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Real Time Digital Simulation of Wide Area Protection and Control Schemes Using Phasor Measurement Units

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SUMMARY

Simulation has played an important role in the reliability, stability and operability of power systems. Power networks are starting to change and new technologies are starting to emerge. New methods of power generation (wind, solar, fuel cells, etc) and power transmission with voltage source converter technology such as Multi-Modular High Voltage DC (MMC HVDC) are being introduced in our networks.. The power network is becoming smarter, with more sophisticated protection and control devices that use high level communication protocols. With the addition of these new features, simulation becomes a critical aspect in the design and operation of the power network. It is becoming increasingly important not only to study isolated areas of the network, but to study the network as a whole. Phasor Measurement Units (PMU) can be deployed at various locations in the power network and can provide real time monitoring of phase and frequency of system voltages and currents. Currently, PMU data is typically used for offline analysis but research is being done to use PMU's in Wide Area Monitoring Schemes (WAMS) for use in protection and control. PMU data could be used in wide area protection and control schemes to perform actions such as adjust generation, pick up or drop out transmission lines, or shed load. These schemes have the potential to be very powerful and using simulation to understand them and make sure they are secure and reliable is essential.

Several things are required to perform wide area protection and control testing with PMU's. One is the ability to simulate the power network in real time. To test protection and control schemes using PMU's, closed loop testing is essential, and closed loop testing can only be performed alongside a simulation that is running in real time. Another critical aspect to the testing of PMU devices is having an absolute time reference shared between both the simulation and the devices under test. If this time reference is not shared between both the simulated and external devices, there will be a phase angle drift between the two sources which may lead to inaccurate results.

The RTDS® Simulator is a real time power system simulator and is used around the world for closed loop testing of protection and control schemes. This paper will show how the RTDS Simulator can be used to test the static and dynamic performance of individual PMU's. Once the individual PMU's are tested, further studies can be done looking at wide area protection and control schemes. By using a synchronizaion device, the GTSYNC card, the RTDS Simulator time-step can be synchronized to an external time source (ie. GPS clock). The time reference signal can either be in 1 Pulse Per Second

(1PPS) or IEEE 1588 format. In addition, a method for streaming PMU data using the IEEE C37.118 format from the simulation to the outside world using a firmware devoloped for the Ethernet communication card (GTNET-PMU) will be discussed. With the RTDS Simulator, the possibility exists to perform an entirely software simulation using PMU's and a Phasor Data Concentrator (PDC). Additionally, using an external PDC and PMU's in combination with simulated PMU's will be discussed. This paper will show that it is possible to test wide area protection and control schemes using both physical and modelled PMU's with the RTDS Simulator.

KEYWORDS

PMU, PDC, 1 PPS, 1588, RTDS.

1. Introduction

Modern power systems are ever evolving and new technologies are constantly emerging. One of these technologies is Phasor Measurement Units (PMU). PMU's are devices that measure voltage and current phasors and transmit the measurements to a central location for monitoring and control. PMU's can be used in conjunction with real time digital power system simulators to perform wide area protection and control studies.

This paper will first describe the background of real time digital simulation and the requirements for wide area protection and control testing. Real time digital simulators such as the RTDS Simulator are commonly used to simulate power systems with closed loop protection and control studies. This paper will highlight the developments in real time digital simulation as well as the simulation requirements that make wide area protection and control studies possible. It will also discuss the different ways in which PMU's can be tested using the RTDS Simulator.

2. Real Time Digital Simulation

Simulation has played an important role in the development of power systems into the modern, complex networks they are today. Before digital simulation was an option, analogue simulators were used exclusively. Analogue simulators are composed of scaled down models of actual power system components (machines, transmission lines, loads, etc). While they provide very accurate representations of the networks they model, they do have several drawbacks. They are very costly, typically take up a large physical area, it can take days or sometimes weeks to configure the simulator to the test network, they are prone to excessive losses leading to optimistic results, the flexibility to represent different circuit configurations is limited, etc.

