Implementation of an Experimental Wide-Area Monitoring Platform for Development of Synchronized Phasor Measurement Applications

Moustafa Chenine, *Student Member, IEEE*, Luigi Vanfretti, *Member, IEEE*, Sebastian Bengtsson, and Lars Nordström, *Member, IEEE*

Abstract-- **Synchrophasor-based Wide-Area Monitoring and Control Systems (WAMC) are becoming a reality with increased international research and development. Several monitoring and control applications based on these systems have been proposed, and although with a relative small adoption, they are currently supporting the operations of some large transmission system operators. It is expected that the continued research and development of phasor data applications will enable the *miracle* of "Smart Grids" at the transmission level. The authors have realized that this can be achieved in timely fashion only if a research and development platform is developed to simultaneously address issues regarding information and communication infrastructures, and phasor data applications. This paper discusses the preliminary development, and deployment of an experimental wide-area monitoring platform in which several basic applications have been implemented, and that in the future will allow for the implementation and testing of envisioned applications. At its current stage, the platform allows both on-line monitoring and off-line analysis. In the future, it will be the cornerstone to a wider platform enabling research on phasor data applications that intrinsically account for ICT aspects.**

Index Terms—**Wide Area Monitoring System, Wide Area Monitoring and Control Systems Performance, PMU-based Applications.**

I. INTRODUCTION

The rising interest in "Smart Grids" has prompted an ever-increasing wave of discussion regarding a more disruptive introduction of information and communication technologies (ICT) to increase efficiency in electricity delivery and power network management. While a great amount of discussion focuses on the increased use of ICT at the distribution level [1], synchronized phasor measurements and their supporting infrastructures are put in the frontline from the transmission system perspective as enablers of the so called "Smart Transmission Grids" [2].

The current approach for power system operations at the transmission level is to perform most of the monitoring and control actions within an Energy Management System (EMS), which makes use of a Supervisory Control and Data Acquisition (SCADA) system. There are many solutions available and currently used by transmission system companies and system operators, such as ABB's SCADA/EMS Network Manager [5]. Although these systems are mature and dependable, it has not been until recently that wide-area "features" have been added to these systems. However, these features are not broadly adopted and have a reduced number of available phasor-data applications [3]. In addition, these systems where not developed to withstand the strain of managing the data volumes from the streaming of synchronized phasor measurements in an efficient manner [4]. Despite these limitations, there are initiatives in North America which have created specialized systems exploiting measurements from Phasor Measurement Units (PMUs) with the aim of enabling new applications of PMU-data and increasing the utilization of synchrophasors in operations [6].

The enabling technologies of wide-area monitoring systems are PMUs, as the measurement device of choice, and their supporting infrastructure which is formed by communication networks and computer systems capable of handling PMU data and other information (usually called Phasor Data Concentrators (PDCs)). The set of PMUs and their enabling information and communication infrastructures is termed Synchrophasor Measurement Technology (SMT) [7]. With the rising number of synchrophasor installations around the world, stakeholders in the transmission system have a window of opportunity to exploit synchronization, dynamic signatures, and high resolution measurements provided by PMUs. However, the number of applications available to transmission operators for exploiting these measurements seems not to be sufficient to justify investments in SMT, and current projects dealing with this technology are strongly subsidized [8].

If future power systems will hinge on these technologies, they cannot rely on heavily subsided funding as its means to existence, and other drivers are needed. These drivers can be provided by the careful design of reliable phasor data applications that provide an added value for operations and planning, a value which cannot be achieved by other technologies. But to make this a reality, both pieces of the puzzle must be addressed simultaneously: this means that the chosen Research and Development (R&D) approach should

simultaneously address issues regarding information and communication infrastructures, and phasor data applications. Hence, the approach proposed in this article is to develop an application development platform that, because it's based on open source software solutions, it respects the freedom of the researchers from both ICT and power engineering to develop phasor data applications.

A. Purpose

In this paper we present preliminary work that has focused on developing a Wide-Area Monitoring System and basic applications as part of a wider platform for "Smart Transmission Grids" application development and testing at KTH, the Royal Institute of Technology in Stockholm, Sweden.

B. Outline

The reminder of this paper is structured as follows. Section II presents an overview of the basic components of a WAMC system. Section III presents the architecture of the Wide Area Monitoring system under development and discusses its main components, while Section IV describes efforts to develop on-line and off-line applications. Finally, in Section V, conclusions are drawn and future work is briefly outlined.

II. BASIC WAMC COMPONENTS

In the current centralized architecture paradigm, a complete Wide-Area Monitoring and Control (WAMC) System is one where PMU measurements are collected from various locations in an interconnected power system. These measurements are then communicated to a central location where they are used by an assessment or monitoring application that raises alarms and calculates metrics. The alarms raised and computed metrics by these monitoring systems are in turn used to provide operator support to determine corrective actions and to control devices in the power network. Alternative architectures, such as using a few remote PMU signals in a local system for specific control or protection applications, are also possible, but are outside the scope of this article.
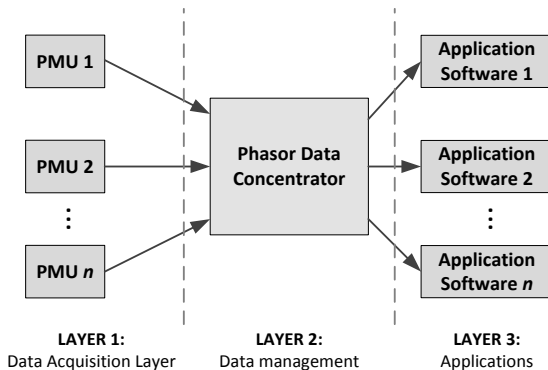

Figure 1: Layers and components of WAMC system.

