Sensor Development for Smart Grid Multi-Agent System Development

Michael J. Spencer, Ali Feliachi, Muhammad. A. Choudhry, Franz A. Pertl, Emily D. Pertl and James E. Smith

Abstract: This paper describes part of the conversion of WVU’s analog power simulator into a micro-grid-of-the-future test bed. The simulator is a hardware representation of the grid which contains traditional hardware, both digital and analog. It is important to note that this simulator is a hardware implementation, and as such is capable of testing smart grid ideas in the most realistic setting available without affecting real customers. This project attempts to fill the gap between the computer simulations and the real world by modifying an existing platform to cost effectively allow real time control of a small scale power grid with real world components and without the pitfalls of testing on the real grid. The simulator modifications included the installation of new digital relays, three phase voltage and current energy meter integrated circuits sensors, and solid state switches. The sensors and energy meter integrated circuits were selected to give the most data possible in a small enough package to be implemented on the existing simulator while considering the hardware data interface. Microcontroller units were investigated and selected based on the desire to provide multi mode communication and state of the art compact processing power. This paper gives an overview of the project and focuses on the energy meter integrated circuits sensor selection, testing and results.

Keywords: Smart Grid, Power System, Hardware Prototype, Real-Time Control, Reconfigurable Power System, Multi-Agent System

1. Introduction

The United States government has recently decided to invest billions of dollars into the existing, and potentially antiquated, power grid in an effort to increase efficiency and reliability. The name given to this new power grid is the Smart Grid. The central idea is that through more intelligent devices and communication systems on both the consumer and utilities side, the grid reliability and efficiency can be improved by autonomous reconfiguration, disaster mediation and potential real time consumer interaction. This paper proposes to deliver a platform where ideas for automated reconfiguration and control via multi-agent systems (MAS’s) and other control algorithms can be tested. This will be accomplished by converting a small scale analog distribution simulator using 1970’s technology into a micro-grid-of-the-future by the addition of modern digital relay equipment and micro-controlled switches.

The Lane Department of Computer Science and Electrical Engineering at West Virginia University has maintained an analog power simulator that was donated to the University and installed in the 1970s. Figure 1 shows the WVU power simulator in its original configuration. It is a low power hardware replica of a distribution system that contains commercial, industrial and residential loads. Its dimensions are 22 feet long, 8 feet tall and 5 feet deep. Power can be supplied to the loads from different internal and external circuits and generators which can be routed in a variety of ways. The simulator is currently being retrofitted with digital relays, intelligent electronic devices, distributed energy resources (generation and storage), and potentially a Flexible AC Transmission System (FACTS) device. The new digital hardware will be integrated with the older electromechanical hardware, mimicking real world power systems. This will allow the system to be used for research into autonomous reconfiguration schemes.

Figure 1. WVU power simulator in original configuration

1.1 Addition of Digital Relays

Current progress includes the installation new digital relays donated by, Schweitzer Engineering Laboratories (SEL) Inc. This first set of relays was installed next to their electromechanical counter-parts and to be wired in parallel with them. This will allow either, or both, to be used as required. Figure 2 shows these new relays mounted in the simulator. Three of the relays will not be installed at this time, the 300G generator relay and two of the 751 feeder protection relays. These will be reserved for use with the distributed generation equipment to be acquired later.

Figure 2. Power simulator with added digital relays

1.2 Addition of Intelligent Electronic Switches

The simulator still has approximately 100 manually operated switches that allow power to be routed over different paths.
between the generators and loads. The majority of those switches will become redundant when the microcontroller switched, optically isolated, triacs are installed. Each microcontroller unit (MCU) will be paired with an ADE7758 three-phase energy metering chip to monitor node current and node voltage and to allow MCU to focus on communications and higher level intelligence functions. All of the ADE7758 metering chips will be clocked from the same 10 MHz signal making it possible to synchronize waveform sampling across all nodes. If not required for specific simulations, the MCU controlled switches can be turned off and the simulator used in its original configuration.