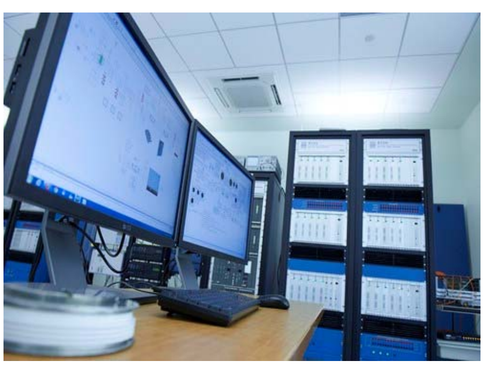

Figure 1: RTDS Simulator Installation

In the late 1960's an electromagnetic transient simulation algorithm was developed by Dr. Hermann Dommel [1]. In this algorithm, the trapezoidal rule of integration is used to convert integral equations, which result from nodal analysis of the power system, into algebraic equations. Application of the trapezoidal rule requires that the solution be computed only at discrete instants in time, rather than a continuous solution. The time between computed instants is known as the time-step and is denoted Δt. Typically for power system simulation, the time-step is chosen to be on the order of 50 microseconds (μs).

It wasn't until the early 1990's that techniques were developed that made it possible to perform digital simulations in real time. Tools had existed to perform non real time or 'off-line' simulations. An off-line simulation of the system's response over 1 second can require minutes or even hours of computer execution time. In a real time simulation, the simulation of the system's response over 1 second is computed in exactly one second. In a fully digital simulation, all calculations required to determine the power system's state are completed in a real world time exactly equal to the simulation time-step.

Real time digital simulators are widely used around the world. When working with power systems, it is important to have a tool to study and test various network configurations and different strategies for protection and control systems. The following section describes simulator requirements for testing with PMU's.

3. Simulation Requirements for PMU Testing

There are several requirements that must be satisfied in order to test protection and control schemes with PMU's. The first requirement is a real time digital simulator that performs electromagnetic transient simulations. RMS or single-phase simulations do not yield the necessary results for PMU testing. Transient response and harmonics must be included to properly test these devices and systems. The simulator and its results should be reliable and tested against industry benchmarks. If the simulation results cannot be trusted, neither then can the behaviour of the device under test.

The simulator must operate over a wide frequency spectrum, from DC up to electromagnetic transients. Even though PMU's, like relays, deal only with the fundamental system frequency, sometimes they do not operate with faster transients and other phenomenon. This is why it is important to test the entire system under as realistic conditions as possible in order to thoroughly test under all possible scenarios.

The simulator must be able to operate for extended periods of time. Long term stability and reliability of protection and control schemes is extremely important and in order to be assured of these, simulations may need to be run over days or weeks. Furthermore, the simulation results must be able to be trusted completely. When connecting any equipment to the simulator, whether it is a protective relay or a PMU, the only way to know for sure that the device is operating correctly is if the results of the simulation can be trusted. This is important so that the simulation results are not called into question if the device mis-operates.