Thus, the basic components of any WAMC system are the following: PMUs, PDCs, a PMU-based application system (which itself is comprised by different information

technologies and underlying algorithms), and finally a communication network [9].

Similarly to traditional SCADA systems, there are three layers in a WAMC system. Figure 1 illustrates this logical architecture. In Layer 1, the WAMC system interfaces with the power system on substation bars and power lines where the PMUs are placed, this is called the Data Acquisition layer. Layer 2 is known as the Data Management layer, in this layer the syncrhophasor measurements are collected and sorted into a single time synchronized dataset. Finally, Layer 3 is the Application Layer; it represents the real-time PMU data-based application functions that process the time-synchronized PMU measurements provided by Layer 2.

III. ARCHITECTURAL DESIGN OF AN OPEN WAMS PLATFORM

The *open*WAMS platform currently deployed at KTH is comprised by several components. These include components that sort PMU data and those that exploit the sorted data. The PMUs are deployed in various universities in the Nordic Region, and also include an FNET device. This section provides an overview of *open*WAMS, beginning with the overall architecture of the system and then describing the main parts that compose it. Most of these components have been deployed or are undergoing development, while others are still under planning.

A. Overall Architecture

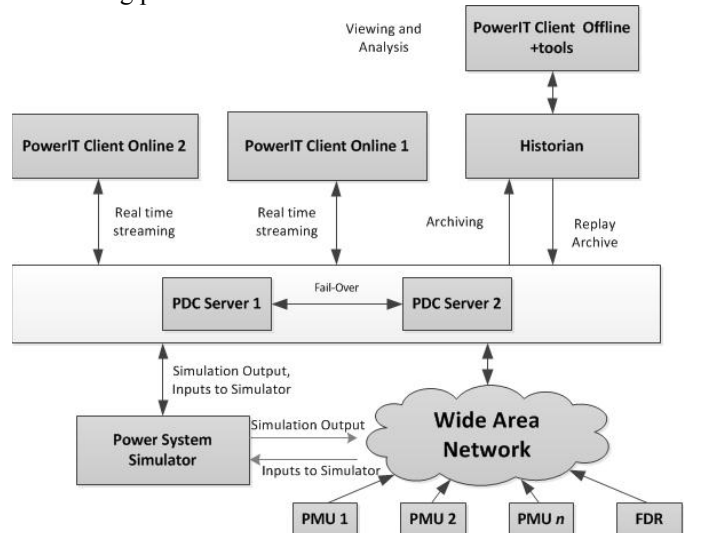Figure 2 depicts the main components of the Wide-Area Monitoring platform.

Figure 2: The KTH Wide Area Monitoring Platform

As mentioned earlier, PMUs are deployed in various Universities in the Nordic region. Most of these PMUs are actually connected to the distribution grid, rather than the transmission grid. The PMUs have been equipped with step-down transformers that bring the three-phase distribution level voltage to instrumentation level; the current is not being measured by these instruments. There are currently 5 PMUs deployed of which 4 are operational. Furthermore, a Frequency Disturbance Recorder (FDR) device [10] is also deployed at KTH which streams data both to the *open*WAMS platform, and the F-NET server at University of Tennessee [10].

There are currently plans to integrate a real-time power system simulator to the system, whereby measurements, device's status, and other data can be extracted from the simulator and be feed into the WAMS system. This is attractive because by exploiting the input/output capabilities of the simulator, it becomes possible to implement and test closed-loop applications.

There are currently two PDCs deployed, these PDCs collect measurements and forward them as a single continuous data stream to either the historian system (which archives the data) or to client systems (which consume the data). In the case of the latter, the data stream from the PDC is time-aligned and may be down-sampled.

B. openPDC

The PowerIT Platform is built around the *open*PDC system [12]. *open*PDC is an evolution of the SuperPDC originally developed at the Tennessee Valley Authority [13]. The system processes any type of time-series measurement data in a protocol independent fashion. This is possible due to the system's extensible modular design. In fact, openPDC is architecturally split into three layers, the Input, Action and Output layers, each with its specific set of functionality, Figure 3 illustrates this architecture. The Input, Action and Output layers deal with measurement acquisition, measurement processing and measurement routing and forwarding tasks respectively.
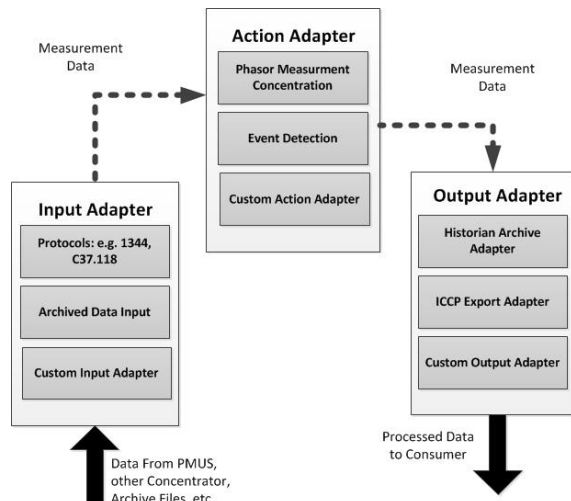

Figure 3: Functionality Layers in openPDC's architecture

The Input Adapter Layer allows the development of input adapters that can support several protocols. An input adapter takes measurements from different devices or systems that use different communication protocols and makes them available to the Action Layer. Currently *open*PDC supports input from devices using IEEE C37.118, IEEE 1344, Virginia Tech F-NET, and BPA PDCStream, among others [13]. The input adapter also allows development of customized inputs for interfacing with other systems. For example, *open*PDC supports reading archived data from a historian (as explained in the next section) back into *open*PDC. Other customized inputs can be developed to link conventional SCADA systems or interfaces sending simulated outputs from power system simulators/emulators.

