PMU simulation and application for power system stability monitoring

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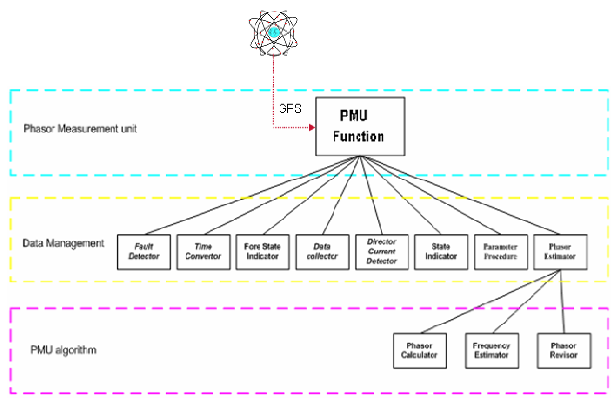
ABSTRACT

Wide Area Monitoring System consists of measuring the angle shift between the sub-networks using Phasor Measurement Units (PMU). These new schemes are promising since a direct measurement of this quantity makes no assumption of the impedance of the tie-lines between the monitored sub-networks. Even if this technology is still at an early stage, a few pilot projects have been already initiated by major utilities over the world.

Synchrophasor measurements are becoming one of the new features available in some multifunctional protection devices. There is an ongoing discussion in the industry regarding the integration into the line protection. At this time, since the actual requirements for such measurements is fairly limited and they are used predominantly by non-protection applications, many protection professionals express preference to keep such functions in stand alone or disturbance recording devices. On the other hand, there are new requirements for development of system integrity protection schemes (SIPS) that may need the integration of phasor measurements in the relays.

It is anticipated that over the next five to ten years over 500 to 1,000 PMUs will be deployed world-wide. Each PMU typically monitors 6-8 phasor quantities, such as voltages, currents, and frequency, all of which are time-stamp synchronized using a Global Positioning System (GPS) satellite.



As shown above, the PMU data are synchronized with UTC time from a GPS receiver with accuracy of <1microsecond and captured at a rate of 10,12,15,20,30 and 60 frames per second at 60 Hz, and can be used to support:

- System Model Validation,
- System Monitoring under diverse conditions,
- System Protection and Control,
- Adaptive remedial action schemes,
- System Operator Interfaces,
- Alarming of sudden power flow changes,
- Disturbance analysis (post-mortem),
- Harmonic Status.

Smart PMU could also offer event triggering based on Over-Current, Under/Over-Voltage, Under/Over-Frequency and Under/Over df/dt thresholds as well as status change. The Event Data Types will be either Phasors, Waveforms and Individual Phase Phasors.

This paper discusses to the application of PMUs to detect power system anomalies. The focus is on using a PMU simulation tool to extract information pertaining to small signal instability from power system simulations as well as real recorded COMTRADES.

The paper describes a new tool developed specifically to simulate PMU measurements on a PC in order to understand the impact of filter response times and data transmission frequency on the information that can be gleaned from PMU measurements. Also presented are the results of application of this new tool and the conclusions drawn from this exercise. The new tool also provides the facility to test and study solutions offline before they are actually deployed.

The use of the simulation application allows testing of real physical networks (Ethernet) to assess traffic load and propagation delay of PMU data for multiple device configurations without the need for complicated changes to physical devices.

1. INTRODUCTION

This paper starts off by covering the need for PMU measurements and basic principles of synchronised measurements by giving a brief description of the architecture and implementation of a real PMU. The hardware and software components and interactions that affect the measurement are also discussed.

A PMU Simulator architecture is presented with some example applications which can be developed using this tool.

The results of analysis done on synchronised measurements using the simulation also presented.

2. SYNCHRONISED MEASUREMENTS

Ever increasing grid complexity has made it difficult to predict and anticipate contingencies. This is mainly due to deregulated electricity market, transmission network underinvestment and growing number of renewable but less predictable wind farms generation. Spate of Blackouts in the recent past have made utilities all over the world much more aware of the need for power system wide monitoring and control. One of the fundamental requirements to achieve that goal is to have a common measurement reference. A few technology enablers have emerged which have lead to development of a new kind of measurement paradigm. The technology enablers, that are basis for the new wide area monitoring and controls implementation, are:

- GPS (Global Positioning System)
- Ethernet Communication

This new type of measurement device is a Phasor measurement unit (PMU).