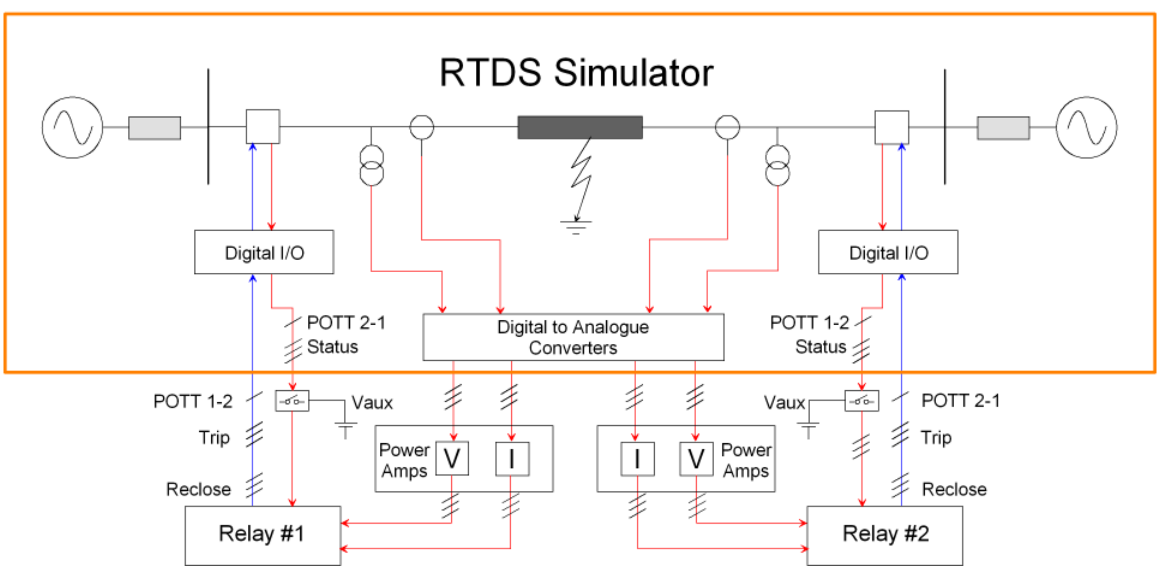

Figure 2: Closed Loop Protective Relay Testing

Typical control and protection functions must be available for the simulator. Often, protection systems are overlooked when testing control schemes or representing large scale systems. It is essential to represent the protection systems of a network in detail as certain control actions may cause tripping of an external protection system. Generic models of standard protection devices (distance, differential, busbar, generator, etc) must be available to be used in the simulation. Standard control models also must be available. These controls include generator controls (governor, exciter, PSS, etc), tap changer controls as well as generic controls for FACTS and HVDC devices. In addition to being able to simulate control and protection functions, it is necessary for the simulator to be able to perform closed loop testing with physical devices. Figure 2 shows a schematic of how the RTDS Simulator can be used to test protective relays by exchanging analogue and digital signals between the relays and the simulation. Other devices, including controls and PMU’s can be connected to the simulator in a similar fashion.

The communication used in closed loop studies should not be limited to only hard wired analogue and digital signals. High level communication protocols are now available and are widely used throughout the power systems industry. IEC 61850 GOOSE, IEC 61850-9-2 Sampled Values, and DNP3 are a few of the protocols that the simulator should support. In order to test wide area protection and control systems, there needs to be a communication path to and from the simulator and one or more of these protocols may need to be used.

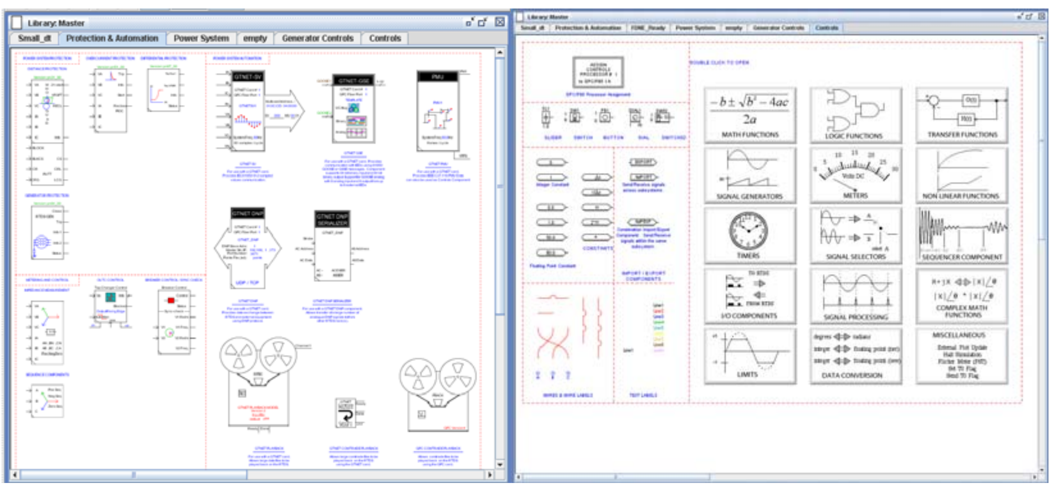

Figure 3: RTDS Simulator Protection and Control Libraries

Networks containing PMU’s are often quite large. The ability to perform large scale real time simulations becomes critical when investigating wide area protection and control schemes. Large scale real time simulations provide a more detailed representation of the network behavior than standard transient stability simulations. Among other things, real time electromagnetic transient simulations provide a much better frequency response (DC to ~3 kHz), more detailed representations of power electronic installations (as opposed to nominal frequency approximations), real time feedback, and the ability to interconnect with physical devices. By including detailed models of the protection and control as part of the simulation studies, a more complete representation of the large scale network behavior is provided.

