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Technical Report TA User Project **3D-Power**

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Abbreviations

<i>DER</i>	Distributed Energy Resource
<i>TA</i>	Trans-national Access
<i>PMU</i>	Phasor Measurement Units
<i>uPMU</i>	Micro Phasor Measurement Units
<i>AIT</i>	Austrian Institute of Technology
<i>FSU</i>	Florida State University
<i>PTP</i>	Precision Time Protocol
<i>TAI</i>	Temps Atomique International / International Atomic Time
<i>PDC</i>	Phasor Data Concentrator
<i>ROCOF</i>	Rate of Change of Frequency
<i>CNS</i>	Communication Network Simulation

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Executive Summary

Distribution networks are increasingly turning to dynamic and complex systems as new paradigms are becoming more ubiquitous such as the integration of distributed energy sources, software enabled power electronic inverters and controllable loads. The interconnectivity and interdependency of all these newcomers introduce numerous novel events in dynamic, transient and steady state scales which are unknown for the conventional monitoring, diagnostics, protection and distribution automation systems. Measurement devices like synchrophasors (e.g., PMU) together with real-time data processing and analysing are becoming more and more important to tackle these challenges even in distribution systems. This project is an effort to leverage the special type of PMU sensing devices for distribution networks which is called Micro-synchrophasor (microPMU). The study takes advantage of a realistic experimental setup by AIT SmartEST together with the new advancements in machine learning, signal processing, and time series analysis to diagnose new classes of events in distribution level - like high impedance faults, topology variation, and stability - that may be caused by power electronic inverters and distribution automation. This will be achieved with the sophisticated Hardware-in-the-Loop (HIL) and Software-in-the-Loop (SIL) facilities in the AIT under the ERIGrid Transnational Access program.

The figure below presents a graphical view of the proposed scheme of real-time evaluation framework for the development of the 3D-Power.

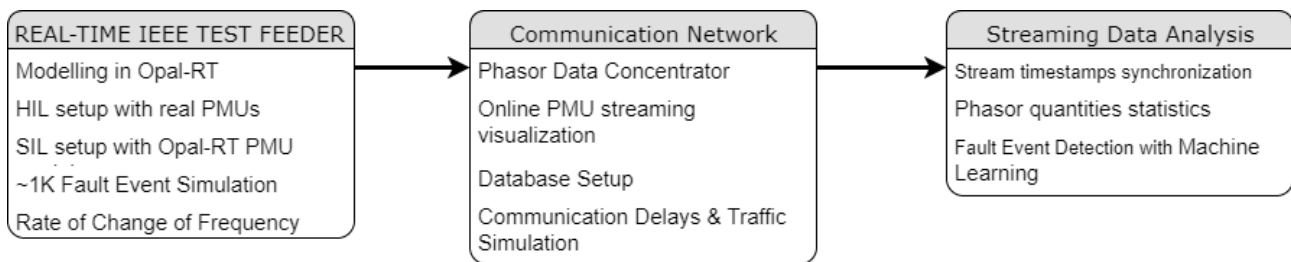


Figure 1: Overall Scheme of 3D-Power Testbed Tasks

In general, the 3D-Power project is divided in the following steps or specifications:

1. **Real-time HIL Test Feeder Setup** - the user group has developed a model in Opal-RT where thousands of fault event have been simulated under normal and load conditions. These events were monitored with an ARTEMES PMU and a PSL PQube (uPMU) in a hardware-in-the-loop setup. HIL measurements are compared with virtual Opal-RT PMU units created inside the model.
2. **Communication Network** - real time data was streamed complying the IEEE C37.118 standard for PMU GPS synchronized measurements and then gathered in an open source Phasor Data Concentrator (OpenPDC) for its online visualization. This stage includes the database setup for the storage of the events monitored. Taking advantage of the SmarTEST laboratory at AIT, an OMNET++/CORE communication network setup was implemented to emulate the real distribution network latencies.
3. **Data Analytics for Diagnostics Applications** - measurements taken from the HIL and SIL setups serve as a data repository for machine learning algorithms developed by the user group at Florida State University. The objective of the machine learning techniques used is to classify and detect abnormal operational conditions such as electrical faults.

1 General Information of the User Project

USER PROJECT INFORMATION	
User Project Acronym	3D-Power
User Project Title	Data-Driven Detection of Events in Power Systems (3D-Power): Event Detection in Power Distribution Networks Using PMU Measurement and HIL Test beds.
Main scientific/technical field	Distribution Network Monitoring, Phasor Measurement Units, Synchronization, Hardware-in-the-Loop Tests, Data Analysis, Event Detection, Distributed Energy Resources
Keywords (5 max., free text)	Monitoring, Diagnostics, Synchronization, PMU, Networked Inverters, Distribution
Host Research Infrastructures	AIT Austrian Institute of Technology
Starting date for the access	July 14th 2017

2 Research Motivation

2.1 Objectives

The FSU EriGrid project has the following objectives:

1 - Creating an experimental setup providing realistic scenarios in a distribution test feeder model with simulating PMU data streams using the HIL facilities in AIT SmartEST. This includes the following:

Task 1.1. Create or apply a model in Opal-RT based on the taxonomy models available in the IEEE Distribution Test Feeders and model validation.

Task 1.2. Establish the HIL interface with synchrophasor measurement devices with the model simulated from task 1.1 using the Opal-RT D/A interface and amplifier.

Task 1.3. Establish a synchronization between virtual PMUs modelled in Opal-RT/RT-Lab helped with GPS/Real Time communication cards.

Task 1.4. Compare performance of different PMUs from different vendors (PSL, ARTEMES, Arbiter)

2 - Add the communication layer associated with the monitoring systems including uPMU and PMU, and a Phasor Data Concentrator (PDC) for the distribution feeders implemented in Task 1 using the SIL capabilities in AIT SmartEST. Moreover, this will include the following:

Task 2.1. Create the model of Phasor Data Concentrator (PDC) and PMU communication link with the CORE communication simulation software. The communication network model will comply with international standards such as IEC 61850 and IEEE C37.118 to emulate real-field measurements in distribution networks.

Task 2.2. Integrate the communication network model into the distribution feeder model on the Opal-RT HIL platform.

Task 2.3. Test the data stream from PMU to the Opal-RT HIL resembling a real field experience with CORE with different stream traffic, time latencies in the communication structure.

3 - Data mining, data repository and data analysis from the real-time cyber-physical platform from the implemented HIL & SIL in tasks 1 and 2 and apply the developed machine learning and shape-based time-series analysis algorithms in FSU to explore advantages of PMU devices for fault detection in distribution networks. This will include scenario building, test design, and streaming the real-time data from the modeled PMU and the actual PMU in objectives 1 and 2.

Task 3.1. Scenario building for different type of faults, with changing fault impedances, and fault locations.

Task 3.2. Implement the developed machine learning methods in FSU for event detection on data streams from Opal_RT.

4 - Reporting the results and provide future plan for expanding the study in 2018, and future publication plan.

Task 4.1. Report for EriGrid 2017 and Publication Plan

Task 4.2. Future work and expansion strategy in 2018

2.2 Scope

Electrical power systems is expected to deliver undistorted and uninterrupted sinusoidal rated voltage and current at the rated frequency to the consumers. Any deviations and abrupt changes from the nominal magnitude and/or frequency are treated as a anomaly which can translate in the risk of malfunction or damaging of electrical and electronic devices. These disturbances can be caused by human error, equipment failure, and environmental intervention. Power systems faults

and anomalies followed by cascading effect can increase the risk of outages, given the interconnection and interdependency of devices within the electrical grid. The high number of disturbances caused by combinations of abnormal events and their interaction in the grid present a challenge for building high fidelity mathematical models of the power system. Therefore, data-driven and modelless tools are needed for detection and classification of power system anomalies.

The smart grid revolution is creating a paradigm shift in distribution networks including the dramatic increase in the adoption of distributed energy resources (DER), electric vehicles, energy storage, and controllable loads. This transformation imposes new challenges on existing distribution infrastructure and system operations for stockholders, engineers, operators and customers. Unfortunately, distribution networks historically lag behind transmission networks in terms of observability, measurement accuracy, and data granularity. The changes in the operation of the electric grid dramatically increase the need for tools to monitor and manage distribution networks in a fast, reliable and accurate fashion. The introduction of powerful and accurate measurement devices in the distribution network side such as Phasor Measurement Units (PMU) and the recently introduced Micro-PMU (uPMU) [2], support these tools as a reliable solution.

This project intends to advance towards the applications of high-precision PMUs using an Opal-RT Hardware-In-the-Loop setup combined with the communication network model and OpenPDC platform to emulate the actual Phasor Data Concentrator (PDC) that collects data from multiple actual PMU made by different vendors. The vendors including PSL, ARTEMES and Arbiter. Furthermore, this work is focused on obtaining a customizable data repository that mimics the real-field with Opal-RT HIL simulation with different measurement devices for distribution network. More information about PSL, ARTEMES and Arbiter PMUs is available in the appendix A_C.

Data sets that include the different anomalies mentioned are scarce and often unlabeled making it difficult for new machine learning, signal processing, and statistical methods to be tested and validated. Hence the proposed experiment paves the way for understanding needs and requirements for PMU data in laboratory setups for future standardization related testing objectives.

This project was performed during the summer 2017 in four main tasks:

1. Creating an experimental setup providing realistic scenarios in a distribution test feeder model simulating actual and virtual PMU data streams using the Opal-Rt HIL facilities in AIT SmartEST.
2. Adding the communication layer associated with the monitoring systems including uPMU and PMU, and a Phasor Data Concentrator (PDC) to the HIL testbed.
3. Data mining, data repository and data analysis from the real-time cyber-physical data from the implemented HIL & SIL in tasks 1 and 2 and apply the developed machine learning and shape-based time-series analysis algorithms in FSU to explore advantages of PMU devices for fault detection in distribution networks.
4. Reporting the results and provide future plan for expanding the study in 2018, and future publication plan.

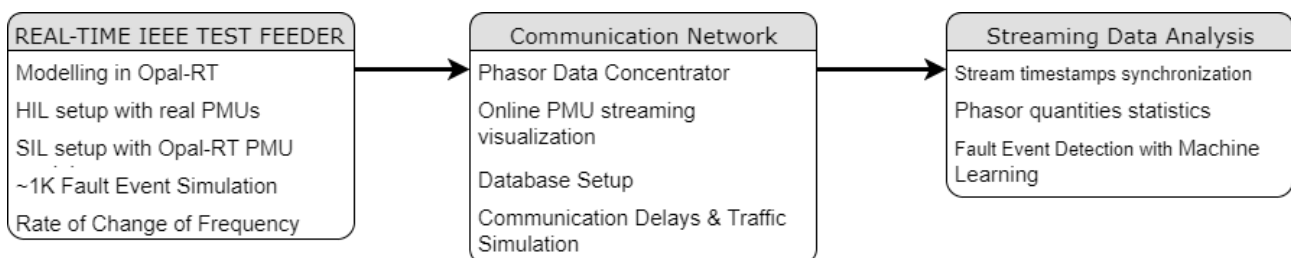


Figure 2: Overall Scheme of 3D-Power Testbed Tasks

3 State-of-the-Art and State-of-Technology

Electricity networks are the most interdependent, spread out, dynamic, and vulnerable networks, displaying different behaviors within the temporal spectrum of 1 microsecond to decades and the spatial spectrum of millimeters to thousands of kilometers. Transmission networks rely mostly on supervisory control and data acquisition (SCADA) systems. The average sampling time in SCADA is 15 minutes with a capability for 5-second measurements. Synchrophasors (PMUs), which provide 60-120 measurements per second, have been introduced to the grid in the last decade [1]. However thus far, they have not been utilized to observe the entire grid. Historically, distribution networks have lagged behind transmission systems in terms of observability and data granularity. Considering the large number of connected DER Inverters and controllable loads in distribution networks in coming years, the lack of observability will create more challenges for distribution network reliability, stability and security. Additionally, data processing techniques need to be adapted for power distribution system applications.

Moreover, the traditional monitoring systems such as SCADA are not designed for processing heterogeneous data with different time scales. Above all, the actual monitoring systems in distribution networks lack the integrity to observe interdependency between different components or the dynamics of the grid under different conditions. This project aims to fill the gap in interdependence and interoperability studies using the SmartEST facility.

The PI, Dr. Arghandeh, has an extensive experience in distribution monitoring system design, power systems transparency, power system physical-based modeling, and data analysis applications. With the UC Berkeley team, he was involved in the development of the "Microsynchrophasor (uPMU) for distribution network" with a U.S. DOE ARPA-E grant [2]. Micro-PMUs are high accuracy, high resolution PMUs customized for power distribution systems [3]. The actual data from μ PMUs enables visualization of never before observable quantities, and to develop novel applications in power distribution networks. Using the PMU data, the PI has developed topology detection [4], state estimation [5], phase identification [6] and fault event classification [7] applications for distribution networks. Additionally, the "IEEE Working Group on Distribution Power Quality Monitoring", of which Dr. Arghandeh serve as secretary, is in the process of revising the IEEE-1159 standard for monitoring systems to include new types of sensors. The proposed research in AIT if success will provide a valuable dataset for the IEEE WG of Power Quality Monitoring standard revision.

The time synchronized PMU data includes huge amount of information regarding behaviour of power system in normal and abnormal conditions. Recent advancements in data analytics specially in the field on statistical inference and machine learning help engineers to find more understanding about systems performance and health. Several work studies have been performed in the field of machine learning and data driven modelling of power systems with PMU data streams. Brahma et. al [14], proposed PMU data streams as solution to visualize the dynamics in Power Systems with several machine learning methods such as SVM, Shapelet, and Slope Shapelet based methods. Their PMU measurements dataset consisted of over 1000 real-field events, being the majority unlabeled, which were insufficient for testing and training. Therefore, they performed an offline simulation to manage the ML task. In [15], Innah et. al proposed a simulated testbed consisting only of virtual PMUs in a 14 Nodes test feeder. A similar approach was performed by Chandra et al. in [16] for real-time state estimation in a 39 nodes test grid. In [17], Liang et al. present an expert system approach for fault types classification that does not require the topology of the network. This method was validate with a small dataset of 60 fault events recorded by BPA's power grid. Another Wavelet-based approach by Kim et al. in [18]. In this approach, a large number of PMUs were required for testing and validating their technique for generator trip detection (anomaly), as well as having real-field data measurements.

From the discussion above, it becomes clear that there is a necessity for a Hardware-In-the-Loop (HIL) and Software-In-the-Loop (SIL) testbed setup for different measurements and communication streams of synchronized data (PMU). Moreover, a testbed for validating PMUs from vendors side by side was not exist to the knowledge of this team. In fact, none of the studies from the literature review presented above introduces a real-life and controlled PMU measurements approach necessary for

validating different Machine Learning algorithms. As stated in the objectives part of this report, the main goal of this project was creating an experimental setup providing realistic scenarios in a distribution test feeder model simulating actual and virtual PMU data streams using the Opal-RT HIL facilities in AIT SmartEST. Well known and unresolved issues in the power grid may be overcome if studied under controlled environments such as network topology configuration, fault impedances, regulated switching. Moreover, simulating a large number of anomaly events is key for validating and testing machine learning techniques.

Several real-time platforms have been developed for HIL simulation mostly for action-control setup and tuning. The FSU user group suggested using of Opal-RT/RT-Lab as a solution for modelling different power quality event scenarios. RT-Lab is fully integrated with MATLAB/Simulink that has been used widely in many fields of engineering. Additionally, it provides a real-time power systems simulation environment along with a reliable PMU model that works under the IEEE C37.118 protocol.

Furthermore, to develop a HIL-SIL testbed environment, GPS and computational environment clock synchronization becomes key for the integration of real and virtually modelled PMUs. A Precision Time Protocol, or PTP, is a network-based standard that provides nanoseconds of synchronization which makes it a perfect fit for PMU synchronization applications. Therefore, one of the most used approaches for different time clocks synchronization is to utilize a GPS-locked PTP Master for generating a clock standardized signals while a network interface card synchronizes the different local hardware clocks [18]. A RSG2488 RUGGEDCOM [20] is a well-established industrial solution to act as an IEEE 1588 master clock while a Oregano Systems syn1588® PCIe NIC is the interface card of choice for Opal-RT hardware. The data sheet is available in appendix.

The FSU team has expertise and track of research in machine learning method application for event detection and diagnostics in power system. Existing machine learning methods for diagnostics most frequently adopt supervised learning frameworks and depend on explicitly labelled data by utility engineers which are expensive and sometimes unavailable. In recent years, the availability of massive streaming data from the smart grid imposes new algorithms and optimization for machine learning frameworks. In our recent study to minimize the need for expert knowledge, we proposed a novel a shape-based analysis used for fault type classification has been developed by the user group [11]. This method uses a novel approach based on a time-alignment under Fisher-Rao metric technique to preserve the time-series shape of a fault signal and perform a classification process with hierarchical clustering. The ERIGRID opportunity give the FSU team a chance to implement its novel data-driven event detection methods on the realistic data sets that achieved from numerous simulation scenarios on AIT SmartEST HIL facility.

4 Executed Tests and Experiments

4.1 Test Plan

Figure 3 shows the overall scheme of the evaluation framework for the experimental setup of real-time PMU data streaming under fault conditions. A real-time simulated distribution grid (e.g. IEEE test feeders) was modeled in the multicore Opal-RT real-time simulator provided by the Smart Electricity Systems and Technologies Laboratory (SmartEST) connected to three PMUs from different vendors. There are a number of virtual PMUs using PMU model provided by Opal-RT company. The network of virtual and actual PMUs operates under normal conditions prior to setting different fault types (balanced and unbalanced) to obtain random fault scenarios for detection and classification testing purposes. Signals coming from the real-time environment will be connected to the interface of the voltage amplifier so that a synchrophasor device (provided by the FSU user group and TU Wien) is able to read them. Communication setup complies with the IEC 61850 and the phasor magnitude, and angle measurements are then streamed under the IEEE standard C37.118. In order to understand the communication dependencies of fault detection and classification in real-time, a communication network is simulated resembling the different streaming latencies experienced when sending real-field measurement data. The user group used the network layer under the CORE environment provided by SmartEST. An open-source phasor data concentrator (i.e., OpenPDC) used to retrieve the synchrophasor readings and store them in the database with support for free alternatives such as PostgreSQL. Finally, the machine learning and statistical algorithms in R executed to determine the fault event locations and classification.

The following section describes different test experiment setups while also presents their primary objectives, standards used, lessons learned and results. Additionally, an outline of the components used and equipment setup is also provided.

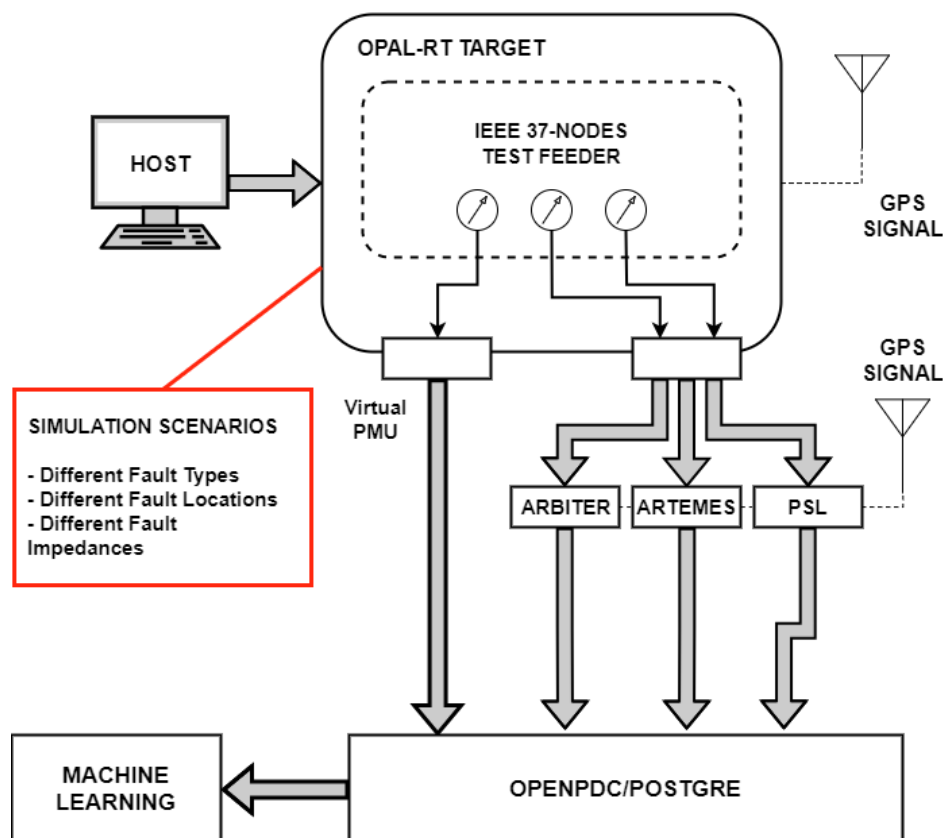


Figure 3: Overall Scheme of 3D-Power Testbed Equipment

4.2 Standards, Procedures, and Methodology

4.2.1 Standards used in the tests

IEEE C37.118.2-2011

As mentioned throughout this report, measurements in Power Systems are very important when performing different control during normal operations. A few decades ago, one of the paramount challenges for electrical engineers is monitoring accurate voltages and currents given that monitoring devices can be located far from each other. Nowadays, time synchronization allows the monitoring network to locate phasors in the same diagram, with more precise frequency, and shift angle readings. Synchronized electrical parameters are obtained from the network by Phasor Measurement Unit (PMU) which can stream data with highly accurate GPS clock time stamps.

Standard C37.118.2-2011 is intended to cover synchrophasor measurements and synchrophasor data transfer for power systems. The standard specifies messaging including types, use, contents and data formats for its use with any suitable real-time communication protocol between PMUs, phasor data concentrators (PDC), and other applications [13].

IEEE Std 1588:2008

IEEE Std 1588:2008, Precision Time Protocol, or PTP, is a standard that provides the different methods for allowing accurate time and frequency transfer from a master to a slave device in a communication network. The most used way of communication is Ethernet, but it can be used with many other technologies. This standard does not specify performance requirements and therefore it is up to the user to choose the right 'profile' for its time synchronization.

4.2.2 Network Models

Test Feeder IEEE 37 bus

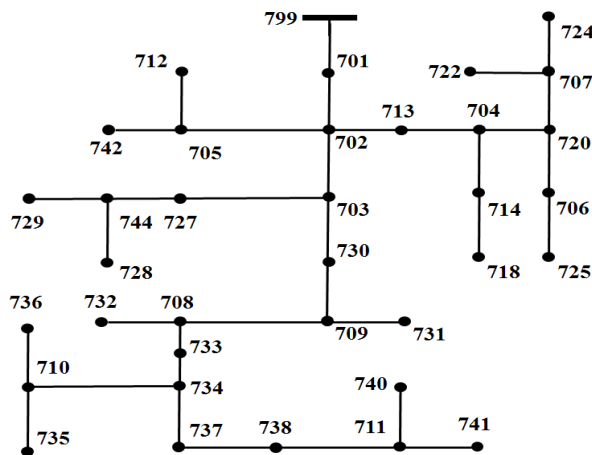


Figure 4: IEEE 37-Nodes Test Feeder [13].

Presented first in [13], the IEEE 37-Nodes Test Feeder is part of a test bed composed by several real-life test feeders. The purpose of its creation is to provide a standardized group of radial feeders for distribution analysis algorithm testing and development. The IEEE 37 nodes test feeder (see Figure 4) provides the essential components and characteristics of a distribution system such as:

- Three-wire delta operating at a nominal voltage of 4.8 kV.
- Substation regulator consisting of two single-phase units connected in open delta.

- Constant PQ, constant current and constant impedance spot loads.
- The loading is very unbalanced.
- Considerable number of nodes and laterals.

Different experiments were performed with the IEEE 37-nodes test feeder model during the execution of the 3-D. Specifically, all experiments with simulated model were performed in RT-Lab/Opal RT in a real-time HIL test setup.

Figure 6 shows the voltage drop diagram modelled in PowerFactory showing the distance of the node with respect to the main feeder and its corresponding voltage. It can be observed that the node with the largest voltage drop is 711 while the node with the longest distance distribution line connection is node 728.

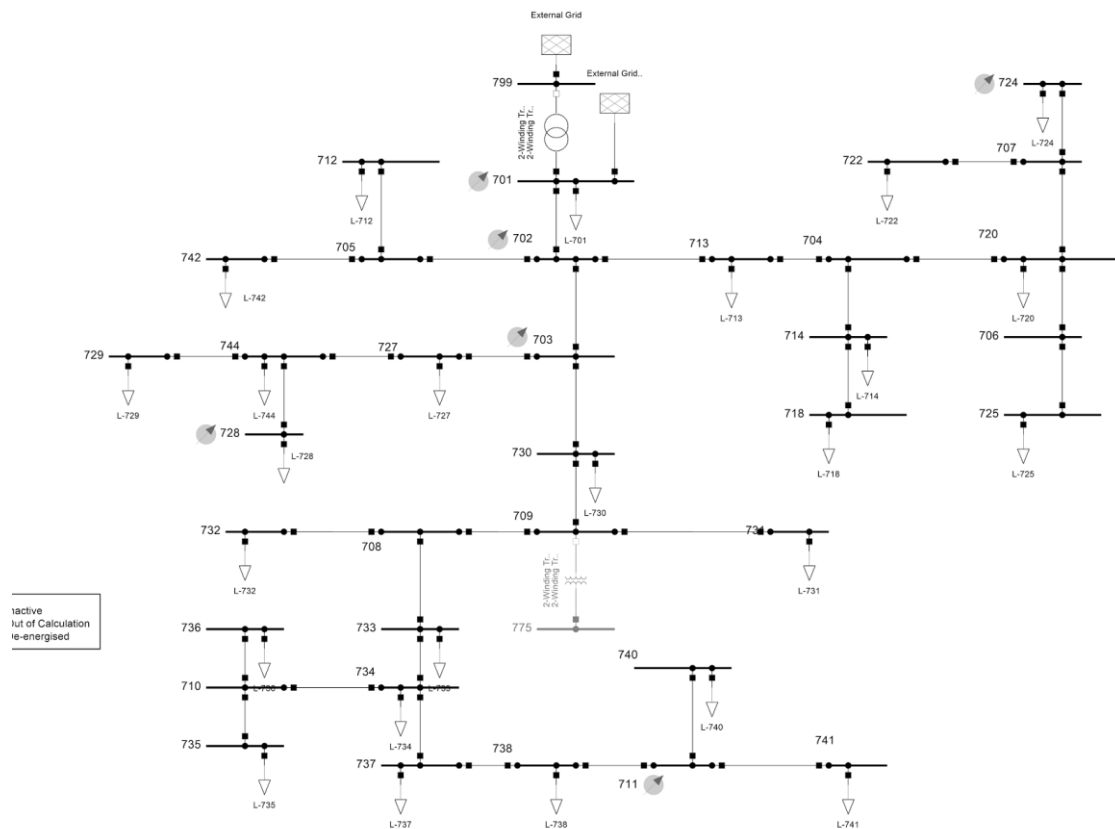


Figure 5: IEEE 37-Nodes Test Feeder in PowerFactory [13].

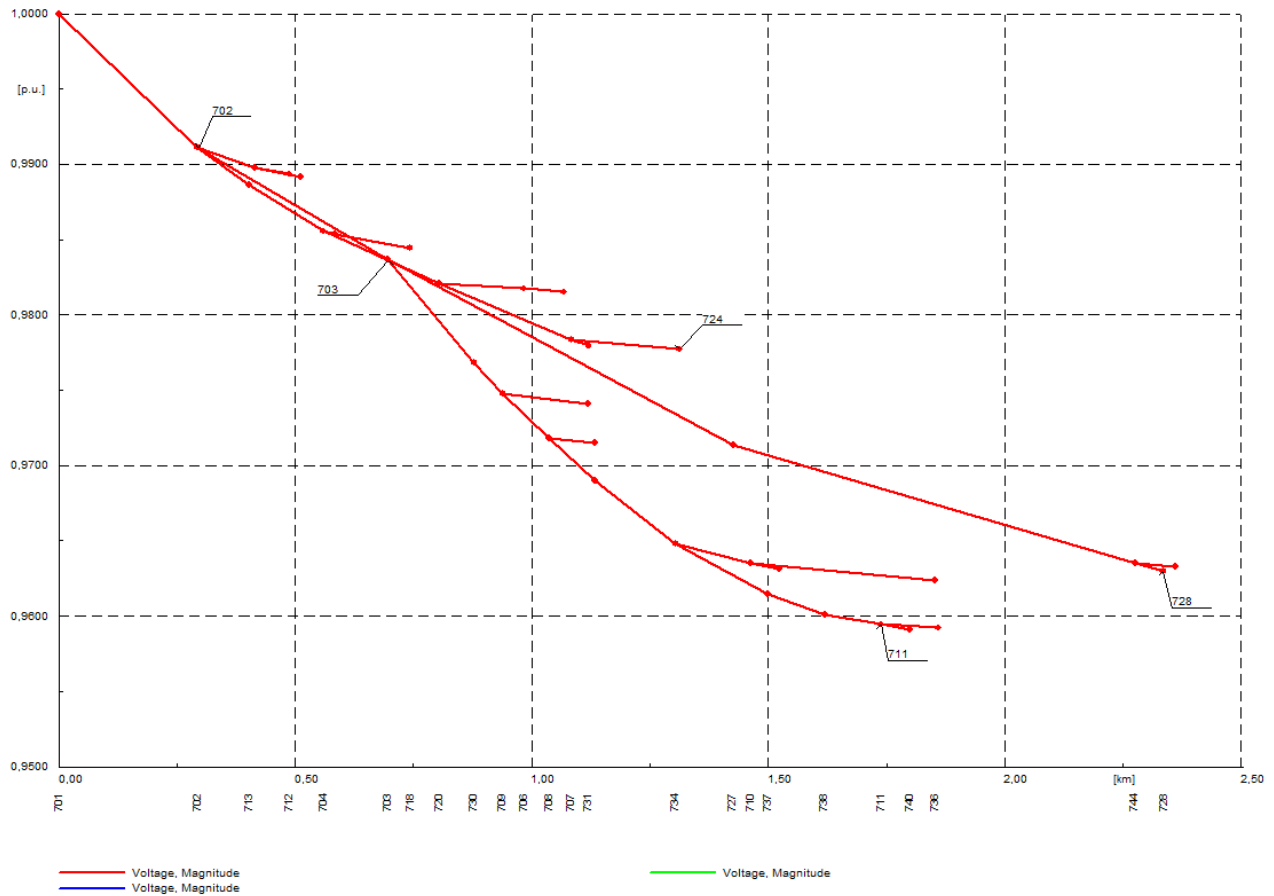


Figure 6: Voltage Drop Diagram (balanced) of the IEEE 37-Nodes Test Feeder.

Note: It is shown balanced here in order to label monitored nodes

4.2.3 Description of Testbed Components

The following are brief descriptions regarding main components have been used in 3D-Power testbed. The catalogue and fact sheet for each component is available in the appendix.

PSL MicroPMU

Traditionally, Phasor Measurement Units or PMUs have been largely utilized for monitoring transmission networks providing magnitude and voltage angles location across an specific grid. The big advantage of using PMU, and their key feature, is that the timestamps are provided by a GPS locked signal. This feature makes accurate power flow possible between two different locations as they deliver precise angle different (up to 1/360th of a cycle). To measure effectively the effects of distributed generation, a PSL microPMU has been introduced as a powerful accurate and reliable tool. These devices are used in distribution networks for providing the same kind of measurements that a transmission side PMU could provide.



PSL MicroPMU

The microPMU is capable of measuring both voltage and current measurement from the line at 120V-230V while also being able to use analog inputs for lower ranges of voltage. The microPMU complies with IEEE C37.118 protocol for PDC streaming. It is worth remarking that while using the analog inputs, the microPMU is not able to stream its data as it is working as a power quality meter and not a PMU. Some of the most general features of the microPMU are listed below:

- Phasor measurements/second: 10, 25, 50, 100
- Analog inputs: 3
- Rate of data frames transmission: 10, 25, 50, 100
- Range: 100V~690V

Figure 7 shows the web interface of the microPMU where it can be seen the different measurement options that this can provide. This interface is constantly updating within seconds to show the most recent measurements.

Find more information at: <https://www.powerstandards.com/product/micropmu/highlights/>

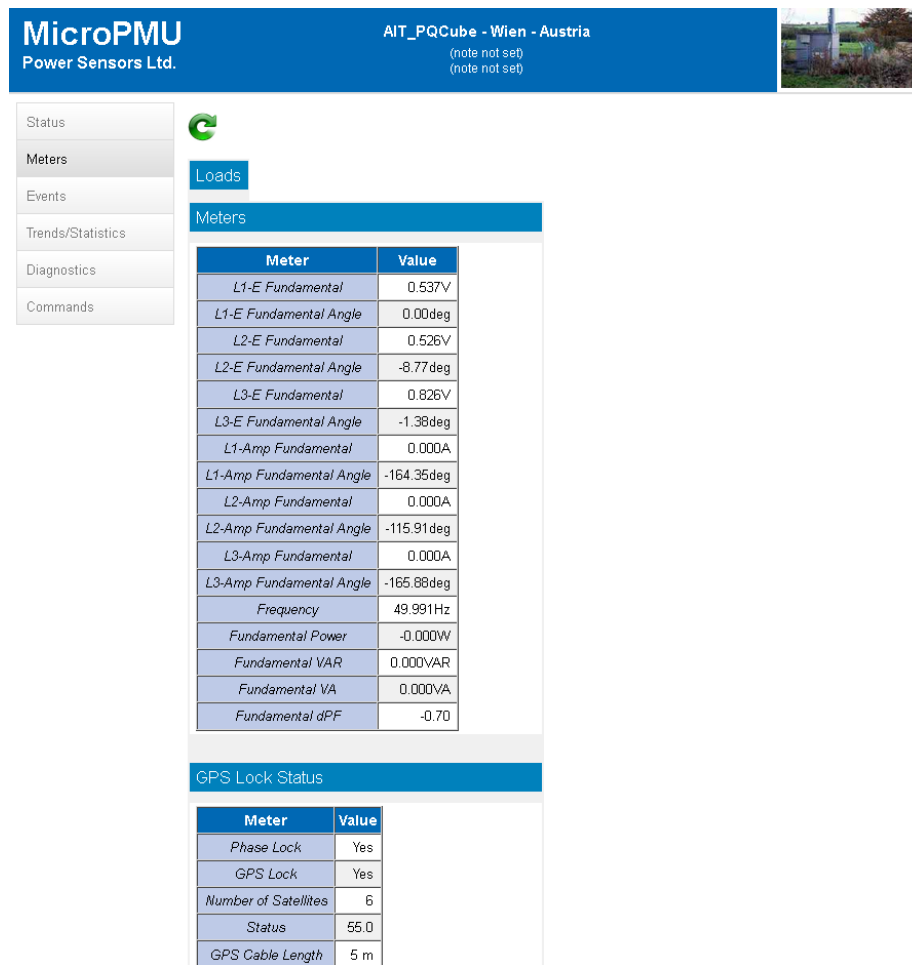


Figure 7: Web interface for PSL PQube mPMU
Note: No inputs are sensed for the screenshot

Artemes AM-10-PA2

The AM-10-PA2 power quality measurement device with PMU functionality was provided for the experiments from company Artemes. Originally only providing the protocol implementation of the C37.118 2005 standard it was extended by the developer team to provide more than 50 fps reporting rate. It was focus and intended to test and benchmark the system and the extended functionalities in the validation test bed.

