR) in order to maintain an output voltage magnitude. Figure 1 shows the overall schematic of Generation Stations and its components. The AVR model is a half-wave phase-controlled thyristor type Automatic Voltage Regulator and forms part of excitation system for brushless generators. Excitation power is derived directly from the generator terminals. The output voltage of generators should be maintained by applying offline parameter settings by available potentiometers on AVR module. The Frequency Drive can be used with 3-phase AC induction motors rated from 1/3 HP up to 25-HP on voltages from 120-V single-phase to 600-V three-phase. Programmable digital and analog I/O allows the drive to be configured for many application specific tasks such as multiple preset speeds, electronic braking and motor jogging. For implementing a smart grid with control, programming via Microsoft windows has been used in order to control the frequency and change the output active power of generators. The used control modes of this drive are:

1. Vector Speed (for single-motor applications requiring higher starting torque and speed regulation)
2. Vector Torque (for single-motor applications requiring torque control independent of speed)

B. Transmission Line Model

All transmission lines are designed at different length of π-model of lines, in which every line has its own boxes with series inductor (which has internal resistance) and two parallel capacitors (with internal resistor) in each phase as is shown in Figure 2. In case of fault or any other kind of events, such as over-load, all lines are protected by fuses in order to prevent components on the test-bed from being damaged. The line components are designed for 132.8-V, 25-A current per phase, and the power transferring capacity for the three phase system in nominal voltage (120-VL-G) is 9-kVA. The design of the lines allows for a five wire connection (three-phase, neutral and ground), which allows for implementation of different types of line combination.

C. Bus Model

For switching and measurement purposes, special boxes have been built by undergraduate students in order to implement a bus model. Figure 3 shows one of these buses which have three inputs and three outputs. Each input/output has a 530-V, 25-A solid-state relay, whose switching can be controlled by a 5-V DC voltage. This voltage can be applied by DAQs and a computer controller. Each phase has its own PT and CT which has a voltage ratio of 20:1 and current ratio of 3:1, respectively. PTs are connected between phases and ground, so they can present line to ground voltage. The secondary side of these CTs and PTs are connected to communication terminal and then to the DAQs.

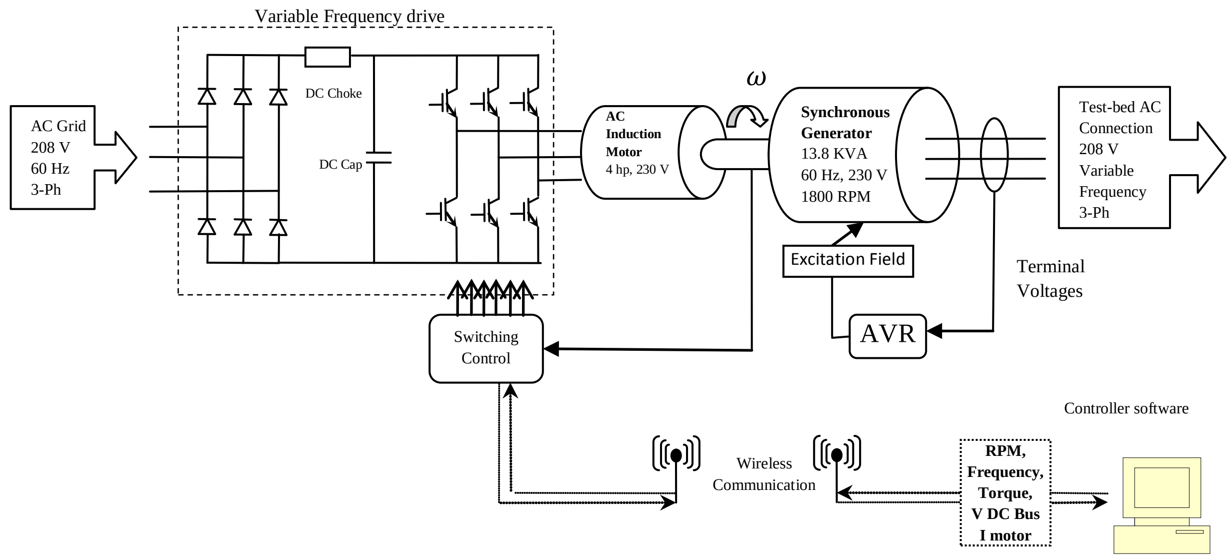

Fig. 1: Overall schematic of a generator station on the Test-bed and its components

