Multipurpose Open System Architecture Model of Wide Area Monitoring

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Abstract—This paper elaborates developed custom open system architecture for processing, archiving and visualization of phasor data with the extended archiving capabilities and managing such data. Presented multi-purpose and open system architecture is able to communicate and collect synchronized measurements from different sources such as the phasor data concentrator, virtual PMUs, SCADA and synchrophasor vector processor. Collected data are filtered and processed with the originally developed algorithm for power system real time monitoring purpose.

Index Terms — wide area monitroing, phasor measurement unit, real time applications, WAM architecture, PDC

I. INTRODUCTION

The Croatian power system is located in the central east part of the well meshed UCTE interconnected system. Due to substantial power transits that take part from northeast to southwest, the Croatian power system is of great importance for power supply in other countries in the neighborhood. For system security reasons enhanced monitoring and control of corridor loading is required. The main purpose of the first wide area monitoring system was to contribute the optimization of energy transit without violating the voltage instability risk and to get experience of the phasor measurement technology.

The Wide Area Monitoring system has been implemented in the Croatian transmission system for already 5 years. In this operational time the system was enhanced and extended in different stages and timing. The first system installed had the ability to monitor real time voltage stability on a 400kV corridor, as well as the average line temperature. After the first convincing experience of this system, the next step was the extension of the system with new PMUs to cover the 400kV transmission network. Five new PMUs were installed in five significant 400 kV substations in order to record frequency and positive sequence phasor quantities such as 400-kV node voltages and currents in outgoing 400 kV transmission lines.

In this stage the complete monitoring system was improved with new applications such as frequency, power oscillation, phase angle and voltage stability monitoring on 400kV corridors. Acquisition of synchronized phasor measurements from the power system found out to be of great value for post-disturbance analysis and study of the dynamic behavior of the power system. The WAM interface is realized with a commercially available of – the – shelf application adapted for the operator. As the experience in the WAM system grew the needs and requirements for a more open and adoptable system arise. Real time acquisition of phasor measurements into a central unit with an interface completely configurable and custom made for different user types was the next step to be accomplished. This paper describes the system architecture for the wide area monitoring system developed in the Croatian TSO. The system architecture was dictated by the intended applications to be used: complete observability of the 400kV network with a user friendly interface, voltage stability on power system level, frequency stability monitoring, phase angle stability, eigenvalue analysis, SCADA interface, integration with the state estimator and data storage.

The wide area monitoring system has to be able to satisfy different requirements from different user profiles involved in the use of the WAM system. From the operator point of view a good, easy to navigate system visualization with an alarming system is the main issue. Data archiving and event recording is of main use in the power system performance and post disturbance analysis. This and many other requirements had to be fulfilled in the new WAM system architecture.

II. SYSTEM DESIGN

A. System overview

The pilot project of monitoring the 400kV line Tumbri – Žerjavinec was actually the beginning of the development of the wide area monitoring project in the Croatian power system. Both nodes were recognized as an important link for energy transit through the Croatian power system, so two PMUs were installed. The phasor data concentrator was installed in the National Dispatching Center in Zagreb. In addition to basic monitoring functions and collection of phasor data, two advanced applications were applied to assess the permissible 400kV line loading, Line thermal monitoring and Voltage Stability Monitoring. This stage was completed in 2003. First encouraging experience of monitoring the 400kV line, especially during the reconnection process of the 1st and 2nd UCTE synchronous zone in 2004, served as a good basis to initiate the extension of the WAM system with new PMUs and a new phasor data concentrator. The complete foreseen extension was the second stage of the WAMS development and it was finished in 2007 [2].

