Synchronized Sampling Uses for Real-Time Monitoring and Control

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***Abstract*—Real-time monitoring of power system conditions can help control center operators maintain adequate situational awareness. This paper addresses a set of visualization tools for future generation of switchable networks, with a particular emphasis on visualization used in the control center. While synchrophasor measurements are proven to enhance awareness of system operators, it remains unresolved how user interfaces that will aid operators in making decisions should be incorporated in existing interfaces for SCADA functions. This paper is aimed at developing an integrated visualization tool that will seamlessly incorporate time correlated information from synchrophasor measurements, SCADA and non-operational data. This will result in intelligent operator tools for alarm processing, fault analysis and breaker switching management, which will increase the effectiveness of power system visualizations and reduce the time needed to make decisions.**

I. Introduction

Currently large amounts of data are collected by Phasor Measurement Units (PMUs), and other Intelligent Electronic Devices (IEDs) at the substation level. Beyond the traditional Supervisory Control and Data Acquisition (SCADA) data collected by Remote Terminal Units (RTUs), very little PMU or other IED data are integrated into current Energy Management System (EMS) solutions [1, 2].

The goal of this paper is to investigate the potential benefits of integrating information obtained by PMUs and other IEDs into the control center real-time monitoring and control solution. It describes development of new software aimed at automated fault location and visualization.

With the growth of power system complexity, a major disturbance could trigger hundreds or even thousands of individual alarms and events, clearly beyond the ability of any control center operator to handle. To adapt to the new situation, intelligent alarm processor has been developed to aid operators recognize the nature of the disturbances. Meanwhile, various fault location algorithms have been presented in the literature in the past [3-5]. In order to be able to evaluate which algorithms are applicable for a given fault event, different data sources (measurements) should be utilized and the idea of optimized fault location which takes into account both temporal and spatial considerations has been proposed [6]. In addition, knowing the real-world environment around fault location and construction of involved equipment could enable utility staff to clear fault quickly and efficiently. Designing graphical user interfaces (GUIs) that can effectively convey the results of fault analysis still remains a challenge in the utility industry.

Besides alarm processing and fault location, some other applications such as cascading outage analysis and condition-based maintenance also need to be considered in the new visualization software. By presenting the analysis results through GUIs, operators, as well as maintenance crews and protection engineers will be able to monitor and evaluate real-time conditions of both power system and its components. Fig. 1 summarizes the objectives and expected contribution of our developments.

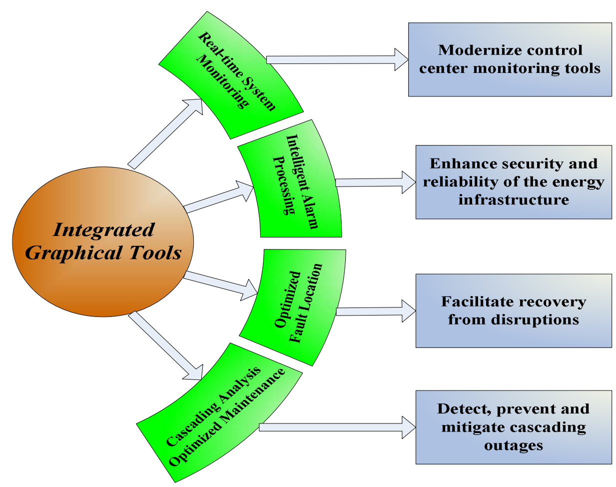

Fig. 1: Objectives of the new graphical tools for control center

The reported development was coordinated by the Consortium for Electric Reliability Technology Solutions (CERTS), and funded by the Office of Electric Transmission and Distribution, Transmission Reliability Program of the U.S. Department of Energy.

This paper starts with the investigation of specific requirements for data sources and applications, and then continues with a discussion of the functional designs of the integrated graphical tools. Finally, a complete implementation specification for the control center visualization tools is investigated. Conclusions are given at the end.