The Action Adapter Layer, allows the implementation of functionality that process the stripped down measurements provided by the Input Adapter Layer. A good example of such functionality is the phasor time alignment adapter, where measurements coming from the Input Adapter Layer are sorted, time-aligned and possibly down-sampled before begin forwarded to the next layer. The Action Adapter Layer also supports two more functionalities which are of interest, namely real-time event detection and real-time calculated measurements. Real-time event detection tasks process incoming measurements and checks whether they fall within a range of preset parameters, if they don't than the event task informs subscribers of such occurrences, and example of an event detection task that is bundled with *open*PDC is frequency excursion detections [14]. The calculated measurement functionality allows for the definition of new measurements that are not directly collected from remote devices, but are instead calculated at the PDC from remote measurements as they arrive. A simple example of such a calculated measurement that can be derived is active power, which would be calculated within *open*PDC and then forwarded to applications requiring it, or to other adapters.

Finally, the Output Adapter Layer of the *open*PDC provides functionality whereby measurements processing by Action Adapter Layer are queued for processing or forwarded to subscribers. This includes the possibility of re-encapsulating the data in several protocols. Examples of output adapter bundled with *open*PDC are IEEE C37.118 concentrator output streams, Inter Control Center Protocol (ICCP) file export, Comma Separated Values (CSV) File Export, and Historian Archiving output.

The *open*PDC system deployed for the *open*WAMs currently uses IEEE 1344 to communicate with most PMUs and IEEE C37.118 to communicate with one PMU. Furthermore the FDR deployed at KTH uses F-NET to communicate with the PDC. In all cases the concentrated output stream is defined in IEEE C37.118.

They are actually two *open*PDC system deployed as part of the *open*WAMS, this is done to study provide load balancing and fail-over capabilities. In the former the back-up PDC assists the primary PDC when the traffic load increases, so as to maintain performance. In the latter the back-up PDC is bought on-line when the primary PDC fails. These features are somewhat possible to configure with *open*PDC and our deployment is meant to study these configurations and performance in such cases.

Another interesting feature is data replay using the *open*PDC. Where archived data from the Historian (see next subsection) is retransmitted to the *open*PDC software which in turn treats the data as if it is from PMUs and can stream it back to the client applications, in this case the PowerIT client system.

C. Historian.

The historian system is built around the *open*Historian [15]. The *open*Historian system is very much related to the *open*PDC system, in fact they are built using the same architectural framework, and is as extensible as the *open*PDC system.

The main function of the Historian is to archive and store measurement data for future off-line analysis use. The Historian stores the data in flat binary archive files. It does not use a conventional relational database management system as such systems become inefficient when managing large amounts of data. This is because they would require large indexes and it would take a substantial amount of time to retrieve the required data [16].

As depicted in Figure 2, the Historian is a standalone server system that receives a stream of data from the PDC and stores that data locally, that data storage facility is currently 2 terabytes but that can easily be extended increase storage capacity.

D. PowerIT Client system

The purpose of the PowerIT client system is to offer a platform for on-line and off-line analysis, and testing. Figure 4 below gives an overview of how functionality is partitioned in the PowerIT client and associated tools. The system has the following application categories:

- On-line real-time monitoring.
- On-line real-time event processing.
- Off-line replay of data for monitoring.
- Off-line replay of data for analysis.
- Server and client management.

This system has been designed to offer a multiuser environment where users have access to certain system functionality according to assigned rights, such as on-line monitoring, off-line analysis tools, and server configuration.
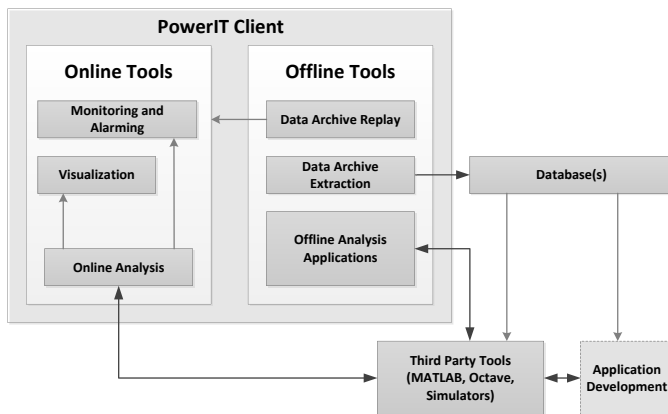

Figure 4: Functionality of the PowerIT Client System

The PowerIT client system makes use of many of the libraries associated with the *open*PDC, for example the TVA Code Library [17] and *open*PDC's Phasor Protocol Library.

The architecture of the PowerIT client is fairly straightforward. The system is built around a reconfigurable connection object that can connect using several protocols to either a PDC server, measurement historian and or a remote device.

The applications in the system are designed to plug-in to the global connection object and subscribe to events fired by that object. A global connection object event can be for example a new measurement from the server that has been received, in which case, the applications responds by utilizing this measurement according to its task.