2. Research and Development Potential

The system, with its new functionality will provide the capability to test and refine future grid handling problems while still remaining familiar to the likely operators and designers. The authors and their colleagues have been doing research on using distributed intelligent agents with communication capability for several years as a solution to the communications bottleneck and information overload that are fundamental problems of the present day grid. This multi-agent system (MAS) approach has been computer simulated in software only, now real world hardware with its associated timing and throughput issues is needed to better and more realistically explore the concept; the upgrade to the simulator is designed specifically with these capabilities in mind. The communication requirements and processing capabilities needed for studies on MAS were at the forefront of the hardware selection process. Naturally, the hardware is also applicable to other ideas such as immune system based algorithms for intelligence adaptive control of the grid.

One of the first problems to be addressed by the upgraded simulator was the reconfiguration of the system in response to an outage. With the newly available intelligent connectivity there will be ways to route power around faults and restore power to much of the system. MAS algorithms [1] have direct applicability here as do the immune based approach [2]. Once this problem has been explored, any of the results of lessons learned have been reported, more subtle and complicated predictive control scenarios can be investigated.

With the ability to monitor load flow at virtually every node comes the capability to determine optimum power flow through the system, as well as to automatically prioritize and shed load when needed. Distributed generation can be brought on to abate a critical condition all made possible through using the distributed intelligence built into the system. These are all ideas that will be explored with the simulator with a tremendous potential impact on the grid-of-the-future.

Communications is a critical component of any distributed intelligent system and models have shown that a multilayered communication scheme can offer a dramatic improvement in communication integrity and throughput. The MCUs chosen to act as the distributed intelligence were picked in large part for their ability to communicate via many distinct ports. Ethernet, Can bus, and RS-232 which could be adapted for wireless proposes are all available to the algorithm explorer.

Recently Moheuddin et al. [3], published a paper on the optimization of the number and placement of distributed agents in a system that is scalable, meaning the algorithm employed to pick the placement and number was unaffected by the size of the system. Their work could be implemented and verified on this new hardware simulator system with potentially great impact on the evolving smart grid.

Cyber security is a critical concern in the new grid and the simulator upgraded plans are sensitive to this requirement. A feature of the chosen MCU’s is handling cryptographic processing, not with the main processor, but through a dedicated cryptographic co-processor. These MCU’s were specifically designed for secure mode operation and there is no processing overhead for implementing state-of-the-art security measures.

3. Intelligent Electronic Switch Hardware Selection

The digital relays bring the micro grid simulator up to the current state-of-the-art, but to allow for advanced reconfiguration algorithm testing, automation of the manual switches on the simulator is desired. It would have been convenient to specify commercial relays for this function, but their size and cost would be prohibitive. The solution was to design a compact solid state switch controllable by a microcontroller and integrate node current and voltage sampling.

A search revealed which compact microcontrollers excelled at both processing and communication to provide the algorithm developers as large a canvas to try their ideas on as possible. A prototype board from Freescale™, the M52259DEMOKIT was selected. It has a 32-bit, 80MHz processor with 512 Kbytes of flash memory, 64 Kbytes SRAM, and a cryptographic accelerator unit to allow for secure communications without taxing the main processor. It includes two USB ports, one 10/100 Ethernet port, an RS-232 port and a high speed CAN bus interface, all in a 3 in x 3.5 in double board package. Figure 3 shows the prototype board highlighting its communication ports.

From the beginning of this project it was determined that communication was a high priority. This was driven by the desire to test MAS ideas and from the need to have multiple communication paths insuring data integrity. The determining factor for selecting this particular MCU board was the number of communication ports available. Both CAN bus and Ethernet can be used for a multiple wired communications scheme and the RS-232 port can then be dedicated to a wireless module. This still leaves the on board diagnostics USB port available for programming and the QSPI for interface with the ADE7758 power meter chip. The remaining USB port could be used for a memory device and that still leaves an I²C interface available for future use.
In addition to communications it was also apparent that security is critical. To address this, the MCU comes with a dedicated cryptographic coprocessor to specifically handle secure communication and no additional overhead cost.

Other components selected where the triacs. The power simulator allows voltages up to 750 VAC and currents in the 5 ampere range. The snubberless triacs rated for 8 amps at 1,000 VAC were selected to allow a safety margin. The triacs are driven by opto-isolators specifically designed to work with triacs. Non-zero crossing devices were chosen to avoid potential problem during powering up when all three phases are switched simultaneously.