Below is a list of some of the specifications from the Artemes AM-10-PA2. For further information, please refer to the appendix section for the catalogue.

- 24 bit
- 10K samples/sec/channel
- 4V, 5C, 4 low voltage inputs
- DC
- Range +/-1600 V, 6kV isolation
- Options: GPS, CAN, MODBUS



Figure 8: Artemes AM-10-PA2 providing 2 MSamples/Sec/channel

Figure 9 shows the online web interface for visualizing and displaying data during recording as well as offline analysis and time series analysis.

For more information on this, please refer to: <https://www.artemes.org/index.php/en/130-artemes-pmu>

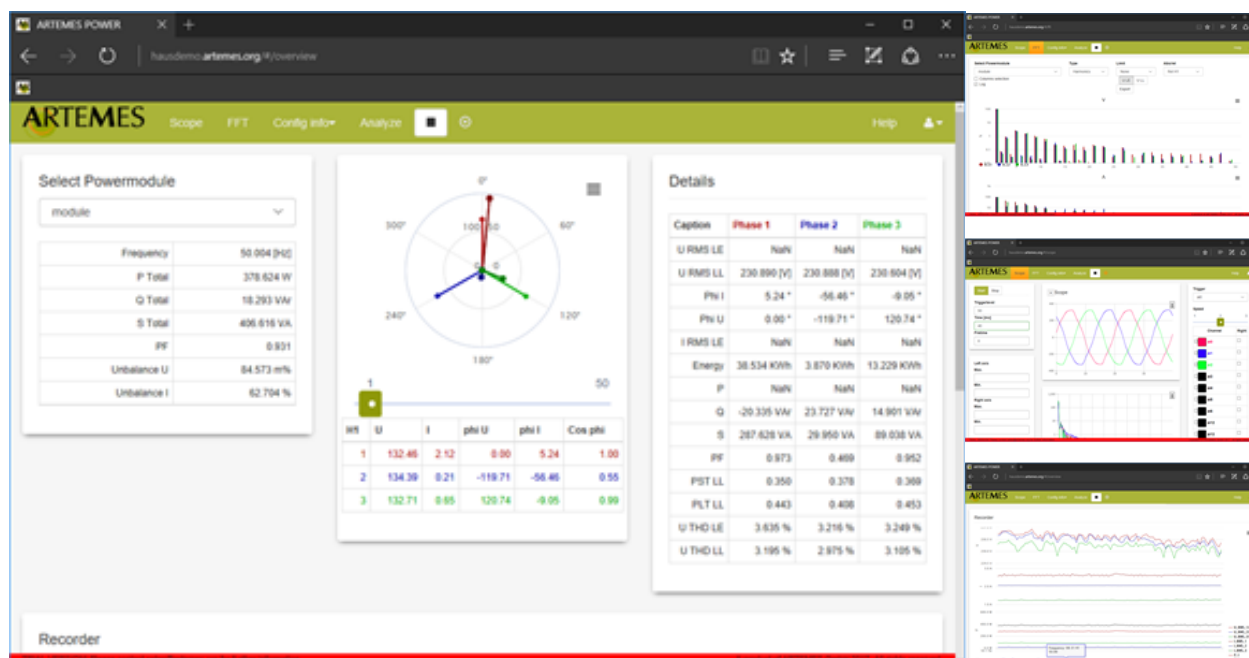


Figure 9: Web interface for Artemes AM-10-PA2 providing real time visualization and offline analysis

Spitzenberger & Spieß PAS 30000 linear power amplifier

In the experiment the linear amplifier is used to change the frequency according to a sequence set with an external application. A trigger signal is sent from the amplifier before the measurement sequence is starting, which is used to synchronize the PMU data.

The topology of the linear amplification stage is consisting of multiple linear MOSFET's controlled in parallel in such way that the characteristics are adequate to a discrete MOSFET operated in the linear region. The control of the amplifier can be either executed with the help of 2 internal oscillators or via an external input signal. This external analogue voltage signal is used for the PHIL testing system having a dedicated input range of maximum 5 V p (3.535 V rms). The amplifier features 2 different output ranges (135 V and 270 V). Thus, having activated the 270 V range, which is most commonly used at PHIL tests, an input voltage signal of 3.011 V rms results in a driven output voltage of 230 V rms.

Find more info at: <http://www.spitzenberger.de/Technische-Daten.aspx>



Figure 10: Spitzenberger 3 phase grid simulator

Siemens RUGGEDCOM RSG2488 - PTP Master Clock

The need for a PTP source to synchronize Opal-RT and real PMUs was met by Siemens which provides us the RSG2488 for the experiments. Without the friendly support and immediate reaction it wouldn't have been possible to meet the experiment's requirements in time. A GPS antenna which was connected to the switch has been provided as well.

Description: Utility-grade, field upgradable, non-blocking 28 Gigabit port layer 2 switch to provide broadband local area network. The RSG2488's modular flexibility provides up to 28 non-blocking ports that can be configured as 10/100/1000TX copper, 100FX or 1000SX fibre.

Precision timing: RSG2488 can operate as an IEEE 1588 transparent clock, ordinary clock, master clock and supports both 1-step and 2-step operations. The available PTP module also allows the RSG2488 to get timing information from GPS and serve as a grandmaster clock for downstream time recipients.



Figure 11: Siemens RuggedCom RSG2488 providing PTP master clock for time synchronization

Opal-RT FPGA Input/Output Interface

The SmartEST lab has an Opal-RT target with a PF610095S01 system capable of holding the following input and output (I/O) configuration:

Slot Number	Function
1	16 Analog Out, 16 Analog In
2	16 Analog Out, 16 Analog In
3	32 TSDIn, 32 TSDOut
4	32 TSDIn, 32 TSDOut

For 3D-Power, only the analog outputs are necessary for streaming the measurements of the Opal-RT/RT-Lab model. Table below shows how the channels were connected to the FPGA PF610095S01 system. It is worth mentioning that each analog output used was required to be configured in the model to have the Opal-RT target send the signals required to measure.

Table 1: Configuration of Opal-RT I/O Interface FPGA outputs

Relation between Simulink blocks and OP5330 Simulink block library path: RT-LAB I/O \ Opal-RT \ OP5142 \ OP5142EX1 OP5142EX1AnalogOut OP5142_1-EX-0000-1_3_4-C3_C1_C3_C1_EB_EA_EB_EA-01-01.bin				
Slot # (Block #)	Description	Channel	Name	Measurement
	Icon Name: OP5142EX1 AnalogOut			
1(1)	OpFcnOP5142EX1AnalogOut Parameters Controller Name 'OP5142EX1 Ctrl' DataIn port number 1 Number of AOut channels 8	0	+CH00/-CH00	ARTEMES VOLTAGE PHASE A
		1	+CH01/-CH01	ARTEMES VOLTAGE PHASE B
		2	+CH02/-CH02	ARTEMES VOLTAGE PHASE C
		3	+CH03/-CH03	ARTEMES CURRENT PHASE A
		4	+CH03/-CH03	ARTEMES CURRENT PHASE B
		5	+CH03/-CH03	ARTEMES CURRENT PHASE C
		6	+CH03/-CH03	

		7	+CH03/-CH03	
2(3)	OpFcnOP5142EX1AnalogOut Parameters Controller Name 'OP5142EX1 Ctrl' DataIn port number 3 Number of AOut channels 8	0	+CH00/-CH00	PSL uPMU VOLTAGE PHASE A
		1	+CH01/-CH01	PSL uPMU VOLTAGE PHASE B
		2	+CH02/-CH02	PSL uPMU VOLTAGE PHASE C
		3	+CH03/-CH03	PSL uPMU CURRENT PHASE A
		4	+CH03/-CH03	PSL uPMU CURRENT PHASE B
		5	+CH03/-CH03	PSL uPMU CURRENT PHASE C
		6	+CH03/-CH03	
		7	+CH03/-CH03	

GPS Signal Receiver

In order to receive GPS signal for PMUs and PTP source to work properly, the four different GPS antennae (Artemes, PSL, Arbiter, RuggedCom) have been installed outside the lab to have direct view on the satellite. Only the larger active antennae can receive full signal from within the lab.

4.3 Testbed Configuration

The following section describes the different experiment setups. The overview table indicates the time plan and additional information on the data and model. Although many tests were performed daily, seven experiments involving the major progress and results will be presented in the following subsections of this report.

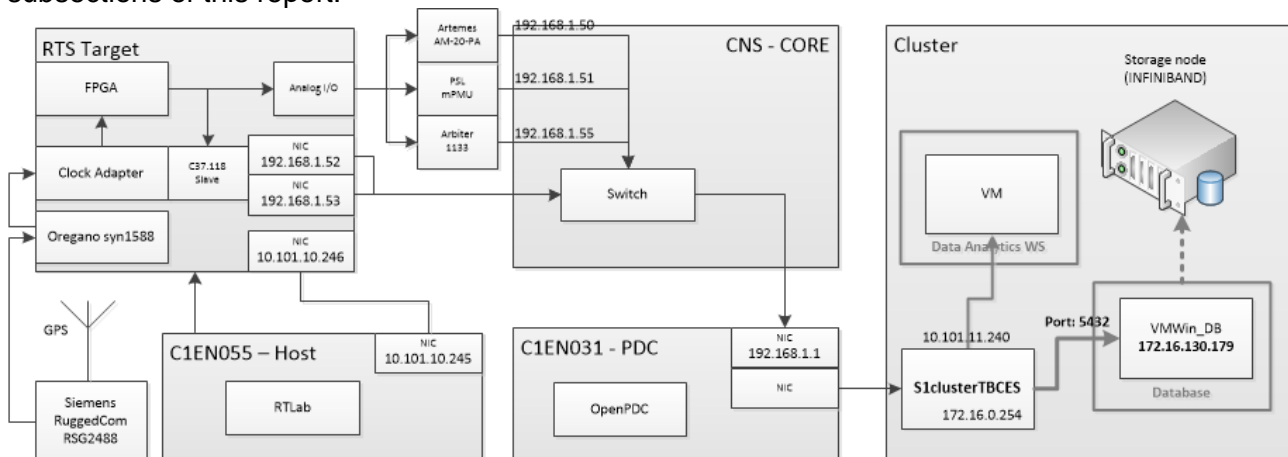


Figure 12: Detailed setup for most of the experiments

The following table shows the timeline of the performed experiments.

Table 2: Timeline of 3D-Power Experiment Setup

Date	Name	Description	Components
27.07.2017	Fault Experiment 1	Comparison of PMUs (TVE, GPS accuracy) for Real PMU connected to OpalRT Analog Out	Opal-RT Target FPGA I/O interface Artemes PMU PSL MicroPMU
31.07.2017	Fault Experiment 2	Simple network (2 sources, 2 loads), Faults	Opal-RT Target
01.08.2017	Multiple vPMUs	Simple network, no sync	Opal-RT Target
04.08.2017	Experiment 4: ROCOF	2 rPMUs, Frequency Change, connected to network amplifier	Opal-RT Target FPGA I/O interface Artemes PMU PSL MicroPMU AIT Spitzenberger
08.08.2017	IEEE37 bus fault model - 2 vPMUs - 2 rPMUs	no external GPS sync von vPMUs 1 fault location	Opal-RT Target FPGA I/O interface Artemes PMU PSL MicroPMU
09.08.2017	IEEE37 bus faults - 6 vPMUs	3 fault locations, script for looping with random R	Opal-RT Target
10.08.2017	IEEE37 bus fault	Communication network simulation	Opal-RT Target FPGA I/O interface Artemes PMU PSL MicroPMU CORE
11.08.2017	IEEE 37- fault R	Fault Resistance variations	Opal-RT Target
11.08.2017	IEEE37 fault + CNS	Real PMU on different CNS setups	Opal-RT Target FPGA I/O interface Artemes PMU PSL MicroPMU
14.08.2017	IEEE37 fault full sync	full synchronization, UTC/TAI offset post-processed	Opal-RT Target FPGA I/O interface Artemes PMU PSL MicroPMU

4.3.1 Test Procedures

The main objective of the test setups was to determine the different synchronization challenges and complexities of having different vendors equipment for power quality monitoring. Therefore, it was crucial to have a benchmark monitoring system that would serve to determine the correct time stamps, magnitude, and angle measurements without having the real world latencies and limitation such as transmission lines losses and noise.

In this regard, the experiment setups built for obtaining PMU measurements can be divided into two types: (1) Real-time simulation with FPGA output and (2) Combining real PMU and virtual PMU measurements. The first one includes only an HIL setup while the second consists of a hybrid SIL-HIL configuration. These setups will be described in the following subsections.

Using real time simulation and using FPGA output

The figure below shows the general scheme for comparing the measurement coming out of the I/O interface of the Opal-RT system. For this case, only the real PMU devices are available for monitoring as depicted. The output analog channels from the FPGA I/O interface were used to connect the different PMU devices used in the experiment. Moreover, the three PMU brands used (PSL, ARTEMES and ARBETER) were connected in order to compare their signals with the virtual ones provided by Opal-RT. While PSL and ARTEMES units have both voltage and current measurements, the ARBITER unit was used only as a voltage monitor. For this configuration, the timestamps are provided by the GPS signals provided by each PMU device. All measurements are collected by OpenPDC through a C37.118 protocol and then stored in a database managed by PostgreSQL.

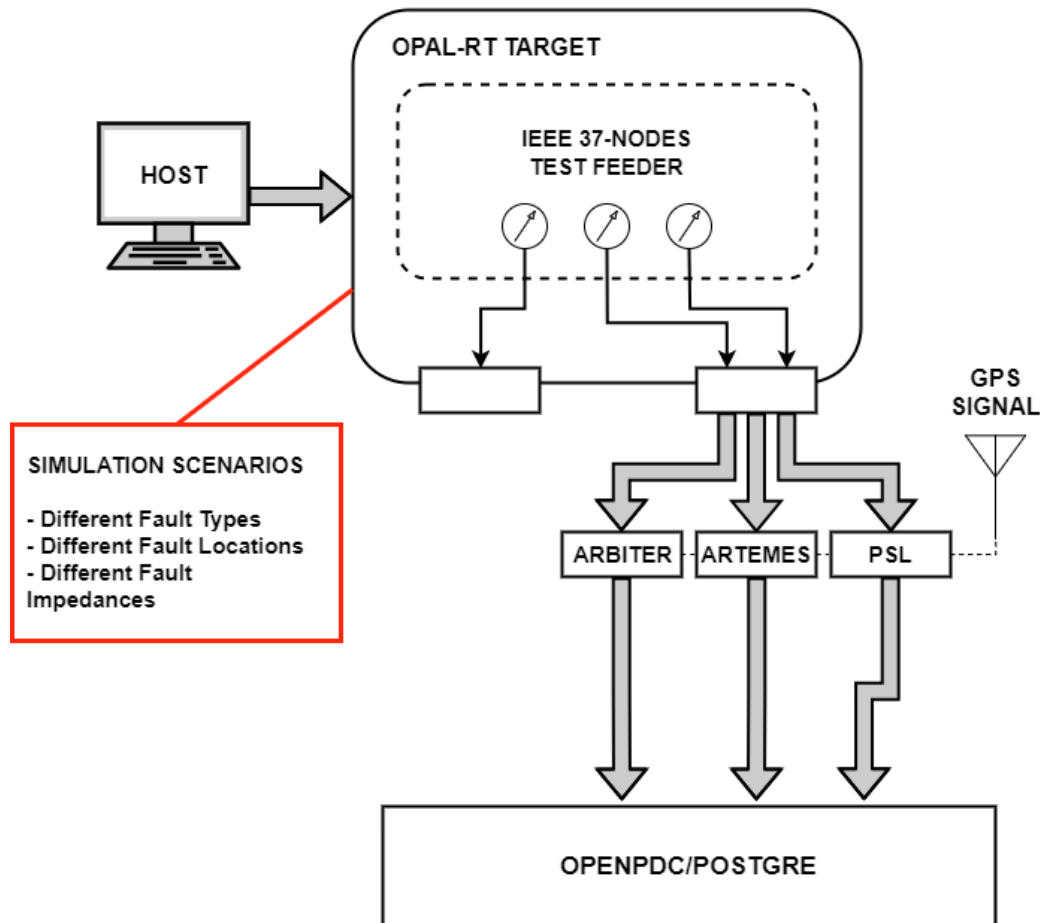


Figure 13: Real PMU measurements setup using FPGA outputs

Combining real PMU and virtual PMU measurements

The figure below shows the general scheme for comparing the real and virtual PMU measurements. For this case, measurements are streamed to the real and PMUs while the a virtual PMU block model from the RT-Lab/Simulink is used for comparison. All measurements are then gathered by OpenPDC and then stored in a database.

For this setup, the Opal-RT target is fully synchronized and GPS-locked with a PTP Master RSG2488 RUGGEDCOM connected to an Oregon Systems syn1588® PCIe NIC that serves as the interface card for synchronizing the FPGA outputs with the internal clock of the target. This configuration gives a full GPS synchronization between Real PMUs, the target's internal clock, and the FPGA output I/O. For more information on this, please refer to *Issues and Problems during test-setup*.

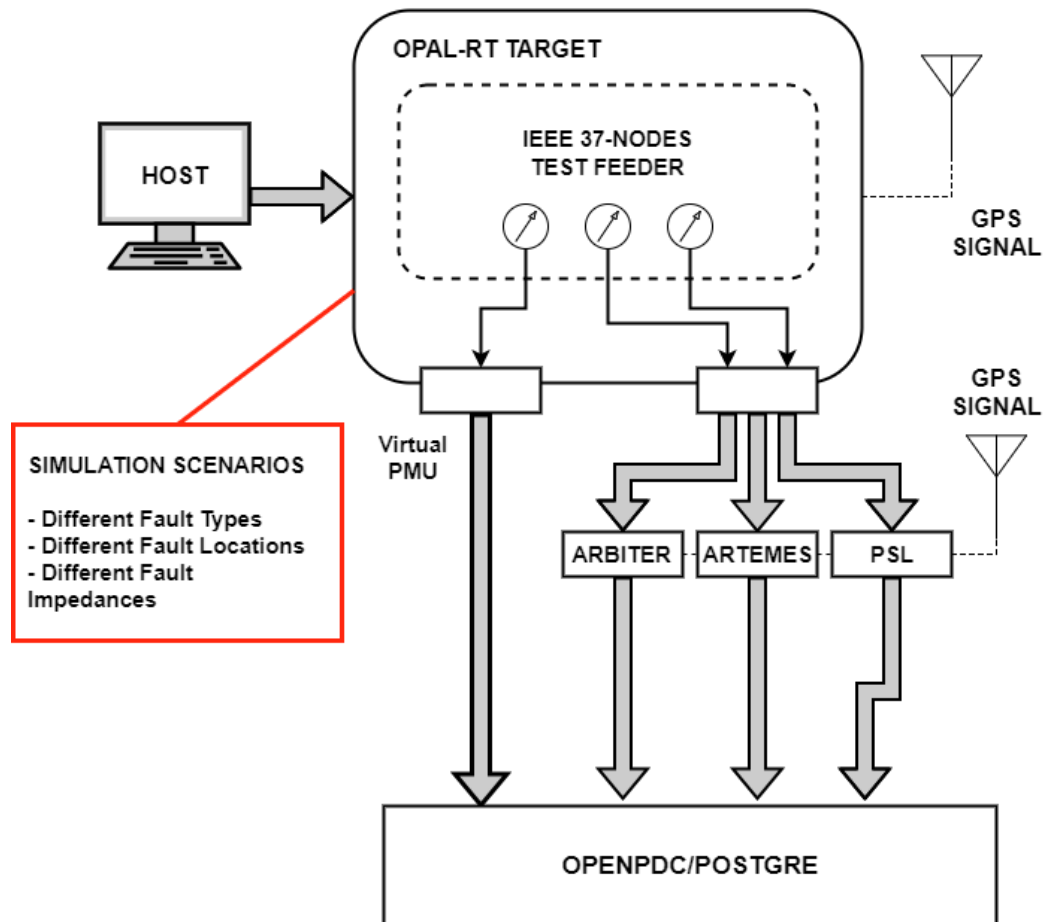


Figure 14: Virtual and Real PMU measurements setup using FPGA outputs

Experiment 1: Simple Fault with Real PMUs

Short description

Name	Simple Fault - real PMUs
Objective	Test PMU behaviour along line with simple faults
Duration	< 1 minute
Results	Monitored fault event, phase shift along line
Challenges	Setup and connect PMUs, Validate two phasor measurements
Lessons Learnt	PMU configuration, DB connectivity (ADO PostgreSQL Adapter connection string)
Outlook	Real time processing, analysis and tracking of phasors

Setup

Equipment	PMUs: mPMU, Artemes
Connectivity	Analog output for voltage and current (+15V signals) OpenPDC inputs from PMU and outputs to database storage

PMU setup	100 samples per second reporting rate
Database	PostgreSQL on VM in Cluster

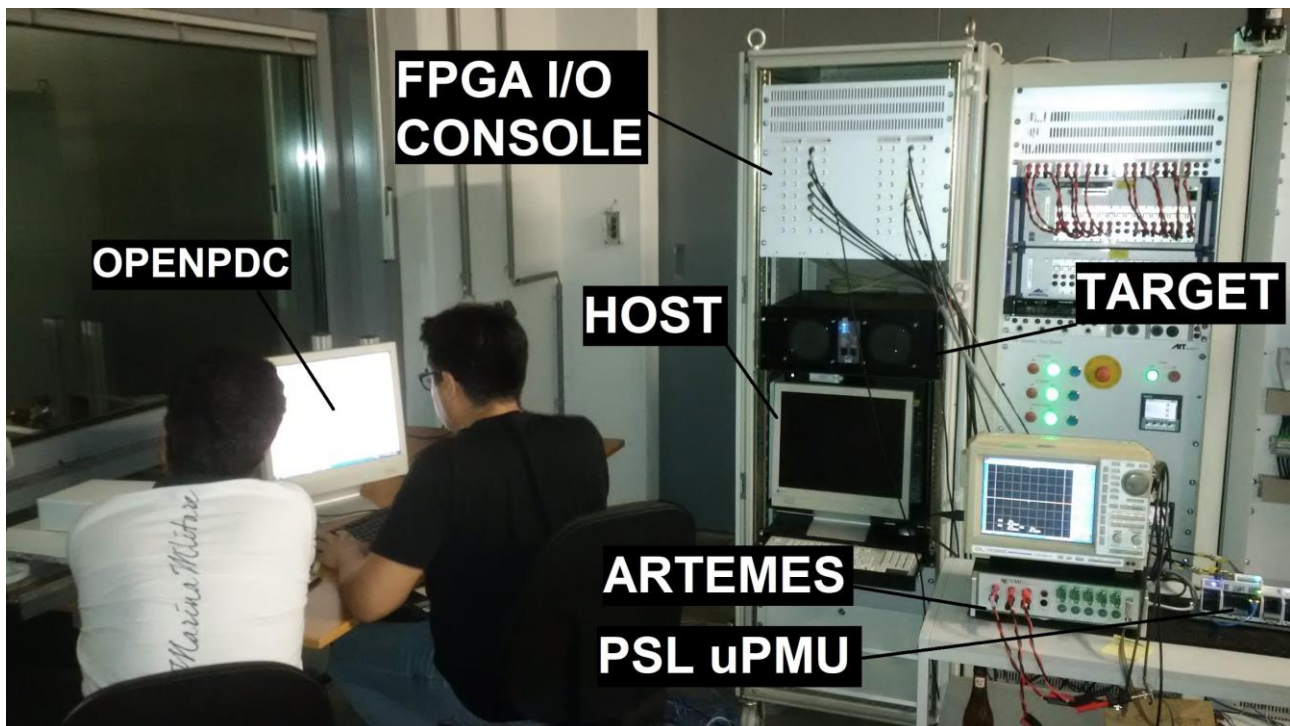


Figure 15: Physical Setup for Experiment 1.

Notes: User group members (from left to right): Reza Arghandeh, Jose Cordova.

Models

The single line diagram is shown in Figure 16. The experiment consists of a fault location between two different sources. Figure 18 shows the RT-Lab model in Simulink. It consists of the grid model and console for interacting with the model (e.g. event by setting fault type).

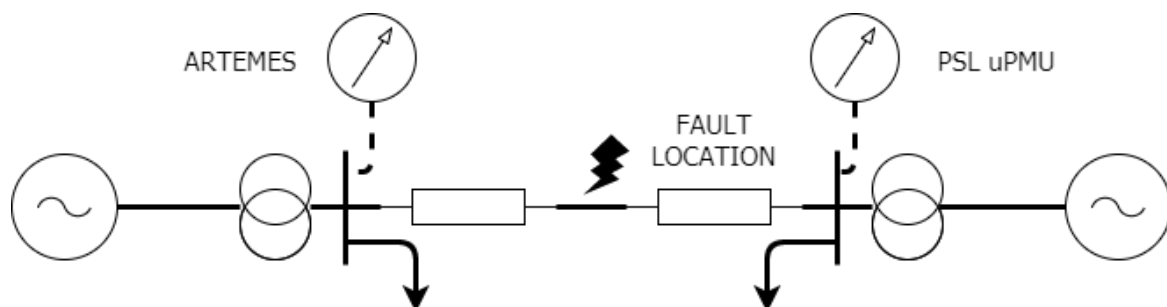


Figure 16: Single Line Diagram for Experiment 1.

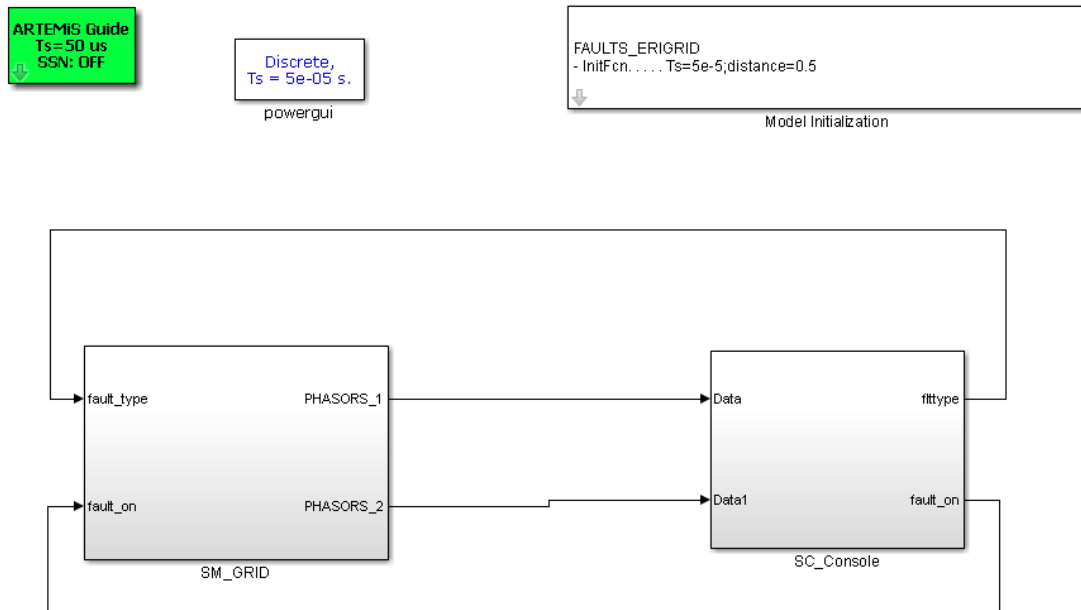


Figure 17: RTLab model for the simple fault experiment

The simple grid model for this experiment is shown in Figure XXX. It has two buses where the PMUs are attached and one line where the fault is taking place.

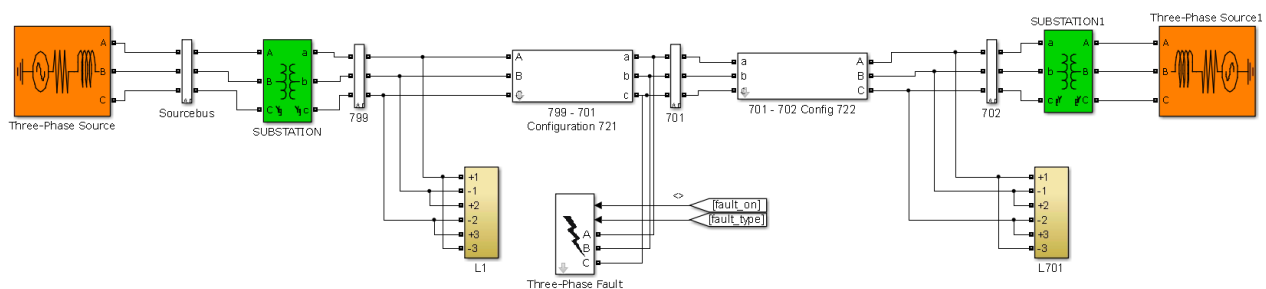


Figure 18: Grid model for the 'simple fault' experiment.

In Figure 19 the setup and configuration for using the FPGA analog outputs is shown.

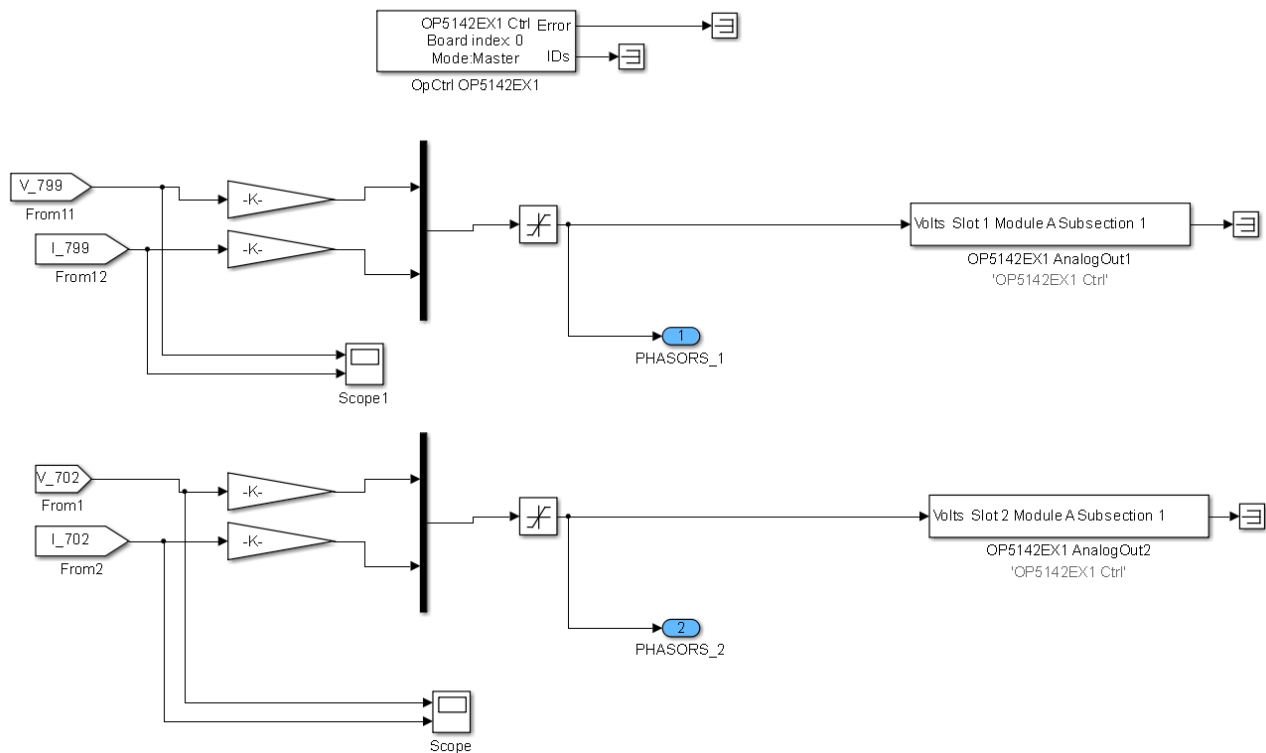


Figure 19: Setup of the the FPGA analog outputs for PMU connection to each side of the line.

Results

Run 1 (Example)	<p>Experiment: Simple Fault Table: timeseriesmeasurement_exp1 Experiment start/end: 2017-07-31 17:13:34+00:00/2017-07-31 17:15:31.640000+00:00 PMUs: ['ARTEMES', 'PSL_UPMU'] ARTEMES : 2017-07-31T17:13:47.360000000 2017-07-31T17:15:31.640000000 PSL_UPMU : 2017-07-31T17:13:34.000000000 2017-07-31T17:15:18.990000000</p>
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The figure below shows the recorded magnitude of one phase during fault situation. The PMU Artemes was not yet synchronized with GPS, since the antenna cable needed to be extended to lock on satellite signals.