Finally, one of the most important requirements for testing wide area protection and control schemes with PMU devices is the ability to synchronize the simulation as well as the devices under test to an external time source. The simulator must be able to be synchronized to highly precise time protocols such as 1PPS and IEEE 1588. The following section will discuss the developments that have been made to make this time synchronization possible with the RTDS Simulator. It will also detail the development of the PMU model as well as PMU testing applications.

4. Development

4.1 Simulation Time Synchronization

In order to investigate PMU technology for smart grid applications, the simulation time-step must be able to remain synchronized to an external time source. The synchronization must also be maintained over an extended period of time. The deviation from the time source should be minimal so the simulation time-step does not drift away from the time source.

In a real time simulation, the time-step is defined as the time between each discreet solutions of the network simulation. As the simulation proceeds, new samples for voltages and currents are computed with each successive time-step. With these values, the solution of the network can be calculated based on proven and well-defined mathematical equations and the current time-step and are 100% accurate within the simulation. The RTDS Simulator uses a piece of hardware called a Giga Transceiver WorkStation Interface (GTWIF) card to generate the time-step and supervise the simulations. The time-step clock is produced by a crystal oscillator onboard the GTWIF. As each crystal oscillator has an inherent tolerance, the time-step specified by the simulation will always deviate by a very small amount from the actual time-step produced. When performing digital to analogue conversions, the interface hardware of the RTDS Simulator has the oscillator error introduced and the d/a conversion introduces some additional errors (gain, offset, noise). The oscillator on the GTWIF card has a specified worst case error of +/- 100 parts-per-million (ppm). This means that a simulation with a system frequency of 60.0 Hz could appear at a worst case of 60.006 Hz to external equipment.

In the initial development phase, a test was performed using a non-synchronized 60 Hz simulation and a synchronized GE D60 PMU. The PMU measured 60.001 Hz which corresponds to an error of 16.7 ppm which is well within the specification of the GTWIF. In order to obtain a minimal drift in the GE PMU output frequency, the system frequency in the simulation was adjusted. The adjustment was from 60.0 Hz to 59.9981 Hz which corresponds to an error of around 20 ppm and correlates with the frequency adjustment and measurement method. However, even with this manual adjustment, phase drift was observed.

RTDS Technologies has developed a facility which allows the GTWIF to synchronize to a highly accurate time source. The development of a new peripheral called a Giga Transceiver Synchronization (GTSYNC) card was required. The GTSYNC can provide synchronization to IEEE 1588 v2, copper BNC one pulse per second (1PPS), or optical ST 1PPS time sources. The GTSYNC also has an onboard clock which it uses in the absence of an external time source (ie. it can act as the master time reference for the simulation and external equipment). When the synchronization begins, the GTWIF determines how much adjustment is needed for each time-step using a 10 ns resolution. Prior to the start of the simulation, the GTWIF will count the number of time-steps that occur between the 1PPS signals. If the actual count differs from the theoretical count, the GTWIF will distribute the time-step adjustment evenly throughout the following 1PPS interval. This correction of the GTWIF oscillator error takes place for the

Figure 4: Analogue output synchronized to the 1PPS

duration of the simulation, thus ensuring a constant phase reference of the simulation signals with respect to the external time reference and subsequently the equipment connected to the simulator.

Figure 4 shows the synchronization of the simulation time-step (red trace) to the rising edge of the 1PPS (yellow trace). The RTDS Simulator analogue output zero crossing (purple trace) is shown to occur at the same time as well. Figure 5 shows a typical setup to synchronize a 1PPS signal from a satellite clock to the RTDS Simulator. Typically, the satellite can provide IEEE 1588, IRIG-B, and 1PPS outputs which can be used by external devices.