Applications also import a global configuration manager. The global configuration manager simplifies the management of various configurations related to connection between the client system and the PDC. The configuration manager can also handle configuration changes in remote devices if the client is directly connected to them (and therefore bypassing the PDC). An example of the kind of information handled by the configuration manager is the number of measurements published by the PDC server and what type of measurements they are, i.e. voltage phasors, frequency values etc. In fact, the configuration manager also subscribes to the events of the global connection object but only to those events relating to configuration changes. By importing the configurations manager, application can dynamically respond to changes in the system configuration. Figure 5 depicts the main architectural components of the PowerIT client system.

As illustrated in Figure 4, the PowerIT client systems is also designed to offer tools to support off-line analysis and data management such as tools to easily extract archive data for viewing directly in the application or for processing inside other application systems like MATLAB.
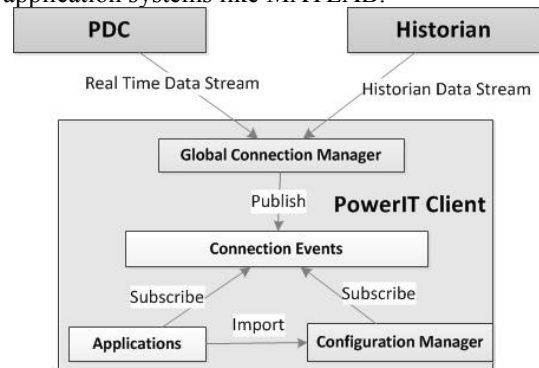

Figure 5: The main architectural component of the PowerIT client system

IV. Application Development using an open WAMS Platform

Using the infrastructure and components described in the previous section, applications where built. These applications as mentioned earlier, are categorized as on-line or off-line applications. On-line application process fast moving data as they arrive to the client system, measurement by measurement. In contrast off-line applications process data that is archived and stored, and this is usually done on a batch volume of data.

A. Online Monitoring Applications

Two on-line applications have been implemented in the PowerIT client system. The first application is an average frequency monitoring display, and the second application is an online electromechanical model estimation system. The next two subsection describe these applications

1) A Simple Average Frequency Monitoring Application

The Average Frequency Monitoring application in the PowerIT client calculates the average frequency given a set of frequency values from several PMUs. The application is an adaption of the Frequency Monitoring function of the Power Calculations Adapter that is bundled with *open*PDC[14].

The Average Frequency Monitoring application calculates the average frequency as each value arrives at the client

system this is done simply by adding each frequency value to the frequencyTotal variable and then dividing by the number of frequency values received.

The application also allows plotting the frequency of each PMU on the same graph as the average frequency trend. Figure 6 shows the average frequency calculated from three PMUs as the blue curve while the green curve represents the frequency of a PMU in the north of Sweden (named LTU).
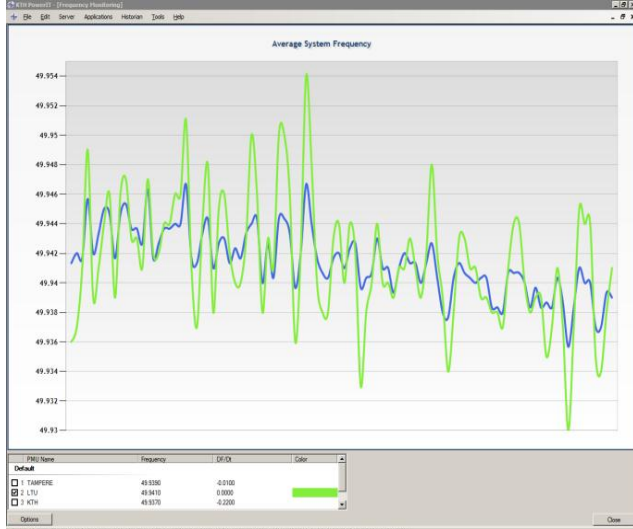

Figure 6: Average Frequency Display - The blue line shows the computed average frequency from all the devices, the green line shows the frequency from the LTU PMU – the x-axis is a moving window of configurable size

2) Online Electromechanical Mode Estimation

The on-line mode estimation application is based on work outlined in [18] where archived data is used to estimate electromechanical properties of power systems. The application collects real-time measurements for a pre-specified time window and then processes these measurements in two steps: first preprocessing the data buffer, and then performing a spectral estimation. Figure 7 below shows a screenshot of this application.
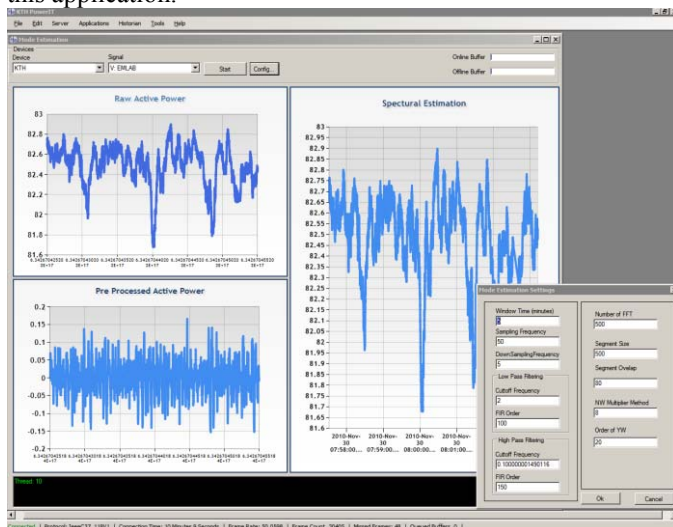

Figure 7: Model Estimation display in the PowerIT client system[1]

---

[1] Note to Reviewer: this figure needs updating due to Visual Studio issues.