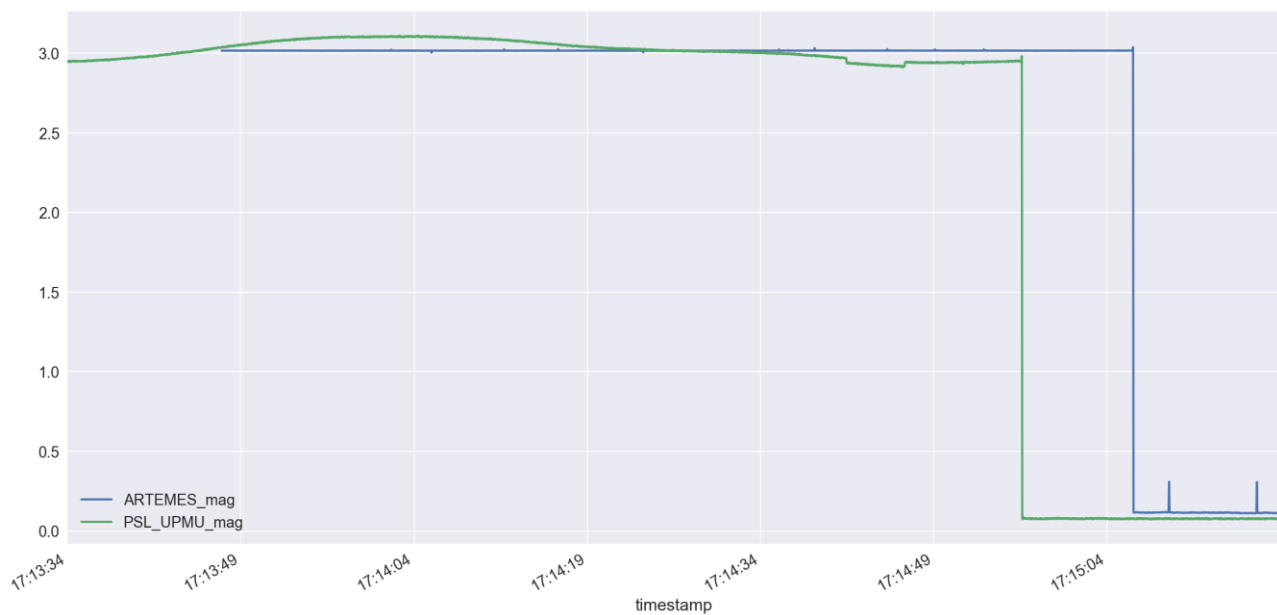


Figure 20: Magnitudes of one phase from two PMUs for experiment 'Simple Fault'.
Note: No GPS synchronization is in place for PMU Artemes at this time of the experiment.

Experiment 2: Simple Fault with Virtual PMUs

Short description

Name	Simple Fault
Objective	Test PMU behaviour along line with simple faults
Duration	< 1 minute
Results	Monitored fault event, phase shift along line
Challenges	Validate PMU principle of two phasor measurements
Lessons Learnt	Configuration and Setup of C37.118 slave driver of Opal RT
Outlook	Use for validation and benchmarking of real PMUs

Setup

Equipment	OpalRT Target PMUs: Two instances of virtual PMUs (C37.118 slave driver for Opal RT) Routers (1Gbit, 100Mbit)
Connectivity	In OpalRT model the C37.118 slave is connected to the models signal OpenPDC inputs from PMU and outputs to database storage
PMU setup	100 samples per second reporting rate
Database	PostgreSQL on VM in Cluster

Models

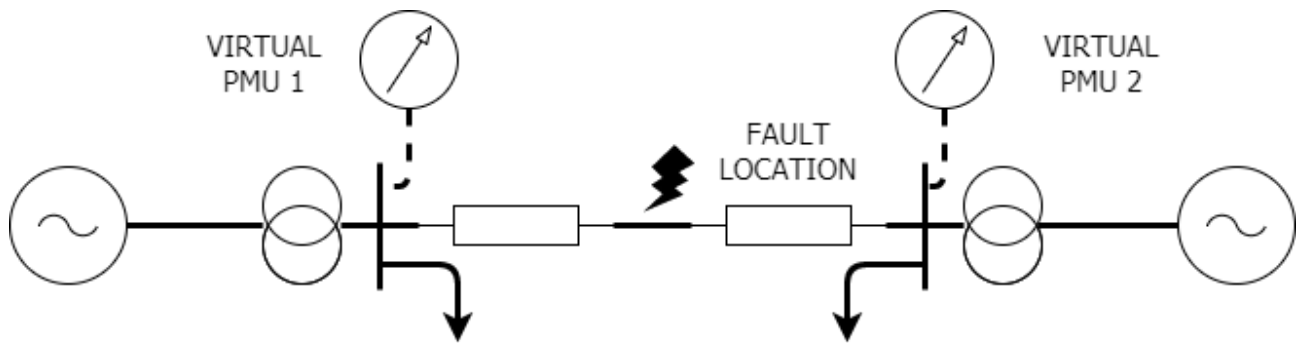


Figure 21: Single Line Diagram for Experiment 2.

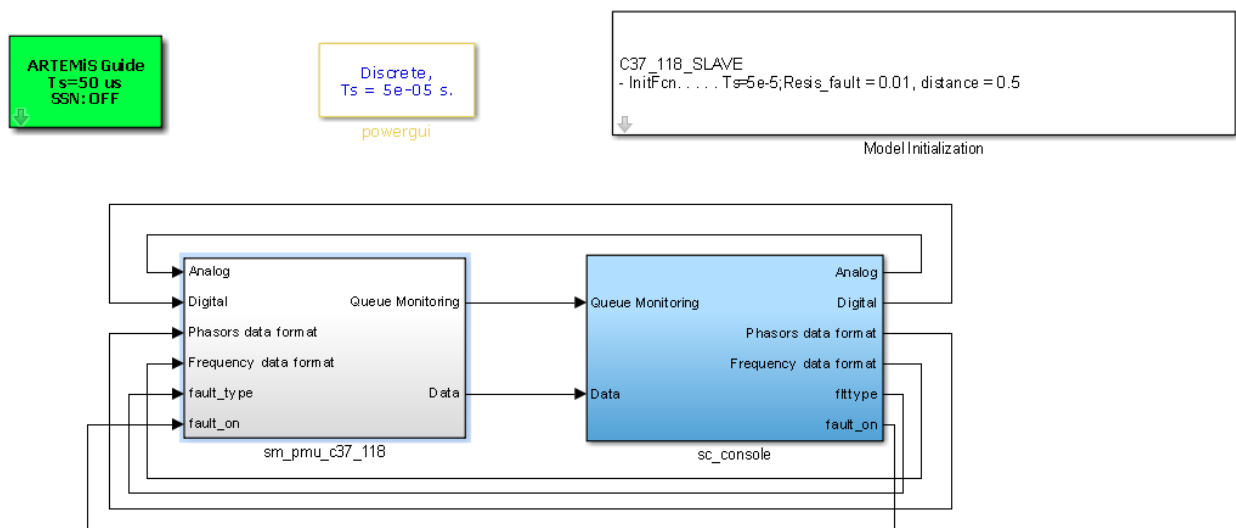


Figure 22: RTLab model for the simple fault experiment with virtual PMUs

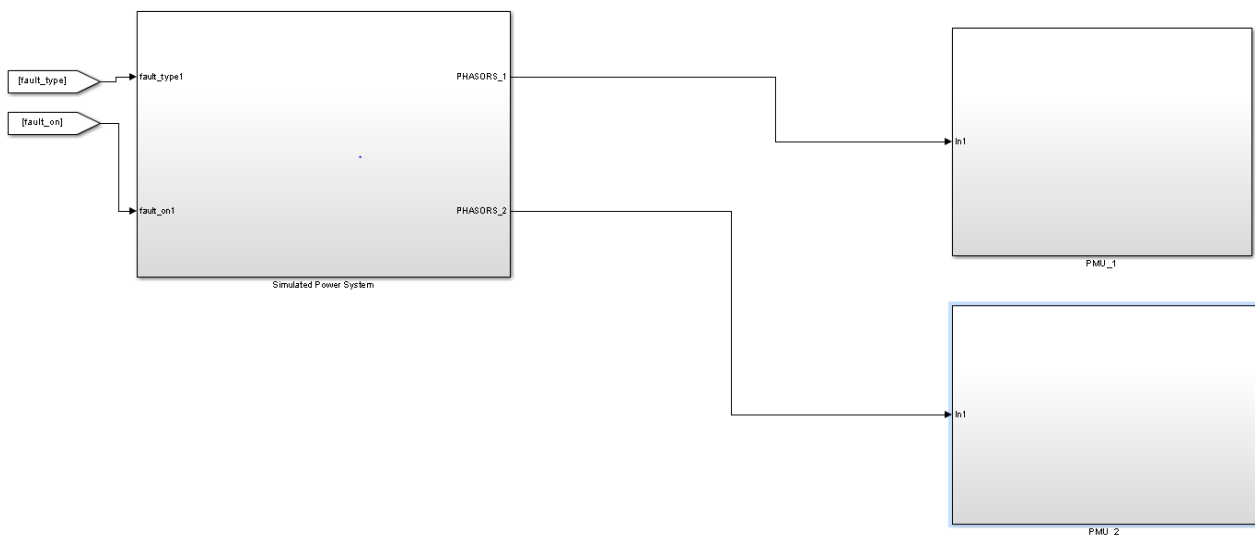


Figure 23: Configuration for the virtual PMUs.

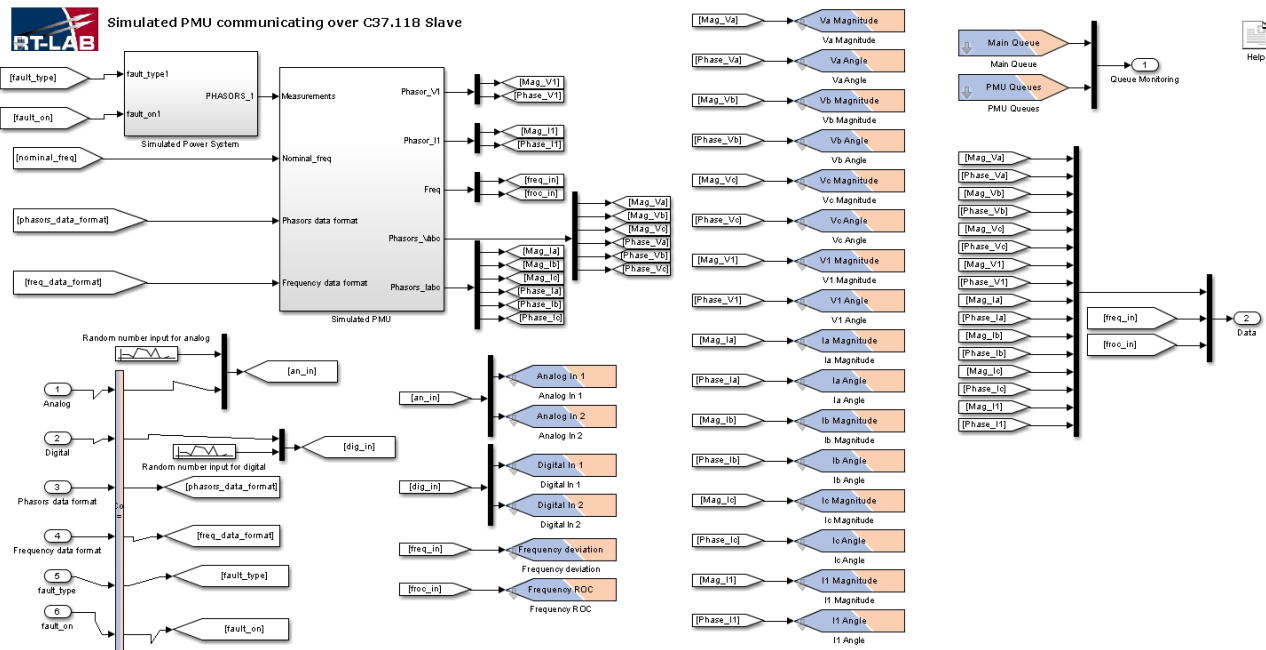


Figure 24: Connection and assignment for a virtual PMU (C37.118 Slave).

Data Points		Connections	
In & Out		All Status	All Systems
C37.118 Slave	(24)		
Queue Monitoring			
Slaves	(24)		
OPALRT-PMU_1	(12)		
Phasors	(12)		
PHASOR 1	(2)		
Magnitude		C37_118_Slave/sm_pmu_c37_118/PMU_1/Va Magnitude/OpOutput/port1	
Angle		C37_118_Slave/sm_pmu_c37_118/PMU_1/Va Angle/OpOutput/port1	
PHASOR 2	(2)		
Magnitude		C37_118_Slave/sm_pmu_c37_118/PMU_1/Vb Magnitude/OpOutput/port1	
Angle		C37_118_Slave/sm_pmu_c37_118/PMU_1/Vb Angle/OpOutput/port1	
PHASOR 3	(2)		
PHASOR 4	(2)		
Magnitude		C37_118_Slave/sm_pmu_c37_118/PMU_1/Ia Magnitude/OpOutput/port1	
Angle		C37_118_Slave/sm_pmu_c37_118/PMU_1/Ia Angle/OpOutput/port1	
PHASOR 5	(2)		
Magnitude		C37_118_Slave/sm_pmu_c37_118/PMU_1/Ib Magnitude/OpOutput/port1	
Angle		C37_118_Slave/sm_pmu_c37_118/PMU_1/Ib Angle/OpOutput/port1	
PHASOR 6	(2)		
Analog			
Digital			
Frequency ROC			
Frequency deviation			
OPALRT-PMU_2	(12)		

Figure 25: Configuration and drag and drop wiring of the PMU connections with the C37.118 driver

Results

Time synchronization has not been in place during the run of this experiment for the OpalRT simulation. It was later installed and added to the setup.

Run 1 (Example)	Experiment: Simple Fault Table: timeseriesmeasurement_exp2 Experiment start/end: 1969-12-31 23:14:51.630000+00:00/1969-12-31 23:17:20.030000+00:00 PMUs: ['OPALRT-PMU_2', 'OPALRT-PMU_1'] OPALRT-PMU_1 : 1969-12-31T23:14:51.630000000 1969-12-31T23:17:20.030000000 OPALRT-PMU_2 : 1969-12-31T23:14:51.630000000 1969-12-31T23:17:20.030000000
--------------------	--

Figure 26 shows the recorded magnitude of one phase during fault situation. The PMU 'OPALRT-PMU_1_mag' shows the slack voltage and therefore no change in level. No PTP based time synchronization is in place for OpalRT at the time of this experiment. It was installed and set into operation for later runs only. The PMU has been synchronized to the Oregono oscillator based time source, but not to real world reference clocks.

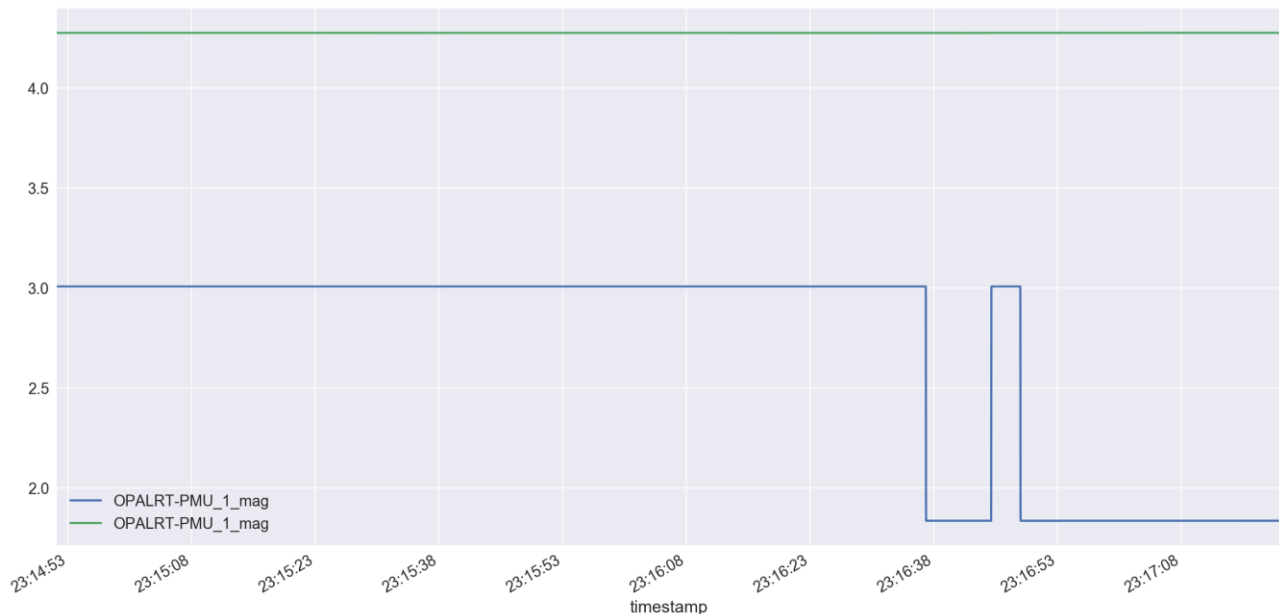


Figure 26: Voltage magnitudes of one phase from two virtual PMUs for experiment 'Simple Fault'.



Figure 27: Phasor magnitude and angle responses due to different fault types

Experiment 3 - Comparing Power Measurement from Different PMUs

A simple model transmitting a constant active and reactive power was built in order to determine the vector error on the GPS synchronization clocks of both PSL uPMU and ARTEMES PMU. The experiment consisted of observing the angle change from the physical device measurements. Both measuring devices were connected to the same node.

Short description

<i>Name</i>	<i>PMU Comparison</i>
<i>Objective</i>	<ul style="list-style-type: none"> - Compare the timestamps of the different signals provided by the ARTEMES and PSL uPMU. - Compare the magnitude and angle measurements of the different signals provided by the ARTEMES and PSL uPMU. - Compare the changes in the measurements given different Power inputs to the signals measured by the ARTEMES and PSL uPMU.
<i>Duration</i>	3 Days
<i>Results</i>	Steady state measurements
<i>Challenges</i>	Synchronization of PMUs, Analysis of measurements, Data handling
<i>Lessons Learnt</i>	Stream handling and batch processing process of data concentrator and output adapters
<i>Outlook</i>	Automate for error benchmarking (e.g., TVE); Response and delay time

Setup

<i>Equipment</i>	<ul style="list-style-type: none"> - Opal-RT Target - mPMU and Artemes - Routers (1Gbit, 100Mbit)
<i>Connectivity</i>	OpenPDC, PostgreSQL (Cluster)
<i>PMU setup</i>	100 samples per second reporting rate
<i>Database</i>	PostgreSQL on VM in Cluster

Expected Outcome:

- Voltage vs time plots of ARTEMES and PSL uPMU magnitude signals
- Voltage vs time plots of ARTEMES and PSL uPMU angle signals
- Current vs time plots of ARTEMES and PSL uPMU magnitude signals
- Current vs time plots of ARTEMES and PSL uPMU angle signals
- Detect any timestamps anomalies in the PMU and uPMU measurements.

Scenarios

A simple model transmitting a constant active and reactive power was built in order to determine the vector error on the GPS synchronization clocks of both PSL uPMU and ARTEMES PMU. The experiment consisted of observing the angle change from the physical device measurements.

- Steady state: The experiment was run for several days without changing any output signal to observe changes in measurement accuracy and impact on GPS errors.

- Dynamic response: Both measuring devices were connected to the same node. Experiment was performed by setting up the following parameters:

Signal:

- Step 1. 230V, 2300 W
- Step 2. 230V, 4600 W
- Step 3. 230V, 4600 W + 2300 VAR
- Step 4. 230 V, 4600 W + 4600 VAR
- Step 5. 230 V, 2300 W + 4600 VAR
- Step 6. 230 V, 0 W + 4600 VAR
- Step 7. Repeat 1 through 6 with 115V

Models:

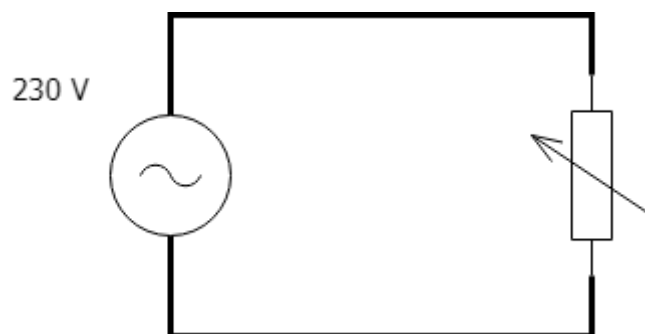


Figure 28: Single Line Diagram for Experiment 3.

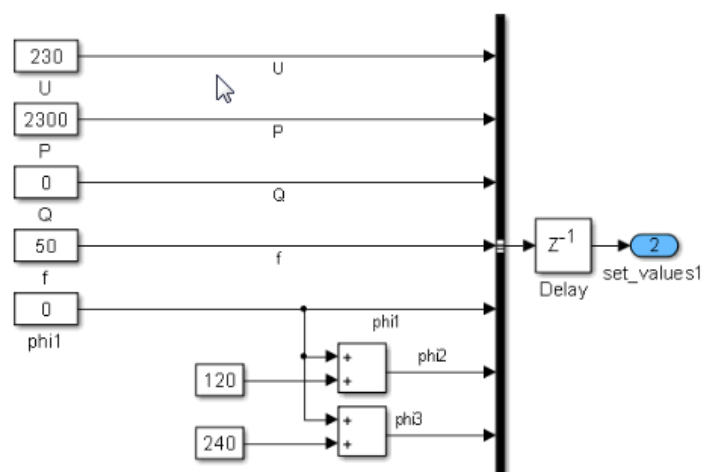


Figure 29: Simulink Model for Experiment 3.

Results:

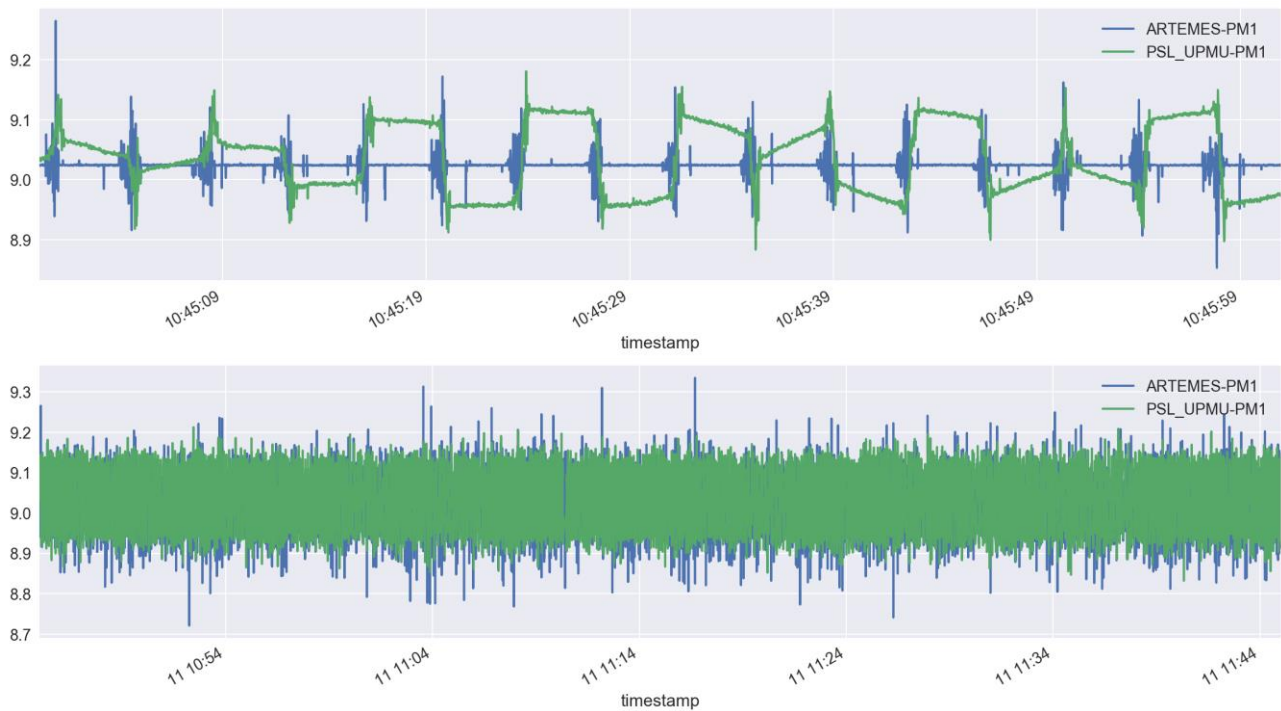


Figure 30: Phasor magnitudes for a) one minute and b) one hour Interval

Note: The above snapshot is an example of observed noise in PMU measurement that may be because of the to Opal-RT FPGA synchronization issue with external GPS clock. The team working with Opal-RT company to resolve the Opal-RT hardware issue.

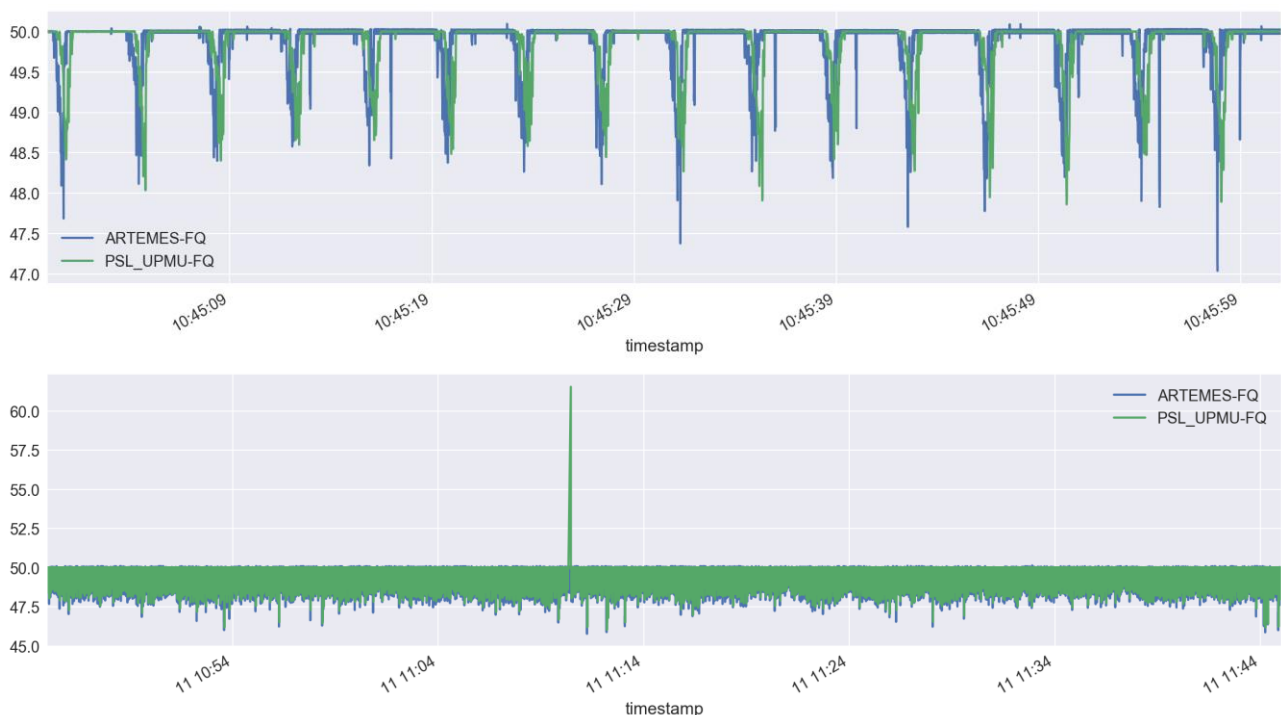


Figure 31: Frequency for a) one minute and b) one hour Interval

The following figures show the distribution of the magnitudes and frequency over the period of 3 days.

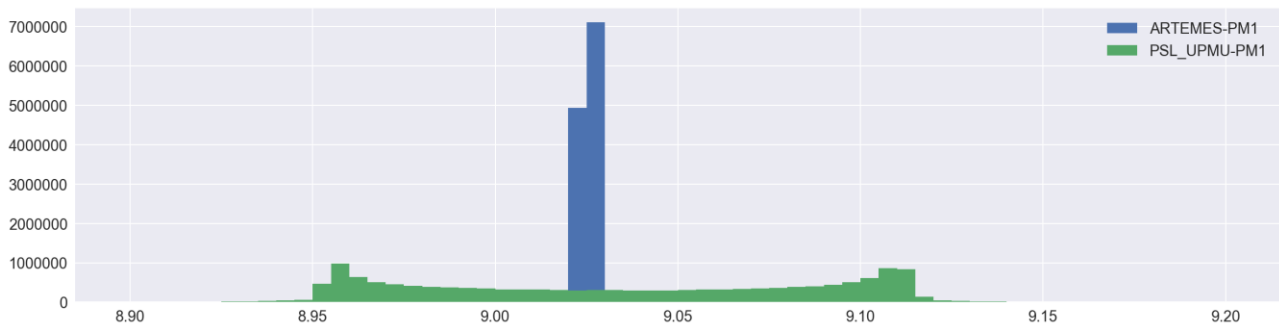


Figure 32: Histogram for magnitudes of one phase for 3 days.
Note: Low frequency oscillations are experienced for the PSL mPMU

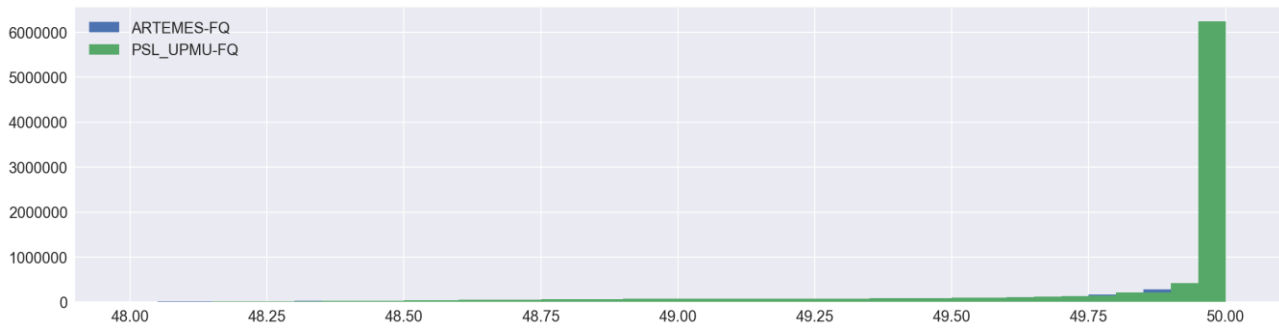


Figure 33: Histogram of frequency for 3 days

Experiment 4: Rate of Change of Frequency (ROCOF)

Short description

Name	Rate of Change of Frequency
Objective	Evaluate PMU reporting timing (latency) for change of frequency with given signal generator
Duration	Minutes
Results	Rate of Change of Frequency (ROCOF), timing of reporting 'availability of measurements'
Challenges	Measure trigger when frequency ramping starts
Lessons Learnt	Amplifier setup, additional analog signal inputs, merge of measurement results
Outlook	Repeat experiment with fixed software, synchronize measurement systems

Setup

Equipment	<ul style="list-style-type: none"> - Power Amplifier: Spitzenberger + Signal generation script - PMUs: Artemes, mPMU - PQ: Artemes: Analog in
Connectivity	OpenPDC, PostgreSQL (Cluster)
PMU setup	Different sampling rates, 100 samples per second reporting rate
Database	PostgreSQL on VM in Cluster

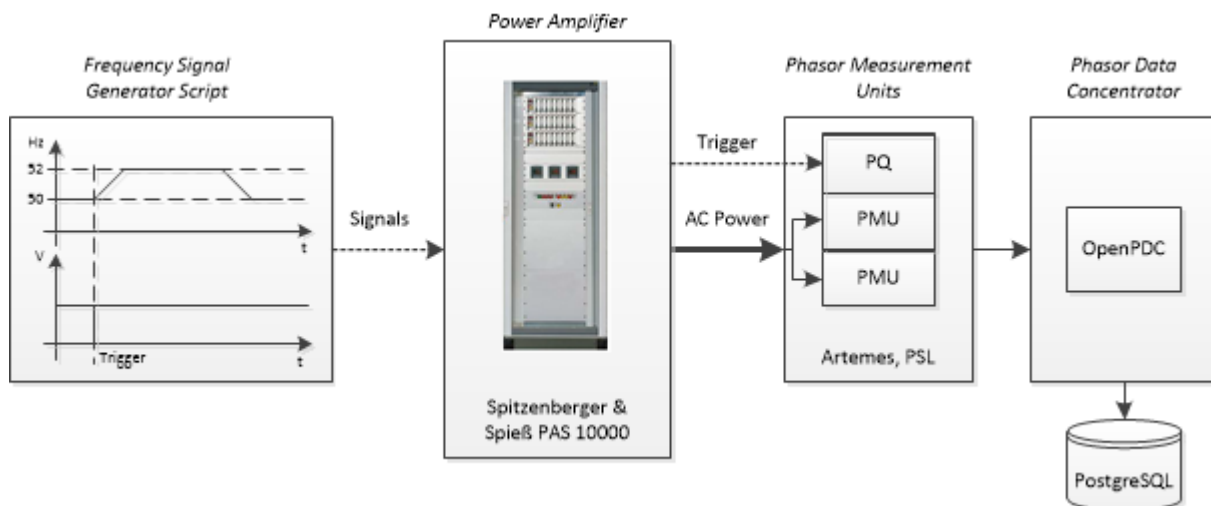


Figure 34: Setup for ROCOF test connecting AC Power amplifier to PMUs. Additionally, the trigger indicating sequence start is recorded

Models

Signal generator programmed to start with 50Hz to change frequency by 2Hz up for one second wait for 60 seconds and reduce by 2Hz within 1 second.

Trigger signal indicates start of frequency change sequence:

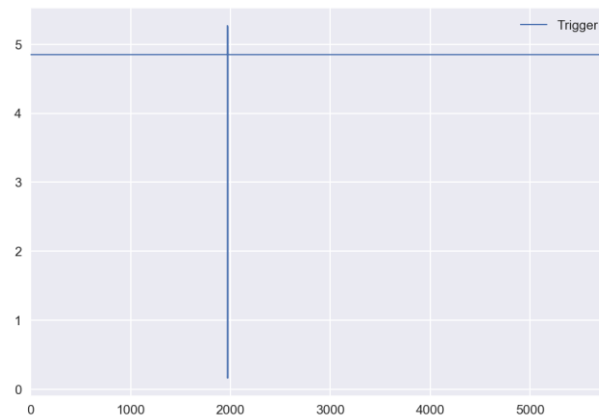


Figure 35: Trigger signal generated by power amplifier, indicating start of frequency change sequence

Results

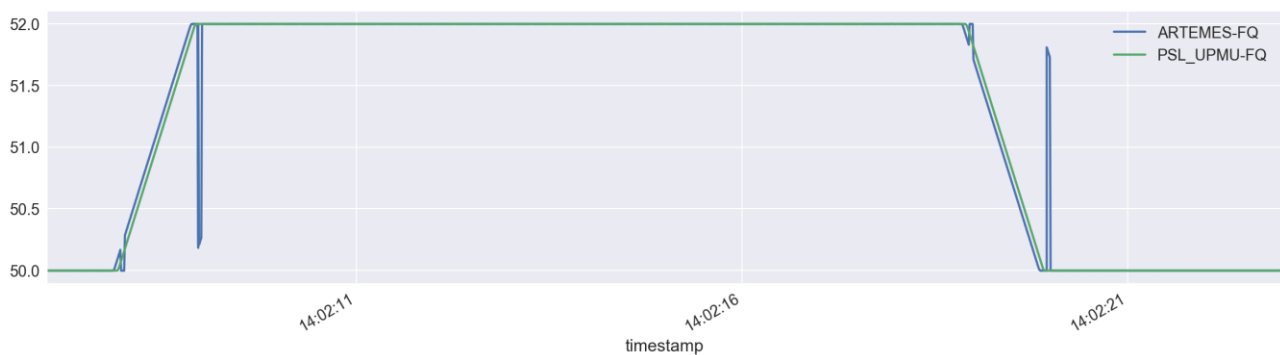


Figure 36: Resulting frequency measurements of two PMUs following a frequency ramp

Note: Spike in the measurement has been reported to ARTEMES company and later fixed with their helps.