The complete overview of the WAM system is shown in Fig 1. Croatian power system consists of four transmission

areas consisting of 400kV, 220kV and 110kV transmission voltage levels. Specific shape of Croatian territory and configuration of the 400 kV network made the choice of PMU locations quite natural and straightforward. In addition to the two existing PMUs at substations Tumbri and Žerjavinec, additional three PMUs were installed at representative 400 kV nodes in the remaining three areas. In such a way the entire 400 kV backbone of the system is being monitored. All installed PMUs are of the same make and type. PMUs are connected to the data concentrator at NDC Zagreb through optical links.
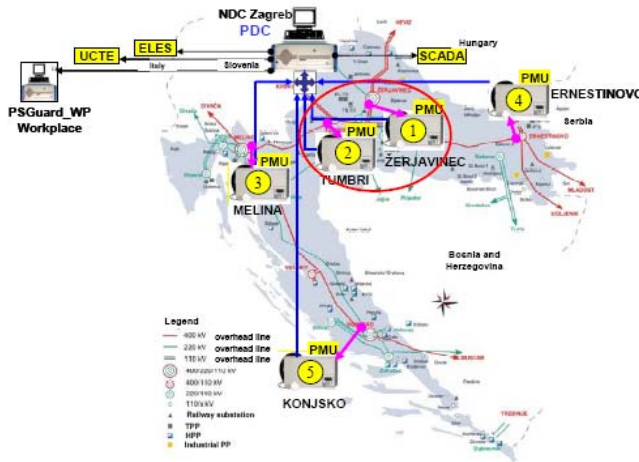

Fig. 1. Overview of PMU placement

The PMUs perform measuring of one voltage and one current phasor (positive sequence values) and calculate quantities such as frequency f, rate of change of frequency $\Delta f/\Delta t$, active and reactive power. The PMU transmits the measurements and derived quantities at a maximum rate of 50 samples per second (Ts=20ms), but the data is captured at a 10 samples per second rate (Ts=100ms). In addition to basic monitoring, data storage and export functions and previously installed functions Line Thermal Monitoring and Voltage Stability Monitoring, several new applications were added: Phase Angle Monitoring, Frequency Stability Monitoring and Power Oscillation Monitoring. Another enhancement of the functional specification was the possibility to exchange phasor data with other TSOs. Archiving of measurements and application results in a cyclic history data base for post-mortem analysis and historical display is allowed with a data storage and export function. Phasor data can be exported in form of comma separated value (CSV) files. Process data are saved in high resolution (0.1 second) while application results and status data are stored in medium resolution (1 second) for duration of four weeks.

B. Set – up delivery of the commercial PDC

The phasor data concentrator installed in the National Dispatching Center runs on a server machine based hardware. It consists of a system monitoring center (master) and three client workplaces. The system consists of different commercial software modules, one of which is the connectivity package which is used to translate the binary

PMU protocols into the OPC standard data protocol [3]. The PMU data is provided in IEEE PC37.118 protocol, although the IEEE 1344 standard is also available. Three different user profiles are configured: administrator, used to administer the whole system; engineer who can configure parameters and add phasors to trend displays and the operator designed for the personnel involved in daily power network operation.

The graphical user interface is a simple representation of the Croatian 400kV transmission network (Fig. 2). All the nodes which are observed with PMUs are represented in blue color, and are associated with voltage, frequency and power measurements which are shown on the display in real time.
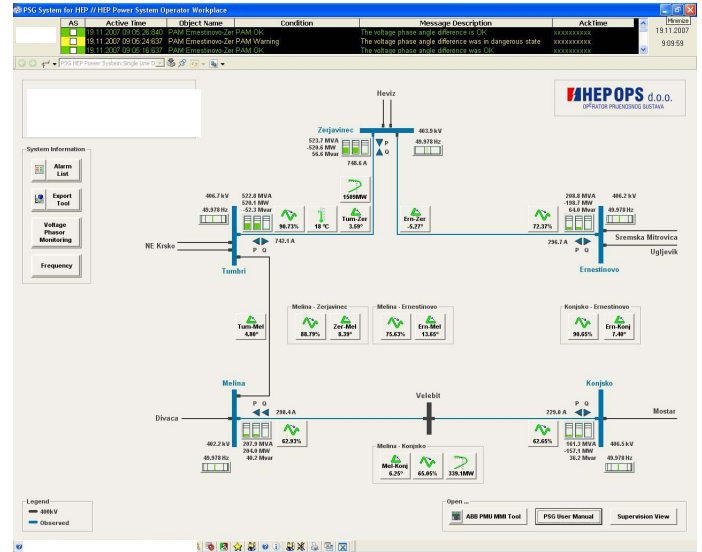

Fig. 2. Graphical user interface

The operator workplace consists of active elements, meaning that clicking on an element it opens a faceplate that displays the measured signals (Fig. 3.). In the same way access to advanced applications (phase angle monitoring, power oscillation monitoring…) is realized.