II. Requirements Specification

A. *Data Sources and Applications*

Currently, the time correlated information in a power system is obtained mainly through three types of equipments: Remote Terminal Units (RTUs) from SCADA, GPS-based equipments (e.g. PMUs), and some other IEDs (e.g. Digital Protective Relays - DPRs, Digital Fault Recorders - DFRs) installed in substations. Each type of measurement methods has its own particular application areas [1]. In order to fully utilize these recorded data, it is very important that information from various data sources, i.e. synchrophasors, SCADA PI historian database and IED non-operational data can be retrieved and integrated. Since different measurement equipment produces data in quite different formats, the conversion of data into certain standard formats is also necessary [5]. After the measurements have been concentrated and converted to applicable data files, they are processed in different application modules, including optimized fault location, intelligent alarm processing, and other applications (e.g. cascading analysis and optimized maintenance). The processing results will then be carried to the control center and presented to operators through the proposed visualization tools.

The applications serve as an essential bridge between data sources and our GUIs. Field measurements are their inputs, and their outputs shall be visualized in control center. Obviously, different applications will generate analysis results with different contents and formats, which need to be carefully specified before they are converted and utilized in visualization tools. Table I provides a tabular description of the application inputs and outputs.

TABLE I. Application Inputs and Outputs

Applications	Input Information	Outputs
Intelligent Alarm Processor	Circuit breaker control signals	1. Timestamp; 2. Analysis result; 3. Suggested actions; 4. Additional information.
	SCADA measurements	
	Phasors	
	Alarm Signals	
Optimized Fault Location	IED samples of voltage and current	1. Estimated fault section (Terminal bus numbers); 2. Fault location within the estimated section; 3. Exact fault type.
	Synchrophasors	
	SCADA measurements	
Other Applications	Phasors or synchrophasors	1. Cascade analysis reports; 2. Maintenance schedule; 3. Suggested operations.
	IED samples of voltage and current	
	SCADA measurements	

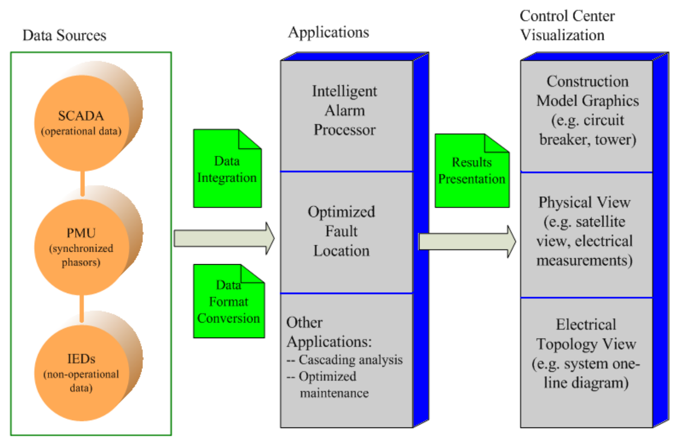

Fig. 2: Data sources, applications and control center visualization options

Fig. 2 gives the relationship between data sources and their applications. It also shows the general relationship between applications and our proposed control center visualization tools.

B. *Control Center Visualization System*

According to our design, three categories of views will be provided by the visualization software. As is shown in Fig, 2, they are Construction Model View, Satellite Aerial View, and System Electrical/Topological View. They will be further explained in Section III. Fig. 3 illustrates the hierarchy of the visualization system.

From the bottom layer of Fig. 3, data collected from GPS-based devices, SCADA and other IEDs are transmitted to the applications located at a higher layer. Commercial software such as PowerWorld, ATP-EMTP and PSS/E are located at the bottom layer and are utilized in short circuit calculation and fault analysis needed within application modules. The control center visualization tools, located at the top layer, are customized developments that are obtaining information directly from the applications, located at the second layer.