2.1. Synchro Phasor definition

A phasor is a complex number used to represent the fundamental frequency component of voltage or current measured to a common time reference (GPS). This common time reference is independent of the geographical position of the measuring device. All measurements are done with the GPS one pulse per second (1pps) as the reference (in accordance with Reference [1]). The 1pps pulse can be from any external source provided the accuracy is in accordance with the requirements.

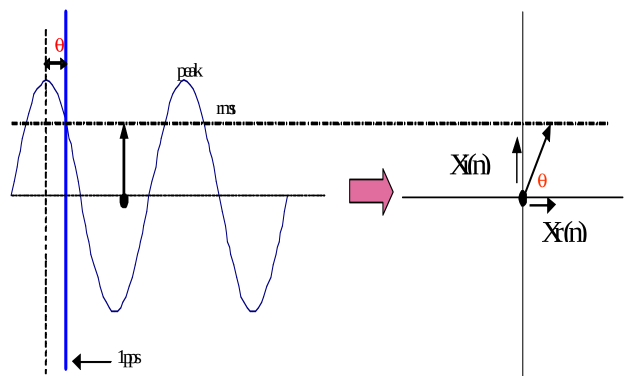


Figure 1: Phasor measurement in relation to the common reference value:

The result of the measurement is a vector X (synchronised phasor) as given below:

$X = Xr + jXi$

$X = (Xm/\sqrt{2})e^{j\theta}$

Where Xm is the peak magnitude of the filtered synchronised vector and θ is the phase angle relative to a cosine function at nominal frequency. IEEE C37.118 specifies that the angle θ is 0 degrees when the maximum of the signal to be measured coincides with the GPS pulse and -90 degrees if the positive zero crossing coincides with the GPS pulse.
Figure 1 illustrates this conversion, where Xi (n) and Xr(n) are the real and imaginary filtered rms components at a particular instance and θ is the phase angle in accordance with Reference [1] . The measured angle is reported over the communication channel in the range of $-\pi$ to $+\pi$ radians.

A primary requirement is the accuracy of the measured phasor. Reference [1] defines the total permitted vector error (TVE) for the static condition at nominal frequency as

$$TVE = \sqrt{\frac{(X_r(n) - X_r)^2 + (X_i(n) - X_i)^2}{X_r^2 + X_i^2}}$$

Where X_r (n) and X_i (n) are the measured real and imaginary components and Xr and Xi are the reference values. This measurement accuracy varies with the magnitude and frequency of the input signal.

2.2. Basic PMU Architecture

The samples from the voltage and current inputs are collected by the A/D (Analog to digital converter) at the rate of 48 samples/cycle but independent of the 1pps input. The sampling interval is controlled by a well proven frequency tracking algorithm in order to respond dynamically to changes in system frequency. This data is sent to the measurement processors which handle the GPS and IRIG-B inputs and provides synchronised phasor measurements. In addition to that a communication processor handles the Ethernet communication. Figure 2 below shows the basic PMU architecture. The synchronised measurements are transmitted upstream over Ethernet (TCP or UDP).

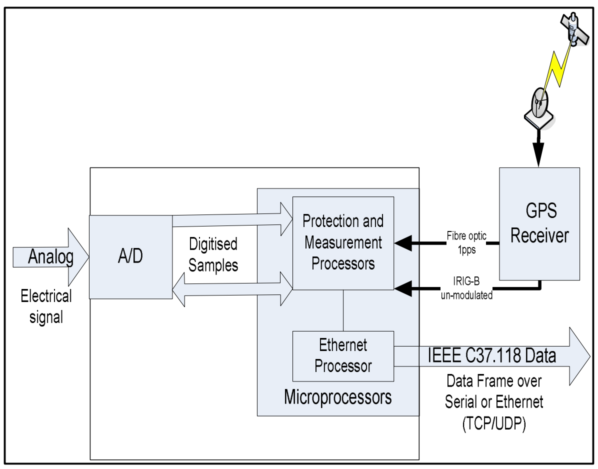


Figure 2: Phasor measurement architecture

The measurement window is centred around the GPS input, which corresponds to UTC (Coordinated universal time).
The measurement window would be as below (Figure 3), with 24 samples taken from before the GPS pulse arrived and 24 samples after. Any phase shift between the centre of the window and the GPS pulse, which can be up to half of sampling interval, is taken into account using a 37.5 MHz internal CPU clock and compensation is applied to the filtered result. The PMU also generates internally a reference time tag every 20 ms (if nominal frequency is 50 HZ) to provide measurements till the next GPS pulse arrives.