The operator looking at the display needs time to see and comprehend the data presented. Measured data changing in the trend display appears as a motion video, which is very impressive to look at but very difficult to derive a sense of the state form. Display involves a human element and the rate at which the information can be perceived and acted upon is limited. Given this limitation a need for a more intuitive and custom made data representation arises. Archiving of the phasor data was a challenging task for the initial PDC as well. At the first set up delivery the initial commercial PDC had a circular data base and storage time of only 4 weeks. The large amount of data needed a secure and automatic backup. Data collected during a disturbance in the power system was manually exported in CSV file format and saved on an external disk. This time – consuming and non reliable way to save data had to be replaced with an automatic event driven data archiving software.
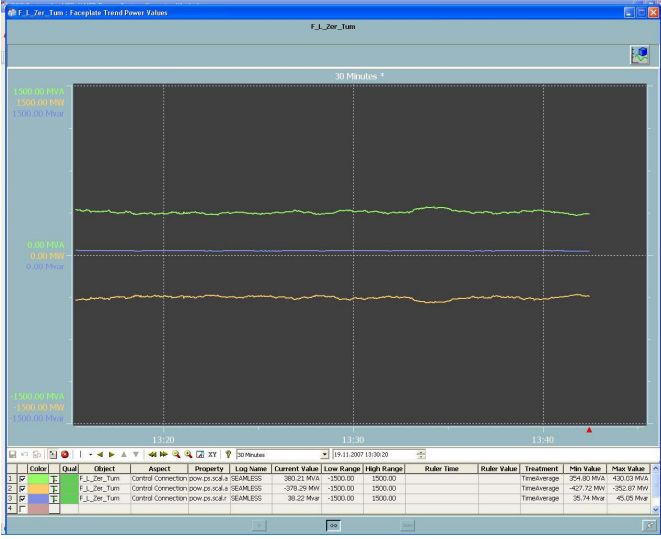
Fig. 3. Power measurement trend display

Collected phasor data is used by different user types in different ways. An intuitive, easy to modify and accessible network model and on-line data representation is crucial for the power system operator/dispatcher. This is not so important for the power system analyst who's mostly interested in a good archiving and data export functionality.

C. Development of custom open system architecture

Development of custom system for processing, archiving and visualization of phasor data started with the idea of extending archiving capabilities in a way which would not require any changes in existing system [1]. This was realized with custom historical data server which acquires data from existing system through OPC-HDA interface and stores data into external MS SQL database which can hold a much larger amount of historical data than existing historical database and is practically limited by available disk size. Additionally, data archiving is event driven with customizable parameters for each measurement or calculation result. In order to further minimize number of unimportant events and thus the size of historical database, hysteresis range parameter is applied on input data which prevents rapid event generation in case of oscillation of data values around threshold value. Events triggered in the process of analyzing input historical data are also stored in database which simplifies later identification of important points in historical database.

Next step in development of custom system was to extract real time data from existing system and potentially other data sources, do some calculations and visualize data to the operator.

The main and the most difficult task to be accomplished was the modeling of a multi-purpose and open system architecture which would be able to communicate and collect data from different sources such as the already existing phasor data concentrator, virtual PMUs, SCADA and synchrophasor vector processor. The system has to be able to manage data from all of these sources, filter data if required, provide real time monitoring, create record of outages and errors, record

and store data [4], [5]. Also, the human interface needed to be adjustable for different user profile requirements. The system architecture block diagram is shown in Figure 4.