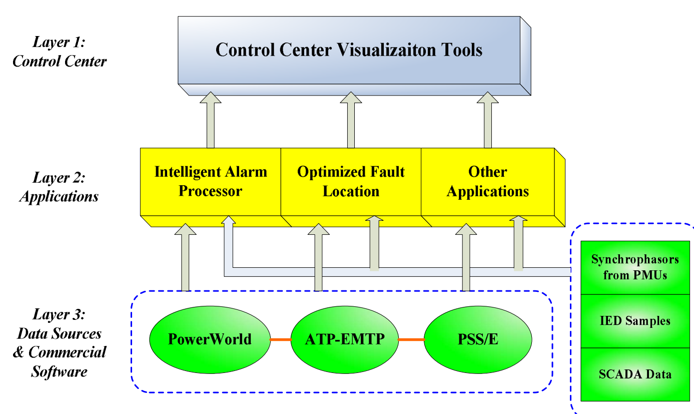

Fig. 3: Hierarchy of the visualization system

III. Functional Design for Visualization Tools

As demonstrated in Fig. 4, the following visualization functions will be incorporated in the graphical tools:

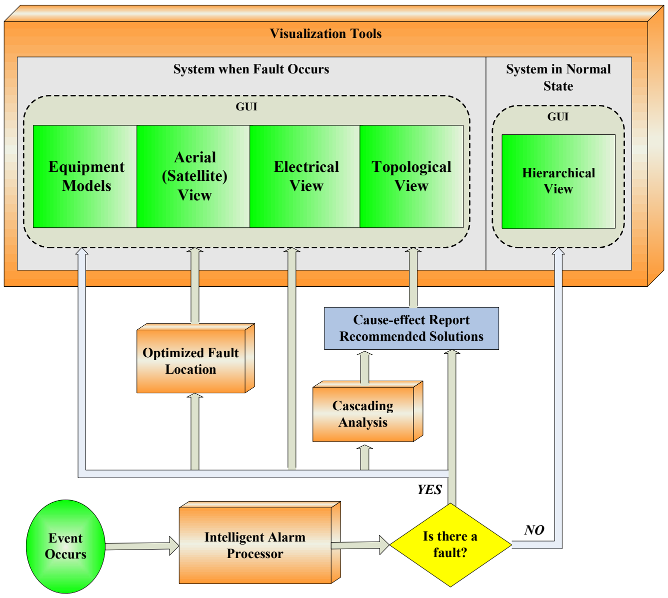

Fig. 4: Functions of Visualization Tools

- Equipment Models (circuit breaker, tower, etc.)
- Aerial View (satellite images)
- Electrical View (one-line diagram, power flow, etc.)
- Topological View (system topology)
- Hierarchical View (steady-state monitoring and analysis)

A. Equipment Model View

The Equipment Model View module is designed to provide constructional and operational view of the equipment of interest. Creating a generic model for each kind of equipment is necessary. Both 2-D and 3-D models are needed for a comprehensive view. Also, animated device operation process is needed to provide a better understanding.

Before showing the equipment models, the GUI needs to know where the faulted area is and which devices are included in that area. This means the faulted reports are required. Thus a data interpreter needs to be programmed first to convert the report to an applicable version.

As soon as the faulted zone has been located and user clicks on an equipment image, corresponding equipment model should pop up immediately. The design of equipment models for constructional view should then be developed and incorporated into the interface. Also, animated equipment operation demo in both 2-D and 3-D modes should be created to provide the operational view. To make the above two types of equipment model interactive, further programming is needed to enable different user functions. By deploying the object oriented programming (OOP) method, we will create different classes to accomplish this task. For example, the function of zoom in and zoom out will be encapsulated into one class. The reason for encapsulation is to prevent clients of an interface from depending on those parts of the implementation that are likely to change in future, thereby allowing those changes to be transparent to the clients. Other interactive functions incorporated within this GUI include flip and rotate, as well as operation curve plotting (e.g. circuit breaker operation).

B. Aerial View

To get a comprehensive view of the terrain around a fault location, satellite image is currently the best tool. The goal of Aerial View module is to convert satellite image into useful information for the purpose of fault location visualization.

It takes several steps to complete this GUI module. First, a data interpreter is needed to convert data and reports from external sources. Next, high spatial resolution images needs to be obtained by accessing the satellite imaging services.