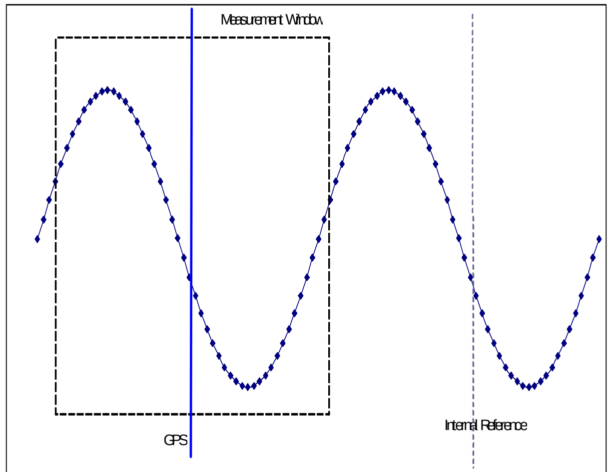


Figure 3: Measurement Window

2.3. Additional Compensation

I addition to the compensation for the phase shift between the centre of the window and the GPS input additional delays need to be considered. The characteristics of the current and voltage transformers along with the phase delay of anti-aliasing filter needs to be compensated for.
Two types of compensations are required, dynamic and fixed. Dynamic compensation is needed for delays that vary with frequency and magnitude of the applied signal but are generally linear and compensation factors can be calculated to cover the range of operation. These relate to afore mentioned anti aliasing filters and instrumentation transformers.
In addition to these variable delays there might be fixed delays in the hardware /software interaction, for example delay in A/D to sample all the channels. It is generally a constant delay and compensation can be applied to the measurement.

Frequency tracking takes care of phase angle errors due to filtering by varying the sampling rate such that the window length is always one cycle regardless of the system frequency.

Figure 4 shows the variation of Total vector error with the variation in magnitude and frequency of the applied signal.

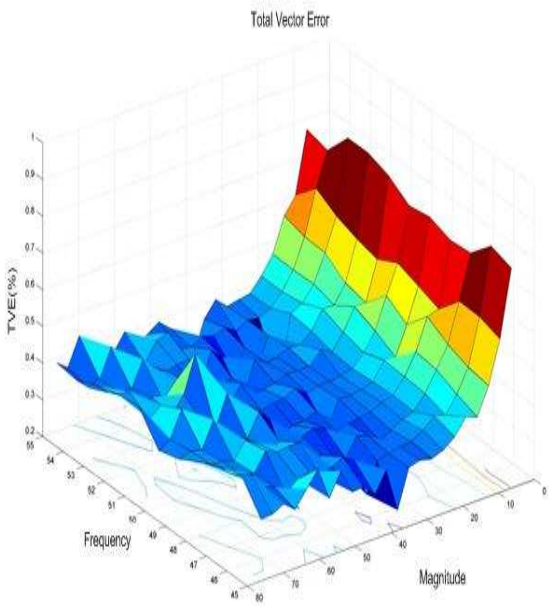


Figure 4: TVE variation with magnitude and frequency

3. PMU SIMULATION

3.1. Introduction

There are a few aspects to simulating PMU data. Firstly a Front end is required to enable the user to confront normal and abnormal system conditions. To be completely free from dependency on any modelling software, COMTRADE files were chosen as the basic starting point. The Front end allows the user to choose any point (time) as the synchronising point (GPS input) and also to select any signals from the file as the available channels for that system bus. It also requires that user assigns the network address and port as it would be done for a real PMU.

Figure 5 shows the basic user interface. Multiple PMU's can be created in this fashion by choosing files which are actual recordings from different nodes in a real system or COMTRADES created from system simulations. There is also an option to loop over a file after data is exhausted.