System architecture is based on the concept of universal data representation and loosely coupled components to achieve maximum flexibility in customizing system for different user requirements without changing the core of the system [6].
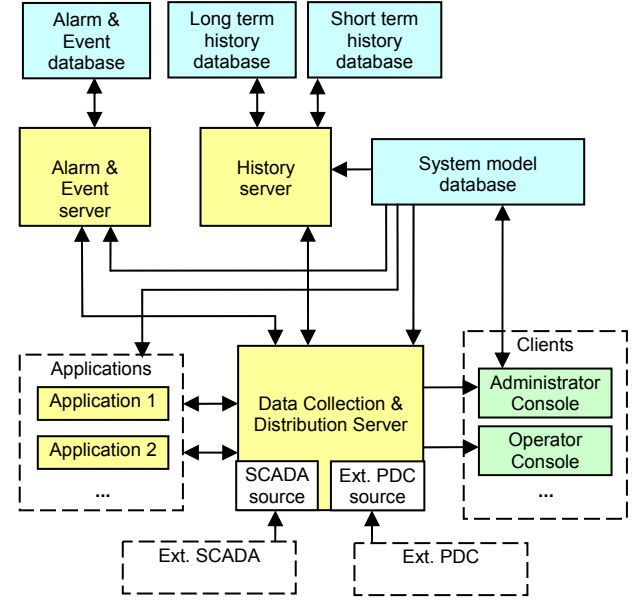

Fig. 4. System architecture block diagram

System is built around the main information data store (System model database) which is used by every system component and which contains information such as classes of data, network model, visual model, application parameters etc [7]. Data store is based on universal data representation in a form which bridges object oriented higher level data representation with relational database and essentially represents a form of object-relational database. System model database is physically implemented as MS SQL database with stored procedures used for reading and writing data. Data representation model is shown in Figure 5. Data is represented through four entity types: resource, link, property and property value. Resource is a general entity type which represents any type of abstract or real object in model. Resource is divided into four types: domain, class, group and object. Domain and group resources are used for hierarchical grouping of classes and objects respectively. Class and property resources together define template for objects which represent real world objects with property values containing actual object data. Resources can be linked together with link entity to form relations between domains, classes, groups and objects. Link entity can link resources in two ways: vertical (parent-child) relation and horizontal (connection) relation.
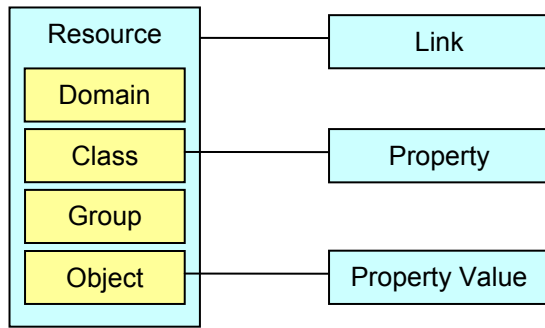
Fig. 5. Data representation model

The advantage of this concept is that the structure of power system model as well as other types of data structures are not predefined and can be changed by user through graphical user interface to fulfill the needs of particular application. For example, if user wants to add new custom calculation application to the system which uses some new power system parameters, he will simply expand the model with these new parameters through graphical user interface. Another advantage is that extension of the system with new calculation applications, visualizations and data sources does not require any changes to the core of the system. This advantage has already been realized in the process of system development where core system components almost did not change since the start of development.

Central part of the system for handling real time data is Data Collection and Distribution Server (DCD Server) which routes data between different data sources such as external PDC or SCADA and external calculation applications and clients. DCD Server is based on publish/subscribe mechanism which allows event based data exchange between different system components. There are two types of components which connect to DCD server: data source and external application. Data sources are special plug-ins which implement required interface for DCD server on one side and specific communication protocol on the other side to enable communication with external data sources. External applications are Administrator and Operator console for system configuration and data visualization, History server for data archiving, Alarm & Event server for alarm and event processing and different calculation applications.

Real time data processing and calculation is performed within calculation applications which run in the background as operating system service. They connect to the System model database to get power system network model, parameters and other information and DCD Server which provides real time data from external sources and other components and allows calculated data to be published and available to other system components. Applications can connect to System model database and DCD Server directly or through special adapter libraries which provide customized data access and formats required by particular application. For example, most calculation applications need simple network model with just two object types: node and line. In such a case it would be

justified to use adapter library which would act as a layer between more abstract data representation in model database and concrete and simple objects required by calculation application.