The processing part of the mode estimation application was originally written in MATLAB. This code was reorganized in to more manageable functions and exported for using the MATLAB NE Compiler[19] as independent libraries to be used by the mode estimation application component of the PowerIT client system.

B. Offline- Analysis Applications

Off-line analysis can be generally categorized in two areas: forensic or post-mortem disturbance analysis, and application development. Availability of data for forensic analysis is of importance because of regulations [20] and it often allows the determination of factors involved in disruptive events [21][22]. Application development refers to the use of archived data for developing new analysis applications that can be used either in on-line and off-line mode. We discuss some of these aspects in this Section.

1) Data Consolidation Layer and Data Management Approach

Despite that the COMTRADE format has been selected for PMU data sharing in North America [23] this data format is not the most convenient for application development and straightforward data analysis. Moreover, the PMU data may not necessarily come from PDCs other than the one owned by the analyst, and may bear a different output data format than the one provided by *open*PDC. In addition, for analysis purposes it might be necessary to consolidate data from other GPS-time synchronized measurement devices (such as Disturbance Frequency Recorders (DFRs) and Dynamic Swing Recorders (DSRs), and other IEDs [24].

PMU data is available from different sources: PMUs, IEDs, and PDCs. In addition to the different sources, the data is also exchanged in many different formats: COMTRADE [25] .cfg and .dat files, delimited text files such as .csv and MS Excel files, and database files from MS Access and MySQL. To handle the diversity of data sources and data formats, and to cater for both the needs of the data analyst and application developer, we propose a data management approach which uses a layer for consolidation of data from different sources.

The data management approach consists of consolidating different data sources as shown in Figure 8. The most important characteristic to note here is that the PowerIT Client provides a "Data Extraction" adaptor. This adaptor can be configured to provide data in different formats. However, because the output data format that is mainly used routinely is the one of *open*PDC, the main goal is to transform the different data sources into this format.

When the data from an external PDC has been extracted to a text delimited format or other by the manufacturer's software, a custom conversion script changes the format of the data to the *open*PDC format, and stores it in plain text or .csv files. A similar approach is taken for consolidating data from specific devices that are not connected to a PDC such as DSRs and DFRs.

Once all the data is available in .txt or .csv files in the same format as data extracted with the "Data Extraction" adaptor, the data bears following format:

$$\{0:I\};\{1:T\};\{2:V\};\{3:Q\}$$

where I is an internal historian identifier for the signal, T is a

time-stamp, *V* is the value of the signal at the instant given by *T*, and *Q* is a data quality indicator. In this case the delimiter ";" separates the identifier, time stamp and value.
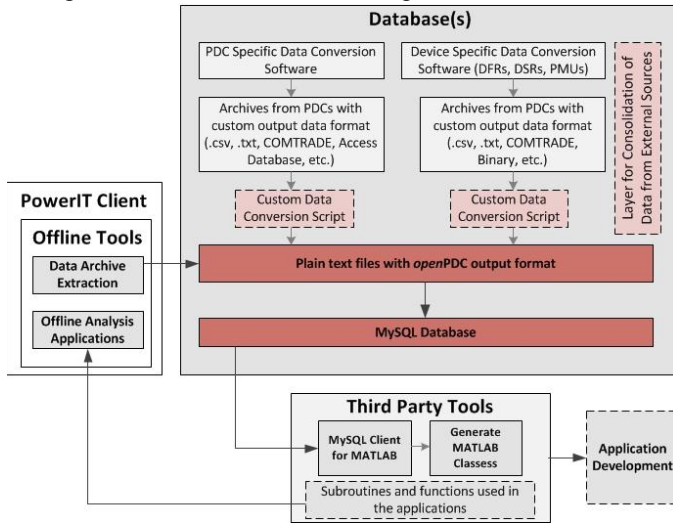

Figure 8: Data consolidation layer and data management approach for off-line analysis application development

For efficient data handling a relational database management system, MySQL, creates a database from the .csv files. The MySQL Client for MATLAB [26] enables this process from within the MATLAB environment, and also imports data from the MySQL database to MATLAB.

When a MySQL database is created the data is loaded into a table. The table contains the columns ID, Time Tag, Value and Quality. Data can then be taken from the table, by selecting an ID, to create .mat files. One of the great benefits of doing this is that the data that comes partially unsorted from *open*PDC now can be sorted by the ascending order of the time-stamp in MySQL. This is done by implementing the proper SQL query within the MySQL client.