Currently, Ikonos, QuickBird and OrbView services are capable of providing very high-resolution satellite images and are available on a commercial basis. The Ikonos satellite is the world's first commercial satellite to collect panchromatic images with 1 meter ground sample distance (GSD) and multi-spectral imagery with 4 meter GSD. QuickBird is a high resolution satellite owned and operated by DigitalGlobe. Using a state-of-the-art Ball's Global Imaging System 2000 sensor, QuickBird uses remote sensing to a 0.61 meter GSD. OrbView also offers one of the high-resolution satellite images. OrbView-5 will offer the highest resolution available to date by simultaneously acquiring 0.41 meter panchromatic and 1.64 meter multi-spectral imagery [2, 7, 8].

2-D satellite images could display the real-world terrain around a position. However, sometimes in system monitoring and control, information such as street and building are not as important as transmission lines and tress. In our design, several features will be integrated in this interface:

- Satellite image of streets, traffic routes and terrain view;
- Zoom in and zoom out of specific area with the image;
- Automatic overlay of transmission lines on the satellite image;
- Automatic indication of the fault location on the satellite image;

By processing the satellite images, we are able to abstract useful information which could be utilized to form the 3-D interactive model. These 3-D models include the critical information which operators are eager to know. The functional design and programming pipeline of the Aerial View module are illustrated in Fig. 5.

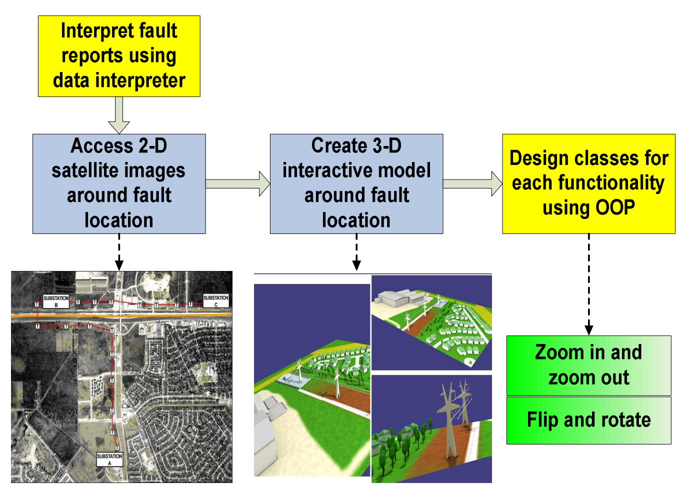

Fig. 5: Programming of Aerial View Interface

C. *Electrical View*

This is another independent module integrated in the visualization tools. Electrical view includes the visualization of alarms, power flows, system one-line diagram etc. As for the GUI, several basic functionalities are designed:

- One-line diagram of power system is established and updated using the real-time data provided by applications;
- Once new fault event is processed the corresponding faulted line of the diagram starts blinking. Description of the alarm is also presented to users;
- Power flow before and after the fault event is calculated and updated on-line, and presented to operators through the interface.

D. *Topological View*

The power grid topology describes connectivity of the various components in the power system. In order to process retrieved fault event recordings, they must be related to a specific position in the network from which they are measured and the information how the measurement positions were interconnected at the time of the fault occurrence. Therefore, the system topology must be known. Beside the connectivity, it is also necessary to obtain information about component characteristics at a specific moment of interest. We design the Topological View module to satisfy the above requirements. The features incorporated in this module include:

- Updated system topology overview;
- Substation number and connectivity view;
- Fault description including accurate fault location and faulted line display;
- Component characteristic and real-time status display;

E. *Hierarchical View*

The last module to be designed is the hierarchical view. Basically this module is a normal state monitoring tool, from which operators can visualize the system real-time topology, one-line diagram and power flow.

When a fault occurs, this module is also responsible for displaying the alarms. This can be accomplished by blinking the faulted lines/zone. Operators could then click that blinking area to check the fault details.

To achieve the above functions, several programming tasks need to be done in a specific order. First, similar to other modules, a data interpreter needs to be coded to convert data into applicable form. Secondly, to show the system topology, one-line diagram, and real-time power flow, an interface to the existing modules is needed. The equipment model view is obtained by accessing Model View module. The Electrical View module is accessed to show the system one-line diagram and power flow results. Topological View module is interfaced to display system topology. Further development may also be required so that the satellite images included in Aerial View module can be incorporated in the hierarchical view.