Integration of all system components shown schematically in Figure 4 is archived by using technology of distributed objects which communicate over TCP/IP protocol. This automatically enables powerful horizontal scaling of the system if more processing power is needed. For example, each calculation can be built as separate service and placed on different servers without changes to the system configuration except making sure that the correct IP address of the DCD server is entered in each calculation service configuration file.

There are two types of client applications with graphical user interface: Administrator Console and Operator Console made for corresponding two types of users.

Administrator Console allows system administrators to configure every system component and modify data and visual model. It currently allows editing model structure, the actual data model, visual model, visual symbols and custom functions. Model structure editor is used for editing domains, classes and properties of previously described data model. It is essentially a template editor which is used to define all structures which will be used to represent actual objects and data. Editor allows creation of domain and class hierarchy with definition of properties for each class and possibility for one class to inherit properties of each parent class. For each class property, various attributes can be defined like, for example, type of value which can be real number, text, image, file or something else. Another part of Administrator Console is a model editor which uses previously defined classes as templates for actual objects which represent real world power system objects or other types of objects which are used internally like diagram, function etc. Administrator Console with model editor is shown in Figure 6.
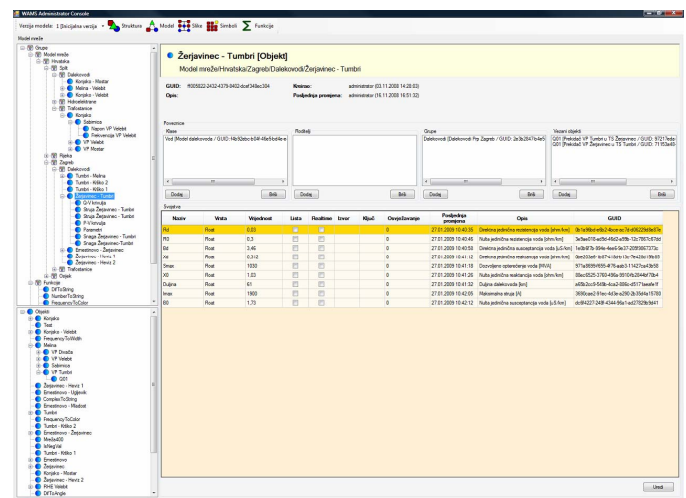

Fig. 6. Model editor of Administrator Console

Model editor allows creation of hierarchical tree of objects and object groups which is represented by parent-child relation in model database. For each object it is possible to

specify any number of classes, parent objects, groups and connected objects. Actual object data is stored in form of property values which correspond to properties defined in classes specified for particular object. In Figure 6, editing of one transmission line object is shown. In the middle of the screen a number of property values defined by transmission line class are visible. They represent transmission line parameters while measurements and calculated values are contained within separate child objects. It should be noted that the value of any real time property is not stored in model database. It is only identified by its globally unique identifier, used in data exchange between DCD server and various applications and in the end eventually stored in historical database.

Visual model editor is another part of Administrator Console shown in (Fig. 7) which allows editing of Visio-style diagrams which can represent any type of vector graphics. Diagram shapes can be drawn using various basic tools or made from predefined or custom shapes which can be edited through symbol editor. The most important feature of the diagram is that it can be made dynamic by binding real time data to shapes. This binding is achieved between shape property and custom function with real time values as parameters which returns value of shape property. Since each shape has plenty of properties, powerful dynamic visual diagrams can be created in this way. For example, user can build voltage angle difference gauge with dynamic arrow which will change its angle proportionally to the voltage angle difference real time data. Also, the gauge can change color if angle difference exceeds predefined limit.
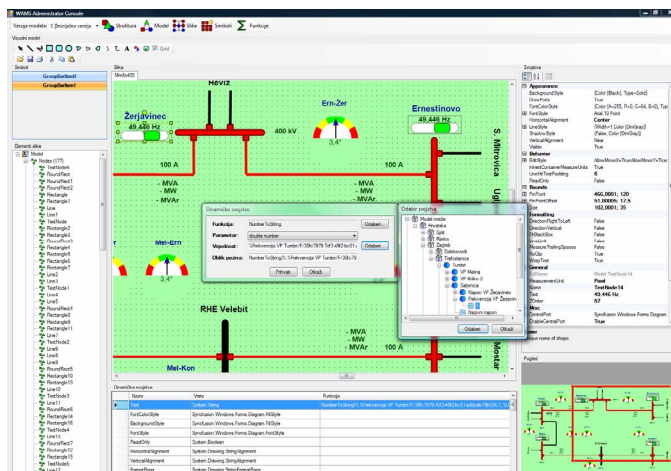