Initially the idea was to use the A/D capability of the MCU to sample current and voltage at the node, but the search for triacs and opto-isolators revealed a multifunction energy meter IC that would perform those and many additional functions leaving the MCU dedicated to processing and communications. The ADE7758 energy metering chip selected is a three phase high accuracy energy measurement IC. It has a SPI interface and a wide variety of relay type features making it ideally suited for this application. It is straightforward to integrate all of these components as shown in the block diagram of Figure 4.

4. Circuit Design and Board Fabrication

Since the ADE7758 is only available in a surface mount package it is necessary to fabricate a printed circuit board using surface mount soldering techniques. A design was drawn up, sent out for fabrication. A surface mount soldering station setup and the components and boards were assembled and tested.

The ADE7758 Poly Phase Multifunction Energy Metering IC has built in analog to digital converters (ADCs) for sampling all three phase voltages and currents. The input range of the ADCs is -0.5 V to +0.5 V so the line voltages must be scaled down to that range with voltage dividers.

Traditionally, current is sensed with a current shunt or an isolation transformer to step down the current. Effectively this converts the current to a proportional voltage which is then sampled and the corresponding current derived from sample amplitude. Alternatively a Hall Effect sensor could be used but were deemed physically too large for this project. While the ADE7758 can be used in the normal current shunt mode, it also features a unique alternative solution.

The voltage induced in the secondary of a transformer is proportional to time derivative of the current in the primary. The constant of proportionality is the mutual inductance between the primary and the secondary. As this scheme generally requires the signal to have zero DC component, the secondary voltage is sampled and mathematically integrated to determine the current though the primary. This has the advantage of near zero power dissipation in the secondary circuit.

As with most analog to digital conversion, anti-aliasing filters are required. The circuit recommended in the manufacturer data sheet is shown in Figure 5 [4].

The output circuits at pins 1 and 17 were not implemented and neither were the clock circuit capacitors. The 5 VDC required by the IC is derived directly from a regulator on the printed circuit board. This ensures that the IC receives a stable voltage. Since the M52259DEMOKIT also requires 5 VDC, both can be supplied from the same source, with the
regulator supply above the 5.5 V leaving ample headroom at the regulator. The regulators rated current is 50 mA and the ADE7758 only requires a maximum of 21 mA.

The M52259 microprocessor uses a 3.3 VDC supply and the ADE7758 a 5 VDC supply, causing an interfacing problem. Fortunately the specifications for the input to the ADE7758 are within the output range of the M52259, and no level shifting is needed. However the input to the M52259 is not specified to handle the logic levels supplied by the 5 volt ADE7758, so a level shifter 74LVC08AD was used for this interface.

4.1 Fabrication

The circuit boards were drawn up using Sunstone Circuit’s PCB123® CAD software and the boards were then fabricated (see Figure 6). Being a prototype, the board was designed to allow minor adjust to the layout. There are places in the triac section layout where snubber circuits can be added if they should be needed. The level shifter is left disconnected with solder pads to allow it to be reconfigured. Parts of the meter chip like the clock and SPI interface are left open with solder pads. With this setup, the clock signal can be supplied by an external clock or an individually dedicated one may be used.

Figure 6. Sense and control PCB layout

In an effort to minimize cost and size, the current sensors were hand wound on salvaged toroid cores for initial testing. The signal integration method for current measurement was chosen to minimize part count and power dissipation since that power would have to be dissipated in the electronic switch. The sensors are simple transformers wound on the toroidal core with about 85 turns of 30 AWG as the secondary and is attached to the ADE7758 ADC input. The about 3-turns 14-AWG primary was connects to the triac. This arrangement makes a very compact transformer that easily fits in the switch box. The toroidal configuration features good tolerance to noise pickup. Testing of the current sensors is shown in Figure 7.

5. Hardware Test and Results

The very high input impedance of the ADCs allows simple voltage dividers to be used for voltage sensing. The current sensor configuration required some experimentation in their design. An evaluation board for the ADE7758 was purchased from Analog Devices. The board package includes LabVIEW™ based software with a graphical user interface that makes it very easy to access all of the chip’s capabilities. A drawback to the evaluation board the obsolete but required parallel printer port board interface. That source code can potentially be modified to alternatively use the Ethernet port and the ADE7758’s could then be accessed though the MCU’s in the intelligent switches.

Despite the lack of data on the surplus toroid cores’ material, only a couple of trials yielded windings ratios that properly mapped the desired current range to the input voltage range of the ADCs. The evaluation board setup to test sensors is shown in Figure 8.