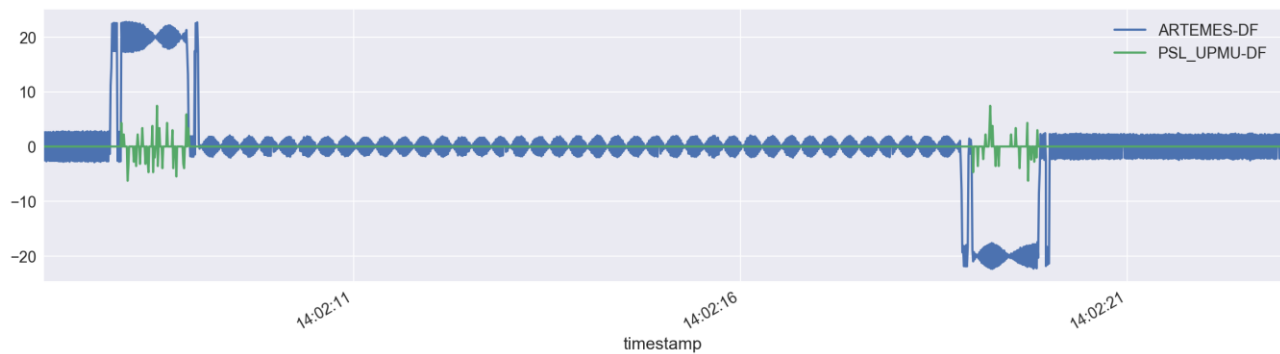


Figure 37: Resulting frequency delta/deviations of two PMUs following a frequency ramp

Note: Frequency oscillations are due to angle measurement problems and have been fixed

Experiment 5 - Simulating Fault Events with 6 Virtual PMUs

Short description

Name	<i>Fault event simulation with virtual PMUs</i>
Objective	<i>Simulate various fault types under different conditions and apply identification method</i>
Duration	<i>Minutes (3 faults) to several hours (500 - 1000 fault sequences)</i>
Results	<i>Data set with different fault scenarios and results for identifying faults based on measurements</i>
Challenges	<i>modeling, real time simulation, scripting of fault sequences, stable simulation, parameter change</i>
Lessons Learnt	<i>RTLab API scripting, data handling, data analysis, method application and analysis</i>
Outlook	<i>Automate and change parameters without model loading</i>

Setup

Equipment	<ul style="list-style-type: none"> - OpalRT with IEEE 37 bus model split into 5 sub models - PMUs: Artemes, mPMU, (later Arbiter) - Siemens Rugged Com, PTP source - Python script for fault sequence simulation and logging for event labeling
Connectivity	<i>OpenPDC, PostgreSQL (Cluster), Siemens Rugged Com</i>
PMU setup	<i>100 samples per second reporting rate</i>
Database	<i>PostgreSQL on VM in Cluster, local CSV historian</i>

Scenarios

Fault sequences of different types, fault locations and fault impedances have been simulated to generate a dataset which is used to train and apply fault identification algorithm.

- Three fault locations are on line 702-703, 703-727 and 710-736.
- Fault types are line-to-ground, line-to-line and all three-lines-to-ground, A-G, A-B and ABC-G respectively.
- Fault distance on the line: are along the lines and should influence the fault impedances. It is most likely that fault distance has not worked when running the simulating the model.
- Fault impedances: 0Ohm, 50hm, 100hm, 250hm and 500hm.

In total the number of sequences are: 3 fault types x 3 fault location x 5 fault impedances x 100 sequences where fault distance and ground impedance should have changed for each of the 4500 fault events.

Models

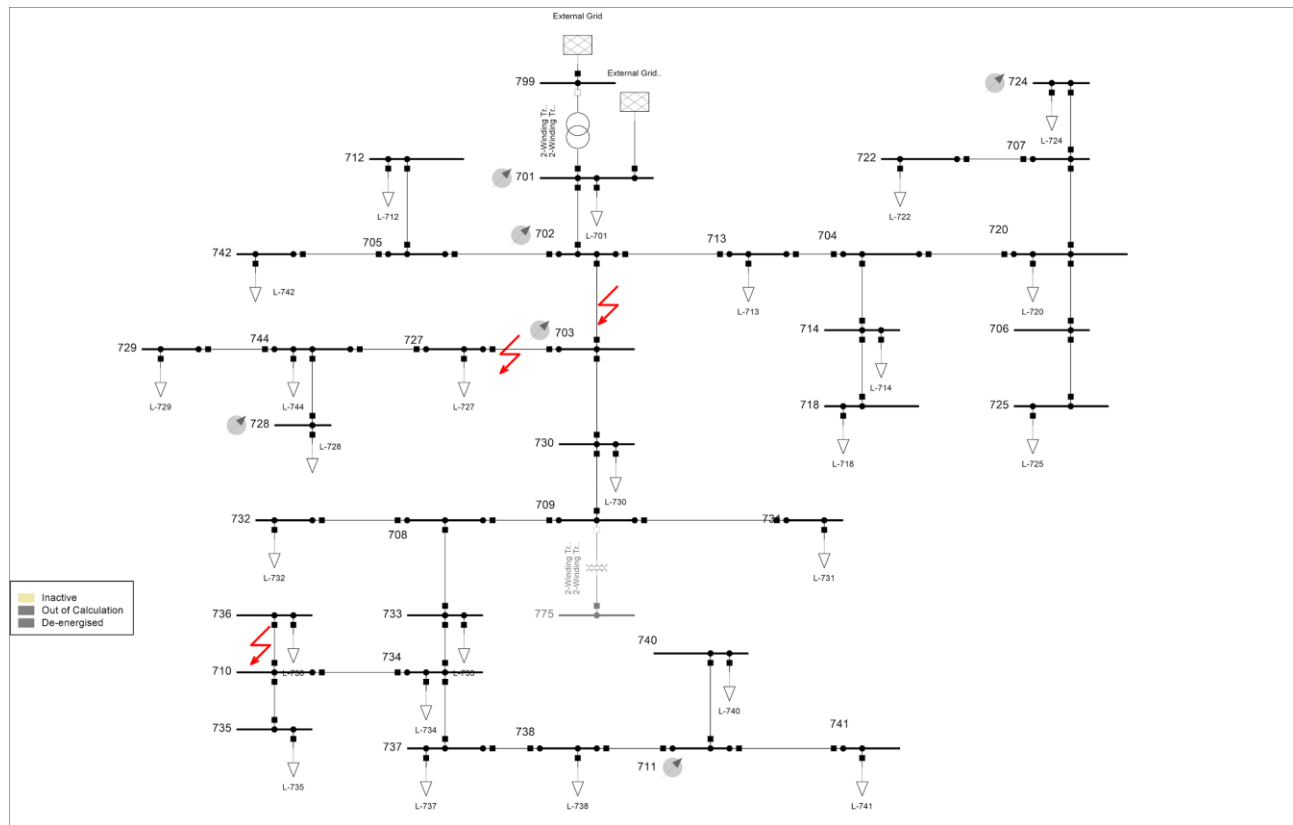


Figure 38: IEEE 37 bus test feeder: Single line diagram with fault locations

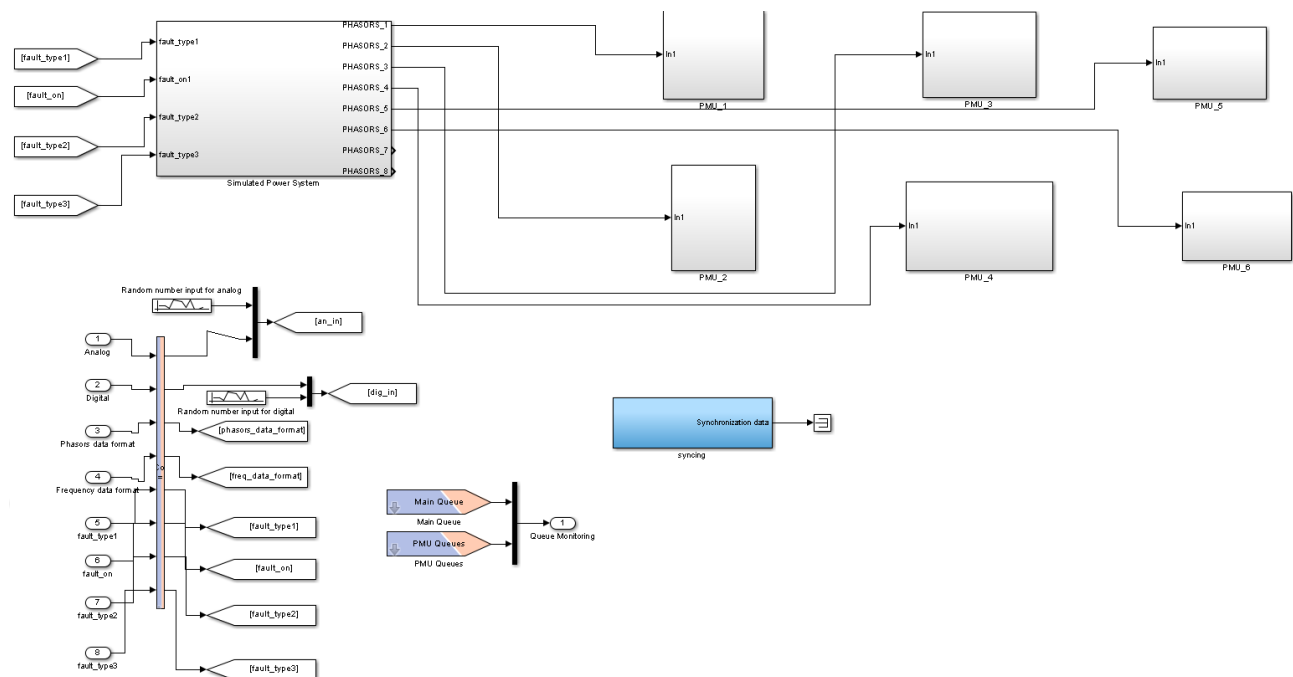


Figure 39: Model for the 6 virtual PMUs

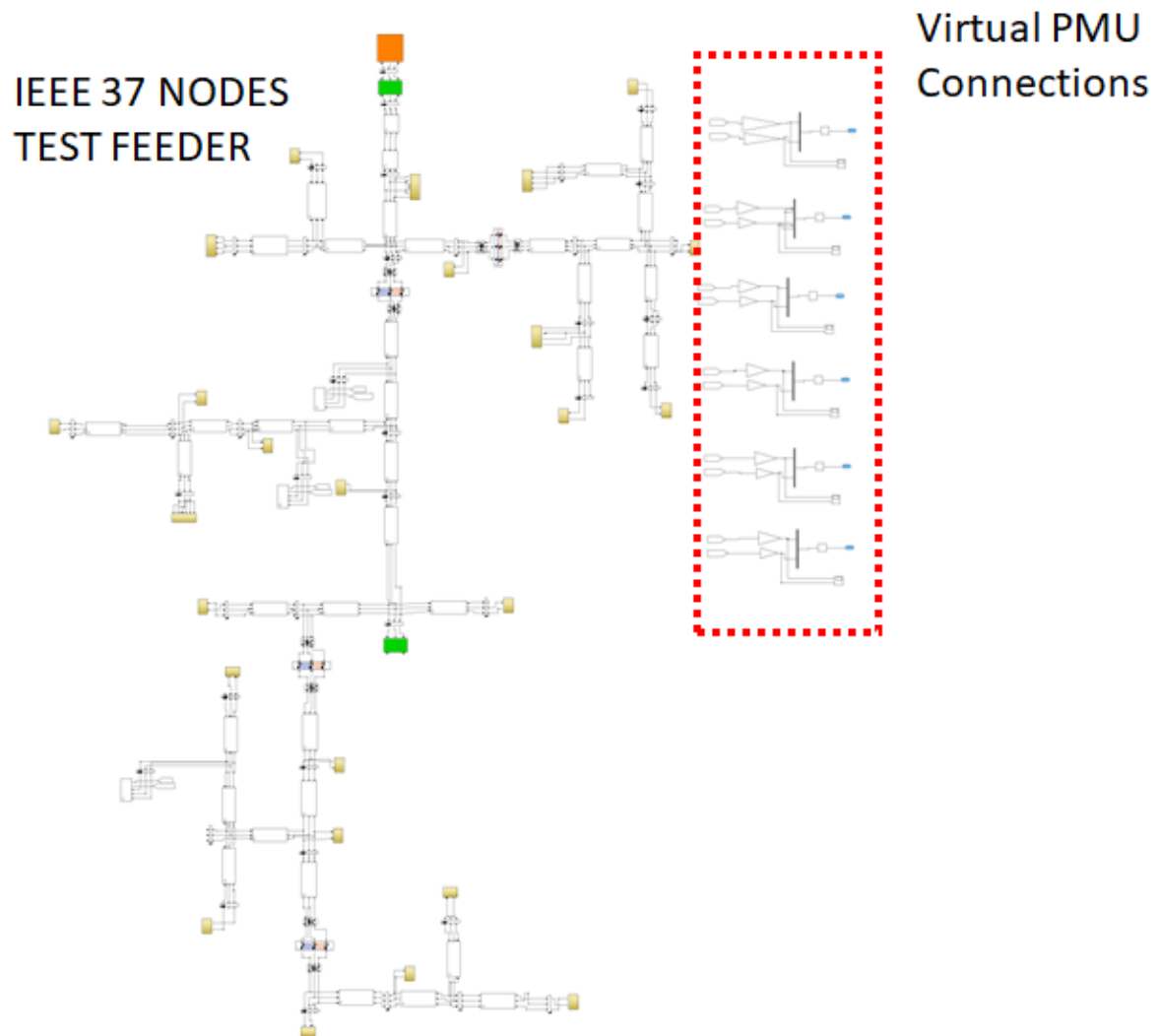


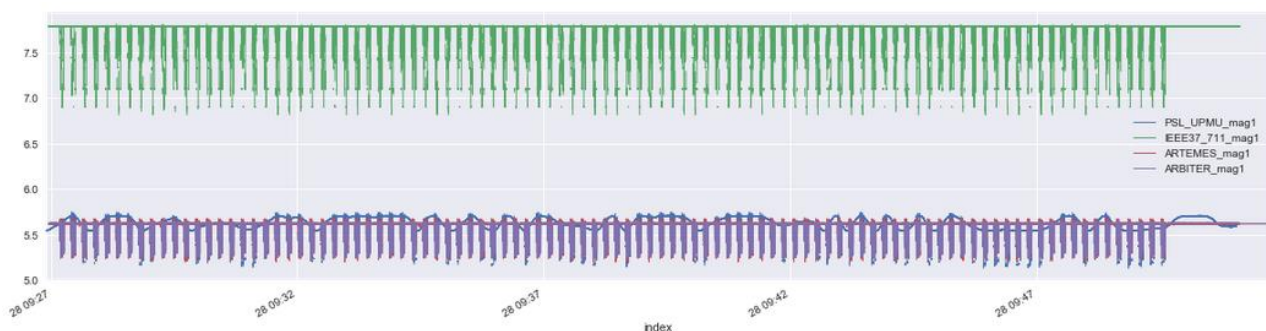
Figure 40: Model of the IEEE 37bus test feeder. The model is split in 5 subparts with Opal-RT SSN solver configuration. Connectors for the virtual PMUs are on the right side.

I/Os	
C37.118 Slave	(75)
Clock	(3)
Synchronized	⇒ C37_118_Slave/sm_pmu_c37_118/syncing /ptp_sync_state/OpInput/port1
Epoch	⇒ C37_118_Slave/sm_pmu_c37_118/syncing /epoch_time_sec/OpInput/port1
Nanoseconds	⇒ C37_118_Slave/sm_pmu_c37_118/syncing /epoch_time_nsec/OpInput/port1
Queue Monitoring	
Slaves	(72)
IEEE37_701	(12)
Phasors	(12)
Analog	
Digital	
Frequency ROC	
Frequency deviation	
IEEE37_702	(12)
IEEE37_703	(12)
IEEE37_728	(12)
IEEE37_724	(12)
IEEE37_711	(12)
Synchronization	(5)
Time	(2)
Seconds	⇒ C37_118_Slave/sm_pmu_c37_118/syncing /epoch_time_sec/In1/Value
Nanoseconds	⇒ C37_118_Slave/sm_pmu_c37_118/syncing /epoch_time_nsec/In1/Value
Info	(3)
PTP Sync State	⇒ C37_118_Slave/sm_pmu_c37_118/syncing /ptp_sync_state/In1/Value
PTP Slave Offset	⇒ C37_118_Slave/sm_pmu_c37_118/syncing /ptp_slave_offset/In1/Value
Sync Accuracy	⇒ C37_118_Slave/sm_pmu_c37_118/syncing /sync_accuracy/In1/Value

Figure 41: Model Configuration: Connections of the PMU signals to the C37.118 slave driver (above) and the configuration for synchronization with the external PTP source via oscillator and clock adapter card and FPGA

Results

The following images show the time series of the fault sequences for different fault scenarios for the real and simulated measurements. It can be seen that some oscillations are taking place for the PSL microPMU device which introduces errors in the measurements. Results showed several timestamps shift between different devices. This will be discussed further in the *Issues and Problems during test-setup*.



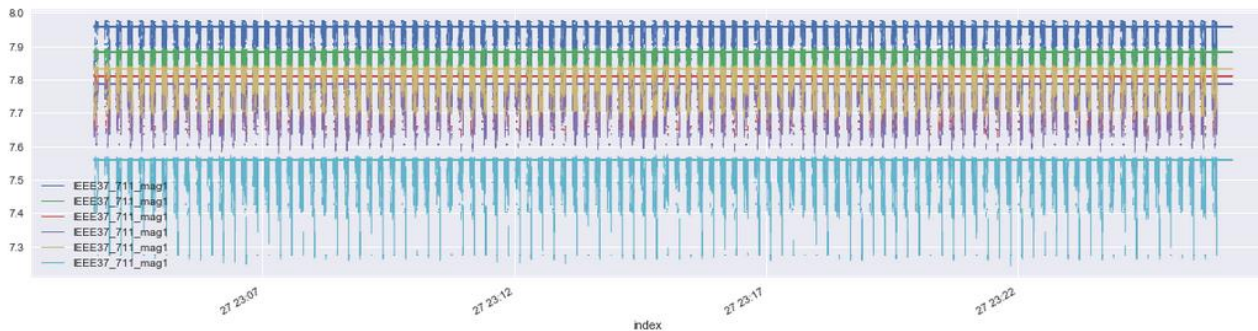


Figure 42: Voltage Magnitude of one phase for three real and one virtual PMU. Time synchronization is based on PTP. Sequence length is 100,

In order to label the fault sequence, location, type in the data set for further analysis the script writes the actual run into a log file. Figure 42 shows the typical output.

```
timestamp, sequence, fault_location, fault_type
...
2017-10-28 11:27:13.394000, 1, C37_118_Slave/sc_console/port7, 0
2017-10-28 11:27:13.688000, 1, C37_118_Slave/sc_console/port7, 3
2017-10-28 11:27:13.980000, 1, C37_118_Slave/sc_console/port7, 0
2017-10-28 11:27:14.272000, 1, C37_118_Slave/sc_console/port8, 0
2017-10-28 11:27:14.564000, 1, C37_118_Slave/sc_console/port8, 1
2017-10-28 11:27:14.857000, 1, C37_118_Slave/sc_console/port8, 0
2017-10-28 11:27:15.149000, 1, C37_118_Slave/sc_console/port8, 2
2017-10-28 11:27:15.441000, 1, C37_118_Slave/sc_console/port8, 0
2017-10-28 11:27:15.733000, 1, C37_118_Slave/sc_console/port8, 3
2017-10-28 11:27:16.025000, 1, C37_118_Slave/sc_console/port8, 0
2017-10-28 11:27:24.005000, 2, C37_118_Slave/sc_console/port5, 0
2017-10-28 11:27:24.300000, 2, C37_118_Slave/sc_console/port5, 1
2017-10-28 11:27:24.594000, 2, C37_118_Slave/sc_console/port5, 0
```

Figure 43: Log file output during scripted simulation run

The log file (see Figure 43) and the data set have been merged afterwards manually in order to select individual events and label them. Figure 44 shows an example.

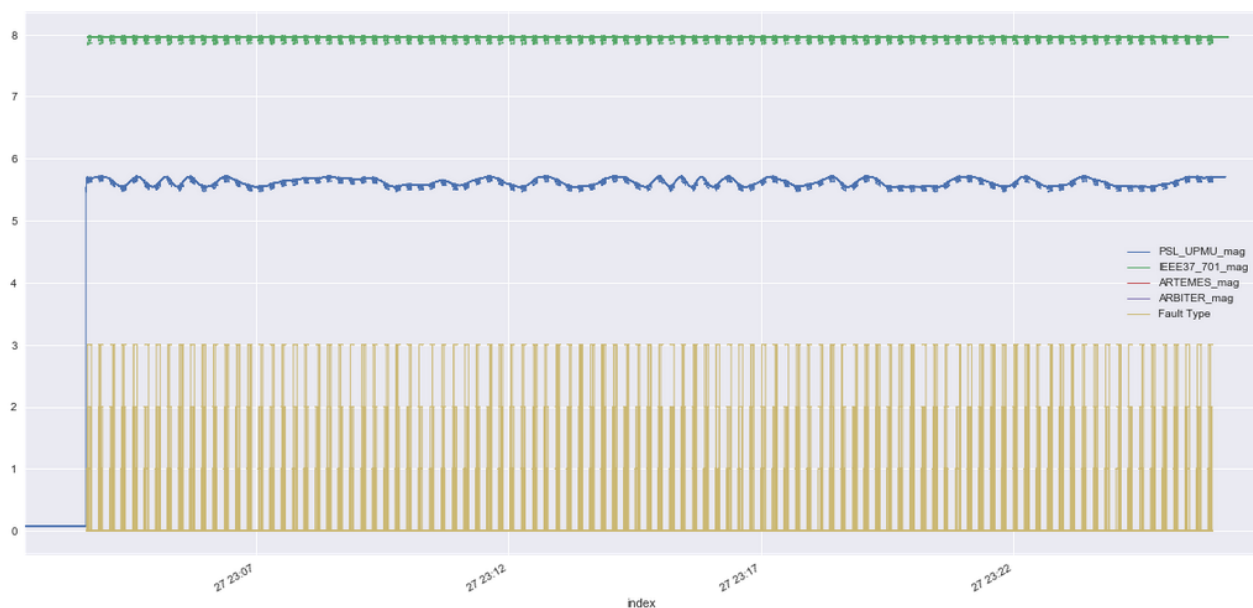


Figure 44: Resulting data set has also labelling of the fault type and fault location as well as fault impedance.

Experiment 6 - Simulating Fault Events Including Communication Network Model

The communication network of the PMUs has been modelled and simulated/emulated using CORE. Bandwidth, packet loss and collisions have been applied to the PMU data streams in order to evaluate impact on delay and availability of the data. Delay time have been measured as time difference between creation (measurement timestamp) and creation of the tuple in the database. Various effects like the output adapter batch processing parameter (e.g. 1000 data points) have direct influence on the round-trip time.

Short description

Name	<i>Fault with communication network simulation (emulation)</i>
Objective	<i>Impact on different communication channel bandwidth and media on latency</i>
Duration	<i>Minutes</i>
Results	<i>Impact on measurement availability</i>
Challenges	<i>Configuration and setup of communication simulation/emulation application</i>
Lessons Learnt	<i>Communication Simulation/Emulation, availability</i>
Outlook	<i>Extend setup with potential cyber attack scenarios</i>

Setup

Equipment	- OpalRT with simple P/Q Output model and interaction console - PMUs: Artemes, mPMU
Connectivity	OpenPDC, PostgreSQL (Cluster), Siemens Rugged Com
PMU setup	100 samples per second reporting rate
Database	PostgreSQL on VM in Cluster, local CSV historian

Scenarios

CNS Scenarios: manual change of power / power factor with different delays / CNS setups

- both real PMUs with CNS
- alternating one real PMUs with CNS and the other without
- both real PMUs with no CNS

Opal-RT / FPGA Output sequence triggered by console input from user:

Table 3: Opal-RT/FPGA Output sequence

Seq	1	2	3	4	5	6	7	8	9	10
U	230	230	230	230	230	110	110	110	110	110
P	2300	4600	4600	4600	2300	2300	4600	4600	4600	2300
Q	0	0	2300	4600	0	0	0	2300	4600	0

Models:

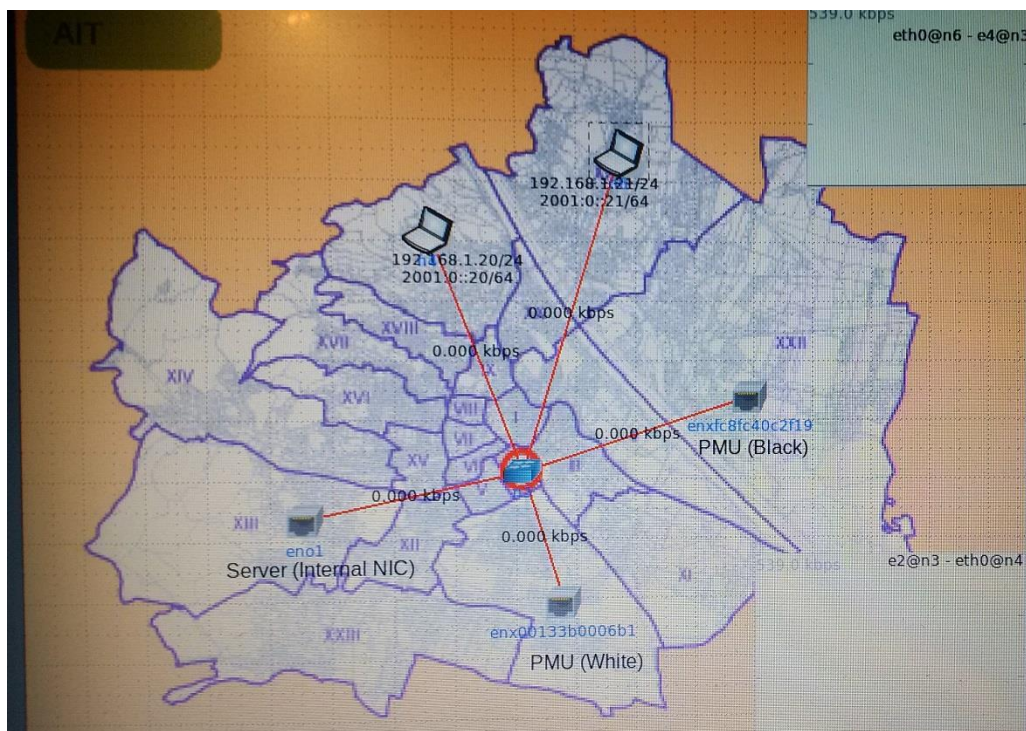


Figure 45: Communication network simulation by emulation using CORE



Figure 46: Setup for experiment 6. User group integrants (from left to right): Matthias Stifter, Reza Arghandeh, Jose Cordova.

Results

In order to evaluate the potential time delay and availability of measurements to upstream processing, the delay between the timestamp of the measurement and the time when it has been written to the database are analysed. The following Figure 47 and Figure 48 shows the frequency of the time delay when both PMUs are connected to the CNS. It could be seen that PSL has slighter longer report time in this round-trip time.

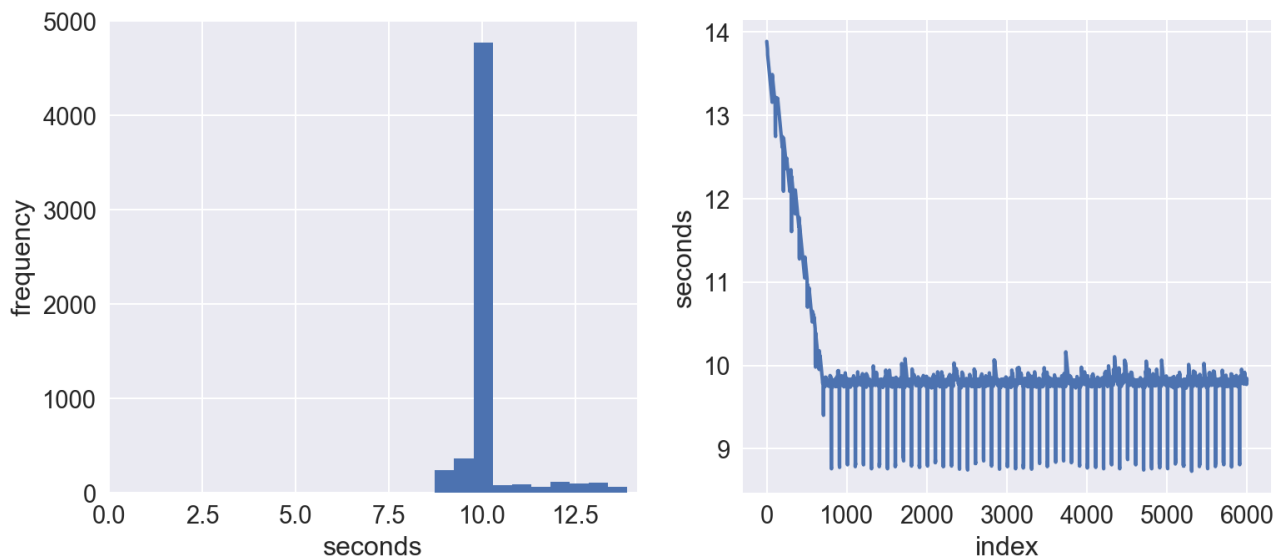


Figure 47: Artemes connected to CNS: Histogram of delay between measurement and storage (left) and evolution of the delay during measurement (right)

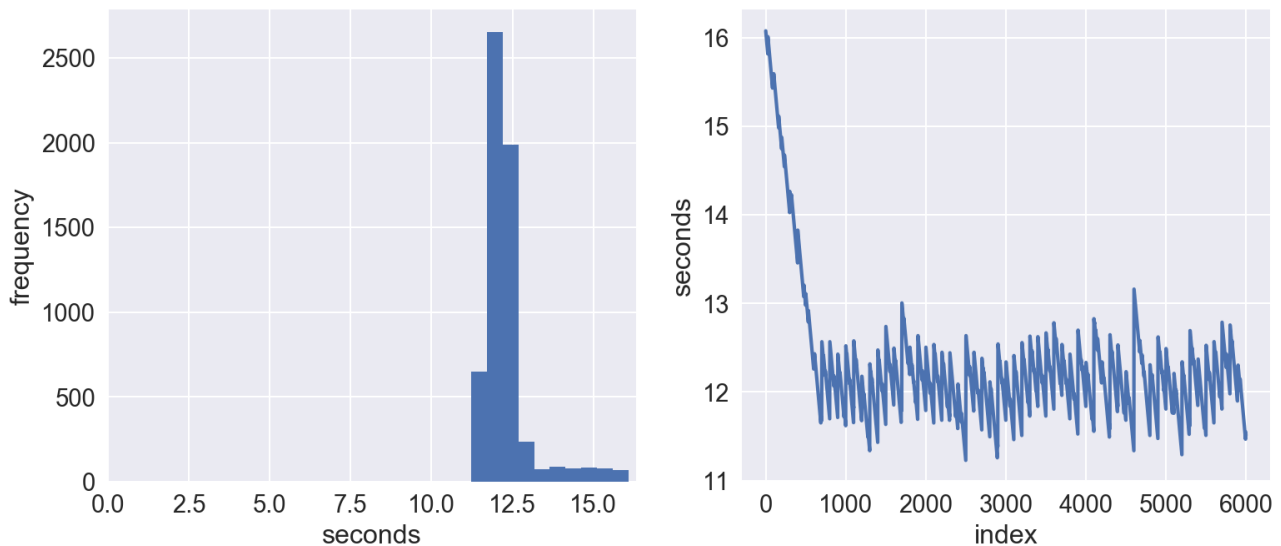


Figure 48: microPMU connected to CNS: Histogram of delay between measurement and storage (left) and evolution of the delay during measurement (right)

To compare the effect of communication on the delay the experiment has been repeated without connecting Artemes PMU to the CNS. Figure 49 shows the effect for only having microPMU connected to the CSN. There is no apparent quantitative change in the delay, which is because due to very conservative influential setting on the CNS. The effect at the start are probably due to other reasons (buffers, VMs, CPU clock) and seem to not affect steady state performance.

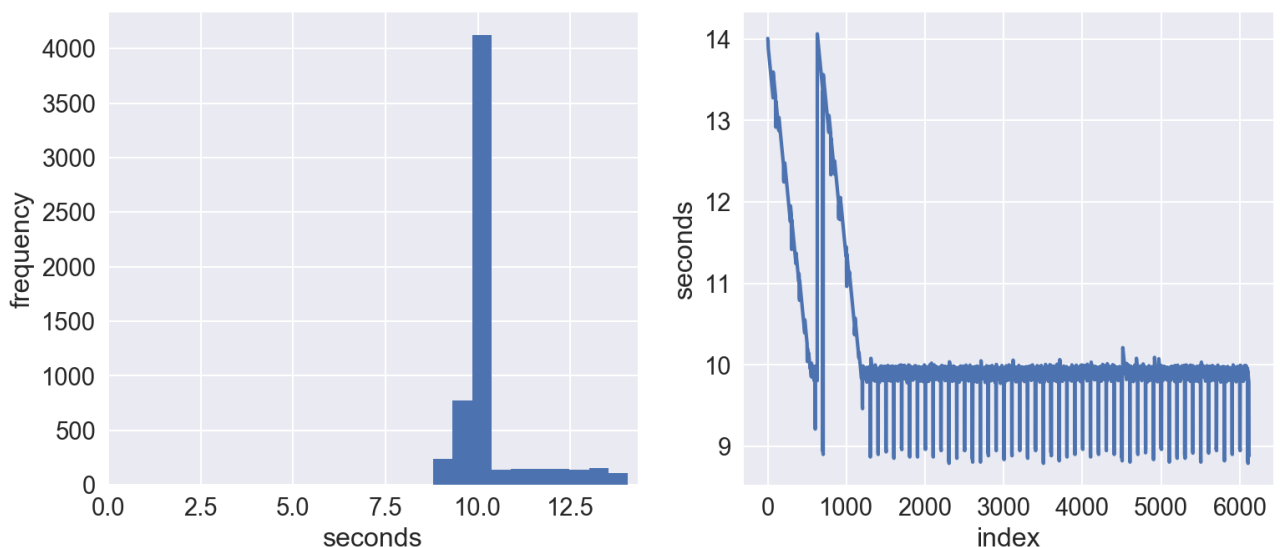


Figure 49: Artemes disconnected from CNS: Histogram of delay between measurement and storage (left) and evolution of the delay during measurement (right)

Experiment 7 - Simulating Fault Events with Real and Virtual PMUs

In this experiment the model has been extended with the output of the voltage and currents for the line to connect and measure with the real PMUs in parallel.

