# The Future EMS Design Requirements

Mladen Kezunovic
Texas A&M University
kezunov@ece.tamu.edu

Anjan Bose
Washington State University
bose@wsu.edu

## Abstract

*The Energy Management Systems (EMS) were invented in the seventies to add computationally intensive applications to the Supervisory Control and Data Acquisition (SCADA) Systems which were introduced as the core infrastructure for scanning the field data in the sixties . Over the last 50 years many EMS functions were implemented and SCADA was further enhanced. Recently, limitations of low scanning capability of traditional SCADA became obvious and new substation Intelligent Electronic Devices (IEDs) such as Digital Protective Relays (DPRs), Digital Fault Recorders (DFRs) and Phasor Measurement units (PMUs) offered much better time resolution of the filed measurements. Such developments led to a question addressed in this paper: how should future EMS systems evolve assuming that new IEDs may be integrated in a common data measurement infrastructure.*

## 1. Introduction

As the central "nerve system" of grid operations and the open electricity market, Energy Management System (EMS) design is undergoing tremendous changes to meet the needs of the evolving utility industry. The Supervisory Control and Data Acquisition (SCADA) system was first introduced in the 1960s, making real-time data collection and process available to system operators. The SCADA solutions based on proprietary computer hardware and software made access to third-party software providers difficult. The goal of the next generation EMS design was to provide open implementation platform [1]. This next generation EMS adopted advanced technologies such as relational database and 3-D graphic displays with much more mature and standardized SCADA functions [2].

Traditionally, Supervisory Control and Data Acquisition System (SCADA) measurements are sent to the energy management systems (EMS) every two to ten seconds [3]. This was considered sufficient since EMS was primarily designed for tracking normal and alert states. The fast development of computer, communication network, and database technologies, and substation intelligent electronic devices (IEDs), as well as the new demands of electricity markets, makes developing a new generation EMS highly desirable [4]. The development is driven by the urge of electric power utilities to improve their service, and the need to accommodate new developments in a smart grid with penetration of smart sensors and distributed generation (DG) among others [5]. This leads to the need of much higher time resolution and precise time-synchronization in the SCADA measurements, as well as more powerful functionalities to deal with emerging monitoring, control and protection needs [6].

An expansion of current EMS applications has been proposed by many utilities as well as research organizations. In [7] the author discussed general requirements on retrofitting an Enterprise Energy Management (EEM) information system to support strategic energy management. BC Hydro proposed XEMS that features a data exchange interface with a legacy EMS and populates a relational database with the schematic of the Common Information Model (CIM) defined in IEC 61970 to drive a new EMS application in a remote Expansion System Server [8]. An N-EMS was designed to assist the temporal, spatial and objective applications of coordinated AVC and MW control, network re-modeling and on-line decision making [9]. All three designs are a retrofit of existing EMS for either enhancement of traditional or implementation of new application. A more evolutionary view of the EMS in the future is presented in [10] whereas [11] approaches for the EMS design from the viewpoint of new and advanced power system applications in the EMS.

More recent discussions are aimed at a future EMS design where standardized solutions will enable additions of different measurement and data processing infrastructures leading to enhanced functionalities and novel designs [12]. It is quite clear that integration of emerging data acquisition infrastructures will be at the core of the new design since the level of investment in the legacy solutions will favor additions and retrofits of existing EMS design rather than totally new EMS solutions, at least for a foreseeable future.

Section 2 gives a background of the limitations of the original EMS design. Section 3 summarizes evolution in the technology development, power system operation and options for future EMS designs. Section 4 focuses on opportunities for enhancement of existing EMS functionalities and elaborates on impacts of substation data integration and data model semantics. Section 5 focuses on data spatiotemporal and communication issues. Section 6 discusses new functionalities, the opportunities for enhanced operator views and capability to correlate events in the physical systems and electricity markets.

## 2. Limitations of the original EMS design

This section has a purpose of explaining the main motivation for writing this paper, which is to explain consequences of the mismatch between legacy and new EMS design requirements when considering data acquisition, management and communication architecture. This discussion leads to the need to specify the mentioned infrastructure for the future EMS design, which is the main contribution of this paper.

## 2.1 Power system operating paradigm

Late sixties witnessed a major blackout in the State of New York, which had a lasting impact on how the power systems were to be monitored and controlled going forward [1]. Numerous studies where performed to set a new power system operating paradigm where Energy Management Systems would have a role of guiding operators through what was considered at the time critical power system operating states shown in Figure 1: Normal, Alert, Emergency and Restorative [6].

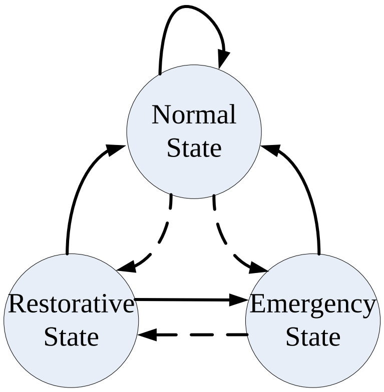


**Figure 1. Paradigm for power system states affecting EMS functionality**

With the proposed EMS design, two distinct power system management goals were firmly established: a) protective relaying, which operated autonomously and automatically and dealt with emergencies, b) energy management systems, which operated system-wide and included operators in the control loop to deal with planning, operations and system restoration. This separation meant that the protective relaying development, which was undertaken system the power systems were invented, would continue as an independent control infrastructure with separate wiring to the instrument transformers and circuit breakers, as well as other elements of the relaying system such as communication systems, interlocking logic and alarm tagging. This opened a need to enhance SCADA infrastructure with several monitoring and control functions, which collectively were designated as Energy Management System.