Figure 7. Current sensors being bench tested with the ADE7758 evaluation board

To test the linearity of the current sensing system it was set up on a laboratory bench where three phase power was routed through variacs. This allowed changing the voltage in addition to varying the load with switchable resistive, inductive and capacitive components. The three phases sampled by the evaluation board were also sampled by a Yokogawa PZ4000 power analyzer.

The LabVIEW™ software only displays numeric ADC codes which need to be properly scaled to the corresponding voltages and currents measurements. The ADE7758 gain and offset compensation was used to calibrate phase to phase amplitude.

For the linearity tests 2000 samples were taken by the ADE7758 and 2 seconds of data were sampled by the PZ4000. Only RMS values were evaluated for both the current and voltage as the LabVIEW™ graphical user
interface provided more precise values in this configuration. The voltage was changed incrementally from 0 to 150 VAC and the ADC values corresponding to voltage and current were recorded, see Figure 9.

![Figure 9. ADE7758 counts versus voltage](image)

The ADC counts versus voltage plots show good linearity until the low end of the range when about 10 VAC is reached. It is interesting to note that phase A has a considerably higher noise floor. Figure 10 is a plot of the counts per volt versus voltage. The data below 10 volts was eliminated for purposes of evaluating the linear range of the setup.

![Figure 10. ADE7758 counts per volt vs voltage](image)

Figure 9 shows the ADC counts versus current of the ADE7758 test setup with the hand wound transformers in the integrating configuration. The plot shows that the setup has very good linearity. The transducers exhibit slightly differences in slope amongst the three phases. Since the gain on all three channels was identical it is likely that the difference is due to the transformers.

Differences in number of turns when the transformer were constructed are a possibility. Such differences can be compensated for with individual channel gain adjustments.

Figure 12 shows ADC counts per amp sampled by the ADE7758. This plot clearly illustrates the relative difference in gain between the phases, as well as the general curve shape across the amperage range tested. The shape could be caused by core material nonlinearity.

![Figure 11. ADE7758 counts versus current](image)

![Figure 12. ADE7758 counts per amp vs amperage](image)

It should be noted that for both current and voltage measurement only a small range of the available ADC counts range was used. The peak to peak values corresponding to a maximum 3.5 amps of the test setup are only -181,000 to +181,000 out of the possible -2,642,412 to +2,642,412 for the 24 bit ADC. The voltage ADC count range tested was even smaller, -2,320 to +2,700. Adjustment of input voltage dividers could potentially reduce the noise floor further.

6. Related Work

There has been considerable work done in the area of automated reconfiguration of power systems but most of that has been via computer simulation. Just within WVU’s Advanced Power and Electricity Research Center much simulation has been done [1,3,2].

S&C Electric Company has developed a system that runs their proprietary software and algorithms. IntelliTEAM II® Automatic Restoration System uses their hardware and select hardware from other manufacturers and is implemented on a real distribution system [5].

Another component of this task was the development of triac switch modules that could handle the voltage and power levels involved with the simulator [6]. Recently work has also been done on the simulator involving wireless communication and an immune system based reconfiguration approach [7].
7. Conclusions and Recommendations

The sense and control boards have been designed and fabricated. A procedure for the assembly of the boards has been developed. All initial board testing has yielded positive results and indicated satisfactory performance. The next tasks are the SPI interface and verification of the sensor filter circuits. The filter circuit verification requires to wait till the SPI communication with the ADE7758 has been established. The 50 in-house assembled boards are ready for installation. Potential future revisions of the board should consider improving the layout of the level shifter and transistor buffer for a more compact easier to assemble package.

The current sensors worked satisfactorily, have an appropriate voltage for the ADE7758 ADCs and exhibit acceptable linear over the range of expected design currents. Potential improvements in size and performance could be made with more careful magnetic core selection, rather than relying on scavenged parts. Once installed, additional experience with the present devices will indicate if more or less coupling is advantageous when used in the power simulator. The evaluation board will be a great tool for exploring this topic in more detail.

The triacs performed well, despite the added crossover noise they are an excellent AC switches for use on the simulator [6]. Snubber designs should be considered to allow switching more inductive loads as needed in the future. The impact of zero crossing opto-isolators should also be explored further.

References