Except the basic functions such as zoom in and out, users will be capable of running contingency analysis such as N-1 analysis to analyze system stability and security. Related analysis reports as well as system power flow information can be stored in files for future use. Similarly, as the software development continues and on-site implementation begins, new functions may be added according to the needs. Here an event-response mechanism will be established. This means the program will be set to continually scan the interpreted data files. As soon as a fault has been detected, the area around the fault will begin blinking as a response to the fault alarm. Another task is to write code to respond to the click actions of users. Once the users click on a certain area on the screen, correlated information such as enlarged pictures or equipment models will show up.

F. *Proposed System Architecture*

To summarize the above functional designs of the visualization tools, as well as the descriptions of the data sources and applications, the entire architecture of the visualization system is shown in Fig. 6.

IV. IMPLEMENTATION CONSIDERATIONS

A. *Implementation Logic*

The overall implementation flow chart of the GUI software is shown in Fig. 7. Embedded in the flow chart are two types of logic: external logic and internal logic. The external logic explains the relationship between applications and GUI software, as well as their implementation sequence. The internal logic explains the relationship and implementation sequence of various functional modules and user interfaces within the GUI software.

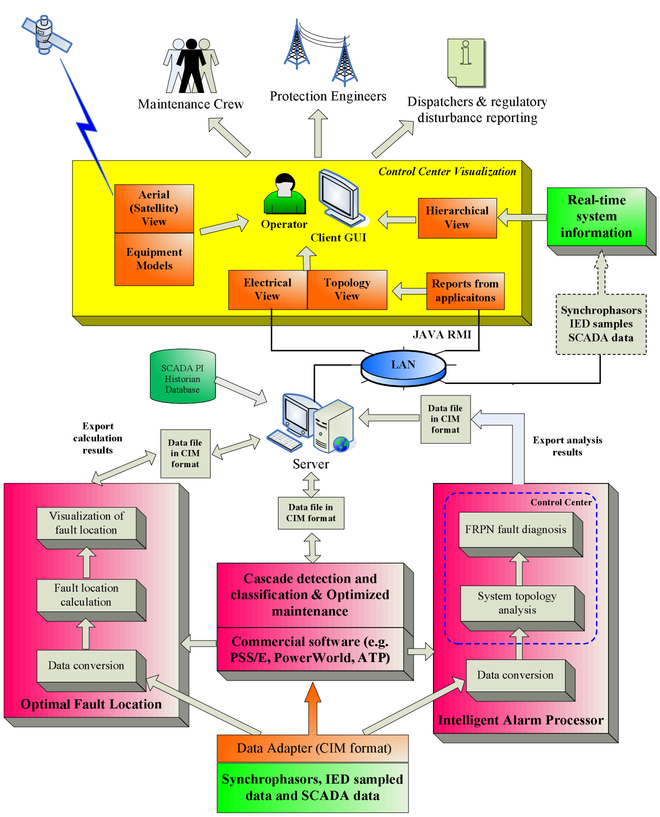

Fig. 6: Proposed System Architecture

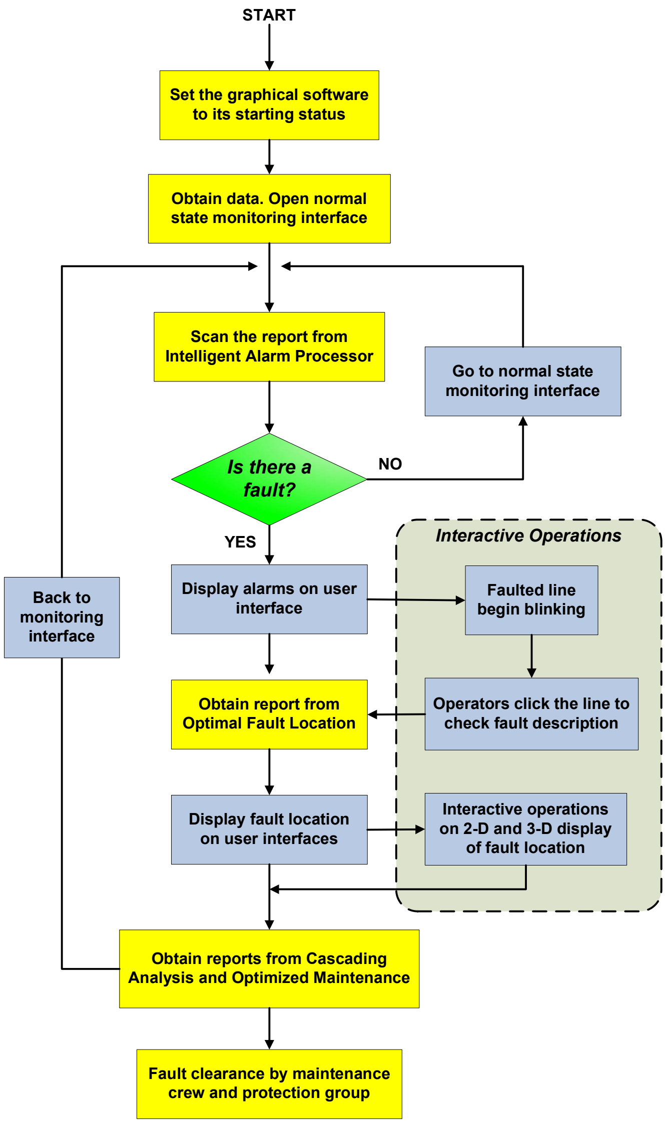

Fig. 7: Implementation Flow Chart of the Software

B. *Information Exchange Structure*

To define the exchange of information between application modules and control center, the inputs to the applications, as well as the data requirements and outputs of each functional module are discussed in Section II. In order to efficiently exchange information, the following requirements must be satisfied:

- A web-based file sharing system between control center computers should be established to send and receive digital data files over the network.
- Since the application output reports are produced and updated from time to time, an on-line data transmission and storage method is required.
- Since the outputs of applications serve as inputs to the visualization tool, a data interpreter should be utilized to convert different data files.

To meet the above requirements, an information exchange structure which possesses the following features is proposed:

- The Common Information Model (CIM), which is defined in IEC-61970, will be utilized as standard data modeling format;
- After converted to CIM format, metadata is stored to an XML file. Application modules will use this file to carry out analysis. Outputs from all applications will also be converted to CIM format for future use;