Short description

Name	<i>Fault event simulation with real and virtual PMUs</i>
Objective	<i>Simulate various fault types under different conditions and apply identification method</i>
Duration	<i>Minutes (3 faults) to several hours (500 - 1000 fault sequences)</i>
Results	<i>Data set with different fault scenarios and results for identifying faults based on measurements</i>
Challenges	<i>modelling, real time simulation, scripting of fault sequences, stable simulation, parameter change</i>
Lessons Learnt	<i>RTLab API scripting, data handling, data analysis, method application and analysis</i>
Outlook	<i>Preparing a dataset for fault event classification</i>

Setup

Equipment	<ul style="list-style-type: none"> - OpalRT with IEEE 37 bus model split into 5 sub models - PMUs: Artemes, mPMU, (later Arbiter) - Siemens Rugged Com, PTP source - Python script for fault sequence simulation and logging for event labeling
Connectivity	OpenPDC, PostgreSQL (Cluster), Siemens Rugged Com
PMU setup	100 samples per second reporting rate
Database	PostgreSQL on VM in Cluster, local CSV historian

Scenarios

Like experiment 6, different fault types and locations were taken place while changing their impedances in a scripted manner allowing automated fault simulation setups. The dataset obtained from this experiment was used for classifying the different fault types from a machine learning point of view. Figure 50 shows the model in Matlab/Simulink for this setup depicting both the real and virtual PMU configuration inside the Simulink environment. The scenarios simulated are as follows:

- Three fault locations are on line 702-703, 703-727 and 710-736.
- Fault types are line-to-ground, line-to-line and all three-lines-to-ground, A-G, A-B and ABC-G respectively.
- Fault distance on the line: are along the lines and should influence the fault impedances. It is most likely that fault distance has not worked when running the simulating the model.
- Fault impedances: 0Ohm, 50hm, 100hm, 250hm and 500hm.

Following the same methodology as in experiment 5, a total number of 4500 events were simulated.

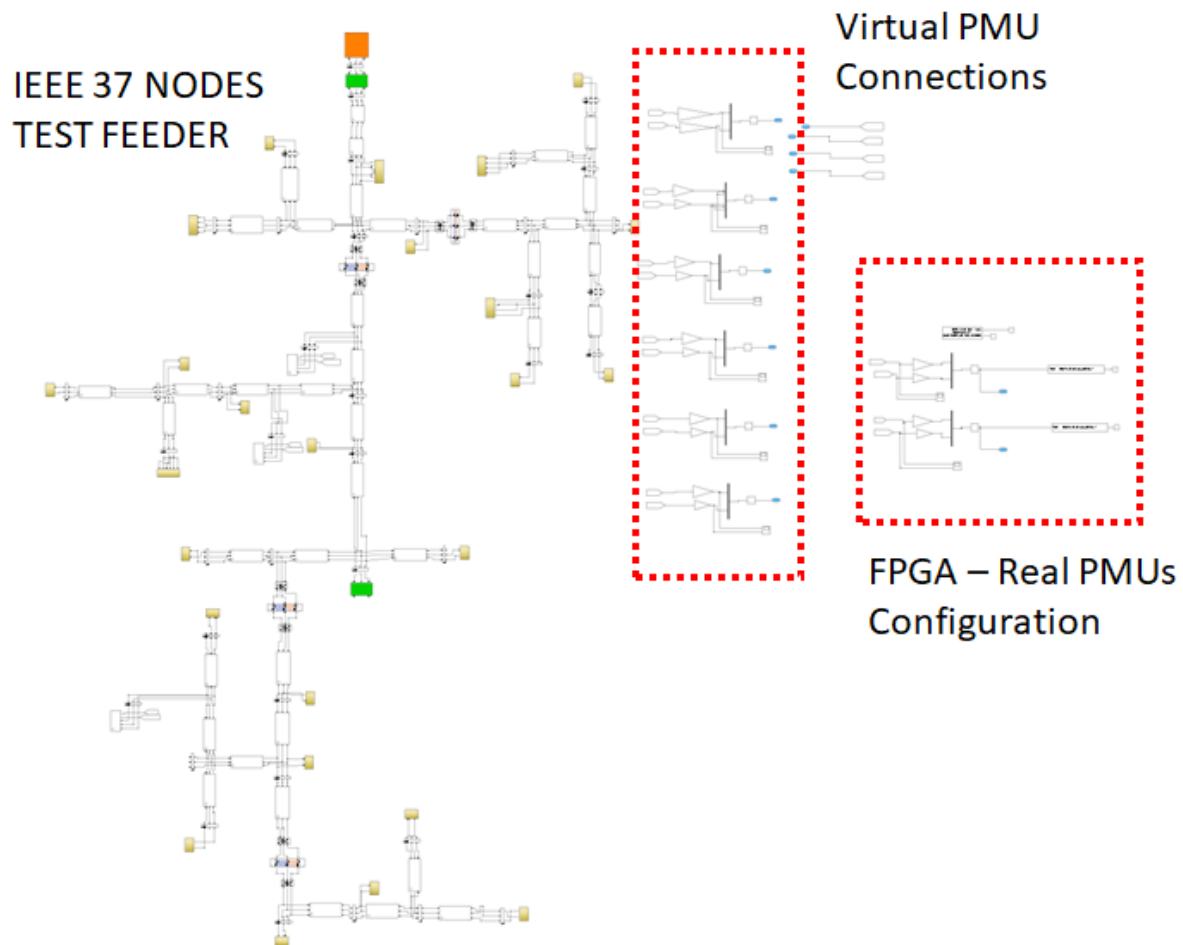


Figure 50: Model of the IEEE 37bus test feeder. The model is split in 5 subparts with the Opal-RT SSN solver configuration. Connectors for the virtual PMUs and the FPGA analog outputs are on the right side.

Figure 51 shows an interval of these simulations for the devices connected and the virtual PMUs from Opal-RT. It can be observed that Artemes device has a similar trend resembling the Opal-RT virtual PMU. However, PSL uPMU does not follow the same pattern showing again an oscillation. This is believed to be taking place given the low range of voltage in which the I/O FPGA interface operates.

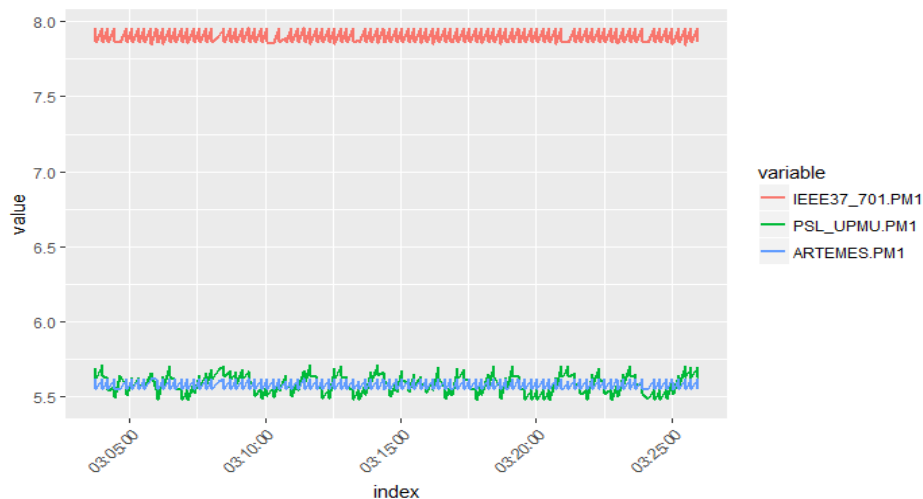


Figure 51: Voltage Magnitude measurements for PSL uPMU, Artemes and Opal-RT virtual PMU.

Single events showing only the interval of time where the fault was taking place are shown in Figure 52, Figure 53, and Figure 54. These pictures depict a single-line-to-ground fault for the Artemes, virtual PMU and PSL uPMU devices. It can be observed that while Artemes (Figure 52) and the Opal-RT virtually simulated PMU (Figure 53) have the same measurements patterns, the PSL uPMU device has some oscillations in its measurements. At every scale, the low range of voltage from the FPGA interface seems to be a limitation for measuring accurate voltage values.

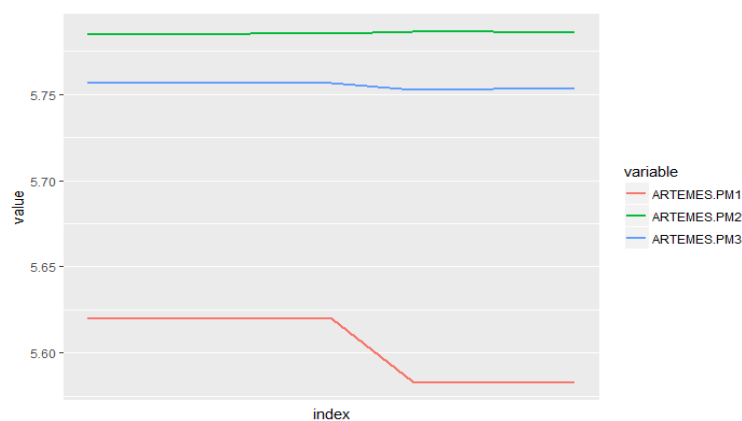


Figure 52: Model of the IEEE 37bus test feeder. The model is split in 5 subparts with the Opal-RT SSN solver configuration. Connectors for the virtual PMUs and the FPGA analog outputs are on the right side.

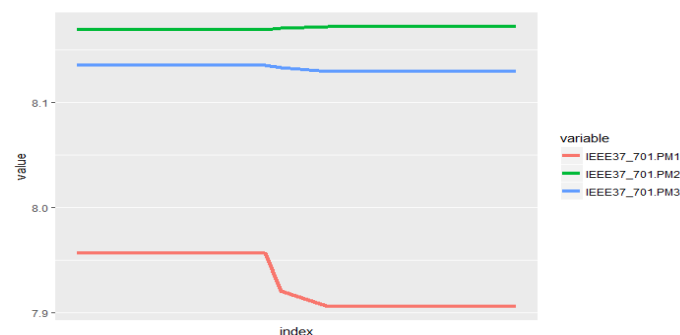


Figure 53: Model of the IEEE 37bus test feeder. The model is split in 5 subparts with the Opal-RT SSN solver configuration. Connectors for the virtual PMUs and the FPGA analog outputs are on the right side.

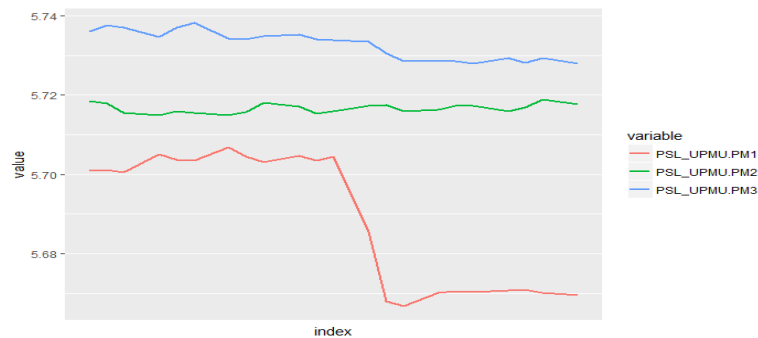


Figure 54: Model of the IEEE 37bus test feeder. The model is split in 5 subparts with the Opal-RT SSN solver configuration. Connectors for the virtual PMUs and the FPGA analog outputs are on the right side.

4.4 Data Management and Data Processing

OpenPDC - PMU data concentrator

An application for concentrating and streaming phasor data is free available software package OpenPDC (<https://openpdc.codeplex.com/>). It is capable of taking input streams from PMUs with various settings and protocol standards. It was also used to convert and stream PMU data to various connectors, namely PostgreSQL, local historian and CSV file.

With the graphical interface and visualization it supports the workflow, setup and verification of the experiment.

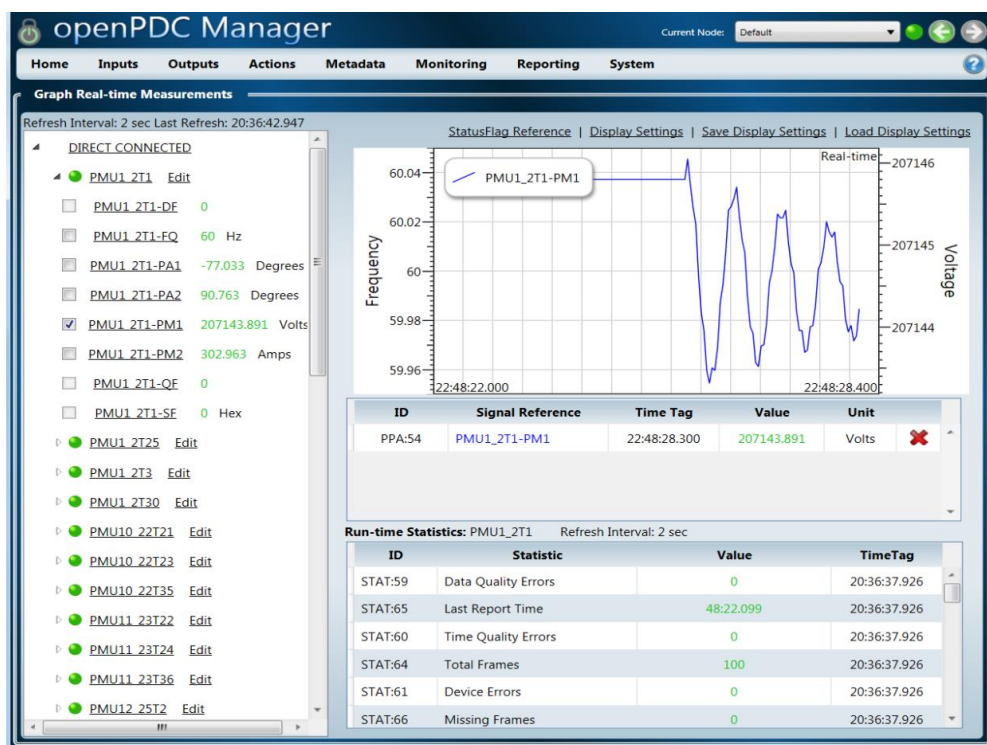


Figure 55: OpenPDC (example screenshot) for receiving, concentrating and streaming

Cluster - Virtual Machine hosted and parallel Databases

The AIT Energy Cluster provided the necessary processing capabilities to store and analyse PMU data streams from OpenPDC or direct measurements. The scalable network file system is based on GlusterFS, a large distributed storage solution for data analytics and other bandwidth intensive tasks.

Interconnection is provided via fast high bandwidth networks, based on Infiniband technology.

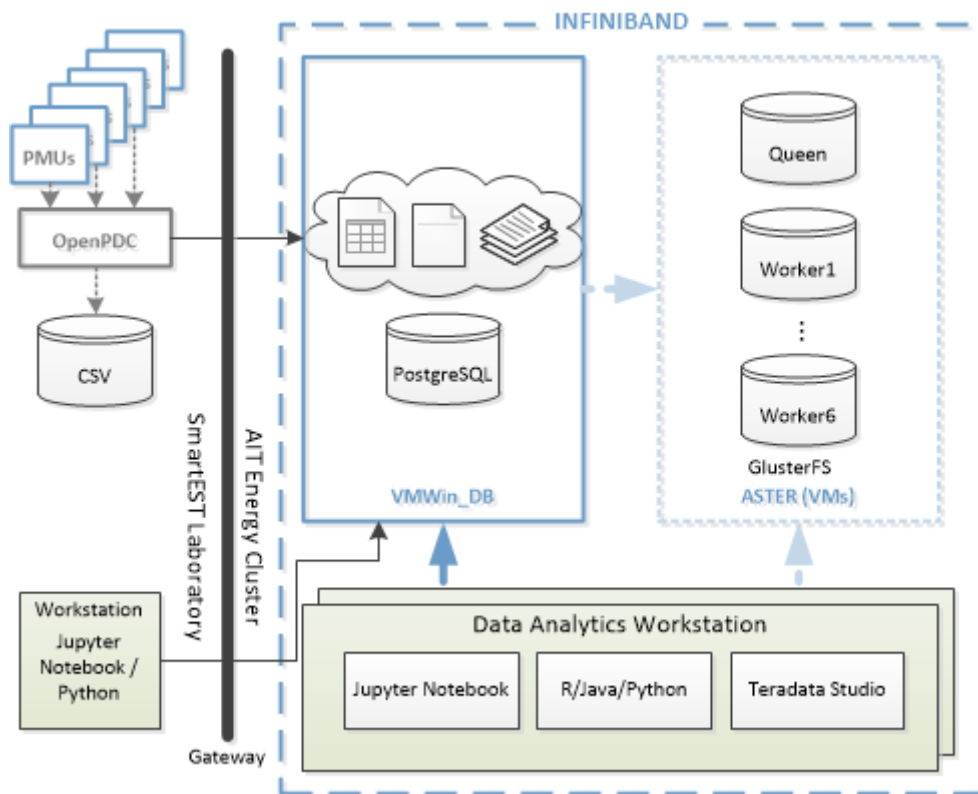


Figure 56: Data processing in the AIT Energy Data Analytics Cluster.
Note: Aster DB was not used in this setup due to time constraints

Python and R processing

In order to analyse the data by performing statistical analysis and visualization, the user group used mainly two different open source software: Python and R.

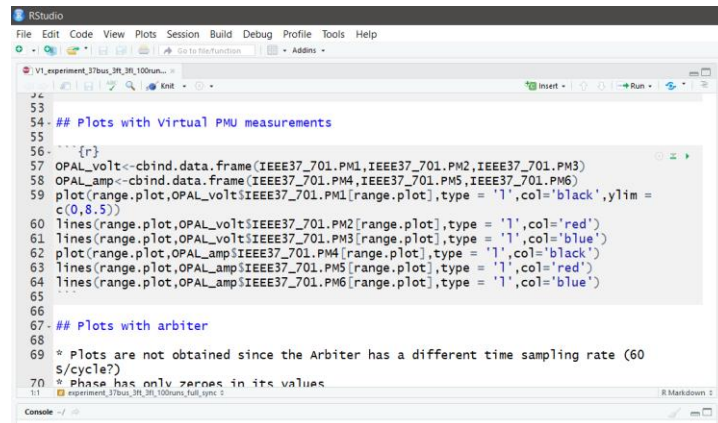
Python features many useful tools and packages for managing databases, functional programming, clean data visualization in a dynamic type system and automatic memory management. Its reliability comes from its large and comprehensive standard library.

R is an open source programming language and software environment for statistical computing and graphics widely used among statisticians and data miners for developing statistical and big data (pattern recognition) tools.

Gitlab and Jupiter collaborative environment for coding

In order to make a fast approach for the analysis of the fault event detection methodology. The user group decided to use Python and R Studio notebooks which were shared and updated simultaneously online. Both notebooks utilized are open-source web applications that contain live code, equations, visualization and comments on the codes used for the analysis. It is perfect for understanding and visualizing different programming languages in a fast and legible manner.

Gitlab is a web interface project repository suitable for sharing and modifying and sharing programming codes quickly with track changes. Figure 57 and Figure 58 show the Rstudio notebook and Jupyter notebook in Gitlab respectively.



```

53
54 ## Plots with Virtual PMU measurements
55
56 ```{r}
57 OPAL_volt<-cbind.data.frame(IEEE37_701.PM1,IEEE37_701.PM2,IEEE37_701.PM3)
58 OPAL_amp<-cbind.data.frame(IEEE37_701.PM4,IEEE37_701.PM5,IEEE37_701.PM6)
59 plot(range.plot,OPAL_volt$IEEE37_701.PM1[range.plot],type = 'l',col='black',ylim =
60 c(0,8.5))
61 lines(range.plot,OPAL_volt$IEEE37_701.PM2[range.plot],type = 'l',col='red')
62 lines(range.plot,OPAL_volt$IEEE37_701.PM3[range.plot],type = 'l',col='blue')
63 plot(range.plot,OPAL_amp$IEEE37_701.PM4[range.plot],type = 'l',col='black')
64 lines(range.plot,OPAL_amp$IEEE37_701.PM5[range.plot],type = 'l',col='red')
65 lines(range.plot,OPAL_amp$IEEE37_701.PM6[range.plot],type = 'l',col='blue')
66
67 ## Plots with arbiter
68
69 * Plots are not obtained since the Arbiter has a different time sampling rate (60
70 S/cycle?)
71 * Phase has only zeroes in its values

```

Figure 57: R Markdown Notebook created for Fault Events Analytics

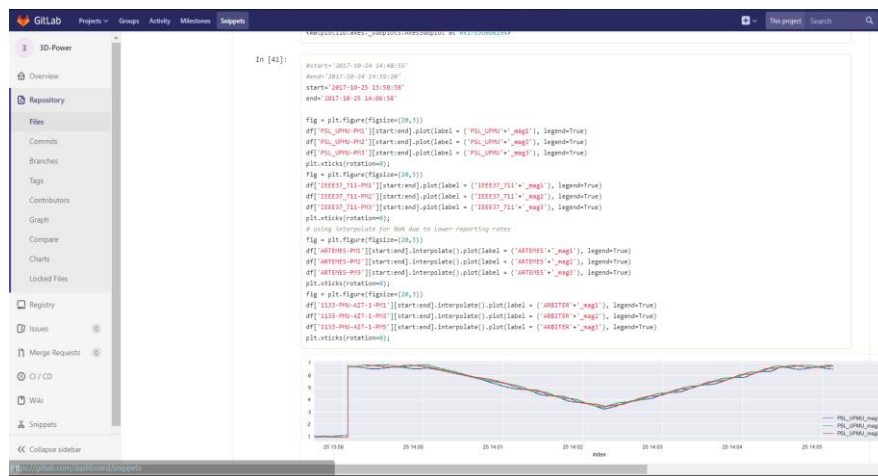


Figure 58: Jupyter notebook with Python versioned in GitLab

Machine Learning Algorithms

In this work, we present a novel approach for interpreting, detecting and classifying power system events based on the shape preserving method called the Registration or Time Alignment under Fisher-Rao Metric. The user group has utilized the RFRM method successfully for disturbances classification in power systems.

In our approach, we provide a new way of characterizing and measuring distance differences between fault events in a power distribution network. The new notion of distance is used to perform a clustering and to categorize fault types. Based on the distances gathered from the training data, *cluster templates* are created for each event type. The event templates are then used to construct a classifier which performance is evaluated in a cross-validation procedure. The readers are encouraged to see reference [7] for a fully detailed explanation of the method.

The following sections describes the overall performance of the clustering algorithm the user group has developed.

5 Results

In this section, the results of the 3D-Project will be provided. It will be divided in the same amount of experiments that were taking place during the stay of the user group. Therefore, we will provide details of the results from experiments 1 through 7.

5.1 Experiment 1 - Measuring Different Fault Using Actual PMUs

This experiment had the objective of connecting two different PMU devices (uPMU and Artemes) at different ends of a simple network to determine the phasor measurements obtained. The setup and connection first presented a challenge since the uPMU could not work with the analog inputs while streaming through the C37.118 protocol. This is a limitation of the features in the PSL and hence the power lines inputs were used as a measurement point. Additionally, the validation of the two-phasor measurement became a challenge since the Artemes PMU was not synchronized with the GPS antenna. The user group used an extension of this cable to be able to lock the satellite signals. However, this became a big first step in the development of the project as the DB connectivity and the PMU configuration for streaming were configured correctly. Also, the faults simulated were in an online environment, allowing the user group to visualize the fault event in real time through OpenPDC.

5.2 Experiment 2 - Measuring Different Fault Using Virtual PMUs

Experiment 2 consisted of having the same setup as in experiment 1 but with two virtual PMUs models in Opal-RT. The monitored fault was able to be visualized through OpenPDC as expected. This was a clear sign that the user group was able to configure the C37.118 slave driver inside the Opal-RT correctly. This was the first visualization of the virtual PMUs responding to fault. At this time, no synchronization had taken place with the Oregano card and therefore there was no synchronization with the real world reference clocks. As expected, there was full synchronization in the clocks between virtual PMUs inside the target. However, the real world reference synchronization presented a greater hardware configuration challenge.

5.3 Experiment 3 - Comparing PMUs Measurements from Different Vendors

Experiment 3 consisted of comparing power measurements between different PMU vendors, Artemes and PSL. The goal was to compare any type of oscillations between the metering devices while streaming and batching the data. The comparison was also extended to magnitude and angle measurements when changing the range of active and reactive power.

In this experiment, the user group handled different streamings and processed them in the database for further offline analysis. The results showed that the PSL microPMU had some oscillations in the measurements due to the low range of voltage that the Opal-RT can provide from its I/O FPGA interface.

Experiment 3 had one of the longest durations in the testing setups, up to 3 days, where it showed again that the PSL microPMU had some oscillations while receiving real-time measurements.

5.4 Experiment 4: Rate of Change of Frequency (ROCOF)

Evaluating response and propagation time of measurements have been intended to be evaluated with this experiment setup. An example application to be utilized with PMU data can be the frequency control (e.g. primary control) of (virtual) rotating masses (e.g. generators, batteries). For a comprehensive analysis, also the communication network needs to be simulated as another experiment setup was intended to include.

5.5 Experiment 5 - System Wide Fault Detection Using Multiple Virtual PMUs

A data set was created through the measurements of 6 virtual PMUs modelled in Opal-RT.

Experiment 5 was the first time that the user group simulated the IEEE 37 nodes test feeder in real time. Also, it was the first time that the user group used the API Python capabilities of RT-Lab for generating a large number sequence of faults controlled by a script written in Python language.

One of the challenges of this experiment was to obtain a stable simulation, as the scripting required reloading the test feeder model to the target which sometimes made the RT-Lab environment to crash. This is an open issue that it still under conversations with the Opal-RT technical support. However, it is suspected that the cause could be a hardware problem. For more on this regard, please refer to the *Issues and Problems during test-setup* section.

It was later learned by the user group that parameters such as fault impedance and transmission line impedance cannot be changed without recompiling the model. This presented a time constraint since compilation takes several minutes which would increase the fault sequence simulation from hours to days.

Results showed that some that some oscillations were taking place for the PSL uPMU device which introduced errors in the measurements. Several timestamps depict a shift between the Opal-RT devices and the real-world. This will be discussed further in the *Issues and Problems during test-setup*.

5.6 Experiment 6 – Simulating Fault Scenarios Considering Communication Network Latency

Introducing communication simulation/emulation using CORE has enabled various aspects and additional dimensions of evaluating PMU applications for distribution systems. In the realized setup we could investigate directly the impact on delays and packet drops. Setting up proper communication model scenarios is an ambitious work. Setting up a 'created' timestamp in the database helped further to evaluate queuing times and gives a first estimate of average processing times and data availability. Various effects like the output adapter batch processing parameter (e.g. 1000 data points) have direct influence on the round-trip time.

Especially scenarios related to cyber security can be analysed and evaluate in detail. A consequent step would be to evaluate directly the impact on communication on the application layer (e.g. state estimation, fault identification).

5.7 Experiment 7 - System Wide Fault Detection Using Multiple Actual and Virtual PMUs

5.7.1 Fault Event Classification with Current Measurements from virtual Opal-RT

Short description

<i>Fault Location</i>	<i>Lines 702-703</i>
<i>Fault Types</i>	<i>Single-line-to-ground, Double-line-to-ground, Three-line-to-ground</i>
<i>Measurements</i>	<i>Current @ Node 701</i>
<i>Fault Impedance</i>	<i>0 Ohms</i>
<i>Measurement Device</i>	<i>Opal-RT Virtual PMU</i>
<i>Results</i>	<i>Overall success prediction rate 25%</i>

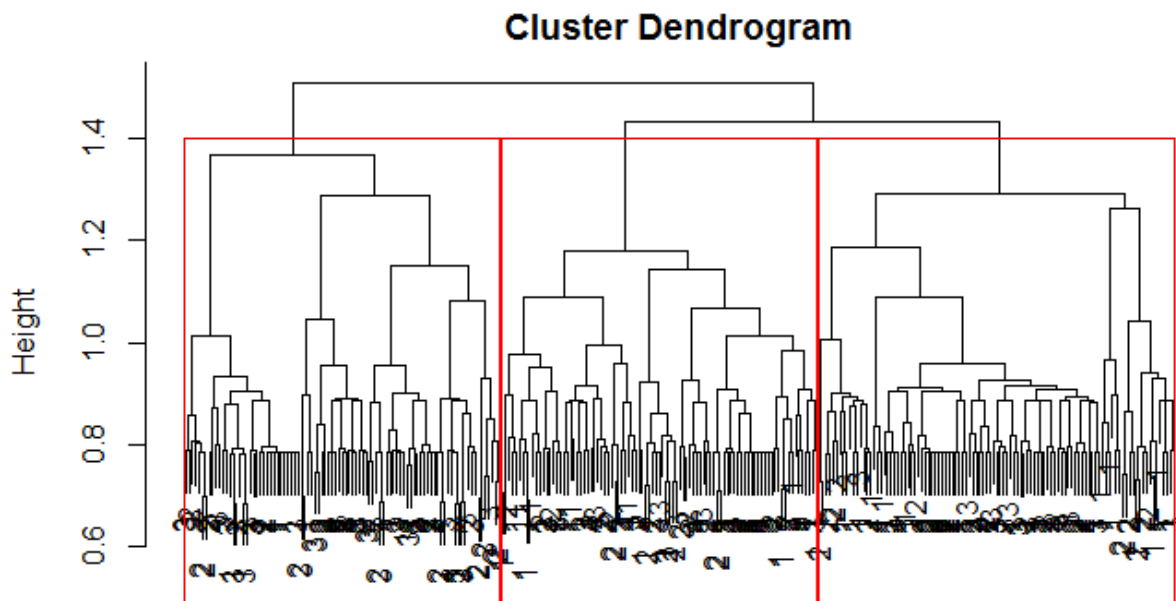


Figure 59: Clustering Dendrogram for Fault Event Classification with Current Measurements from virtual Opal-RT PMU

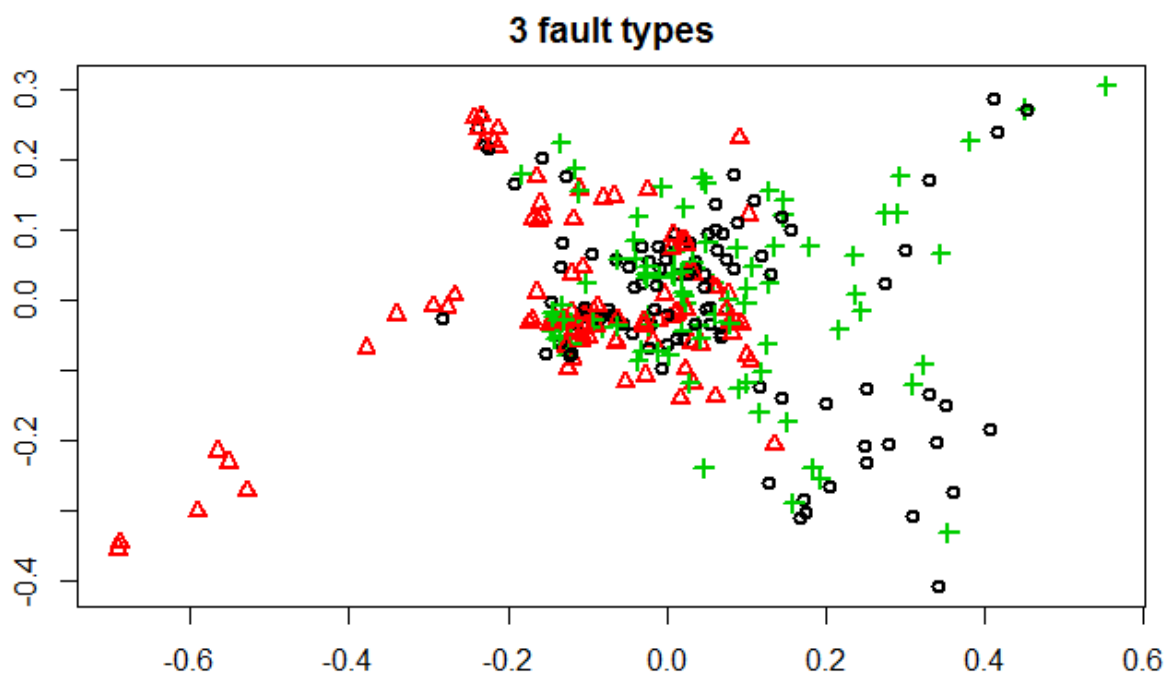


Figure 60: Multidimensional Scaling for Fault Event Classification with Current Measurements from virtual Opal-RT PMU

5.7.2 Fault Event Classification with Current Measurements from ARTEMES

Short description

<i>Fault Location</i>	<i>Lines 702-703</i>
<i>Fault Types</i>	<i>Single-line-to-ground, Double-line-to-ground, Three-line-to-ground</i>
<i>Measurements</i>	<i>Current @ Node 701</i>
<i>Fault Impedance</i>	<i>0 Ohms</i>
<i>Measurement Device</i>	<i>Artemes</i>
<i>Results</i>	<i>Overall success prediction rate 25%</i>