D. Load Model

Different load models have been designed in the test-bed power system by graduate students. The passive loads have a switching capacity of 6 levels parallel resistive loads (each 1 KΩ) with adjustable reactor. The induction motors are used for dynamic model of loads, and they are coupled to a Prony-break in order to apply different mechanical load on their shaft. The motors used are 208 V, 1.4 A, 1/3 HP induction machines. A remote controllable load has also been developed in order to control load value by software in real-time control.
According to system performance the load level can be set by changing reference signal. This kind of load controlling makes the smart grid concept more operational and achievable. Motor load emulator system is shown in Figure 4. As it is shown, this system consists of one 250 W induction machine, operating as an induction motor load, one 250 W DC machine, operating as a separately excited DC generator, a resistive load connected to the DC generator, an IGBT for controlling the field of the DC generator, and finally a freewheeling diode for circulating the field current when the IGBT is open. An anti-windup PI controller provides the proper duty cycle for the IGBT operation. This duty cycle will be applied to the IGBT via the Gate block which converts the duty cycle to the appropriate gating signals.

E. Synchronizer Model

Synchronizers assure that a generator attempting to connect in parallel with the electric system can do so without causing an electrical disturbance to other equipment connected to the same system. In addition, the synchronizer assures that the generator attempting to connect in parallel with the system will itself not be damaged due to an improper parallel action. Hence the synchronizer model has been developed by students, which is shown in Figure 5. Each relay has PTs available on both sides to measure the right and left side voltages. By using the signals, the software environment of synchronizer controller checks the synchronizer conditions. The right side is used for the generator side and the left side is used for the system side parameters. These conditions are shown below:

$$|V_{right}| - |V_{left}| < 3\,V \quad (1)$$

$$f_{right} - f_{left} < 0.1\,Hz \quad (2)$$

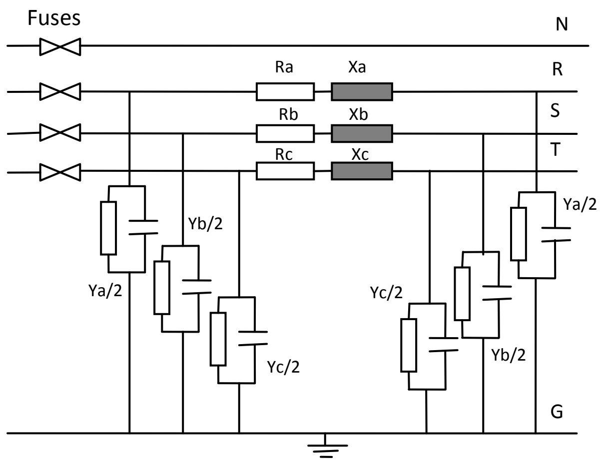

Fig. 2: Line model

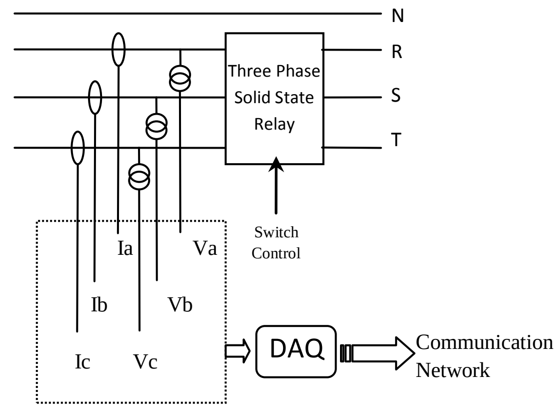

Fig. 3: Bus model

$$\measuredangle V_{A-Right} - \measuredangle V_{A-Left} < 2\, deg \quad (3)$$
$$|\measuredangle V_{AB-Right} - \measuredangle V_{AB-Left}| < 5\, deg \quad (4)$$

V_{right} and V_{left} are the Voltages of right and left side of synchronizer, f_{right} and f_{left} are the frequencies measured in voltage waveform for the right and the left side of the synchronizer, respectively.