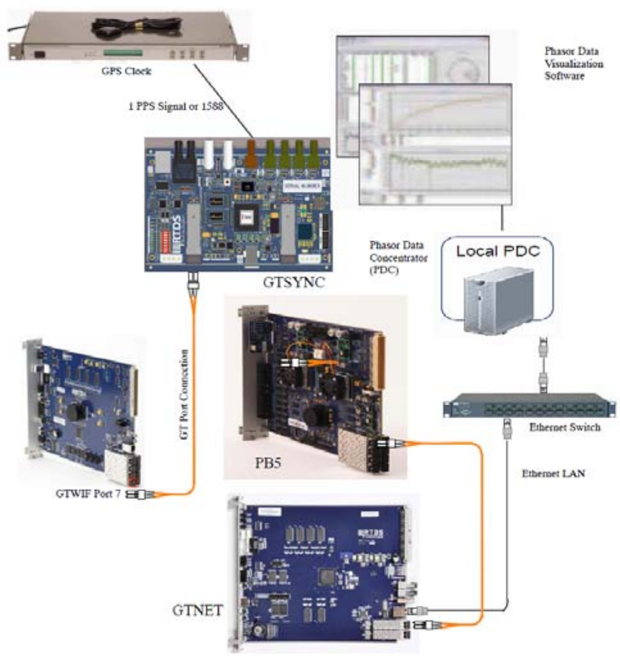

Figure 5: 1PPS synchronization setup

Using the RTDS Simulator to test PMU's can be categorized in two ways, system testing or error testing. System testing would involve a power system network to show the system dynamics. Error testing would involve control components which would generate various waveforms defined in C37.118.1 for total vector error (TVE) tests. In Figure 5, the testing is accomplished using a simulated model of a PMU which runs on the RTDS Simulator's main processing board called the PB5 card. The Giga Transceiver Network InterFace (GTNET) card is the card responsible for ethernet based communication and it is capable of providing several different protocols. One of these protocols, GTNET-PMU, provides a C37.118 datastream out from the simualtion. A Phasor Data Concentrator (PDC) collects PMU data from multiple sources. In most cases, this data is compiled or combined and then resampled to provide custom output streams to an Enterprise Management System (EMS) historian to be used for remote archiving as well as interfaced to custom designed Wide Area Measurement Systems (WAMS). PMU data can be used for a variety of purposes. Some of them are to monitor oscillations, system frequency, angle difference, and the overall voltage stability of the system. A few other examples of uses for PMU data are alarm and operational limit settings, congestion management, and state estimation. Many examples of PMU research topics can be found in the research repository of the North American SyncroPhasor Initiative website. [2]

4.2 PMU Implementation

As more and more PMU's are being deployed in today's power networks, the need to study the way they work and how to use the data they provide is becoming imperative. Based on this need, RTDS Technologies has developed a software PMU model which can be simulated on the RTDS Simulator. Studies can be done completely in a simulated environment or with a combination of simulated and physical PMU's.

The IEEE standard that defined a PMU has undergone changes recently. The standard C37.118-2005 is split into two new standards: one for measurement (C37.118.1-2011) and one for communication (C37.118.2-2011). The older standard did not support the use of IEEE-1588 precise time protocol (PTP) but the newest PMU standard supports the IEEE-1588 power profile. As well, the new standard provides measurement specifications for PMUs during dynamic system conditions. Specifications for

PMU's are also included with the new standard and will be defined for use in Protection (P) class or Metering (M) class applications [3].