Fig. 7. Visual editor of Administrator Console

The functions used currently for visual elements can be written in C# language and are edited in separate part of Administrator Console. It is a rich text editor with syntax coloring and common text manipulation functions. Functions can take any number of real time arguments and parameters to calculate resulting value. Since the function language is C# and functions are compiled with standard .NET C# compiler, there is a great flexibility in writing function code because of the .NET framework in the foundation.

Operator Console is a graphical user interface for system operator and analyst designed with simplicity and interface customization in mind and is used for graphical and textual real time and historical data presentation. Operator console allows users to create personalized views of data by using customized data presentation modules.

Data presentation modules are separate plug-ins for Operator Console which implement required interface and are completely independent small applications for data presentation. Each module can be customized and customization data can be saved to disk which allows building different looking versions of the same presentation module. Modules are displayed in separate windows while the whole workspace is multi window with option to save positions and types of displayed data presentation modules for later switching between views. Operator Console with some opened data presentation modules is shown in Figure 8. In this stage of development there are few basic modules developed: historical events view, graph view of historical data, diagram viewer for displaying diagrams edited through Administrator Console, p-v and q-v curve graphs with actual loading point trajectory and radar and line graphs of voltage and angle [8], [9]. Diagram is made to represent 400kV transmission network with dynamic basic data like frequency, voltages, currents, active and reactive power, voltage angle difference between every node and calculated transmission line parameters.

Fig. 8. Operator Console

History server is another important part of the system which enables power system performance and post disturbance analyses by recording measured and calculated data from different data sources and applications to SQL database. Currently, it is planned to extend current history server which independently archives data from existing system and to integrate it with new system like shown in Figure 4. It will have more advanced features like complex rules with multiple parameters written as C# functions to enable event based data recording for more efficient data storage. Also, it is planned to introduce new data source for DCD server which will connect to History server and

distribute historical data to subscribed clients as real time data in the same way as any other real time data source. This will be the extension of currently built data source which allows replay of historical data from CSV files.

History server reads and writes data into two SQL databases. Short-term history database is the place where data is stored first and it is a relatively small database with maximum history of one day. Because of its smaller size it is much faster to use for frequent history operations like real time data insertion. Data from short-term history database is periodically transferred to long-term history database which is much larger and thus slower but it is not used so frequently as short-term database. History databases are cyclic with configurable data retention interval which means that after defined period of time the oldest data will be automatically deleted.

Last part of the system which is currently under development is advanced alarm & event system which will enable real time recognition of important events by using previously described custom functions. This way it will be possible to recognize event which is triggered by particular combination of various real time measurements and calculations. Also, it will be possible to define appropriate alarm levels for such events.

All events and alarms will be automatically stored in separate SQL database which will allow later identification of important historical events and also simplified navigation through historical data.

III. CONCLUSION

Wide are monitoring is rising system that extends number of input data by deploying new PMUs in the power system in 10 millisecond intervals. Meeting such demands need new methods and architecture wide area monitoring system. This paper proposes multi-purpose and open system architecture that is able to communicate and collect synchronized data measurements from different sources such as the phasor data concentrator, virtual PMUs, SCADA and synchrophasor vector processor. Collected data are filtered and processed with the originally developed algorithm for power system real time monitoring purpose. Presented model with the corresponding software algorithm is a modern wide area monitoring solution.

IV. REFERENCES

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