All of these steps are not done manually, a small Graphical user interface (GUI) was constructed in MATLAB's GUI Design Environment (GUIDE). It incorporates the conversion process from the point where the data is in common format all the way to MATLAB, Figure 9 below illustrates this GUI.
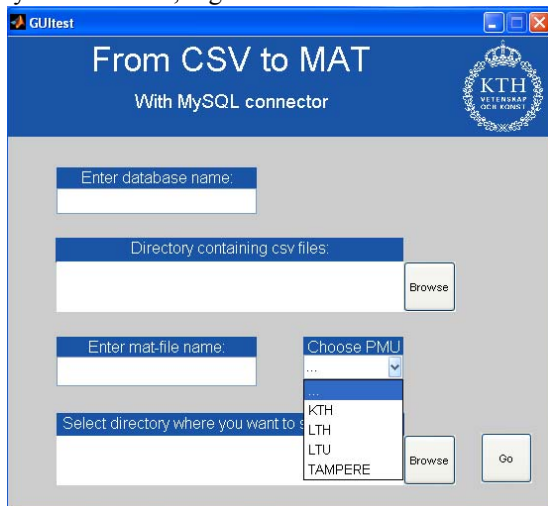

Figure 9: MySQL to MATLAB data conversion GUI

2) PMU Data Attributes for Data Analysis and Application Development

MATLAB data is organized in classes and structures for particular dates or events. Data structures and classes provide a compact and organized mean to handle PMU data for analysis: each signal from a PMU is defined as a class or structure, and each of the attributes of this signal is defined as a field. To illustrate these features, some of the fields of the structure for the frequency signal of the PMU at KTH (`kth_f`) are shown below:

```
kth_f =
      ttag: {1148731x1 cell}
      data: [1148731x1 double]
      tnum: [1148731x1 double]
      info: 'Nov. 2010 Data Archive, KTH PMU
            Frequency Signal, 01-Nov-2010'
```

Note that a given class can bear additional data structures or fields providing other information for analysis and software development, as shown by the `kth_f.info` field. Using data structures allows the inclusion of not only the data, but also additional information about the signal.
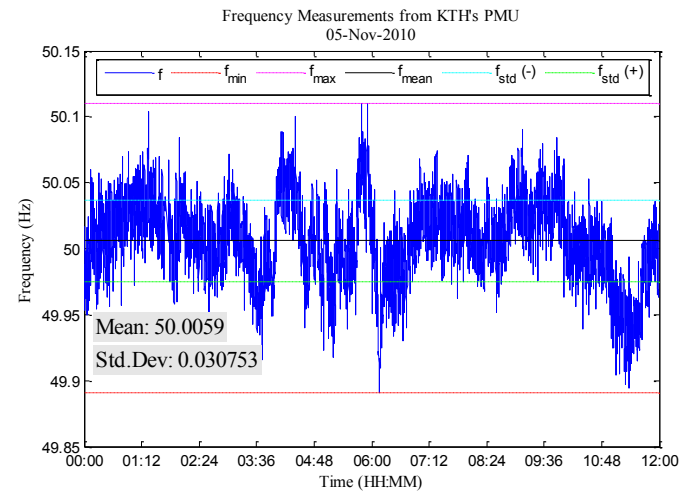

Figure 10: Frequency measurement analysis off-line application

3) Development of off-line applications

Data analysis can be readily carried out by having all the data stored in data structures. Operations, manipulation, and visualization can be standardized and done quickly.

a) Frequency measurement monitoring application

A simple off-line application for extracting features of frequency measurements from the PMU at KTH was recently developed; this example helps to show why the chosen data management approach is important. This application consists of a set of MATLAB functions that provide plots of measurement data for any time interval, and that computes different statistics on the data which are displayed in the plot and are provided also as an output of the application. A plot from the output of this application is shown in Figure 10, within this application the statistics are computed by using the signals attributes:

```
% computing measurement statistics
fmin = min(f.data);
fmax = max(f.data);
fstd  = nanstd(f.data);
fmean = nanmean(f.data);
```

Note that the `kth_f` structure is received by the application in the new structure "`f`", this generalization allows the application to be used by data from any other PMU.

There are several applications currently being developed using this approach. Note that as explained above, the availability of data in a transparent and ready to use format allows for development to be pursued in a straightforward manner.

b) Electromechanical mode estimation application

The on-line mode estimation described in the previous Section has its roots in the on-going development of an electromechanical mode estimation off-line application. This application is being developed so that electromechanical mode properties can be routinely estimated from archived data from different power systems [18]. The application estimates the frequency spectrum of a given signal using different spectral techniques, and computes damping estimates using energy methods [28]. The application is built using three steps, the first step being pre-processing of data, the second is spectral estimation, and the third is damping estimation. The application has been designed so that any spectral technique can be evaluated and studied by including it in a separate function; these techniques include parametric and non-parametric methods. Discussion of these techniques is out of the scope of this paper and can be found in [27]. A sample output of this application from spectral estimation is shown in Figure 11 for a data set from the Mexican Power System, a GUI similar to the one in Figure 9 is currently being developed.
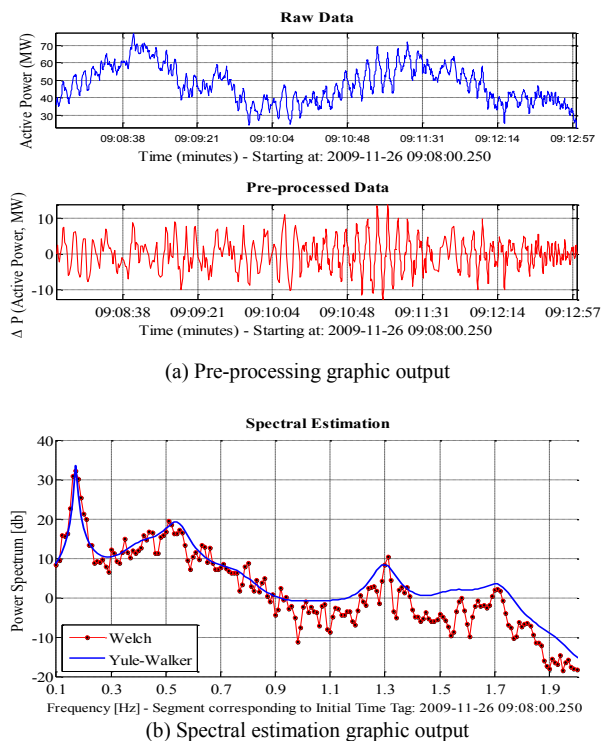