The PMU model developed to run on the RTDS Simulator includes a Discrete Fourier Transform (DFT) based model utilizing a phase-locked loop (PLL) for frequency tracking and sample time adjustments. The P class and M class reference models from the IEEE standard C37.118.1 Annex C have also been implemented. One GTNET card can support and stream data from eight separate PMUs thus allowing for testing of large scale WAMS. Additional GTNET cards can be added when more than eight PMU's are used within a simulation. Figure 6 shows the typical steps used within the reference PMU to process the input signals [3]. A GTSYNC card provides the absolute time-reference and the simulation data is sampled using a fixed sample rate. The quadrature oscillator operates at nominal frequency and is used to perform complex multiplication of the input signal. The low pass (LP) filters are Finite Impulse Response (FIR) and remove the double frequency component thus leaving the real and imaginary part of the original input signal. For P and M class the LP filters are implemented using symmetrical FIR filters with an odd number of stages. The P class filter co-efficients are calculated using a triangular window and the M class filter co-efficients are calculated using a windowed "sinc" function multiplied with a Hamming window. Each sample is time-stamped and compensated for the group delay of the LP filter. The phasor estimate at the center of the estimation window is unbiased by the actual system frequency and does not require further phase correction when the time-stamp at the center of the window is used. The P class samples data at 15 samples per cycle and the M class samples data at 16 samples per cycle at nominal frequency.

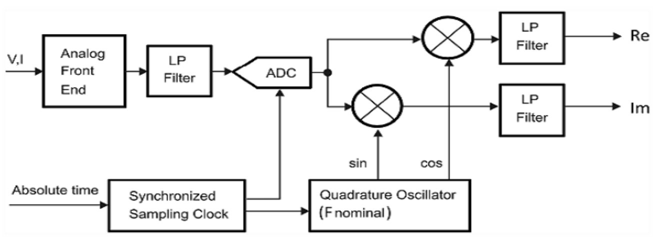

Figure 6: PMU phasor signal processing reference model

Although the block diagram in Figure 3 explains the concept of the reference model quite well, there are some subtle changes that need to be done for it to work on a real time digital simulator. The simulation data must be interpolated when sampled because the PMU sample rate may not be an integer multiple of the simulation time-step. The quadrature oscillator must also be interpolated by the same amount as the simulation data. The maximum reporting latency allowed by C37.118.1-2011 is 2/Fs for P class and 5/Fs for M class where Fs is the reporting rate [4]. Therefore the LP filter order must have latency less than the maximum allowed by the standard and also allow for other delays. The LP filter order can be quite large at the lower reporting rates and exceed the amount of available RAM. For example, an M class PMU operating at nominal 50Hz with a reporting rate of 10Fs requires a filter order of 700. The number of variables for just one PMU would be equal to 12,618. Because the RTDS Simulator model was designed to support eight