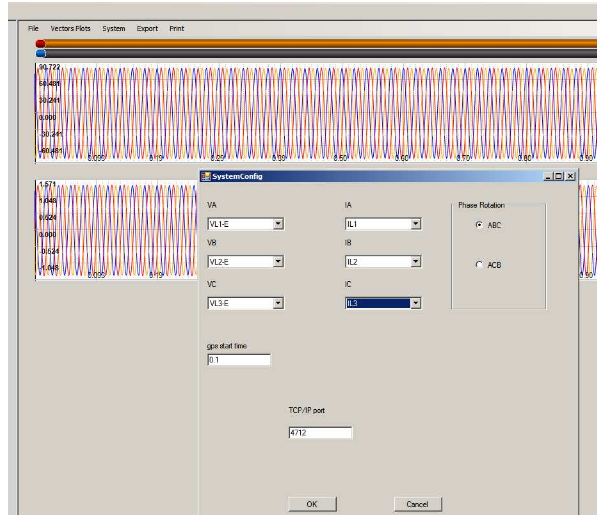


Figure 5 : Simulator Front End

Another non trivial aspect is make sure that the simulator will behave exactly like a real PMU within some tolerance as the time tags are derived from the micro second time field in the COMTRADES. Figure 6 shows the PMU phase A Voltage measurement when the GPS input is specified to occur at 0.1 seconds into the file , exactly when the positive going zero crossing occurs on that phase and the simulator correctly shows the phase angle as 270 degrees (-90).

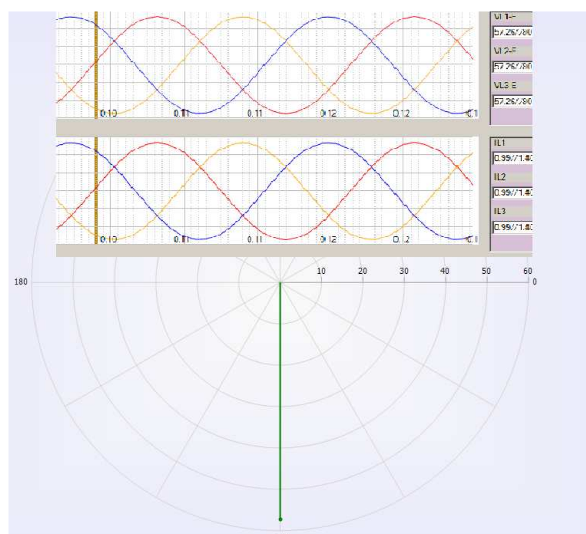


Figure 6 : Simulator Measurement

3.2. Architecture

The PMU driver provides the simulation of the PMU measurement at the application layer, the frame translation at the presentation layer and the provision of server capabilities (the session layer) over TCP or UDP. The driver is designed to provide instances of a single PMU, allowing many PMUs to be simulated on a single machine but controlled from a single application. The driver also provides the capabilities to simulate PDC transmissions containing the data of many PMUs. The implementation is multi-threaded so as to take full advantage of multi-core technology that is common place in today's desktop and laptop machines. The potential simulation options are given in the diagram below (see Figure 7).

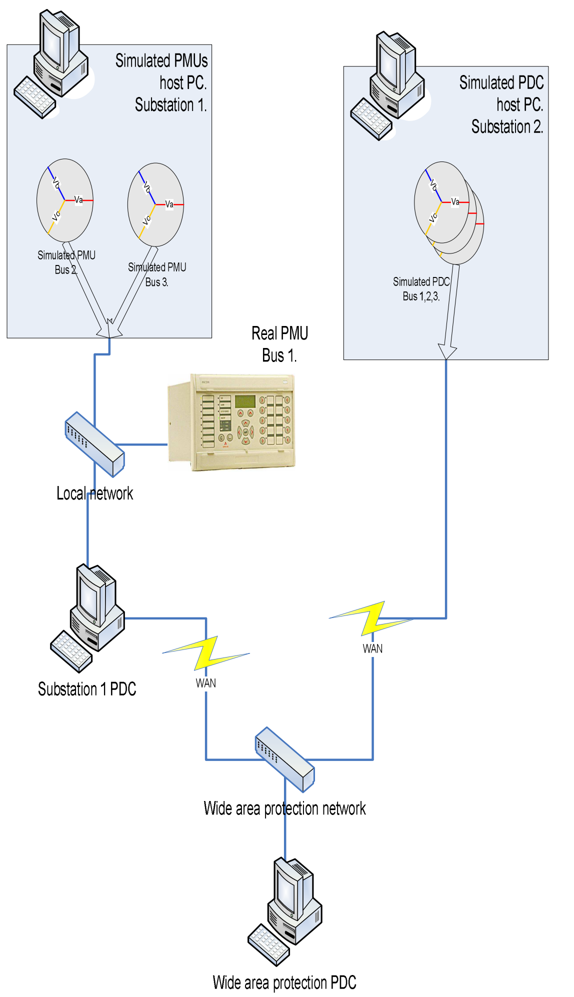


Figure 7: Potential Applications of PMU and PDC Simulated Devices

The use of simulated PMUs has many benefits for power system application developers who are looking to improve system stability through wide area analysis. These benefits include:

- Real network analysis without the need for actual PMU hardware. This provides important loading and propagation delay information, especially when data is being passed over third party communications infrastructures.
- Functional testing of PDC (Phasor Data Concentrator) capabilities using a predefined set of test data, allowing quicker evaluation of the PDC's ability to time align, resample and transmit data to an upstream device, all without real power system inputs.
- Realistic testing of Wide Area Protection algorithms under conditions of communications instability without the need of complicated configuration.
- Reduction in time and cost of testing

4. APPLICATION OF PMU DATA

4.1. Angular Instability

A typical angular instability case was chosen where a severe system condition lead to multiple pole slips In this case a small generator is out of synchronism with a much larger system.

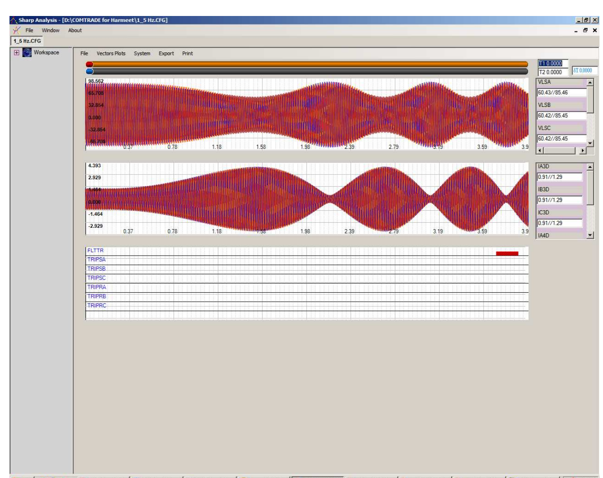


Figure 8: Pole Slip COMTRADE

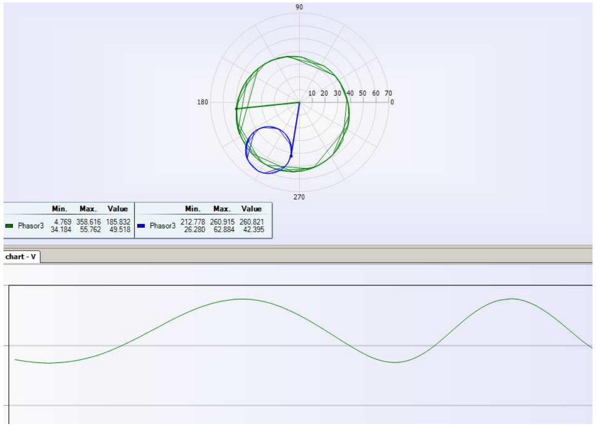


Figure 9: PMU Data From Both Ends

Figures 8 & 9 show the captured sample data and the PMU output. The upper half of figure 9 shows the two voltage vectors with the small generator showing major angular excursions (slips) compared to comparatively small deviations in the larger system.

The bottom half shows the voltage profile of the weaker system during a slip as it would be captured by a PMU at that bus.

4.2. Small Signal Detection

A test system was created to produce a slightly damped system oscillation, note the very gradual decay in the peak amplitude in Figure 10, by combining a damped 49 Hz and 50.5 Hz signal.

$$\text{Signal}=150.e^{-0.3t}.\ \sin(2*\pi*49*t+\pi/4) + 160.\ \sin(2.\pi.50.5.t+\pi/5)$$

The data was applied to a PMU and Figure 11 shows the real Component of PMU measurement and the Prony fit derived from the PMU measurement. The output from the analysis is shown in Table1.