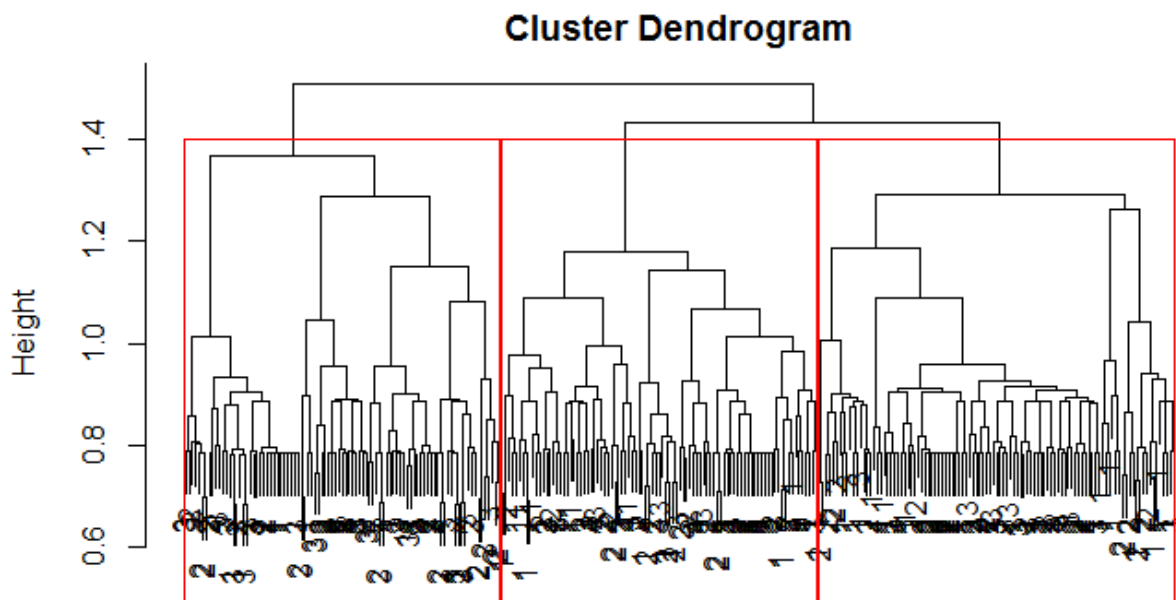


Figure 61: Clustering Dendrogram for Fault Event Classification with Current Measurements from virtual Artemes PMU

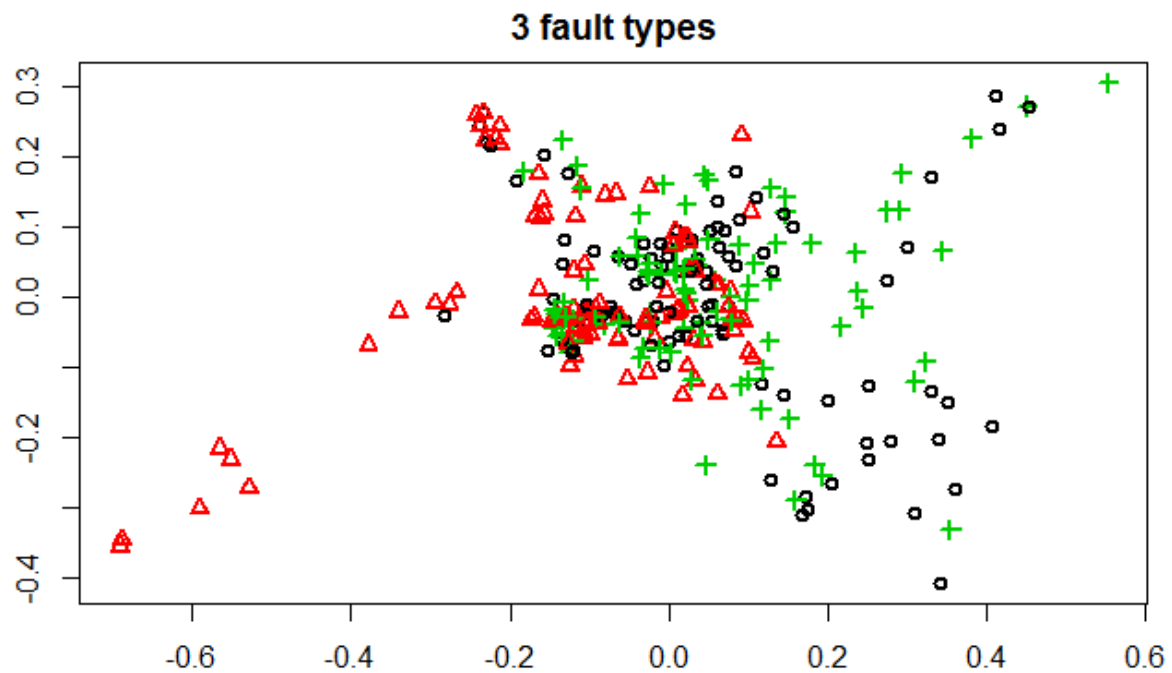


Figure 62: Multidimensional Scaling for Fault Event Classification with Current Measurements from virtual Artemes PMU

5.7.3 Fault Event Classification with Current Measurements from PSL

Short description

<i>Fault Location</i>	<i>Lines 702-703</i>
<i>Fault Types</i>	<i>Single-line-to-ground, Double-line-to-ground, Three-line-to-ground</i>
<i>Measurements</i>	<i>Current @ Node 701</i>
<i>Fault Impedance</i>	<i>0 Ohms</i>
<i>Measurement Device</i>	<i>PSL uPMU</i>
<i>Results</i>	<i>Overall success prediction rate 13%</i>

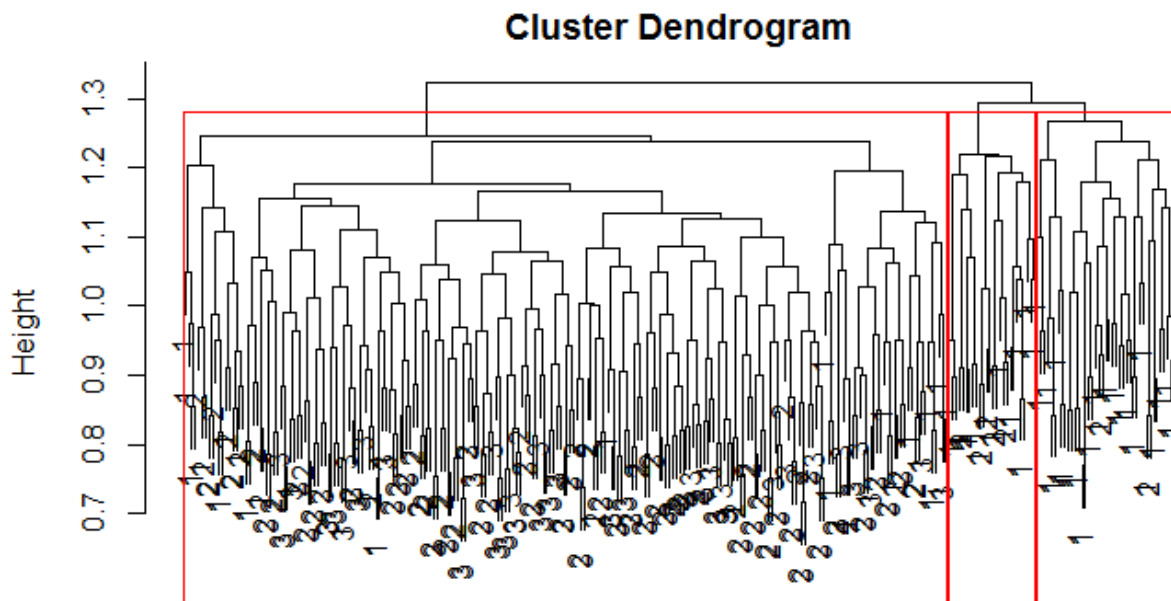


Figure 63: Clustering Dendrogram for Fault Event Classification with Current Measurements from virtual PSL microPMU

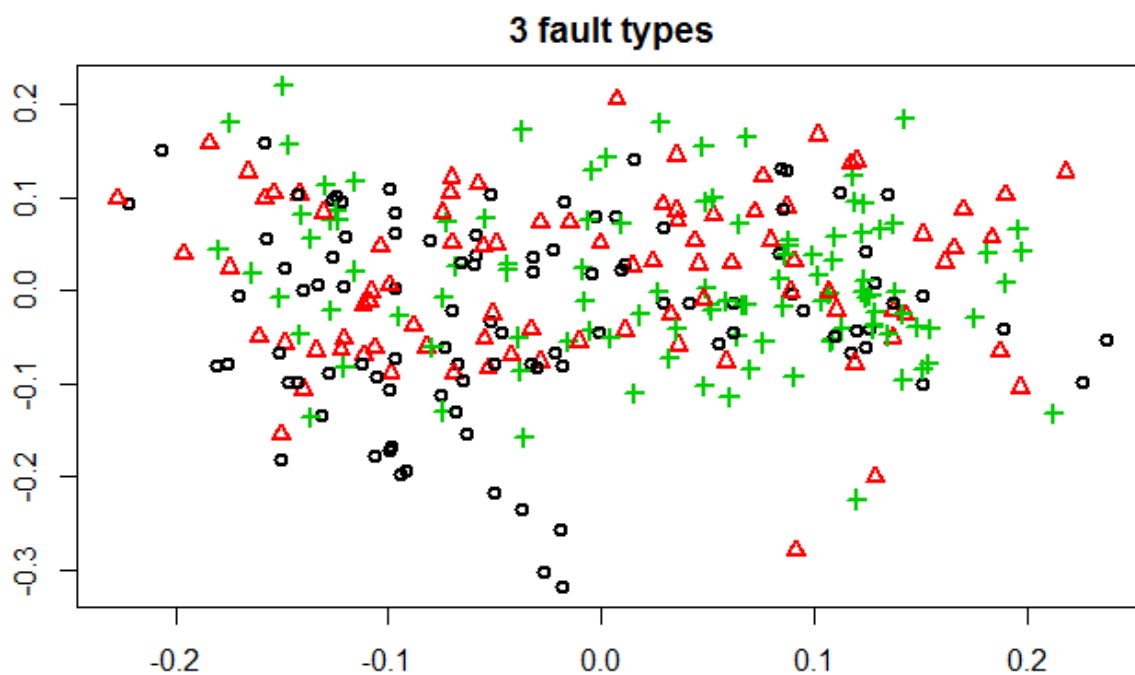


Figure 64: Multidimensional Scaling for Fault Event Classification with Current Measurements from virtual PSL microPMU

5.7.4 Fault Event Classification with Measurements from Arbiter PMU

Short description

<i>Fault Location</i>	<i>Lines 702-703</i>
<i>Fault Types</i>	<i>Single-line-to-ground, Double-line-to-ground, Three-line-to-ground</i>
<i>Measurements</i>	<i>Voltage @ Node 701</i>
<i>Fault Impedance</i>	<i>0 Ohms</i>
<i>Measurement Device</i>	<i>Arbiter</i>
<i>Results</i>	<i>Overall success prediction rate 30%</i>

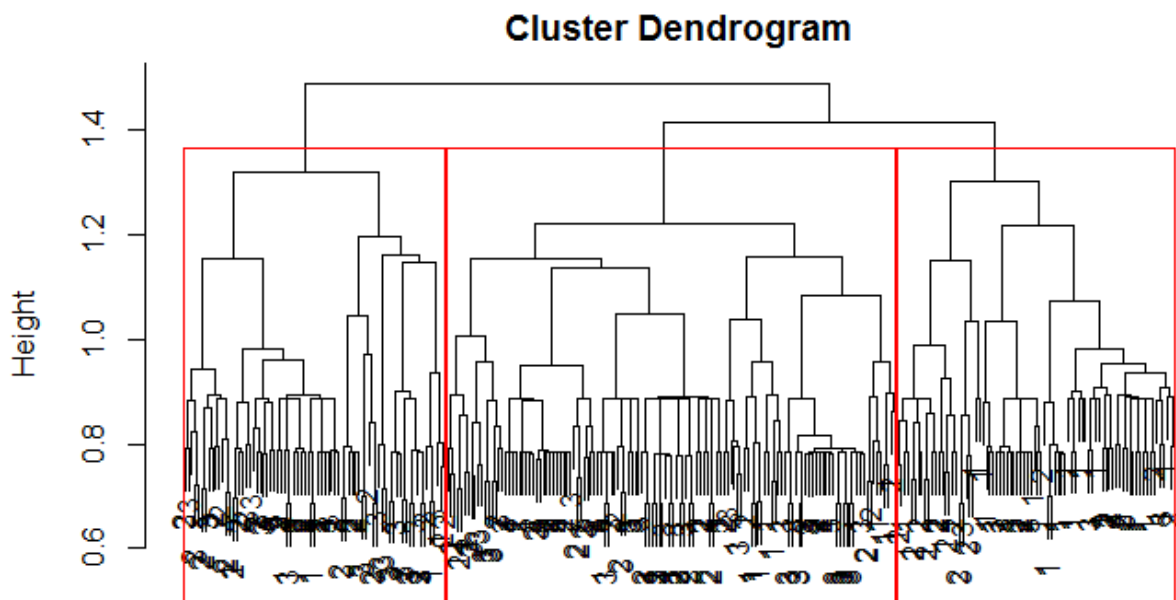


Figure 65: Clustering Dendrogram for Fault Event Classification with Voltage Measurements from virtual PSL microPMU

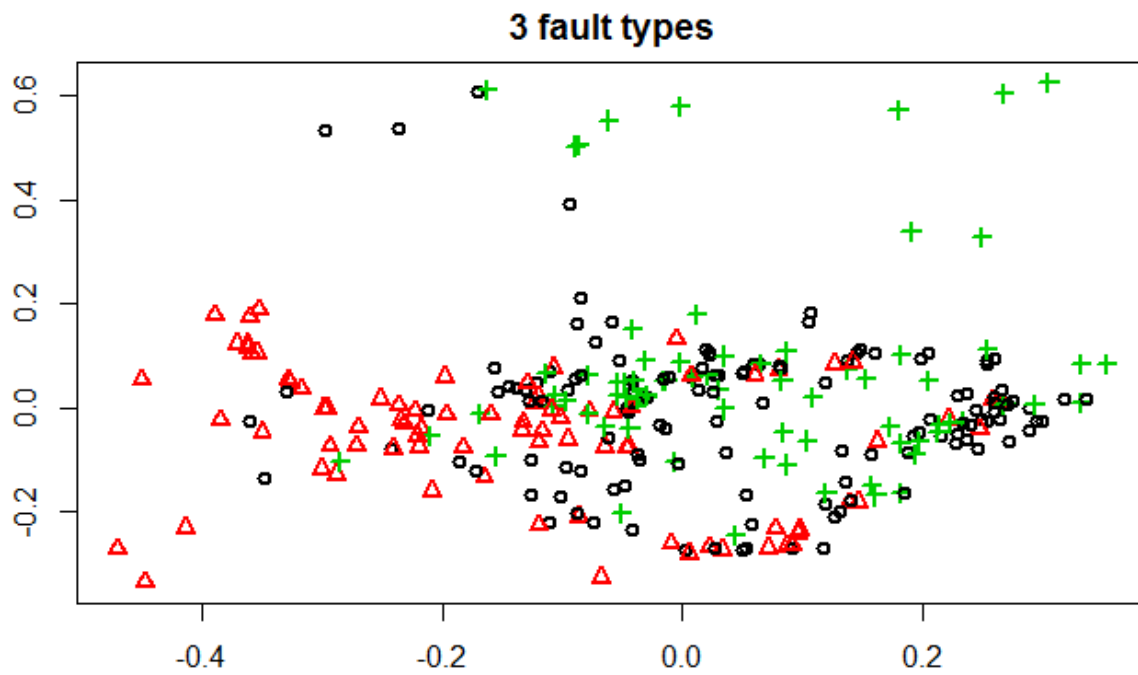


Figure 66: Multidimensional Scaling for Fault Event Classification with Voltage Measurements from virtual PSL microPMU

6 Conclusions

In the 3D-Power project, we made a testbed that provides realistic scenarios of a distribution test feeder model with PMU data streams simulations. The primary objective was providing a testbed for the integration of multi vendors PMU devices that are already used in power distribution networks monitoring. Also integrating virtual PMUs in Opal-RT environment with actual PMUs. However, the user group encountered several challenges and limitations given the novel characteristics of the project. The majority of these difficulties were resolved, and many lessons were learned both from the software and hardware side of the project and will be described in this section.

Regarding hardware setup, utilizing different PMU devices from multiple manufacturers (PSL, Artemes, Arbiter) inherently introduces dealing with different sampling rates, configurations, calculation algorithms, and as it was determined, different time synchronization references. In the first experiments, the user group came upon different synchronization issues between the virtual and real PMUs. Synchronization involved various technologies such as the Siemens PTP master RuggedCom and Oregano card interfacing with the Opal-RT Target. It was determined that the PTP master was using AIT time reference while the PMUs had a UTC reference. This issue was not solved by extracting the measurements streams from the database as hardware configurations do not allow shifting their timestamps. For power systems applications, time synchronization is crucial and developing a testbed of real field resemblance should include precise time stamps. In the end, this challenge was resolved by the user group.

The PMU devices presented different limitations and challenges. The PSL micro PMU could not stream data under the C37.118 standard when working with the analog inputs which was critical for the 3D-power development. However, the use of low ranges of voltage coming from the Opal-RT I/O interface introduced some oscillations in the microPMU measurements which were impossible to recognize until the data was analyzed in a Python environment. The Artemes devices were adapted to the higher reporting rates from the other devices installed which also introduced a shift in the time stamps transmitted. It can be concluded that different manufacturers present their solutions and when trying the integration of devices leads to many technical challenges.

In the database configuration, single-threaded SQL connection adapter presented a limitation for storing all the data streams produced in the testbed. A temporary solution was to store the streams in CSV files which were used in the analytical part of the project. However, the file size can become an issue in future simulations.

Regarding software, the simulation tool of choice was the Opal-RT/RT-Lab environment. RT-Lab is fully integrated with Matlab Simulink which makes the modeling easier with its graphical user interface. However, the fault event sequence simulation via API Python-based scripting presented a challenge for the user group. The complexity of the experiment with several hardware components integrated made the system crash after in the middle of the simulation, hence requiring a physical reboot of the system. In future work, a collaboration with Opal-RT and their technical support may result critical for overcoming these delays.

It was concluded that the fault impedance is a parameter cannot be changed in the middle of a simulation, given the solver characteristics of RT-Lab. The models loaded into the target need loading and compilation periodically to change these parameters which can become time-consuming given the complexity of the model used.

The user group is working closely with the different PMU manufacturers involved in the development of this project. PSL microPMU and Artemes have shown interest in testing their devices in the 3D-project setup. It is clear that there is potential in testing different PMU devices in search of bugs in their firmware and also determining future required features. The user group has proposed a collaboration with the vendors to address typical power systems problems. Additionally, Siemens has shown interest in the tests performed with their technologies. Accordingly, the user group will

attempt to expand the interest of the manufacturers to a full collaboration with their research and technical staff.

7 Open Issues and Suggestions for Improvements

7.1 Issues and Problems during test-setup

7.1.1 UTC Synchronized in Real Time Simulation

Issue:

Synchronization to real-world time of real-time simulation

Solution:

To synchronize the real-time simulator (RTS: Opal-RT) and the virtual PMUs with real PMUs it is necessary to use a high precision oscillator card *Oregano syn1588®* PCIe NIC with *OCXO Oscillator*. This enables the RTS to use the IEEE1588 based time synchronization to sync to the given time clock (e.g. GPS) with the needed precision (NTP is not enough). Since the RTS simulation also uses FPGA output for the real PMUs to sense, the time sync signal needs to be propagated directly to the FPGA hardware via an adapter card. Finally it enables the simulation (virtual PMU - C37.118 slave) and the hardware output to be synchronized to the given external time source.

First a 1PPS based signal from a capable GPS antenna (*NavSync CW46*) via SMA, 50 Ohm, 3V3 signalling using an NMEA data stream to the serial PC port was used to synchronize the RTS. Unfortunately, the Opal-RT driver was not supporting the additional NMEA stream tagging the UTC timestamp for the card. This setup was only able to synchronize within given ns accuracy, but was not able to 'know' which date and time (UTC timestamp) it was. An alternative would have been to use a IRIG-B capable device which delivers also the timestamp information additionally to the sync signal.

In the next setup a *Siemens RuggedCom RSG2488* capable of providing a PTP source was used. The PTP protocol uses Ethernet based communication which includes the synchronization and timestamp information.

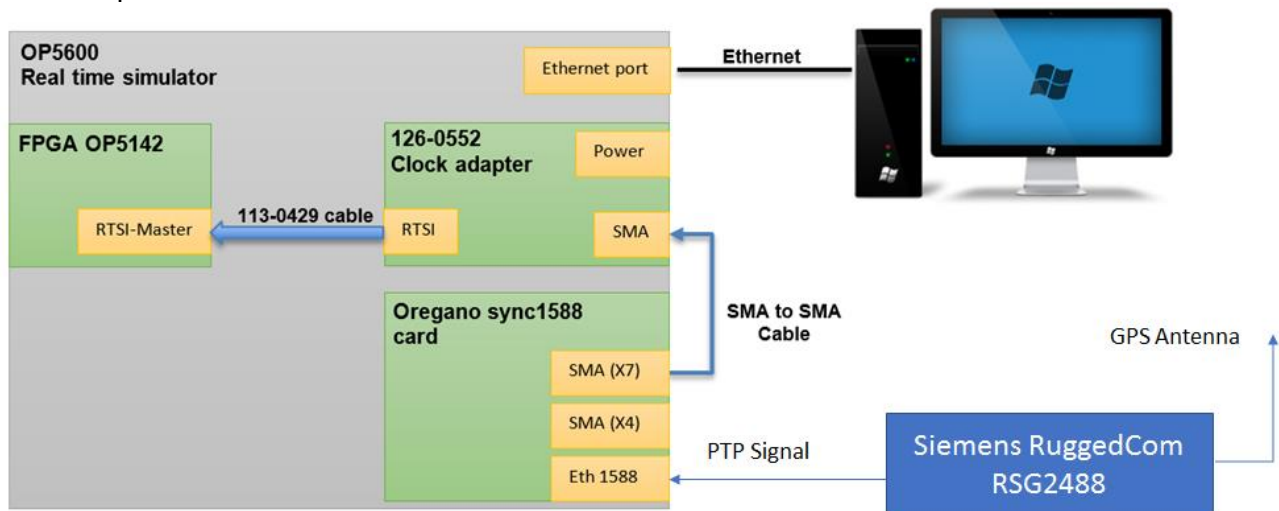


Figure 67: Showing the time synchronization kit necessary to sync simulation and analog output to GPS

Configuration on the PTP master clock was lacking the correct settings for the Opal-RT card before finally a synchronized simulation was possible. The card was not switching to slave mode and accepting sync signals from the PTP master:

```
Synchronization: Successfully initialized card #0
Synchronization: Launching PTP stack with command ->
```

```

/usr/opalrt/v11.1.4.59/common/bin/modules/oregano/1/tools/ptp -power -i eth3 -D
P -I false -p 250 -v2 -v 2
Synchronization: Opening shared memory...
Synchronization: Successfully opened shared memory
Synchronization: Waiting 15 seconds for the synchronization...
Synchronization: External sync accuracy set to 100000 nanoseconds
Synchronization: PTP sync state set to 'Listening'
Synchronization: PTP sync state set to 'Master'

```

The PTP configuration on the RuggedCom needs the following configuration in order to be detected as PTP master from the Oregano card and successively from the Opal-RT synchronization driver when using GPS as a primary time source:

Administration >> System Time Manager >> Precision Time Protocol >> Configure Global Parameters

```

PTP Enable          Yes
Clock Type          Ordinary Clock
PTP Profile          Power Profile
Ethernet Ports       All
VLAN ID             Disable
Class Of Service     Disable
Transport Protocol   Layer 2 Multicast
Grandmaster ID      9
Startup Wait         10 s
Desired Clock Accuracy 1 us
Network Class        Non-IEEE1588 network
1 Step Master Clock  Yes

```

Administration >> System Time Manager >> Precision Time Protocol >> Configure Glock Parameters

```

Domain Number       0
Sync Interval        1 s
Announce Interval    1 s
Announce Receipt Timeout 3
Priority1             1
Priority2             1
Path Delay Mechanism Peer-to-Peer
Slave Only           No

```

Even after setting up everything correctly to get a working environment, Opal-RT still has error messages at the first run and completely hangs simulation when the model is stopped after it runs with the second start attempt:

```

ERROR: Synchronization: Error. Failed to open card 0
ERROR: Synchronization: Error. Validate that the card is properly connected to the
simulator and that board ID configured properly
ERROR: I/O Manager: Synchronization initialization error. I/O is disabled.

```

The hanging of the simulation is still an unsolved issue remaining at the time writing this report. Only rebooting the machine is bringing it back to normal operation.

7.1.2 Synchronization of Real and Virtual PMUs

Issue:

Different time bases between virtual and real PMUs

Solution:

Phasor timestamps of virtual PMUs and real PMUs are gapping of exactly 36 seconds. They are perfectly synchronized with ns accuracy, but not on the second base. It turned out that PTP used TAI as time base - which includes leap seconds taking slowdown of Earth's rotation into account -

whereas PMUs using UTC as their time base. Even with the Oregon driver setting (-U 36) for UTCOffset it is not possible to shift the as PTP slave acting RTS in time forward:

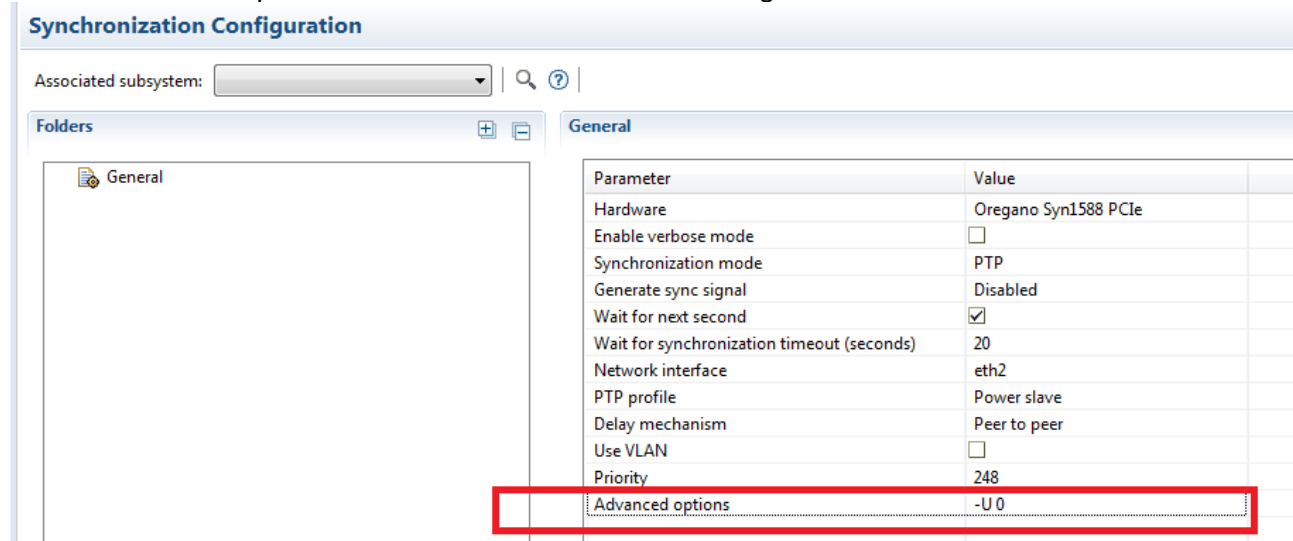


Figure 68: RTLab Driver settings for taking UTCOffset into account (but only if in PTP Master mode)

Using Wireshark to inspect the PTP signal and the correct UTCOffset was done in order to find out if the RuggedCom send the correct information. Since the RuggedCom is connected and locked to the external GPS signal it ignores the manual UTCOffset configuration and uses the GPS source based timing.

(Untitled) - Wireshark@RTServer_Simulator

File Edit View Go Capture Analyze Statistics Help

Filter: **ptp** + Expression... Clear Apply

No.	Time	Source	Destination	Protocol	Info
2	0.132004	94:b8:c5:53:41:c0	Ieee1588_00:00:00	PTPv2	Announce Message
3	0.145960	94:b8:c5:53:41:c0	Ieee1588_00:00:00	PTPv2	Sync Message
4	1.132101	94:b8:c5:53:41:c0	Ieee1588_00:00:00	PTPv2	Announce Message
5	1.146041	94:b8:c5:53:41:c0	Ieee1588_00:00:00	PTPv2	Sync Message
7	2.132187	94:b8:c5:53:41:c0	Ieee1588_00:00:00	PTPv2	Announce Message

Frame 2 (136 bytes on wire, 136 bytes captured)

Ethernet II, Src: 94:b8:c5:53:41:c0 (94:b8:c5:53:41:c0), Dst: Ieee1588_00:00:00 (01:1b:19:00:00:00)

Precision Time Protocol (IEEE1588)

- 0000 = transportSpecific: 0x00
 - ...0 = 802.1as conform: False
 - 1011 = messageId: Announce Message (0x0b)
 - 0010 = versionPTP: 2
 - messageLength: 122
 - subdomainNumber: 0
- flags: 0x000c
 - 0... .. = PTP_SECURITY: False
 - .0.. .. = PTP profile Specific 2: False
 - ..0. .. = PTP profile Specific 1: False
 -0.. = PTP_UNICAST: False
 -0. = PTP_TWO_STEP: False
 -0. = PTP_ALTERNATE_MASTER: False
 -0. = FREQUENCY_TRACEABLE: False
 -0 = TIME_TRACEABLE: False
 -1.. = PTP_TIMESCALE: True
 -1.. = PTP_UTC_REASONABLE: True
 -0. = PTP_LI_59: False
 -0. = PTP_LI_61: False
- correction: 0.000000 nanoseconds
 - correctionNs: 0 nanoseconds
 - correctionSubNs: 0.000000 nanoseconds
 - ClockIdentity: 0x94b8c5fffe5341c0
 - SourcePortID: 1
 - sequenceId: 4955
 - control: Other Message (5)
 - logMessagePeriod: 0
 - originTimestamp (seconds): 1502467485**
 - originTimestamp (nanoseconds): 256016536

Figure 69: Network package inspection on the PTP message for error tracing

In a post-processing step the virtual PMU were shifted forward in time by 36 second in order to sync TAI and UTC based timestamps.:

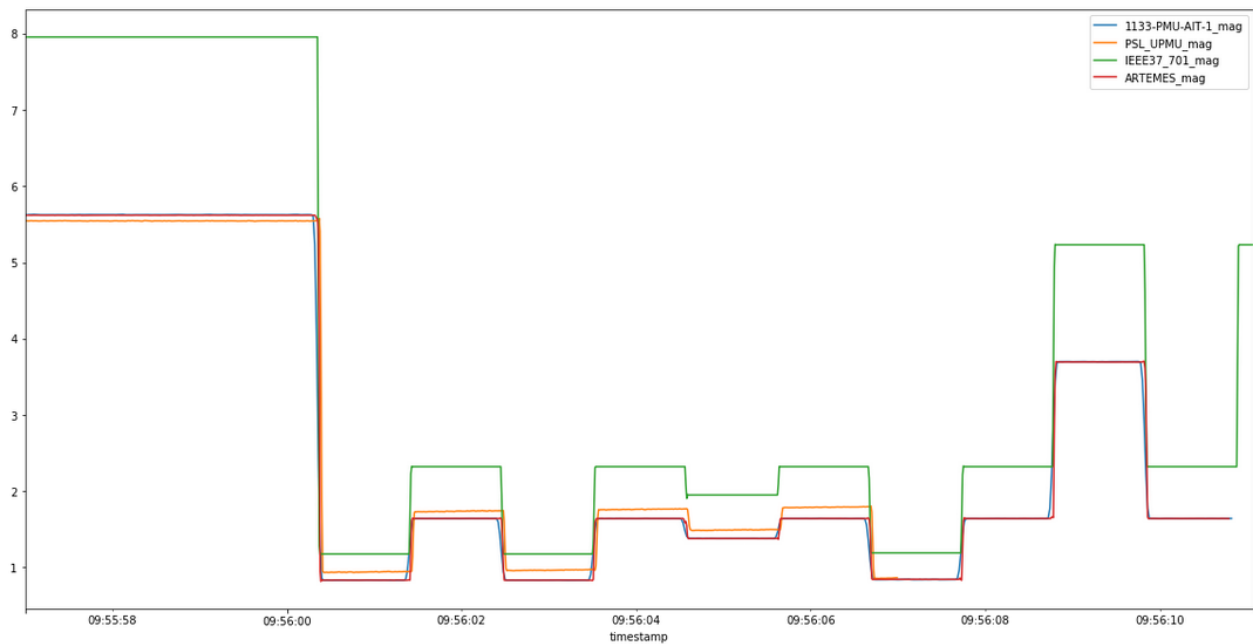


Figure 70: Time synchronized magnitudes of one phase from one virtual and three real PMUs during a fault. Note: Virtual PMU has been shifted by 34 seconds due difference in TAI and UTC time offset.