Real-time Monitoring and Control Platform

A. Data Acquisition Devices

There are several different real-time operating systems available on the market today: Programmable Logic Controller (PLC), Real-time Digital Simulator and National Instrument Data Acquisition Devices (NI DAQ). The option which was considered and implemented was the use of the National Instruments real-time modules. The monitoring system is built with NI data acquisition modules on several NI DAQ platforms. The main elements include several NI USB-6259 (32 analog inputs, 16-bit; 1.25 MS/s single-channel and 4 analog outputs, 48 digital I/O; two 32-bit counters), NI PCI-6071E (1.25 MS/s, 12-Bit, 64-Analog-Input Multifunction DAQ), and NI 9206 (Isolated Wireless Voltage Input: 16-Ch, 16-Bit, 250 kS/s). Finally, NI compactDAQ-9188 has been used to extend the reach of high-speed data acquisition to remote electrical measurement and controlling from across the lab to the Ethernet and connected computers.

B. Real Time LabVIEW Software

LabVIEW graphical system design software has been selected because of its ease of use and seamless integration with NI DAQ hardware. LabVIEW is a graphical programming tool for test, measurement, and automation and is widely used as a virtual instrumentation tool. It allows students to develop sophisticated measurement, test, and control systems using intuitive graphical icons and wires that resemble a flowchart [12]. One of the major advantages of LabVIEW, apart from being simple to use, is the ability to work with a number of hardware interfaces using real world analog and digital signals. LabVIEW programs work as simulation or

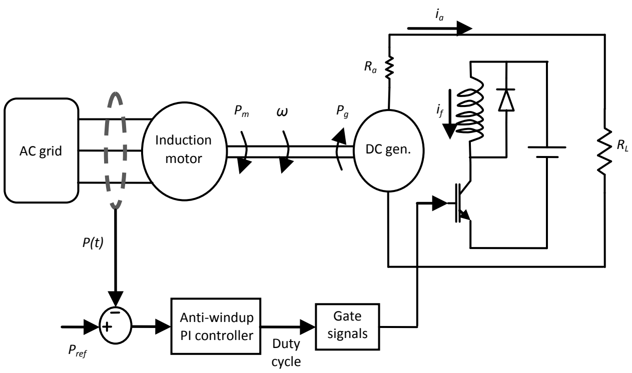

Fig. 4: Motor load emulator model

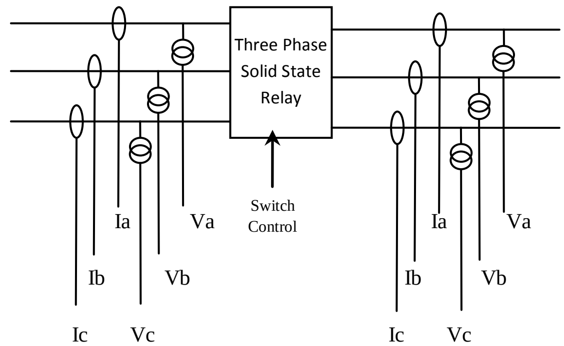

Fig. 5: Synchronizer model

data acquisition applications depending on the requirement using custom built hardware from National Instruments. This consists of two windows, a block diagram window where the actual graphical code is written and the front panel where the output can be visualized. The manner in which LabVIEW works, it ties the creation of user interfaces (called front panels) into the development cycle. The programs/subroutines are called Virtual Instruments (VIs) in which each VI has three components: a block diagram, a front panel, and a connector panel. In the test-bed power system lab, students programmed the application using LabVIEW which provides a real-time view of the entire system on a primary screen and a live view of all analog values displayed as VIs. LabVIEW also provided the flexibility to display all analog signals in a graph and record them on-demand and on an external trigger.