(a) Pre-processing graphic output

(b) Spectral estimation graphic output

Figure 11: Results from the mode estimation application

V. CONCLUSIONS AND FURTHER WORK

In this paper we presented preliminary work on the development of an open Wide Area Monitoring system. The *open*WAMs platform is made up several components, most of which are open source. This has allowed us to experiment with different architectures and to begin building new monitoring and analysis applications, some of which were presented in this paper. The system is a valuable asset as it helps expedite research and development efforts within the field of wide area situational awareness in terms of algorithms implemented in practice using *real* data, which would otherwise be solely based entirely on simulation results. The platform also helps in determining and evaluating the impact and limitation of ICT systems on the genuine reliability and usability of these algorithms, again this is done by implementing algorithms and evaluating their performance on real data in real-time fashion as opposed to off-line batch processing.

On-line applications that process sub-second incoming continuous streams of measurement data have a greater number of challenges and constraints. These applications have to check in real-time the quality of the data before processing it. If the data was inaccurate or distorted this could lead to an application failure or worst, producing misleading results which could deceive the operators. Another aspect is the overwhelming volume of incoming data that a client system has to process, which could inhibit performance. Future work will focus on implementing more algorithms and evaluating such ICT challenges and constraints.

VI. ACKNOWLEDGMENT

VII. REFERENCES

[1] G. T. Heydt, "The Next Generation of Power Distribution Systems," *IEEE Transactions on Smart Grid*, vol. 1, no. 3, pp. 225 –235, 2010.

[2] A. Bose, "Smart Transmission Grid Applications and Their Supporting Infrastructure," *IEEE Transactions on Smart Grid*, vol.1, no.1, pp.11-19, June 2010.

[3] M. Zima, M. Larsson, P. Korba, C. Rehtanz, G. Andersson, "Design Aspects for Wide-Area Monitoring and Control Systems," Proceedings of the IEEE , vol.93, no.5, pp.980-996, May 2005.

[4] J. Patterson, "The Smart Grid: Hadoop at the Tennessee Valley Authority (TVA)," Cloudera Blog, http://www.cloudera.com/blog/2009/06/smart-grid-hadoop-tennesse-valley-authority-tva/, June 2, 2009.

[5] M. Patel (RAPIR Chair), "Real-Time Application of Synchrophasors Improving Reliability," North American Elecricity Reliability Corporation, Princeton, NJ, Tech. Rep., 2010, available on-line: http://www.naspi.org/news/rapir final draft 20101017.pdf.

[6] M. Parashar and J. Mo, "Real Time Dynamics Monitoring System (RTDMS): Phasor Applications for the Control Room," in *42nd Hawaii International Conference on System Sciences, 2009 (HICSS '09)*, Jan. 2009, pp. 1–11.

[7] S. Chakrabarti, E. Kyriakides, Bi Tianshu B, Cai Deyu, and V. Terzija, "Measurements get together," *Power and Energy Magazine, IEEE* , vol.7, no.1, pp.41-49, January-February 2009.

[8] US Department of Energy, "Smart Grid Investment Grant Selectee Information," On-line at: http://www.oe.energy.gov/recovery/1264.htm

[9] C. Marinez, M. Parashar, J. Dyer, and J. Coroas, "Phasor Data Requirements for Real Time Wide-Area Monitoring, Control and Protection Applications," CERTS/EPG, EIPP-Real Time Task Team. January 2005.

[10] Yingchen Zhang; Markham, P.; Tao Xia; Lang Chen; Yanzhu Ye; Zhongyu Wu; Zhiyong Yuan; Lei Wang; Bank, J.; Burgett, J.; Conners, R.W.; Yilu Liu; , "Wide-Area Frequency Monitoring Network (FNET) Architecture and Applications," *Smart Grid, IEEE Transactions on* , vol.1, no.2, pp.159-167, Sept. 2010.

[11] F-NET Server Web Display, available on-line at: http://fnetpublic.utk.edu/

[12] *Open*PDC: The Open Source Phasor Data Concentrator, available on-line at: http://openpdc.codeplex.com/.

[13] Jian Zuo; Carroll, R.; Trachian, P.; Jingyuan Dong; Affare, S.; Rogers, B.; Beard, L.; Yilu Liu; , "Development of TVA SuperPDC: Phasor applications, tools, and event replay," *Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century,* 2008.

[14] openPDC Adapter String Connection Syntax, available online at: http://openpdc.codeplex.com/wikipage?title=Connection%20Strings&referringTitle=Documentation.

[15] The Open Source Time Series Data Historian, available online at : http://openhistorian.codeplex.com/

[16] A. Armenia, J. H Chow, "A Flexible Phasor Data Concentrator Design Leveraging Existing Software Technologies," *Smart Grid, IEEE Transactions on*, vol.1, no.1, June 2010.