7.1.3 Low Frequency Oscillations in PMU

Issue:

Low oscillations with varying frequency and amplitude 0.10V on the analog output of Opal-RT

Setup:

- Opal-RT 37-nodes model with fault in 3 locations with 3 different fault types
- Three real PMUs and 6 virtual PMUs (Opal-RT C37.118 slave models) are connected to various nodes

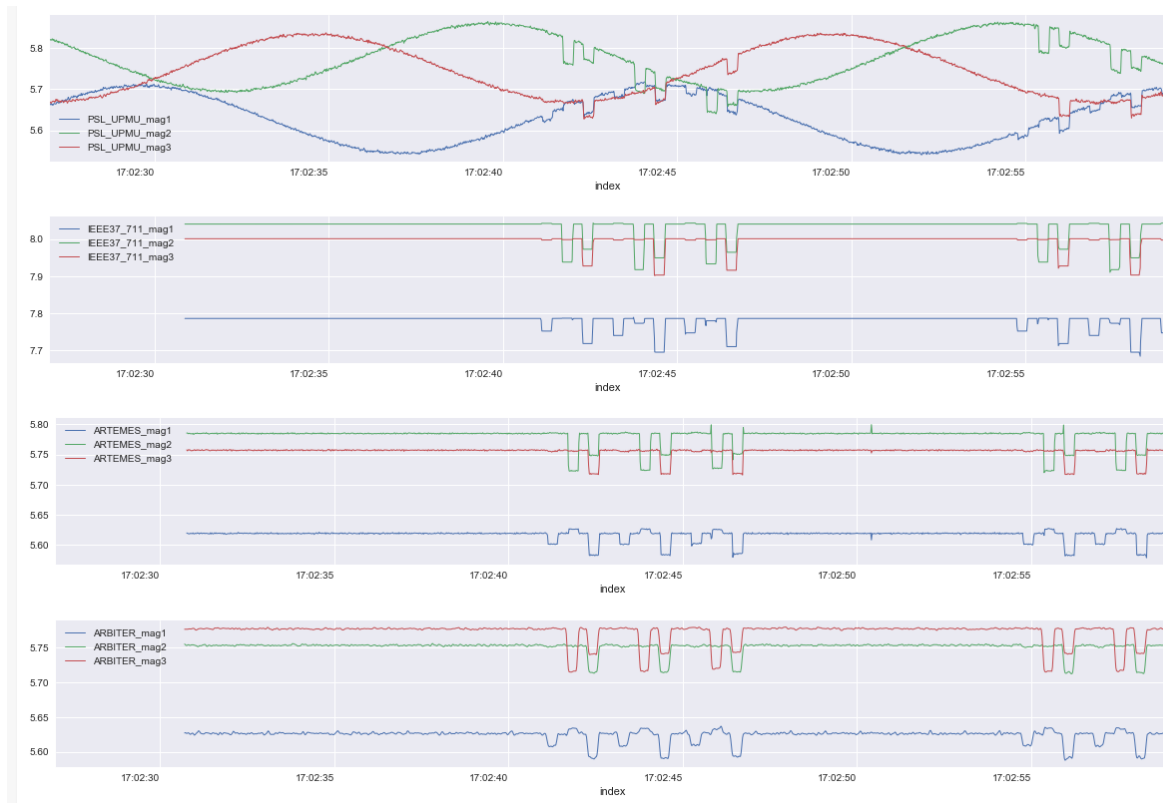


Figure 71: Comparison of measurements of three real PMUs and virtual PMU (50Ohm fault)

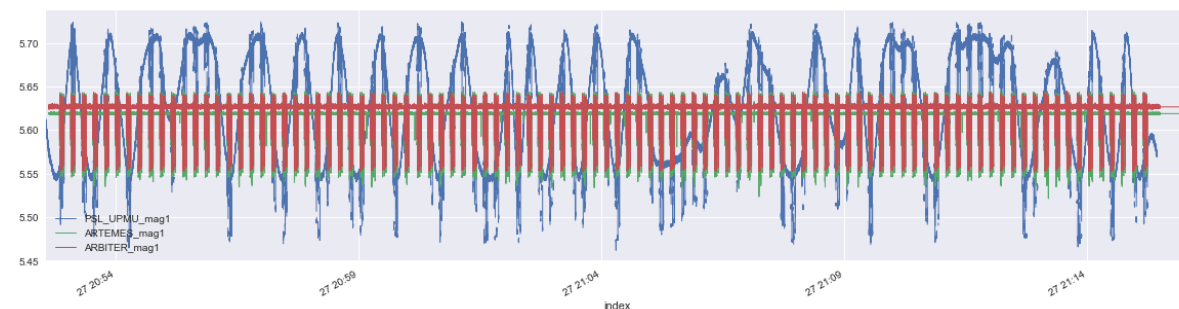


Figure 72: Comparison of measurements of three real PMUs and virtual PMU (25Ohm fault)

Possible reasons:

- Analog output of Opal-RT is not accurate
- Setup with 50Hz and 60Hz maybe a problem

Further test:

- Check with other measurement devices on the output, e.g. oscilloscope, PMU
- Check settings of microPMU with PSL

7.1.4 Gaps in Data Streams and Missing Data

Issue:

PMU Phasor streams from openPDC to database showed irregular gaps.

Setup:

Same as the experiment setups described above

Solution:

Error checking was done on network routers, connectivity, Ethernet card I/O performance, SSH tunnels (cluster connection), OpenPDC, computer performance on CPU and memory (both on the OpenPDC processing as well as the DB cluster Virtual Machine) as well as on OpenPDC connection configurations like batch processing size and local queuing buffer size. The VM hosting the Database has 20 cores and 112GB RAM memory, which shouldn't be a problem for the amount of data.

The most probable bottleneck was considered as the single threaded SQL connection adapter. As a proposed solution is to parallelize the number of ADO adapters (e.g. each serving 2-3 PMUs) to facilitate multiple CPU processing on the DB server. For the time being a local streaming CSV adapter was used for file based exporting of PMU streams.

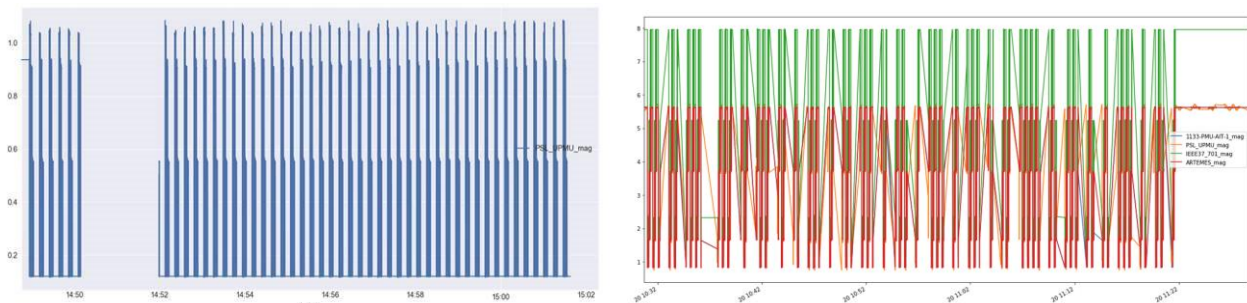


Figure 73: Gaps in the resulting data streams in the database table due to single processed adaptors

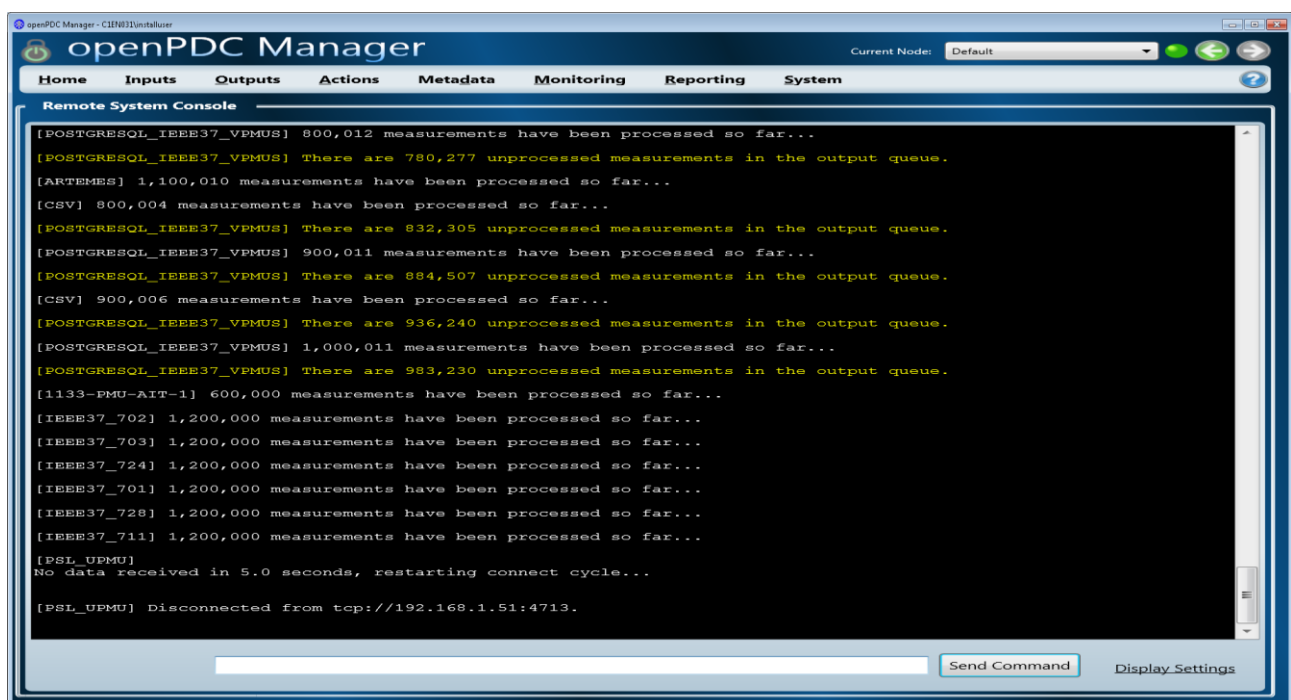


Figure 74: Queuing problems for streaming to database with one output adapter

To analyse the delay time, it takes from creation of the phasor to storing in the database it can be

seen that the measurements are 'queuing up' and introducing delay times of 50 seconds and more (Figure 75). This is directly proportional with the number of phasors streamed over one output adapter.

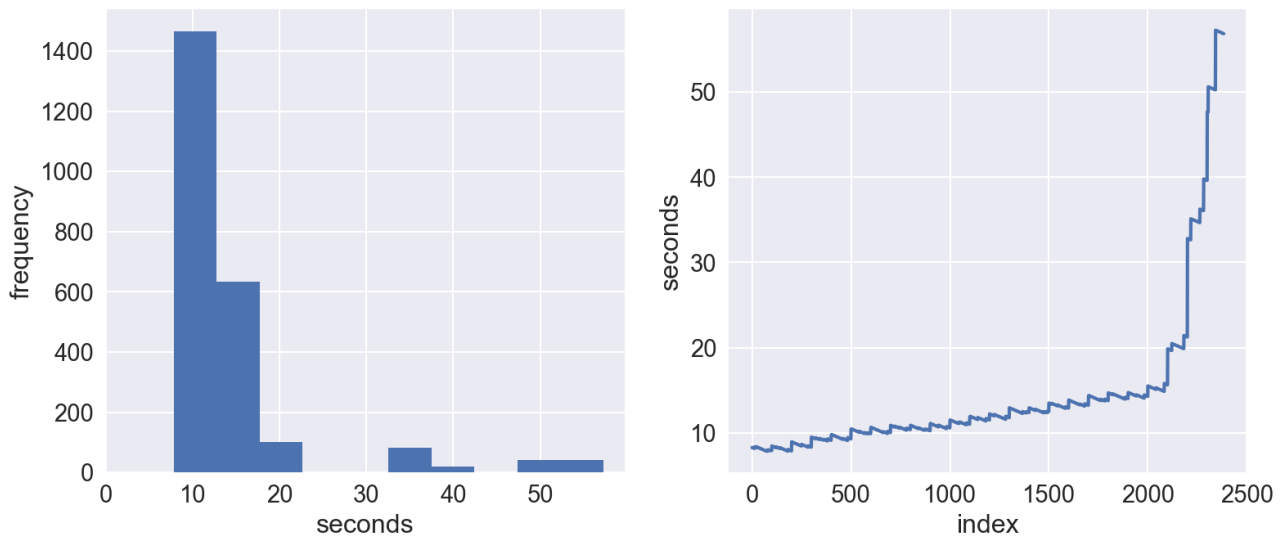


Figure 75: Queuing problems for streaming to database with one output adapter - delay time

7.2 Work with Manufacturers for Device Related Issues and Bottlenecking

PSL

Some problems with the correct configuration have been experienced. An issue happened when the low voltage analog input was used for the +/-16Volt analog output. It is not possible to use the high sensitive analog inputs together with the PMU functionality of the device. Another still open issue is the low frequency oscillations on top of voltage magnitudes.

Artemes

The PMU standard has been adapted for the experiments to support the new 2011 standard with higher reporting rates. This caused some internal signal processing problems especially with timing and sensing. The Figure 76 shows and the problem of 2 seconds time lead and the fact of spiking exactly after on seconds back to the old value. The problems and bugs have been fixed together with decent support, testing and collaboration efforts.

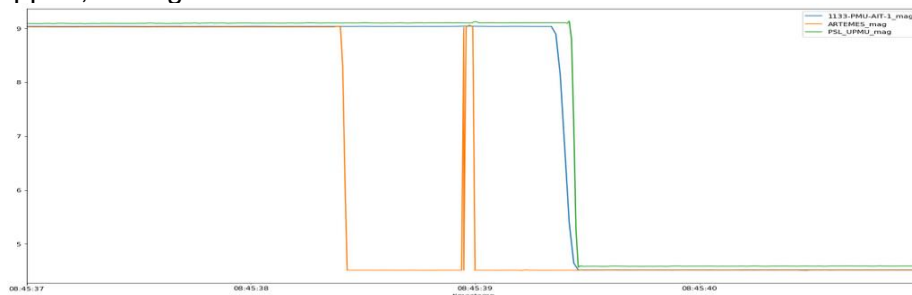


Figure 76: 2 Seconds time lead for Artemes device

Siemens

The Siemens RuggedCom Switch RGS2488 was used as a PTP time source. It was only after tracing

the network communication and with help of the support that it has been identified that the PTP used TAI time base incorporates leap seconds and differs from the UTC based PMU time stamping. Even UTCOffset parameters and didn't change the fact that the Opal-RT driver acting as PTP slave was not able to alter the time offset. In a post-processing step this has been corrected for analysis.

Opal-RT

Setup and configuration for real-world PTP synchronization was a complex tasks. Configuration and tuning of models was also complex in connecting signals and achieving synchronization with the simulation and FPGA based hardware. Simulation stability prone to some model loading and resetting problem.

7.3 Established, ongoing and future collaborations

- **PSL:** The commercial available PMU device is a measure for the industry and opens up many applications in the distribution network. The project gained a lot of insight in using high precision and reporting PMUs for various experiments. Further work on the issue with the low frequency overlay are expected.
- **Artemes:** The Austrian based company lend the PQ/PMU device which we used for all the experiments. We are very thankful for the strong support of helping setting up the environment, extending the software for higher reporting rates and fixing issues which popped up. It was a mutual benefit for all participants. Potential tests and benchmarks on the extended processing software are planned
- **Oregano:** With the Vienna based provider of high precision PTP oscillator cards which is used by OpalRT time synchronization kit it was made possible to achieve the projects objectives. Strong support and providing a IRIG-B source at the beginning was very helpful and we are very thankful for the collaboration.
- **Opal-RT:** Mutual understanding and support, as well as feedback on possible issues and potential applications have been reached. Sharing of models and knowledge, as well as support on PMU C37.118 driver have been thankfully received and well appreciated.
- **Siemens:** With the support of Siemens by lending the RuggedCom PTP source, it was possible to conduct the experiments and finally establish a UTC/TAI synchronized simulation.
- **TU-Vienna:** Due to the experiments with the validation testbed it was possible to also collaborate with the Technical University of Vienna on communication aspects and use the Arbiter PMU device also for some experiments. Further collaborations are planned.

7.4 Open Issues and Future Works

It was intended to focus on real-time processing of data streams in order to be able to evaluate potential requirements and applications based on PMU for distribution systems. Hardware-in-the-loop (HIL) and Software-in-the-loop (SIL) setup and configuration, device configuration and operation as well as modelling and simulation were delaying some of the data analytics work planned to be done.

The FSU User group will submit for the project 4D-Power as part of the 3rd call of TA EriGRid. The project will propose to continue with different open issues presented and addressed in this report such as modeled DER power electronic inverters or actual inverters that may be integrated in the model for studying the DER inverter interdependency and interoperability under different scenarios. Preliminary options are (a) Opal-RT based inverter (b) Real Inverter with HIL interface and/or (c) Typhoon HIL based inverter simulation.

Additionally, the User group will propose to continue simulating different power systems scenarios to create a data repository for power systems applications. While 3D-Power was able to provide a fully synchronised phasor measurement network, more simulation sequences are needed for Event Detection, Topology Detection, Inverters Health Monitoring, DER Integration Studies , State Estimation, and other power systems issues.

7.5 Dissemination Planning

The expected outcomes of this research project including but not limited to:

- (1) Building a validation framework to characterize the interdependency and interoperability of power electronic inverters using synchrophasor devices (e.g. Micro-PMUs or PMUs).
- (2) Explore the impact of time synchronized measurements in distribution networks on event detection.
- (3) Develop a testbed for validating machine learning based methods for diagnostics using spatiotemporal data stream from the HIL and SIL simulations.
- (4) Joint publication, seminars and organizing a workshop in an IEEE PES conference such as PESGM, PowerTech and PSCC in 2018 as well as input for ongoing reports in IEEE working groups and task forces.

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18. D. I. Kim, T. Y. Chun, S. H. Yoon, G. Lee, and Y. J. Shin, "Wavelet-Based Event Detection Method Using PMU Data," *IEEE Transactions on Smart Grid*, vol. 8, no. 3, pp. 1154–1162, May 2017.
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9 Annex

9.1 Annex Database Connectivity (OpenPDC and PostgreSQL)

OpenPDC ADO output adapter

The following connection string has been configured in order to be able to connect to PostgreSQL database via ADO adapter:

PostgreSQL

```
TableName=timeseriesmeasurement; IDFieldName=signalid; TimestampFieldName=timestamp;
ValueFieldName=value; DbConnectionString={Server=10.101.11.240; Port=15432; Database=openpdc;
User Id=openpdc}; InputMeasurementKeys={...}; DataProviderString={AssemblyName={Npgsql,
Version=0.0.0.0, Culture=neutral, PublicKeyToken=5d8b90d52f46fda7};
ConnectionType=Npgsql.NpgsqlConnection; AdapterType=Npgsql.NpgsqlDataAdapter}
```

CSV

```
FileName=D:\3D-Power\output\test_arbiter.csv; InputMeasurementKeys={...}
```

PostgreSQL Database

The following SQL query creates a new table in the openpdc table where timeseries measurements are streamed into from OpenPDC:

```
-----
-- NEW table
-- and created timestamp for latency analysis
-- NOTE: bigint not working for timestamp
-- NOTE: increase sequence numbering for each entry
-----
-- Table: timeseriesmeasurement

-- DROP TABLE timeseriesmeasurement;

CREATE TABLE timeseriesmeasurement
(
    id bigserial NOT NULL,
    signalid uuid NOT NULL,
    "timestamp" character varying(24) NOT NULL,
    value real NOT NULL,
    created timestamp with time zone default (now() at time zone 'utc'),
    CONSTRAINT pk_id_exp1 PRIMARY KEY (id)
)
WITH (
    OIDS=FALSE
);

ALTER TABLE timeseriesmeasurement
    OWNER TO postgres;
GRANT ALL ON TABLE timeseriesmeasurement TO postgres;
GRANT ALL ON TABLE timeseriesmeasurement TO public;
GRANT ALL ON TABLE public.timeseriesmeasurement_id_seq TO public;
```

Column 'created' inserts the actual timestamp of the PC system clock when the row is created. This allows for additional timing analysis.

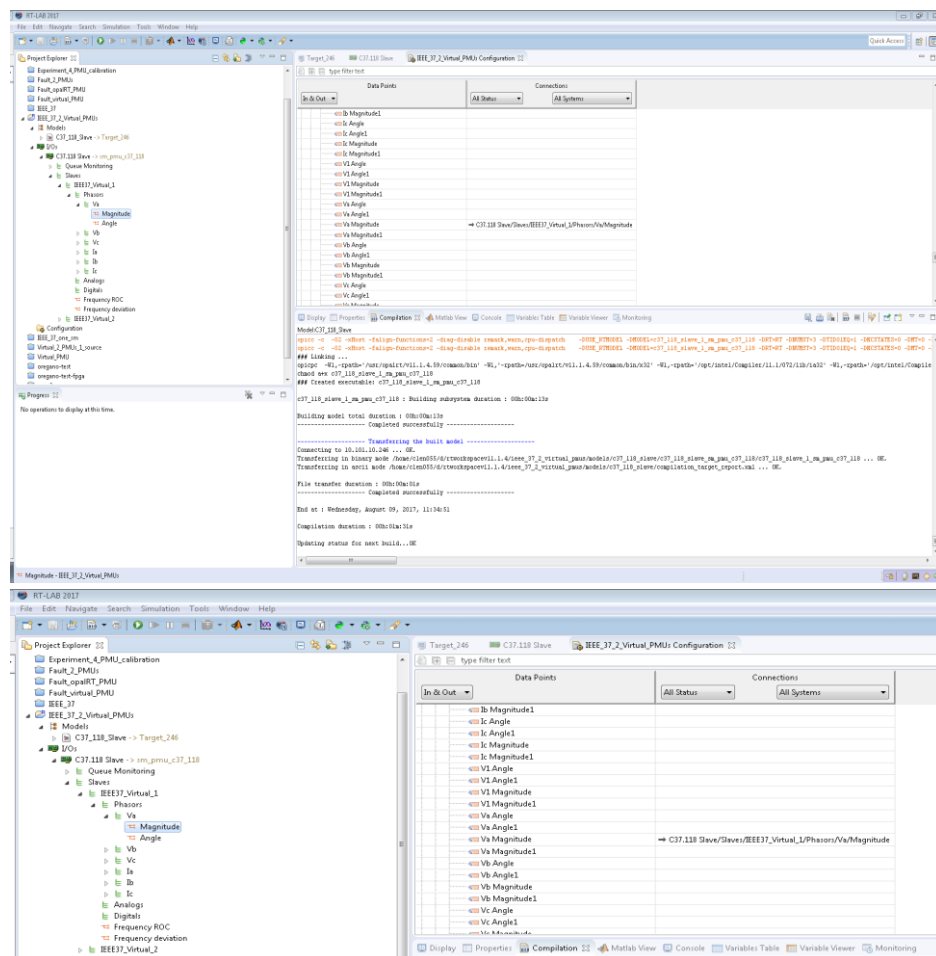
Column 'timestamp' hold the String value of the timestamp, since Epoch time couldn't be converted to SQL timestamp when the experiment took place. Post-processing step for timestamp conversion is done with the following script:

```
-----
-- CONVERT datetime to new table
-- Note: used SS.MS before which might truncate ms info
-----

ALTER TABLE timeseriesmeasurement
ALTER COLUMN timestamp
TYPE TIMESTAMP WITH TIME ZONE
USING to_timestamp(timestamp, 'dd-Mon-yyyy HH24:MI:SS.MS');
```

9.2 Annex PMU use in Opal-RT

To configure the PMU I/Os, drag the parameters to the Configuration tab as shown. Assign each parameters to its corresponding Input Port.



RTLab Configuration of virtual PMU (C37.118 slave) - connecting signals via drag and drop from I/Os → C37.118 Slave to Configuration → In & Out

Synchrophasors for Distribution, Microgrids: PQube® 3 MicroPMU



0,001° & 2 PPM resolution for research projects on distribution grid, microgrid stability

Synchrophasors measure the angle between voltages, and currents, at different physical locations on a grid. Traditionally, synchrophasors have been used to investigate the stability of transmission grids. Distribution grids have much tinier angle differences – too small, and changing too rapidly, to resolve with traditional transmission-type Phasor Measurement Units (PMU's).

Dispersed generation (photovoltaics, fuel cells, battery storage, small wind turbines) on the distribution grid has raised questions about stability of the distribution grid – questions that can be answered with synchrophasor measurements.

The U.S. Department of Energy's Advanced Research Project Agency funded a US\$4 million project to adapt the new PQube 3 into the most precise synchrophasor instrument ever made, with 100 times the resolution of traditional transmission-type PMU's.

The PQube 3 MicroPMU is ideal for research projects that need ultra-precise synchrophasor measurements for investigating stability and impedance questions on distribution grids and microgrids.



PQube 3 MicroPMU Highlights

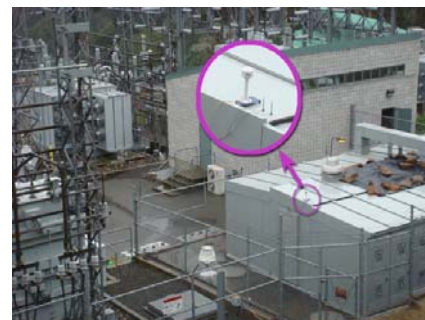
- **0,001° resolution** on voltage and current phase angles, **2 PPM resolution** on voltage and current magnitudes (short term).
- Connects directly to any world-wide power grid voltage: 16.67/50/60/400 Hz, 100V ~ 690V, single-phase or three-phase.
- Fully supports PT's (up to 100kV) and CT's (up to 6 000 amps)
- Ethernet connection – HTTP web page, FTP file downloads and uploads, IEEE C37.118 streaming
- Fully compatible with OpenPDC, the standard phasor data concentrator software.
- **Reference instrument for University of California at Berkeley's Quasar synchrophasor research software, optimized for synchrophasor research on distribution and microgrids.**
- Built-in instrument power for 24-48VDC, 24VAC, and Power-over-Ethernet, with 10-second supercapacitor backup. Optional plug-in modules for 100V-240V power, 30-minute UPS.
- 3 voltage and 3 current angle-magnitude pairs reported 2 times per cycle (100/sec at 50 Hz, 120/sec at 60 Hz)
- Measurement data is recorded in on-board 30 day buffer – tolerates complete loss of communication channel with no loss of research data
- Patent-pending calibrated GPS antenna/receiver is fully electrically isolated for safety – absolutely no electrical connection between GPS antenna/receiver and PQube 3 MicroPMU. Cable is entirely digital, so length is not important.
- Tiny PQube 3 footprint. Can be snapped into electrical panels, distribution poles, pad-mount transformers
- UL Listed, CE-marked, fully certified for emissions and immunity, temperature stability, and more.
- Platform is 100% compatible with Class A Power Quality recorder, Class 0.2% Energy recorder – just upload firmware.

U.S. Government ARPA-E Research Project on Micro-Synchrophasors

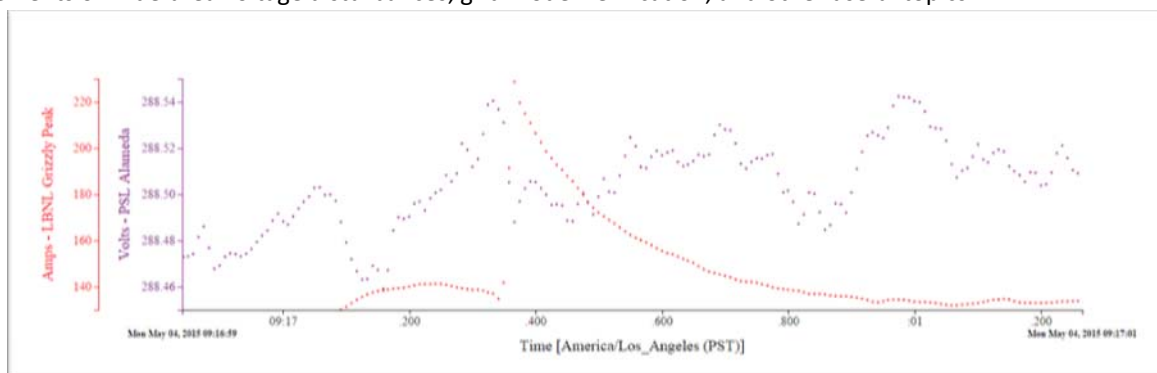
(Award No.DE-AR0000340)

The U.S. Department of Energy's ARPA-E project is a 3-year, US\$4 million effort by Power Sensors Ltd, CIEE, Lawrence Berkeley National Lab, and the University of California at Berkeley.

The project is installing about 100 PQube 3 MicroPMU's at LBNL's substations and U.S. utility distribution grids. Every day, several gigabytes of research data flows from the MicroPMU's to a server at UC Berkeley, where an astonishing new open-source software package called Quasar makes the data available to researchers through a web interface.



Researchers use measurements from the PQube 3 MicroPMU to investigate grid impedances, grid stability, synchronized measurements of wide-area voltage disturbances, grid model verification, and other useful topics.



A small current surge at Lawrence Berkeley National Lab lowers the voltage at PSL, 40 km away. The microPMU's precise time synchronization and ultra-high resolution is necessary to see these kinds of relationships in a distribution grid. Data see here through the web interface of U.C. Berkeley's open-source Quasar software.

PT's, CT's and Micro-Synchrophasors

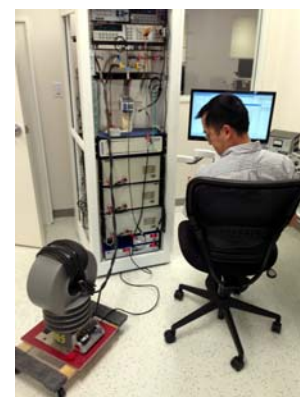
Those familiar with distribution grid Potential Transformers and Current Transformers will quickly recognized that the accuracy specifications of the PQube 3 microPMU greatly exceed the accuracy specifications of PT's and CT's on distribution grids.

The ARPA-E project found two solutions to PT and CT accuracy.

First, the errors in distribution PT's and CT's tend to be large but stable. So measurement differences (over a short time interval) at an individual location contain useful information, even at resolutions that are far beyond the accuracy specifications of the PT's and CT's. Research based on measurement differences may be the best approach.

Second, due to their stability over time, it is possible to calibrate PT's and CT's for magnitude and angle – often to more than an order of magnitude better than original OEM specifications.

The ARPA-E project selected Power Standards Lab (www.PowerStandards.com) to perform these distribution-level PT and CT calibrations.



MicroPMU Data Sheet Revision 1.2

Power Sensors Ltd. 980 Atlantic Ave, Alameda CA 94501, USA

Tel ++1-510-522-4400 Fax ++1-510-522-4455 www.PowerSensorsLtd.com

Micro PMU Specifications

The PQube 3 MicroPMU is a research-grade instrument. The specifications below are given for guidance in developing your research project, and are subject to change. Please contact Power Sensors Ltd to discuss your planned research project with an experienced distribution grid MicroPMU engineer.

PHASOR MEASUREMENTS

Phasor Measurement Method	512 samples per nominal 50/60 Hz cycle, phase-locked to calibrated GPS PPS signal Patent-pending phase-angle calibration methods Digital process similar to IEEE C37.118, but with filters optimized for distribution and microgrid measurements
TVE (Total Vector Error)	Typical TVE $\pm 0,01\%$ Typical short-term TVE stability for differential measurements: $\pm 0.002\%$
Streaming output	100/120 frames per sec – 3 voltage channels , 3 current channels
On-board Storage	8 gigabytes – typically sufficient for more than 1 month of measurements

MAINS MEASURING CHANNELS

Amplitude resolution	0,0002%FS (2 PPM)	(noise floor – useful for short-term difference measurements)
Amplitude Accuracy ($\pm\%$ rdg + $\pm\%$ FS)	Typical : Factory pass/fail: Guaranteed:	$\pm 0,010\%$ (120V - 600VAC L-N) $\pm 0,025\%$ $\pm 0,050\%$ (10VAC - 750VAC L-N).
Angle resolution	0,001°	(noise floor - useful for short-term difference measurements)
Angle Accuracy	Typical : Factory pass/fail: Guaranteed:	$\pm 0,003^\circ$ $\pm 0,005^\circ$ $\pm 0,010^\circ$ 1 Standard Deviation
Measurement Channels	3x Line-to-Earth voltage, 3x Line currents. (Hardware fully supports 4 voltage channels, 4MHz sampling, 8 current channels for Class A Power Quality Recording and Class 0.2% Energy Recording firmware)	

Order Information

Part No: PQ3P-mPMU-0000-00 (includes MicroPMU, PM2 and GPS1-MS1 modules)

Email: sales@powersensorsltd.com

Web site: www.pqube3.com



measurement competence centre
www.artemes.org

24 BIT RESOLUTION



Power Analyser
AM-10-PA2

2 M SAMPLES PER SECOND

Power Analyser AM-10-PA2



- PQ + PMU + PFR + PM + DFR
- 24 bit resolution
- 2M samples/sec. fault recorder and data streaming
- measurements and analyses via web browser
- **ARTEMES** CLOUD interface
- online FFT 2-9 kHz (200 Hz-package) and 8-150 kHz (2 kHz-package)
- 4 voltages and 5 currents
- oscilloscope even on a smart phone
- GPS-synch.

The **ARTEMES** Power Analyser AM-10-PA2 is a strong 24-bit instrument and combines the tasks of energy consumption and power quality analysis with the state of the art possibilities of modern telecommunication technology. Beside the operation via web interface with e.g. smartphone or PC also all post processing opportunities are available via the worldwide web - as a browser application directly on the instrument, on a dedicated server or by using the **ARTEMES** CLOUD service.

Beside classical energy and power analysis according to EN 50160 the instrument offers the new frequency bands up to 9 kHz or 50 kHz and with the option AM-10PA2-Opt 2 MS even up to 150 kHz. Flicker emission and evaluations according to IEC 61400 also belong to the enhanced functionality of the analyser.