Test-bed Architecture and Operation

The overall power system which was implemented in test-bed is shown in Figure 6. This have four generators connected in ring combination and supply loads connected to the load buses in the end of lines which are connected to generator buses. This system includes linking the communication infrastructure of our NI DAQs monitoring system to a common communication network in order to implement supervisory control and data acquisition (SCADA) power system control equipment, and it has the ability to access all measurement data remotely via an Ethernet connection [13]. As shown in Figure 6, the switching action is implemented by the LabVIEW software which consists of manual switching by computer for whole network. The VI allows for a manual connection of the generating station for the user to use, and an automatic synchronization option has been implemented. For generation control scheme, a sub VI has been implemented in the LabVIEW environment, as which measures and compares both sides of the synchronizer for proper synchronous switching action. One of the generators runs at a constant frequency and acts as the slack bus, which maintains the power system at 60 Hz. The other three generating stations are torque controlled, which allows for constant output power to be controlled. Once all the generating stations have been synchronized, the VI allows the user to control the amount of power output from each generator by controlling the torque output of each generator individually. This method is done incrementally to increase or decrease the power output respectively of the corresponding generator.

The other VI was developed to monitor all electrical parameters in every branch. All the feeders have been represented by a front panel similar to Figure 7. In this Figure the real time values of voltages and currents of the feeder are presented in right-top side. In addition, by implementing