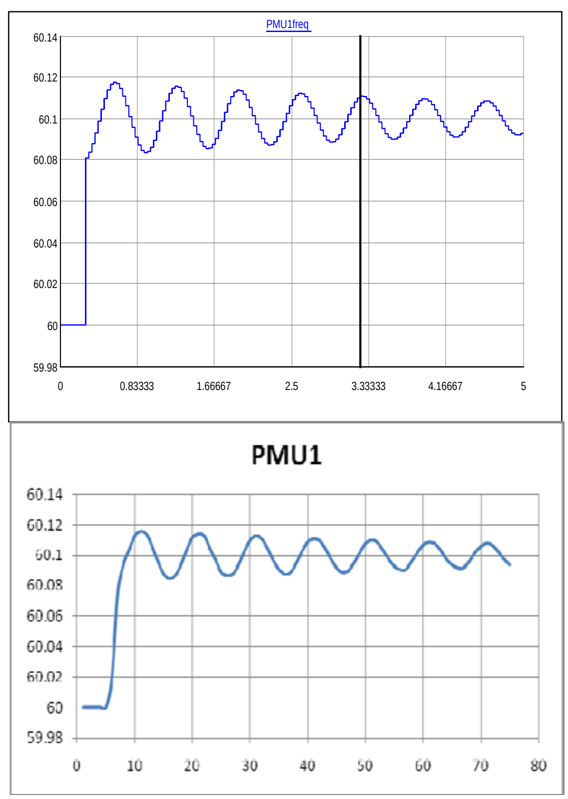

Figure 7: Frequency of RTDS and PMU1 for 0.1 Hz Step

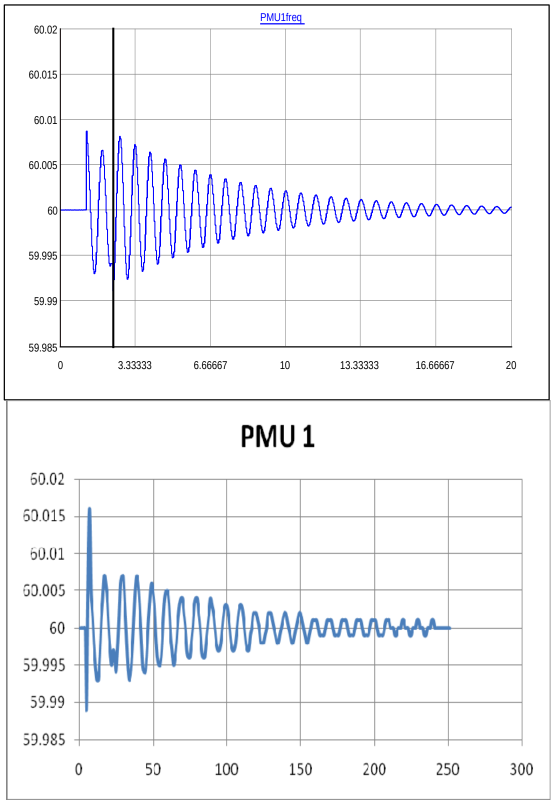

Figure 8: Frequency of RTDS and PMU1 for 0.1 Hz step

PMU's the amount of variables just to process the FIR filters would equal 100,944 for a 50Hz PMU reporting at 10Fs. During development of the RTDS Simulator PMU model the lowest supportable reporting rate was found to be 10Fs at 50Hz. As the reporting rates become lower the filter window length becomes larger to the point that the available memory limit is exceeded. The standard reference model does not provide filter parameters for reporting rates higher than 100Fs or 120Fs. In order to provide reporting rates at 200Fs and 240Fs for 50Hz and 60Hz respectively a 30 tap FIR filter using Dolph-Chebyshev co-efficients was used.

The processing of the simulation data and manipulation of the data into the format defined by the IEEE standard was all done on one of the parallel processing PB5 cards shown in Figure 5. Since each of the eight PMUs operating on the RTDS Simulator is independent, it is possible that all eight PMUs may output data at the same time. Therefore a method to limit servicing of one PMU per simulation time-step was needed; to prevent buffer overflows on the GTNET. When PMU data is ready to be sent to the GTNET a service interrupt flag is set and is cleared once the PMU data is sent to the GTNET via the fiber optic connection shown in Figure 5.

4.3 PMU Model vs. Physical PMU

After the PMU model for the RTDS Simulator was created, various tests were done to compare the results of the model to a physical PMU called PMU1. Figure 7 shows the response of the PMU simulated by the RTDS and PMU1 frequency with respect to the step change of 0.1 Hz. When synchronous machines are included in a simulation the mode of oscillation can be determined in Figure 7 by measuring the period between the zero crossings relative to 60.1 Hz. The mode of oscillation in figure 4 is about 1.5 Hz. The mode of oscillation will change by adjusting the H constant of the machine or if a multi-mass is added to the generator model to provide more than one mode of oscillation. The simulation included a synchronous machine with an inertia constant (H) of 3.5. Figure 8 shows the response of the PMU simulated by the RTDS and PMU1 frequency for a single line to ground fault and subsequent reclose.

5. Conclusion

Several items were discussed in this paper. First, real time digital simulation was introduced. Requirements were given for testing PMU devices and wide area protection and control systems. Recent developments of the RTDS Simulator and how they enable PMU testing were described. Finally, the development of the RTDS Simulator PMU model was described and tests comparing both a physical PMU and the PMU modelled on the RTDS were discussed.

Several things are required in order to perform PMU testing and test wide area control and protection schemes. These include the ability to have a highly accurate large scale real time digital simulation, synchronize the simulation to an external time source, include proven models of common power systems control and protection equipment and provide suitable communication paths to and from the simulator for closed loop testing. These functionalities were developed for the RTDS Simulator and must be present in order to accurately test these types of complicated networks.

This paper has also shown that testing large scale networks and complicated control and protection schemes involving PMU's is possible with the recent developments of the RTDS Simulator.

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[3] IEEE C37.118.1-2011 Annex C

[4] IEEE C37.118.1-2011 section 5.5.9