The Prony method correctly identifies the two frequency modes, amplitudes and the associated damping

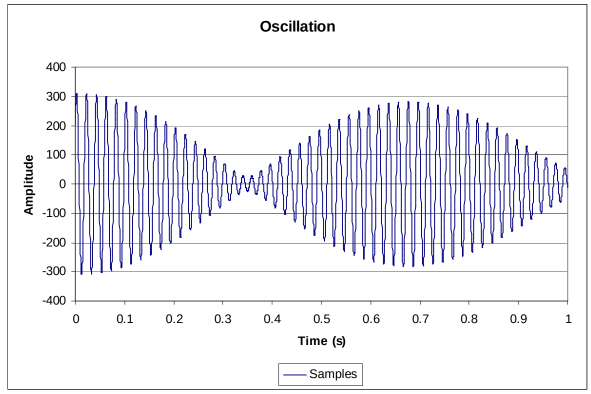


Figure 10: Slightly damped oscillation

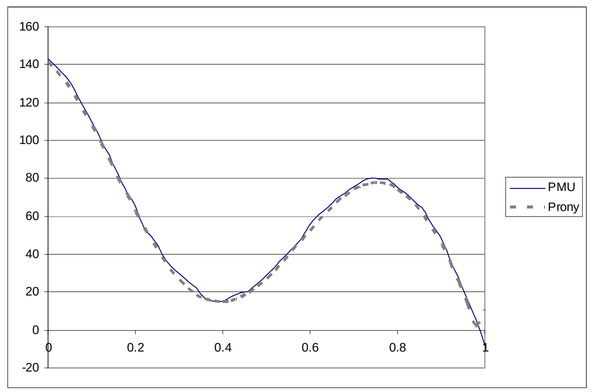


Figure 11: PMU output and Prony fit

TABLE 1 : Prony Output

Frequency Mode	Damping	rms Amplitude
-1	-0.3	52.98
1	-0.3	52.98
-0.5	0	56.58
0.5	0	56.58

5. BIOGRAPHIES

Harmeet Kang has a BE in Electronics Engineering from University of Bangalore, India. He is a registered member of IEEE. He joined GEC ALSTHOM (India) in 1995 as a Relay Applications Engineer and moved to R&D department in UK in 1999. Currently he holds the position of Product Manager WAMPC in Areva T&D (UK). His areas of interest include signal processing, algorithm

Yingkai Sun received his Bachelor degree majored in Power System & Automation from TianJin Univercity, China in 1989. After his graduation, Yingkai worked as a protection and control engineer for TianJin Electric Power Company China. In 1998, Yingkai obtained his M.Sc degree majored in Protective Relaying from TianJin University. Yingkai currently is working in AREVA Automation Canada Inc. as a Sales and Application specialist since joined AREVA on 2008. Prior to AREVA, Yingkai was working in GE Multilin and had been working on several roles including of Sales Manager in Asia and Application Engineer in the R&D team

Damien Tholomier received a BEng in Electrical and Automation Engineering in 1992 from the University of Marseilles, France (Ecole Polytechnique Universitaire de Marseille). Damien joined GEC Alsthom T&D GmbH in Stuttgart, Germany where he worked for 5 years in the Protection & Control department as Power System Applications Engineer. In 1997 Damien moved as Marketing Manager High Voltage Protection Business Unit with Alstom T&D Protection & Control in Lattes, France where he worked on full scheme distance protection algorithms. From 1999-2001 he was Sales & Service Director for Mediterranean Countries and Africa. 2002-2006 he was Marketing & Product Management Director for Alstom T&D and later Areva T&D Automation where he worked on new busbar relay (application of universal topology and CT saturation detection algorithms). He is currently Unit Managing Director in Canada, also responsible for Substation Automation Solutions in North America

Marcus Young received his B.S. (2002) and M.S. (2005) degrees in Electrical Engineering from the University of Tennessee, Knoxville. Marcus joined the Electric Power Research Institute (EPRI) in 2005 and is currently a Senior Project Engineer/Scientist in the Power Delivery and Utilization Sector. His work at EPRI includes development of EPRI's Smart Grid Substation Laboratory, application of distributive resources, power quality, and power applications that utilize high temperature superconductors. Before joining EPRI, Marcus worked for the Applied Superconductivity Group at the Oak Ridge National Laboratory. In this role, he worked to develop and test high temperature superconducting power cables. Marcus is currently a licensed Professional Engineer in the State of Tennessee.

6. REFERENCES

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