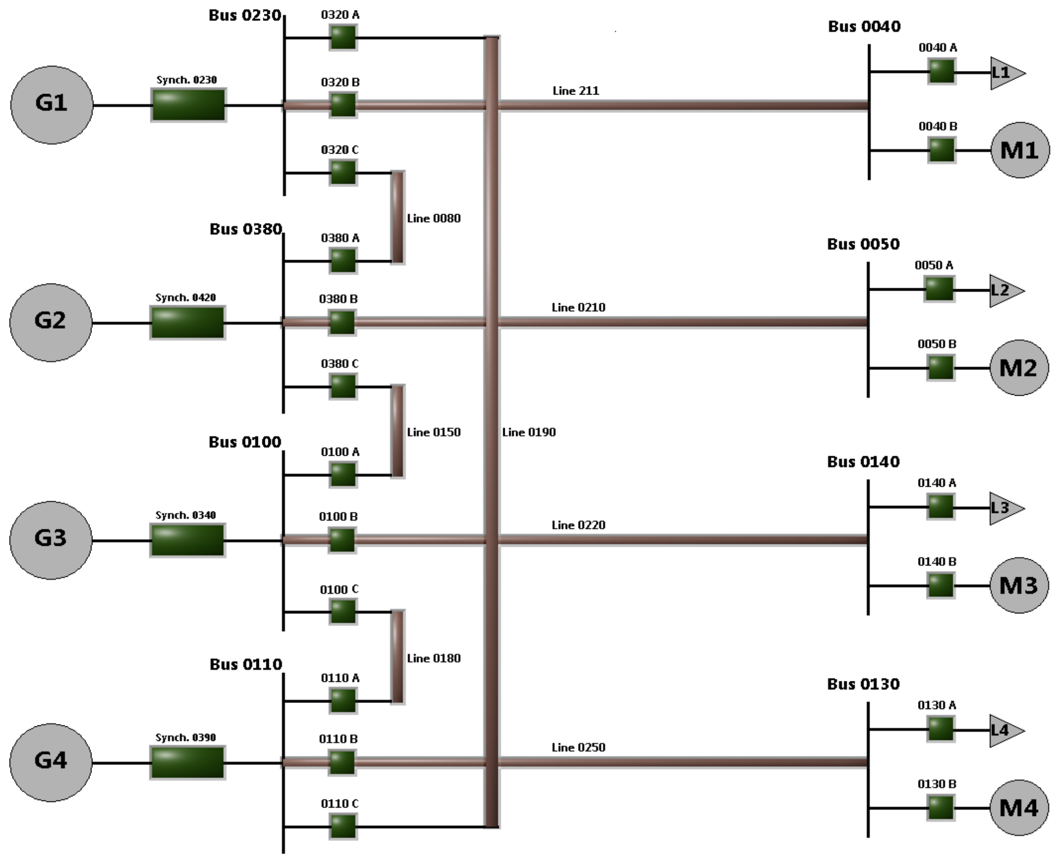

Fig. 6: Overall power system schematic and one line diagram implemented in the LabVIEW Software

proper block diagram including math functions, the zero, positive and negative sequences of voltages and currents, the active and reactive power as well as power factor characteristic of each branch, have been calculated and are shown in the middle-top side of this VI page. The phasor diagram also shows the phase difference between the voltages and the currents of each phase, which can be used as a synchronized phasor measurement by using reference time scale for all the measured signals. Overall, the monitoring system based on NI hardware and software proved to be a highly flexible and easy-to-use solution for our application. The overall view of the test-bed lab has been shown in Figure 8. The next procedure in developing this setup will be connection of renewable generation such as wind, solar, fuel cell and storages such as battery and flywheel to this system. In addition integration of DC network to the AC setup will be studied by their interconnection issues. The system is also intended to be used as an educational tool for students to become more familiar with the new concepts of energy conversion systems and challenges in smart power system.

Utilizing the Test-bed to Teach Students about Smart Grid Infrastructure and Operation

This test-bed is developed to simulate various components in a smart grid, which are under development by our research group. By implementing these hardware and software structure of a smart grid, we can validate and test various scenarios for operating power networks, automation power markets and demand response policies. The testing functions can be divided into key functional elements necessary to implement the smart grid [6]. This structure can help us to achieve adaptive interaction, adaptability, self-healing, efficiency and reliability of electric grid.