Also in terms of measurement connections the AM-10-PA2 offers various possibilities. Beside the single-phase connection and the two-phase connection, three-phase star and delta connection are available as well. In addition, the transformer saving connections Aron and V have already been included. With the standard model AM-10-PA2 even low voltage grids including neutral line and earth conductor can be measured.



energy and power quality
EN 50160, IEC 61000-2, IEC 61000-3, IEC 61400
IEC 61000-4-30 class A
LAN, WLAN and GSM
web technology for operation and post processing via browser
phasor measurement unit

Measurement Functions

Overview - Online

showing a recorder with actual data,
as vectorscope and as numeric values

recording mode or simulation mode
RMS, AVG, Min, Max (10 period values,
adjustable)

RMS, AVG (period values, adjustable
overlapping and duration)

U, I, P, Q, S, D, PF, unbalance, cos phi

flicker, flicker emission

IEC 61000-4-15: 2012 class F1

frequency

symmetrical components

IEC 61000-4-30: 2008 class A

and IEC 61400-21: 2008



Oscilloscope - Real-Time

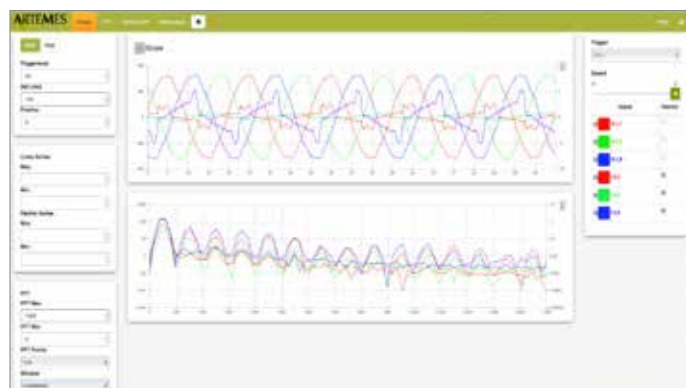
real time-scope in the web browser

voltage and current

scaling left or right, adjustable

FFT with filters:

HANN, HAMMING, RECTANGULAR, BLACK-
MAN, BARTLETT, BARTLETHANN, COSINE,
GAUSS; LANZOS, TRIANGULAR



FFT - Real-Time

voltage, current, power, phase angle

phase and line voltage

bar diagram and numeric values

IEC 61000-4-7: 2009 Class 1

interharmonics

frequency bands 2-9 kHz in 200 Hz-groups

frequency bands 8-50 kHz in 2 kHz-groups or
frequency bands 8-150 kHz (AM-10-PA2-H)





Dynamic Reports

diagrams of individual channels

predefined templates

zoom-in and zoom-out possibilities



Static Reports

report generator to define complete reports,
predefined reports according to:

EN 50160: 2011, energy (ISO 50001)

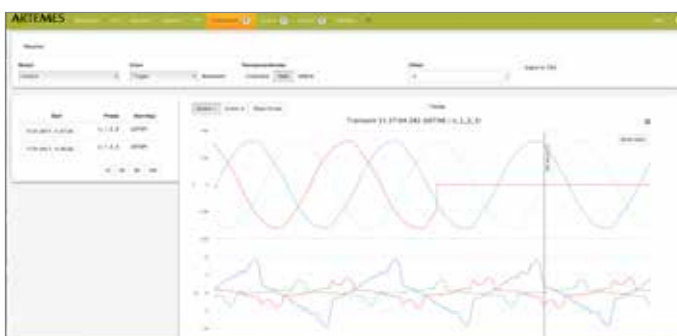
IEC 61000-2-4: 2002

IEC 61400-12-1: 2007
(option AM-10-PA2-Opt Wind)

IEC 61400-21: 2008
(option AM-10-PA2-Opt Wind)

individual diagrams

event statistics



Transient Fault Recording and Data Streaming

fast transient recorder (TFR)

disturbance recorder (DFR)

event recorder EN 50160: 2011

IEC 61000-4-30: 2008

zoom-in and zoom-out possibilities

statistical evaluation: DisDip/Unipede,
CBEMA, events according to EN 50160: 2011

2 MSamples/sec. (AM-10-PA2-H)

data streaming with full sampling rate continuously
possible

Technical Data

		AM-10-PA2	AM-10-PA2-H
voltage inputs		4	4
	range	+/-1.600V	+/-1.600V
	accuracy (on value, 5-100% of range)	0,1%	0,1%
current inputs		5	5
	clamp 5A (order code: AM-CL-5)	AC	AC
	range	5A	5A
	accuracy	0,5%	0,5%
	Rogowski coil (order code: AM-CL-Rog10K)	AC	AC
	range	10 / 100 / 1k / 10 kA	100 / 1k / 10 kA
	accuracy	1%	1%
	DC Clamp (order code: AM-CL-300DC)	AC + DC	AC + DC
	range	150A / 300A peak	150A / 300A peak
	accuracy	0,5%	0,5%
	direct current input (included)	AC + DC	AC + DC
	range	5A	5A
	accuracy	0,5%	0,5%
	other clamps (https://store.artemes.org/zubehoer/stromsensoren/)	on request	on request
measurement parameters	resolution	24 bit	24 bit
	sampling rate	up to 100 kSamples/sec. per channel	up to 2 MSamples/sec per channel
	bandwidth	70kHz	500kHz
additional inputs	low voltage +/- 10V	4 channels / each 144 kSamples/Sec	4channels / each 2 MSamples/sec
measurement values	phase voltages, neutral voltage	✓	✓
	line voltages	✓	✓
	phase currents, neutral current, earth current	✓	✓
evaluation online	web interface	✓	✓
	recorder - diagram and actual values	✓	✓
	scope	✓	✓
	FFT	✓	✓
data processing	flexible report generator on web	✓	✓
	EN 50160	✓	✓
	IEC 61000-2-4 class 1,2,3	✓	✓
	IEC 61400-12-1	option: AM-10-PA2-Opt Wind	option: AM-10-PA2-Opt Wind
	IEC 61400-21	option: AM-10-PA2-Opt Wind	option: AM-10-PA2-Opt Wind
	ISO 50001 energy report	✓	✓
data storage	internal SSD (not rotating)	256 GB	256 GB
	ARTEMES server	licence included (max 3 measurement clients)	licence included (max 3 measurement clients)
	ARTEMES CLOUD	option: AM-10-CLOUD	option: AM-10-CLOUD
communication ports	USB 2.0 / 3.0	2 / 1	2 / 1
	RS485	1	1
	LAN	1	1
	WLAN	✓	✓
	GSM	option: AM-10-PA2-Opt GSM	option: AM-10-PA2-Opt GSM
	CAN	✓	✓
	GPS	option: AM-10-PA2-Opt PMU	option: AM-10-PA2-Opt PMU
EMC	IEC 61326-1 industry	✓	✓
	IEC 61000-4-4 surge, IEC 61000-4-5 burst	4 kV	4 kV
	isolation (AC, 1 min)	6 kV	6 kV
safety	IEC 61010-1	✓	✓
dimensions	width x height x length	390 / 105 / 310 mm	390 / 105 / 310 mm
power supply	AC - V/f	85-264 VAC / 47-63 Hz	85-264 VAC / 47-63 Hz
	DC option instead of AC (AM-10-PA2-Opt DC)	6-36 V DC	6-36 V DC
	internal battery	3 hours	3 hours
power consumption	VA	30 VA	30 VA
weight	kg	5,7 kg	5,7 kg
temperature range	operation	-20°C to +60°C	-20°C to +60°C
	storing	-20°C to +80°C	-20°C to +80°C
order options			
AM-10-PA2-Opt Wind		software option	software option
AM-10-PA2-Opt PMU	wind report according IEC 61400-12-1 and IEC 61400-21, for PMU - phasor measurement add-on including software according IEEE C37.118 and GPS input, for AM-10-PA2	software option	software option
AM-10-PA2-Opt GSM	GSM modem, internal, for AM-10-PA2	hardware option	hardware option
AM-10-PA2-Opt DC	DC power supply instead of AC, without battery	option only available with new instrument	option only available with new instrument
AM-Cloud-1	rent cloud space per month on ARTEMES server	online option	online option

Accessories

ARTEMES CLOUD

AM-CLOUD

ARTEMES CLOUD for safe data storage and worldwide access via the web



external antenna for GSM / WLAN module

AM-10-antenna

external antenna with magnetic bottom



clamp 5 A

AM-CL-5

precise clamp for small currents with Mumetal, from mA to 5 A

Rogowski coil 10.000 A

AM-CL-Rog10k

flexible coil for measuring on bus bars and cables ranging from A to 10 kA



DC clamp 300 A

AM-CL-300DC

current clamp for measuring direct and alternating current, very precise



carrying case

AM-10-TP

carrying case as protection against water, dust and vibration, offers space for measurement instrument and accessories, rollers and extendible handle



screw adapter, 5 black + 5 blue

AM-screwadapter

screw adapter for leads 4 mm

leadfuse for leads 4 mm, 3 black

AM-Leadfuse



magnetic adapter, 5 black

AM-magnetic adapter

alligator clamp, 5 black

AM-alligator clamp



set of voltage leads 4 mm

AM-10-leads

5 leads black, 2 m
5 leads blue, 2 m



For further accessories and additional information please visit store.artemes.org.

Measurements for Power Applications

System Integration and Monitoring Solution

convenient generation
of reports

data compression and data base solutions
for easy and individual use

cloud solutions for continuous and
distributed measurement tasks

automated test sequences
for repeated testings

energy management systems
for commerce and industry

load profile measurings and
multi-channel power analyses

power quality analyses according
to defined standards

qualification of power plants
with renewables

software and hardware solutions
for individual test bench systems

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www.artemes.org



Model 1133A Power Sentinel™

with

EnergyDSA™

Digital Signal Analysis

- Synchronized via GPS
- Revenue Accuracy: 0.025%
- Power Quality: Harmonics, Flicker, Interruptions
- Phasor Measurements for Stability & Flow Analysis
- System Time & Frequency Deviation
- Internal Data/Event Logging
- Two Year Warranty



Specifications subject to change without notice.

Take a bite out of power problems and lost revenue with the Arbiter Systems®, Inc. Model 1133A Power Sentinel™ multifunction measurement unit. Combining six functions into one compact, 44 mm (1.75 in.) tall unit, the Model 1133A offers unprecedented accuracy, flexibility, and features.

Revenue Metering

With utility deregulation, accurate energy measurement is increasingly important. For the first time, Arbiter Systems®, Inc. combines state-of-the-art measurement techniques, proprietary EnergyDSA™ technology, and the accurate, cost-effective time synchronization of our precision GPS clock products in the Model 1133A Power Sentinel™ multifunction measurement unit. The Model 1133A brings laboratory performance to the substation, delivering unprecedented revenue accuracy of 0.025% under most conditions. Compare this to traditional watt-hour meters which are limited to an accuracy of no better than 0.1% in the lab, with increasing errors as conditions depart from the ideal (see figures next page).

The Model 1133A measures revenue more accurately than any meter ever before. The difference between 0.025% and 0.1% is surprising. With many transmission lines wheeling thousands of megawatts of power, the difference in accuracy of 0.075% translates to hundreds of thousands of dollars over a year's time. Even at lower power levels, improved accuracy yields significant revenue enhancement.

Power Quality Monitoring

The Model 1133A's features only begin with its outstanding accuracy in energy measurement. Our proprietary EnergyDSA™ digital signal analysis algorithms provide you with more information than ever before. You

can measure harmonics and K-factor, flicker, interruptions, and log data by time interval, or record out-of-limit events with time of occurrence. You can set limits on any quantity. Also, an alarm contact may be activated, or a dial-up modem call initiated.

System Control and Monitoring

The Model 1133A measures system (absolute) phase angle, system frequency deviation, and system time deviation. See the white paper "Absolute Phase". Phasor measurement data in accordance with IEEE Standard 1344, at a rate of 20 per second, is standard. This data allows for sophisticated, real-time monitoring and control of stability and power flow. These measurements are made possible with the Model 1133A's internal GPS synchronization.

Synchronization

A built-in Global Positioning System (GPS) satellite receiver synchronizes your Model 1133A within 1 µs of Coordinated Universal Time (UTC), which may also be converted to your local time. With synchronization, revenue data can be accumulated in intervals as short as one minute. Other substation equipment, such as digital fault recorders, solid-state relays, remote terminal units, and programmable logic controllers, may be synchronized with the standard IRIG-B unmodulated time code output. This output has sufficient power to drive numerous loads, for example, 40 Schweitzer™ SEL-321 relays.

Data and Event Logging

Thirty-two megabytes of flash memory are standard. This nonvolatile memory can record revenue data, power quality, internally detected faults, alarms, events, and external events. Four optically-isolated event inputs may be used to monitor external events.

Model 1133A

Technology

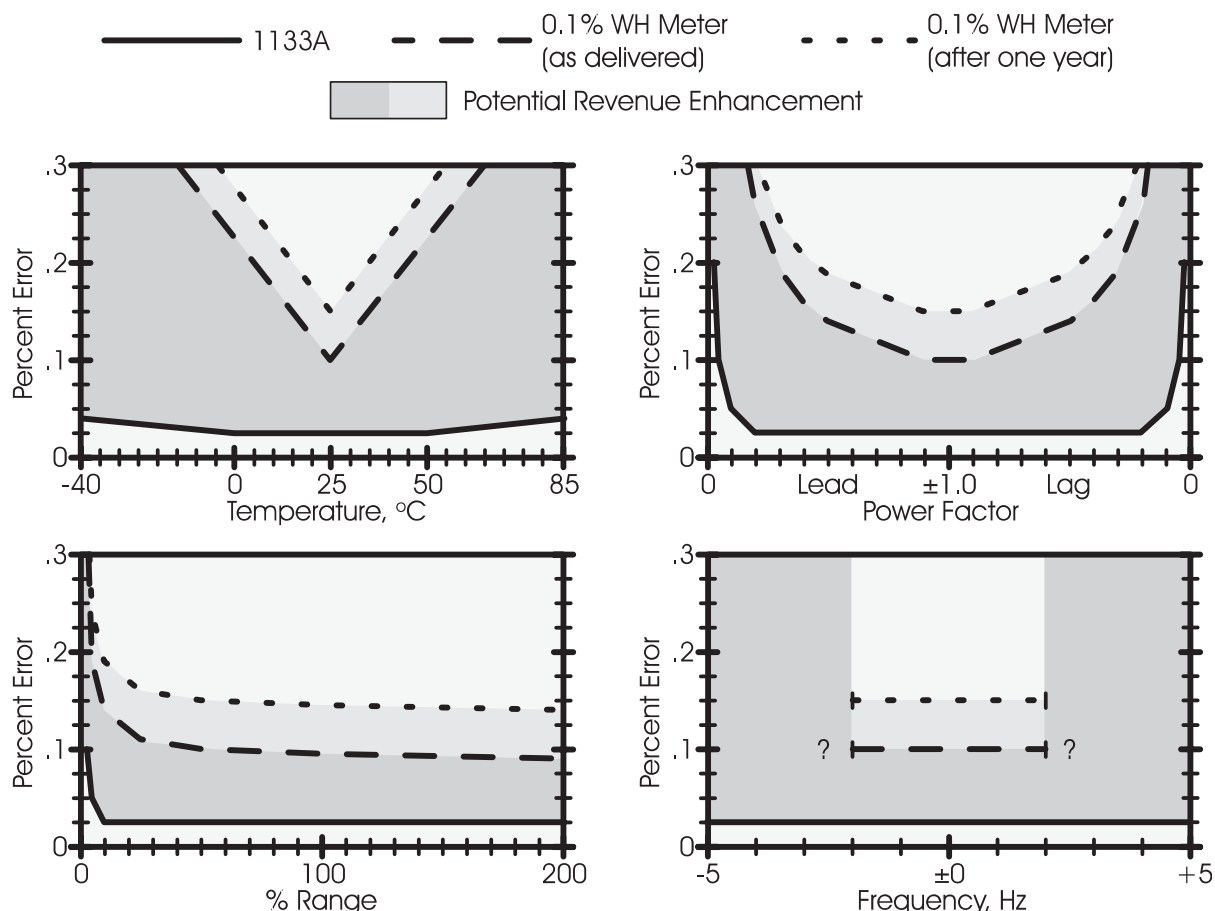
Many years of experience making accurate ac signal measurements and providing state-of-the-art timing equipment is the heart of the revolutionary performance provided by the Model 1133A Power Sentinel™. For example, built-in, real-time autocalibration eliminates many sources of error that would otherwise degrade accuracy. This process measures the output of an internal calibration source, time-multiplexed along with the input signals. A complete set of calibration measurements is executed once each second. By passing the calibration signal through the same measurement circuits as the input signals, drift in component values, temperature sensitivities, and many other errors are completely removed.

This design approach minimizes the number of components that can affect accuracy. Therefore, we can afford to use the best available components in those critical applications. Accuracy is (in a simplified fashion) the sum

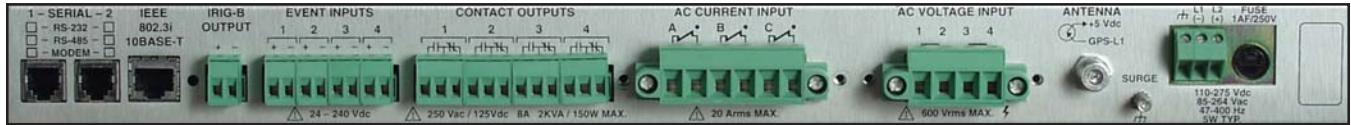
of the imperfections of all of the components that can degrade performance; therefore, by using a small number of highly accurate parts, accuracy is maximized. This is a simple idea, but implementing it properly requires years of experience. See the white paper "What is Accuracy?".

Of course, all of the accuracy in the world means nothing if the resulting signal cannot be processed with equal or better performance. Our proprietary EnergyDSA™ Digital Signal Analysis, an optimized version of the PowerDSA™ analysis developed over the last decade and in use in our Model 931A Power System Analyzer for several years, delivers this performance. We have optimized EnergyDSA™ analysis for the specific requirements of revenue metering and on-line power analysis: speed, accuracy and low cost. Our EnergyDSA™ algorithms measure signals with accuracies characterized not in percent, but in parts per million.

1133A vs. Typical 0.1% Watthour Meter



Model 1133A Specifications



Input

Configuration

3 ϕ	3-element, 2½-element, 2-element, selectable
1 ϕ	2-element, 1½-element, and 1-element, selectable

Voltage

Range (3 ϕ /1 ϕ)	0 to 69, 120, 240, or 480 Vrms, selectable (phase-to-phase for 2 element; phase-to-neutral for 2½ and 3 element)
Overrange	88, 175, 350 or 700 Vrms, nominal

Current

Range (3 ϕ /1 ϕ)	2.5, 5, 10, or 20 Arms, selectable, per element
Overrange	2.9, 5.9, 11.7, or 23.5 Arms, nominal (maximum continuous input current: 20 Arms per element, all ranges)

VA, W, VAR

Range	Product of rated voltage and current ranges and number of elements (2½ (3 ϕ) and 1½ (1 ϕ) element, use 3 and 1, respectively)
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Compensation

CT and PT	Both magnitude and phase compensation, CT with 12 point nonlinear interpolation
Transformer	Both iron and copper compensation

Frequency

Range	45 to 65 Hz, for specified accuracy
Harmonics	To 3 kHz

Input (Continued)

Inputs

Connections	Removable screw-clamp terminal block, accepting 0.2 to 4 mm ² (AWG 24 to AWG 10) solid or stranded conductors
Insulation	400 volts, nominal, to neutral/chassis, surge voltage class III 600 volts, nominal, to neutral/chassis, surge voltage class II Contact factory for more detailed information

Interface

Operator

Status LEDs	Operate (green) Time Set (green) Alarm (red) Fault (red)
Display	2 x 20 character LCD display
Keyboard	8 key for status

Communications

Serial Port 1	RS-232 (1133opt10) RS-422/485 half-duplex (1133opt11) Modem (V.34bis, 33.6k) (1133opt12)
Port 2	RS-232 (1133opt20) RS-422/485 half-duplex (1133opt21) Modem (V.34bis, 33.6k) (1133opt22)
Connectors	RJ-11 modular; two
Ethernet Connector	One, 10Base-T per IEEE 802.3i RJ-45 modular

Protocols

Proprietary	PowerSentinelCSV (PSCSV)
Standard	DNP 3.0, MODBUS, PQ-DIF, IEEE C37.118

Model 1133A Specifications

Interface (Continued)

Programmable Contact Outputs

Type and Number	Form C (SPDT), four (4) sets
Connections	Pluggable 12-pole, 5 mm terminal strip, with four, 3-pole mating connectors included
Rating	250 Vac/125 Vdc, 8 A maximum, 2000 VA/150 W maximum Optional KYZ (solid state) contact rating: 240 Vac, 120 mA, 800 mW max.
Isolation	4000 Vrms for 1 minute to chassis Optional KYZ (solid state) contact isolation: 3750 Vrms Input/Output
Functions, Selectable	Programmable Load Control, with preset times or via system interface Fault <i>Fail-safe (faulted with power off)</i> Alarm <i>Fail-safe</i> Out-of-Lock <i>Fail-safe</i> One Pulse per Hour; contacts closed for one minute at top of hour Optional KYZ contacts Other Functions, as required

Event Inputs

Type and Number	Four, optically-isolated 24 to 240 Vdc (may be configured for 5 V logic level)
Connections	Pluggable 8-pole 5 mm terminal strip, with 4, 2-pole mating connectors
Isolation	4000 Vrms for 1 minute to chassis
Resolution	1 μ s

Flash Memory Data Storage

Capacity	32 MB standard; number of records stored depends on data items selected. See Operation Manual for record length and capacity calculations
Data	Selectable from all functions measured and totaled by the Model 1133A; each record is stored with a time tag
Data Retention	Indefinite; no power or battery is required to retain data

Flash Memory Data Storage (Continued)

Storage Rate	Selectable; default is 15 minutes. Other intervals as short as one minute may be selected. Event data stored upon occurrence
Lifetime	100,000 storage cycles minimum

Specifications

Note: Accuracy specifications include all sources of uncertainty. Except as noted, specifications apply for the full operating range, including temperature (-10° to +50° C), line voltage, input range including specified overrange, power factor, input frequency, and drifts over a one-year calibration interval. Specifications assume synchronization to GPS and operation in 3-element mode or in a well-balanced system where imbalance does not degrade accuracy.

Accuracy

Watts, Wh	0.025% of reading, 10% of range or greater and PF > 0.2 0.005% of VA for PF < 0.2
Underrange	0.0025% of range, below 10% of range
VA, VAh	Same as W, Wh except no PF effect
VAR, VARh	Same as W, Wh except replace PF with $(1 - PF^2)^{0.5}$
Vrms	0.02% of reading or 0.002% range, whichever is greater
Arms	0.03% of reading or 0.003% range, whichever is greater
V ² h	0.04% of reading or 0.004% range, whichever is greater
A ² h	0.06% of reading or 0.006% range, whichever is greater
Phase Angle, ϕ	0.01°, phase-to-phase or voltage-to-current, 10% of range minimum
Power Factor	$0.0002 \cdot \sin(\phi)$, 10% of range min.
Harmonics	0.05% THD or 5% of reading, whichever is greater
Frequency	< 1 ppm (0.0001%) of reading, 50 or 60 Hz nominal, plus timebase error
System Phase	0.03° plus [timebase error • 360° • frequency]
System Time	1 μ s plus timebase error
Event Inputs	$\pm 10 \mu$ s (typical)

Model 1133A Specifications

Power Quality

Harmonics Measurement

Standard	Per IEC 61000-4-7, 100 ms overlapping data window
Measurements	THD, K-factor, rms harmonic current and voltage, rms harmonic current and voltage with K-factor compensation (each harmonic magnitude is multiplied by the square of the harmonic number before summing), individual magnitude and phase
Logged Data	Selectable, may be regularly logged or registered; or event-logged when user-specified limits are exceeded

Interruptions

Logged Data	Selectable, may be regularly logged or registered; or event-logged when user-specified limits are exceeded
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Flicker

Standard	Per IEC 61000-4-15, P_{st} and Instantaneous
Logged data	Selectable, may be regularly logged or registered; or event-logged when user-specified limits are exceeded

Limit Alarms

Functions	Upper or lower limits may be set on most measured functions. Limits may also be set on maximum imbalance (ratio of Zero and Negative Sequence Components to Positive Sequence)
Output	Via system interface and display or contact closure

System Control and Monitoring

System Time, Phase and Frequency

System Time	Unlimited accumulation with $\pm 1 \mu s$ resolution
Frequency	7 digits, xx.xxxxx Hz
System Phase	0 to 360° with 0.01° resolution
Effect of DC & Harmonics	None; Rejected by narrow-band digital filtering

System Control and Monitoring (Continued)

Phasors

Standard	Per IEEE 1344, IEEE C37.118, or PSCSV
Rate	Selectable: 1,2,3,4,5,6,10,12,15,20,30,60/sec for 60 Hz or 1,2,5,10,25,50/sec for 50 Hz. Including frequency and df/dt .

Synchronization

General

Tracking	GPS-L1, C/A code (1575.42 MHz); 12 channel (tracks up to 12 satellites)
Acquisition	2 minutes typical
Accuracy	UTC-USNO $\pm 1 \mu s$ (only need 1 satellite with correct position)
Out-of-Lock Indication	Via system interface and status display; optional, via contact closure

Antenna Characteristics

Mounting	0.75 in. NPT pipe thread (1 in. - 14 marine type) mount
Dimensions	77.5 diameter x 66.2 mm (3.05 in. x 2.61 in.)
Weight	170 grams (6.0 oz)
Connections	F-type
Cable	15 m (50 ft) included; longer cables optionally available

Synchronization Output

Type	One; IRIG-B000 or IRIG-B003 per C37.118 (unmodulated or level-shift), 200 mA peak; pluggable 5 mm terminal strip with mating connector, two-pole
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Timebase Error

GPS locked	Less than 1 μs , when locked to at least one satellite with correct position
Unlocked	10 ppm, typical, after being locked for 10 minutes minimum (< 1 second/day unlocked, typical)

Certifications and Approvals

Compliance to IEC-687 International Standard for AC Static Watthour Meter for Active Energy
 Compliance to IEEE C37.118 Standard for Synchrophasors for Power Systems
 Certificate of Conformance to NIST
 CE mark/label and certification

Model 1133A Specifications

Power Requirements

Standard

Voltage	85 to 264 Vac, 47 to 440 Hz or 110 to 275 Vdc, 5 VA typical
Inlet	Terminal strip with fuse; surge withstand per ANSI C37-90.1 and IEC801-4 standard

General

Physical

Size	1 RU (430 mm W x 44 mm H) rack mount or tabletop; 260 mm deep FMS. Rack mounts included 508 x 381 x 203 mm (20 x 15 x 8 in.), shipping
Weight	2 kg (4.5 lbs), net 5.5 kg (12 lbs), shipping

Environment

Temperature	Operating: -10° to +50° C Nonoperating: -40° to +85° C
Humidity	Noncondensing

Options

I/O

Description	Order No.
IRIG-B Input (C37.118 or C37.118.1): Replaces GPS receiver	1133opt07
Port 1:	
RS-232	1133opt10
RS-422/485 half-duplex	1133opt11
Modem (V.34bis, 33.6k)	1133opt12
Port 2:	
RS-232	1133opt20
RS-422/485 half-duplex	1133opt21
Modem (V.34bis, 33.6k)	1133opt22

Power (select only one)

Description	Order No.
Terminal Power Strip, Surge Withstand, 85 to 264 Vac, 110 to 275 Vdc	1133opt03
Terminal Power Strip, Surge Withstand, 10 to 60 Vdc	1133opt04

Options (Continued)

General

Description	Order No.
Mechanical output relays	1133opt05
Solid-State output relays (KYZ)	1133opt06

Accessories

Included

Description	Order No.
Operation Manual	AS0058400
GPS Antenna, pipe mountable	AS0087800
15 m (50 ft) RG-6 Antenna Cable	CA0021315
Mating Connectors, 2-pole, 5 mm (5 ea.)	CN0019202
Mating Connectors, 3-pole, 5 mm (4 ea.)	CN0019303
Mating Connector, Current Input	CN0030006
Mating Connector, Voltage Input	CN0030004
19 in. Rack Mount Kit	AS0028200
Modular DB9 to RJ-11 Adapter, preconfig	AP0007700
RJ-11 Cable Four-pin crossed, 7 ft	CA0023600

Available

Description	Order No.
15 m (50 ft) RG-6 Antenna Cable	CA0021315
30 m (100 ft) RG-6 Antenna Cable	CA0021330
45 m (150 ft) RG-6 Antenna Cable	CA0021345
60 m (200 ft) RG-6 Antenna Cable	CA0021360
75 m (250 ft) RG-6 Antenna Cable	CA0021375
GPS Antenna Mounting Kit	AS0044600
21 dB In-Line Preamplifier ¹	AS0044700
Antenna Grounding Block Kit	AS0048900
GPS Surge Protector	AS0094500
GPS Antenna Cable Splitter	AP0013400
300 m (1000 ft) Roll RG-6 Cable	WC0005000
RG-6 Stripping Tool	TF0013200
RG-6 Type F Crimp Tool	TF0006400
RG-6 Type F Male Crimp-on Connector	CN0027700
300 m (1000 ft) Roll RG-11 Cable	WC0004900
RG-11 Stripping Tool	TF0013300
RG-11 Type F Crimp Tool	TF0006000
RG-11 Type F Male Crimp-on Connector	CN0027800
Modular DB9 to RJ-11 Adapter, unconfig	AP0007900
Modular DB25 to RJ-11 Adapter, unconfig	AP0008000
19 in. Rack Slide Kit	AS0033100
24 in. Rack Mount Kit	AS0055600

¹ Used for cable length greater than 75 m (250 ft)

Product description

Non-controlled, advanced utility grade, high density layer 2 Ethernet Switch
RUGGEDCOM RSG2488NC is a RuggedRated fully managed Ethernet switch; 56-bit Encryption; up to 28 non-blocking ports; configured as: 10/100/1000TX copper, 100FX or 1000SX fiber. Support six 4-port modules plus two 2-port modules Mixture of fiber optic or copper Gigabit ports with up to 28 Gig Ethernet ports; 40 °Cel to +85 °Cel operating temperature (fanless)



Figure similar

Product type designation	RUGGEDCOM RSG2488NC
Transmission rate	
Transfer rate	10 Mbit/s, 100 Mbit/s, 1000 Mbit/s
Number of ports / maximum	28; Number of ports depending on configuration
Interfaces / others	
Number of electrical connections	
• for operator console	1
• for management purposes	1
Type of electrical connection	
• for operator console	RS232
• for management purposes	RJ45
• for power supply and signaling contact	10-pole terminal block, screwable or plugable, screw contact
Supply voltage, current consumption, power loss	
Product options / wide range power supply	Yes
Product feature	

• Modular power supply	Yes
• Hot-swappable power supply	Yes
Type of voltage supply / redundant power supply unit	Yes
Supply voltage	
• at AC / rated value	88 ... 264 V
Supply voltage / 1 / Rated value	24 V
• Supply voltage / 1 / rated value	13 ... 36 V
• Type of voltage / 1 / of the supply voltage	DC
Supply voltage / 2 / Rated value	48 V
• Supply voltage / 2 / rated value	38 ... 72 V
• Type of voltage / 2 / of the supply voltage	DC
Supply voltage / 3 / Rated value	
• Supply voltage / 3 / rated value	98 ... 300 V
• Type of voltage / 3 / of the supply voltage	DC
Supply voltage / 4 / Rated value	
• Supply voltage / 4 / rated value	85 ... 264 V
• Type of voltage / 4 / of the supply voltage	AC
Supply voltage / at DC	
• rated value	98 ... 300 V
Product component / fusing at power supply input	Yes

Permitted ambient conditions

Ambient temperature	
• during operation	-40 ... +85 °C
• Note	A maximum operating temperature of +85 °C is permissible for a duration of 16 hours
Operating condition / fanless operation	Yes
Protection class IP	IP40

Design, dimensions and weight

Display version / LED panel mounted on the front or on the rear side	Yes
Design	19" rack
Number of modular height units / relating to 19-inch cabinet	1
Number of slots	8
Width	442.4 mm
Height	44 mm
Depth	376 mm
Net weight	8.6 kg
Product feature / conformal coating	optional
Material / of the enclosure	Aluminum
Mounting type	Mounting Kits for different mounting options
• 19-inch installation	Yes

- 35 mm DIN rail mounting
- wall mounting

Yes
Yes

Product properties, functions, components / general

Number of automatically learnable MAC addresses	8192
Storage capacity	
• of the MAC-address table	64 Kibyte
• of message buffer / maximum	1536 Kibyte
Switch latency period	4 µs
Transfer rate / of the switch	108.92 Gbit/s
Product feature	
• no head-off-line-blocking	Yes
• Store & Forward switching method	Yes

Product functions / management, configuration

Product function	
• CLI	Yes
• web-based management	Yes
• MIB support	Yes
• RMON	Yes
• switch-managed	Yes
Protocol / is supported	
• Telnet	Yes
• HTTP	Yes
• HTTPS	Yes
• TFTP	Yes
• SNMP v1	Yes
• SNMP v2	No
• SNMP v2c	Yes
• SNMP v3	Yes
• IGMP (snooping/querier)	Yes
Number of groups / at IGMP	256
Product function	
• for MIB support / by BRIDGE-MIB	RFC4188
• for MIB support / by IF-MIB	RFC2863
• for MIB support / by RMON-MIB	RFC2819
• for MIB support / by RSTP-MIB	RFC4318
• for MIB support / by SNMPv2-MIB	RFC1907
• for MIB support / by SNMPv2-SMI	RFC2578
• for MIB support / by SNMPv2-TC	RFC2579
• for MIB support / by TCP-MIB	RFC2012
• for MIB support / by UDP-MIB	RFC2013

Product functions / VLAN	
Product function	
• VLAN - port based	Yes
Number of VLANs / maximum	255
VLAN identification number	1 ... 4094
Protocol / is supported / GVRP	Yes
Product functions / DHCP	
Product function	
• DHCP client	Yes
• DHCP Option 82	Yes
• DHCP Option 66	No
• DHCP Option 67	No
Product functions / Redundancy	
Product function	
• redundancy procedure STP	Yes
• redundancy procedure RSTP	Yes
• redundancy procedure MSTP	Yes
• eRSTP	Yes
Protocol / is supported	
• STP	Yes
• RSTP	Yes
• MSTP	Yes
Product functions / Security	
Product function	
• IEEE 802.1x (radius)	Yes
Protocol / is supported	
• TACACS+	Yes
• SSL	Yes
Key length	
• with SSL	56 bit
• with RSA	1024 bit
Product function / port-rate-limiting	Yes
Product functions / Time	
Product function	
• SNTP client	Yes
• SNTP server	Yes
Protocol / is supported	
• SNTP	Yes
Standards, specifications, approvals	
Standard	

- for interference immunity

IEC 61000-6-2, IEEE 1613 Class 2, IEC 61850-3, IEC 61800-3

Standards, specifications, approvals / CE

Certificate of suitability / CE marking

Yes

Standards, specifications, approvals / miscellaneous

Certificate of suitability

- IEC 61850-3

Yes

Standards, specifications, approvals / product conformity

Product conformity

- acc. to IEEE 1588 v2-Precision Time Protocol

Yes

Accessories

accessories

Mounting kits, port modules, power supplies, cables, connectors
additional available

Further Information / Internet Links

Internet-Link

- to website: Industry Mall/RUGGEDCOM selector
- to website: Siemens RUGGEDCOM
- to website: Selector for cables and connectors
- to website: Industrial communication
- to website: Industry Mall
- to website: Information and Download Center
- to website: Image database
- to website: CAx Download Manager
- to website: Industry Online Support

<http://ruggedcom-selector.automation.siemens.com>

<http://siemens.com/ruggedcom>

<http://www.siemens.com/snst>

<http://www.siemens.com/simatic-net>

<https://mall.industry.siemens.com>

<http://www.siemens.com/industry/infocenter>

<http://automation.siemens.com/bilddb>

<http://www.siemens.com/cax>

<https://support.industry.siemens.com>

Security information

Security information

Siemens provides products and solutions with industrial security functions that support the secure operation of plants, solutions, machines, equipment and/or networks. They are important components in a holistic industrial security concept. With this in mind, Siemens' products and solutions undergo continuous development. Siemens recommends strongly that you regularly check for product updates. For the secure operation of Siemens products and solutions, it is necessary to take suitable preventive action(e.g. cell protection concept) and integrate each component into a holistic, state-of-the-art industrial security concept. Third-party products that may be in use should also be considered. For more information about industrial security, visit <http://www.siemens.com/industrialsecurity>. To stay informed about product updates as they occur, sign up for a product-specific newsletter. For more information, visit <http://support.automation.siemens.com>. (V3.4)

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