[17] The TVA Code Library, Available on-line at: http://tvacodelibrary.codeplex.com/

[18] L. Vanfretti, L. Dosiek, J. W. Pierre, D. Trudnowski, J. H. Chow, R. García-Valle, and U. Aliyu, "Application of Ambient Analysis Techniques for the Estimation of Electromechanical Oscillations from Measured PMU Data in Four Different Power Systems," European Transactions on Electrical Power, Special Issue on PMU Data and their Applications. doi: 10.1002/etep.507. Available on-line: http://onlinelibrary.wiley.com/doi/10.1002/etep.507/abstract

[19] MATLAB Builder NE for Microsoft .NET framework, available on-line at: http://www.mathworks.com/products/netbuilder/.

[20] "Standard PRC-002-1 – Define Regional Disturbance Monitoring and Reporting Requirements" North American Electric Reliability Corporation (NERC). August, 2006. Available on-line: http://www.nerc.com/files/PRC-002-1.pdf

[21] A. Hauer, D. Trudnowski, and J. DeSteese, "A Perspective on WAMS Analysis Tools for Tracking of Oscillatory Dynamics," *IEEE Power Engineering Society General Meeting, 2007.*, pp. 1–10, June 2007.

[22] J. Hauer, N. Bhatt, K. Shah, and S. Kolluri, "Performance of "wams east" in providing dynamic information for the north east blackout of august 14, 2003," in *IEEE Power Engineering Society General Meeting, 2004*, June 2004, pp. 1685–1690 Vol.2.

[23] E. Allen, "Use of COMTRADE for Exchange of PMU Data, "in NASPI Workgroup Meeting, Vancouver, British Columbia, June 8, 2010, available on-line: http://www.naspi.org/meetings/workgroup/2010_june/presentations/session_01/allen_nerc_use_of_comtrade_20100608.pdf.

[24] Mladen Kezunovic, "Intelligent Design: Substation Data Integration for Enhanced Asset Management Opportunities," *IEEE Power & Energy Magazine*, Vol.6, No. 6, pp. 37-44, Nov.-Dec. 2010.

[25] "IEEE standard Common Format for Transient Data Exchange (COMTRADE) for power systems," *IEEE Std C37.111-1999*, 1999.

[26] R. Almgren, *MySQL Client for MATLAB.* Available online at: http://www.courant.nyu.edu/~almgren/mysql/

[27] D. Trudnowski and J.W. Pierre, in *Inter-area Oscillations in Power Systems: A Nonlinear and Nonstationary Perspective*, ser. Power Electronics and Power Systems, A. R. Messina, Ed. Springer, 2009, ch. Signal Processing Methods for Estimating Small-Signal Dynamic Properties from Measured Responses, pp. 1–36.

[28] D. Trudnowski, J. Pierre, N. Zhou, J. Hauer, and M. Parashar, "Performance of Three Mode-Meter Block-Processing Algorithms for Automated Dynamic Stability Assessment," *IEEE Transactions on Power Systems*, vol. 23, no. 2, pp. 680–690, May 2008.

[29] R.E. Brown, "Impact of Smart Grid on distribution system design," *IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century* , vol., no., pp.1-4, 20-24 July 2008

Moustafa Chenine (Student Member '07) received his B.Sc. from The American College of Greece in 2004, majoring in Computer Information Systems. He then joined KTH–The Royal Institute of Technology where he worked towards his M.Sc. (2006) in Information Systems and Licentiate of Engineering in Electrical Engineering. He is a PhD Student at the department of Industrial Information and Control Systems at KTH, doing research in the field of ICT Infrastructure optimizations for Smart Grid systems, specifically focusing on interoperability, security and performance aspects of Wide Area Monitoring and Control Systems.

Luigi Vanfretti (Student Member '03, M'10) is an Assistant Professor at the Electric Power Systems Division, School of Electrical Engineering, KTH Royal Institute of Technology, Stockholm, Sweden, where he was a Post-Doctoral Research Fellow during May 2010.He obtained the Electrical Engineering Degree (with a Power Engineering concentration) from *Universidad de San Carlos de Guatemala* in June 2005, and received the *Francisco Vela* award for outstanding academic achievement and best undergraduate thesis. During Fall 2005, he was a visiting researcher at the Department of Electronics and Electrical Engineering of The University of Glasgow, Scotland. He received his MS in 2007 and PhD in 2009, both in Electric Power Engineering, from the Electrical, Computer, and Systems Engineering (ECSE) Department at Rensselaer Polytechnic Institute (RPI). During Spring 2010 he was a Post-Doctoral Research Associate at RPI working on synchrophasor applications. He was awarded the Charles M. Close Doctoral Prize from RPI in May, 2010 for his research and teaching work at ECSE. His research interests are modeling, dynamics, stability and control of power systems; applications of PMU data for Smart Transmission Grids, and open source software for power system engineering education.

Sebastian Bengtsson began his studies at KTH, The Royal Institute of Technology, in 2004. He is working towards an M.Sc in Electrical Engineering with main focus on electrical power systems and control theory. He is currently writing his master thesis on power system mode estimation from PMU data at the Electric Power Systems (EPS) department, KTH.

Lars Nordström (M'06) received the M.Sc. degree in electrical engineering and the Ph.D. degree in industrial control systems, both from KTH—The Royal Institute of Technology, Stockholm, Sweden. He is an Associate Professor in Power System Management and Director of the Swedish Centre of Excellence in Electric Power Engineering, an industry-university research center, located at KTH. His area of research is power systems management and related information exchange, including application of decision theory on information system architectures and the application of ICT to power system problems. Dr. Nordström is chairman of IEC TC57's Swedish committee, and a member of the IEC's Strategic group on Smart grids as well as National Cigre SC D2 representative for Sweden.