- XML file which contains outputs of applications will be sent to control center server. The server, which is located in equipment room, is responsible for collecting and saving data files from applications and SCADA PI historian database. It is also connected to client computers through LAN. Information exchanging between server and clients is completed within the network;
- The server and client computers are connected via Java Remote Method Invocation (Java RMI). The Java RMI provides for remote communication between programs written in the Java programming language.
- The proposed visualization tools will be installed in all client computers. Once an event occurs in power system, clients will receive fault reports from the server. Analysis results of different applications will be properly presented to operator through Graphical User Interfaces which are incorporated in the visualization tools.

C. *Roles of Operator and Utility Groups*

After the preprocessing of sampled data in substations and application modules, the control center equipped with visualization tools will now have two distinct features comparing with those of traditional EMS system:

- The substation data and extracted information are shared with different utility groups, including protection engineers, dispatchers, maintenance technicians, etc., making sure the data/information are presented in the form most suitable for a given group;
- Each group receives the best information since the origin of substation data becomes transparent to the users and what they receive is the best information obtained using all available data.

There are several advantages of doing this:

- The information, not data, is sent from substations to the upper levels for the operators to be able to use it in real-time. The information is extracted from the data in the time frame allowing real-time use. This prevents the communication bottleneck. The raw data, if needed, is sent at a later time when the communication traffic is not so intensive;
- The local information is extracted close to the source using abundance of IED data synchronized using GPS receivers. If a coordination of local conclusions is needed for system-wide analysis, this can be accomplished at a centralized location through further exchange of information.

In the proposed system architecture shown in Fig. 6, each utility group will be equipped with a computer with GUI client installed. The clients together with the server are interconnected through a local area network. Operator is at the top level and responsible for monitoring real-time system conditions. Other utility groups also receive information from client computers. The information they receive is not necessarily the same as the one received by the operator, but it is the most relevant information that pertains to their particular responsibilities.