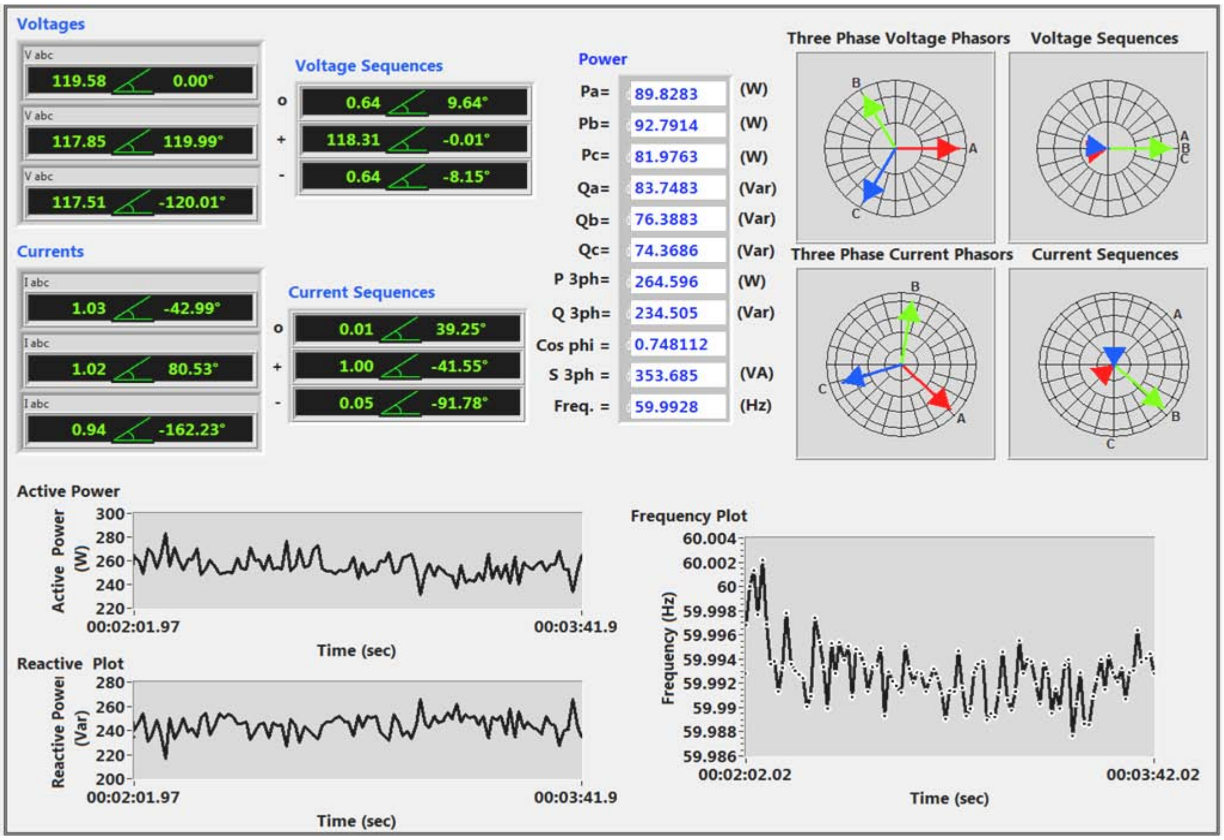

Fig. 7: The measurement and electrical parameter calculation VI for all the feeders

The department offers two courses as electives, one is related to Power System Operation and the other is related to Fault Analysis and Relays Coordination. We used this test-bed to demonstrate the concepts taught in class. Furthermore, the developed system will also be used to implement new power system protection and control ideas relating to new operating regime of the Smart grid. By expanding an already established set of traditional core electric power engineering graduate and under graduate courses, the smart grid lab can provide practical base knowledge in following areas:

- Reactive power control
- Fault analysis and reconfiguration schemes
- Power generation and load balance
- Distributed generation and demand side management
- Optimization and control of renewable energy resource
- Wide area protection strategies
- Advanced power electronics systems
- Hybrid DC/AC network

Students were introduced in the actual development of various parts of the test-bed including transmission lines, busses, relay installation, communication infrastructure, generations and its synchronization as well as computer program developments and the embedded hardware emulators. In addition, this test-bed is now being used as a platform for graduate students to perform their research. The test setup can provide the vision of the future real-time monitoring, and control systems and it can be used for following research areas in power system operation:

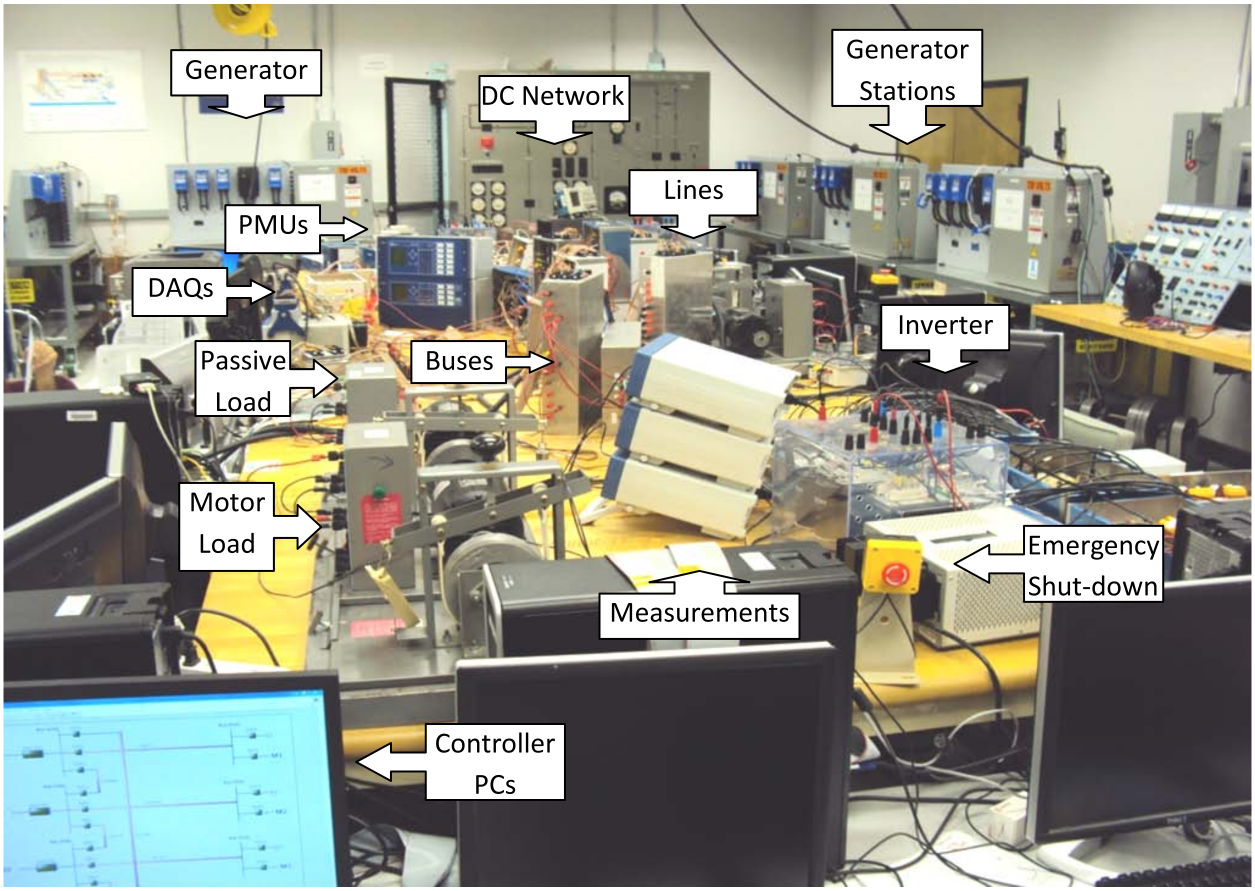

Fig. 8: Test-bed overall hardware implementation setup

- Enhancement in State Estimation (Using PMUs for state measurements)
- Online Dynamic Security Analysis (Steady state and dynamic contingency analysis)
- Measurement-base Stability Analysis (Disturbance monitoring technology by PMUs)
- Probabilistic Risk Analysis (Cascading failures and N-x contingencies)
- On-line Interactive Restoration (real-time restoration after black outs)
- Coordination of Protection and Control System (robust, fast and efficient support of power system by coordination protection and control systems in wide area)
- Intelligent optimization of power production and interactive generation- demand management system
- Designing communication infrastructure of power grid and data storage management

Conclusion:

The Smart Grid design aims are to provide overall power system monitoring, create control strategy to maintain system performance and security, and to reduce cost of operation, maintenance, and system planning. In order to study realistic behavior of a power system, the test-bed power system grid is implemented in the Energy Systems Research Laboratory at Florida International University for different applications, as well as Smart Grid operation study of a power system. The objective of this work is to develop a real time automated power system network and control test-bed at the laboratory level to enhance the power system testing and validation scheme. This is achieved by integrating of different hardware devices and developing communication interfaces between those devices. The overall power system design has been presented with detailed explanations for power system components and the measurement of voltages and current issues. Their communication infrastructure for implementation of real-time power system monitoring and control has also been discussed.

Educational application of laboratory-based smart grid and its real-time analysis capability provide the platform for investigation of the most challenging aspects of a real power system. Beside the power system courses, the laboratory facilities can help undergraduate students to understand the concepts of power system fundamentals such as power system elements models, active and reactive powers, power factor, frequency control, voltage regulation, unbalance sequences concepts from the point of practical view. The graduate students can utilize this setup not only for educational purposes, but also for implementing new and innovative ideas for their research topics related to this integrated and comprehensive test-bed power system.

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