Once an event occurs, the visualization tools will inform operator immediately. Operator could then assign tasks to different groups according to the fault reports and recommended solutions. The maintenance crew will be requested to repair system components identified with accurate fault location while protection engineers will be asked to analyze the fault clearance sequence and dispatchers will be required to re-dispatch the power generation and load flow to balance the whole system.

D. Other Considerations

1) Security consideration

For the system architecture shown in Fig. 6, once the server/client connection has been established, network administrator needs to assign particular accounts and passwords for different utility groups. User identification is strictly verified using user authorization and authentication techniques.

Different utilities will have different procedures for authorization and authentication for the use of the visualization software. Each module and interface should only be accessed by particular utility group who is responsible for that part. Any other groups or individuals will not be allowed to access this module and related graphical user interfaces.

Training of utility staff is necessary before they are permitted to use the visualization software. This is not only for the reason of the security of the local area network, but also for the safety of the entire power system, because any unauthorized or improper operation may cause very severe consequences.

2) Software maintenance consideration

In software engineering, software maintenance is the modification of a software product after delivery to correct design faults, to improve performance or other attributes, or to adapt the product to a modified environment (ISO/IEC 14764).

Our proposed visualization software requires a group of computer engineers for continuous maintenance after it has been installed in control center. The responsibilities of the maintenance group include:

- Monitoring software configuration and on-line application performance;
- Handling problems identified during software utilization;
- Proposing solutions to any new requests from users;
- Making software modification;
- Updating or replacing outdated software.

V. CONCLUSIONS

This paper proposes a set of new visualization tools, intended for the use in control centers for monitoring and control. The following accomplishments and contributions have been reported in this paper:

- The integration of time correlated information from Phasor Measurement Units, SCADA and non-operational IED data has been suggested;
- The existing data sources and the specific requirements of the application inputs and outputs have been explored;
- The five different view modules as well as their functions have been designed and explained in detail;
- The architecture of the data/application/visualization system has been presented;
- As it relates to implementation, both internal and external logics of the visualization system are specified;
- A complete information exchange structure between application groups and control center has been introduced;
- Several other implementation considerations such as security and maintenance are discussed at the end.

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REFERENCES

[1] M. Kezunovic, A. Abur, "Merging the temporal and spatial aspects of data and information for improved power system monitoring applications," IEEE Proceedings, Vol. 9, Issue 11, pp 1909-1919, 2005.

[2] T. J. Overbye, Sakis Meliopoulos, George Cokkinides, "Effective power system control center visualization,", Power Systems Engineering Research Center, Project Final Report, PSERC, May 2008. (Available: http://www.pserc.org)

[3] Chen, C. S., Liu, C. W., Jiang, J. A., "A New Adaptive PMU-Based Protection Scheme for Transposed/Untransposed Parallel Transmission Lines", IEEE Transactions on Power Delivery, Vol. 17, Issue 2, pp. 395-404, April 2002

[4] M. Kezunovic, C. Zheng, "Monitoring power system dynamic performance using synchronized sampling," CIGRE Conference on Monitoring of Power System Dynamics Performance, St. Petersburg, Russia, April 2008.

[5] W. Prince, B. Wollenberg and D. Bertagnolli, "Survey on excessive alarms," IEEE Transactions on Power Systems, Volume 4, Issue 3, pp. 188-194, August 1989.

[6] M. Kezunovic, B. Perunicic, "Automated transmission line fault analysis using synchronized sampling at two ends," IEEE Transactions on Power Systems, Vol. 11, No. 1, February 1996.

[7] S. Kocaman, L. Zhang, A. Gruen, D. Poli, "3D City Modeling from High-resolution Satellite Images," ISPRS Ankara Workshop 2006, Ankara, Turkey, Feb. 2006.

[8] Yoshihiro Kobayashi, George Karady, Gerald Heydt, Matthias Moeller, Robert Olsen, "Satellite Imagery for the Identification of Interference with Overhead Power Lines," Project Final Report, PSERC, Jan. 2008. (Available: http://www.pserc.org)