The state of the art of the technology at the time when the original Remote Terminal Units (RTUs) and Supervisory Control and Data Acquisition (SCADA) systems were developed resulted in somewhat constrained design in comparison what is feasible with today's technology. The RTU and SCADA designers' view at the time was that the following performance characteristics will be sufficient to allow operators to monitor the system, confirm validity of the operating and planning models, and execute control actions to maintain normal operation, steer the system conditions to prevent major blackouts, and successfully restore the system should it experience any emergencies:

- Collect analog measurements from instrument transformers and various sensors using transducers with rather limited frequency bandwidth around the fundamental frequency
- Collect contacts and circuit breaker switches through auxiliary contacts and deploy filters to eliminate impacts of contact bouncing
- Scan analog measurements and contact state every 10-20 seconds by employing the logic of "reporting by exception" assuring that communication channels are not overloaded
- Time-tag new data scans at the SCADA database assuming that the time delays in the communication system will not affect data synchronization between substation events and the time data arrives to SCADA database

## 2.2 Field data monitoring constraints

As a result of the mentioned design decisions for RTUs and SCADA, several data monitoring constraints were introduced:

- The analog-to-digital data conversion approach of scanning vs. synchronous sampling (utilized today and further explained later in the paper), did not allow monitoring of phase relationships between the three phase measurements of voltages and current preventing assessment of fault type and location.
- The long time laps (seconds) between RTU scans did not allow close monitoring of fast (millisecond) switching operations such as breaker autoreclosing and sequence of breaker opening in the lines connected through breaker-and-a-half schemes
- The reporting by exception created only fragmented view of system condition changes introducing a need to deploy state estimation rather than state measurement when trying to find the best match between power system models and measurements
- Time granularity provided with existing time-stamps at the SCADA database does not allow close temporal and spatial correlation (within tens of milliseconds) between events within and among substations

While the above mentioned data acquisition characteristics may look insignificant they actually had a strong impact on the EMS design properties and capabilities and profoundly affect EMS functional framework. This impact is illustrated in the following section where fundamental properties of the data acquisition system and its correlation with the power system monitoring capabilities are examined.

## 2.3 EMS functional framework

Based on the above observations of the data acquisition system design approach and mentioned performance constraints, some major EMS functional framework characteristics were established:

- Data scans could not accurately differentiate between various system switching states and phase unbalances, which resulted in the state estimator developed to monitor positive sequence values and topology processor introduced to try to differentiate between bad data caused by the measurement system v.s. the bad data perception caused by incorrect switching state (topology) detection
- Alarms used to differentiate between normal, alert and emergency states had to be individually traced without an ability to correlate them with protective relay operation, which created an "avalanche" of alarms created by major disturbances difficult to interpret at the time when operator had to have a clear indication of what was actually happening
- Time stamping at the SCADA database prevented an ability to correlate data at the source (substation) establishing a clear temporal and spatial relationship between measurements rendering an inability to use such measurements for direct state measurements or use of such data for model parameter estimation and verification

Since the initial SCADA and EMS design were conceived much technological and conceptual advancement were made and new opportunities for redesign of EMS data acquisition system were pointed out, which caused an ability to improve existing and develop new applications.

# 3. Evolving EMS design path

To appreciate how the new EMS design requirements have emerged one has to follow the development path in several directions: what is the new technology capability, how the power system infrastructure and operation have changed, and why the EMS design approach needs to change in the future.

## 3.1 Technology developments affecting EMS design

With the rapid advancement of technology, wide-spread substation deployment of Intelligent Electronic Devices (IEDs) comes into picture. These computer-based devices can record and store a huge amount of data (both operational and non-operational) with a sampling periodicity depending upon the intended purpose of the device. Their sampling rates are much higher than what is used in Remote Terminal Units (RTUs), and the data is sampled synchronously vs. being scanned in RTUs. In a modern integrated substation automation solution, various types of IEDs are interconnected for monitoring, control and protection purposes. All of the newer models have data recording and exporting capabilities today. The IEDs are triggered by various events such as faults and at that time they record data that is typically not captured by SCADA RTUs such as auto reclosing sequences, transients, and current DC offset [3].

The additional data from IEDs may not only improve existing EMS applications, but may also be utilized to implement new applications. The synchrophasor based Wide Area Monitoring, Protection and Control (WAMPAC) has been proposed to enhance system security in [12], and discussion about its implementation is elaborated in [13]. Automated fault location with improved accuracy, robustness and processing speed is proposed in [14], using both IED data and SCADA data. Condition-based maintenance of circuit breakers proposed in [15] took advantage of the trip coil data to improve maintenance efficiency and reduce forced-outages. These are just examples of the upcoming applications.

## 3.2 Issues in today's electricity grid operation

The expanding size of electric power systems and the increasing complexity in operation have brought up a challenge to detect and mitigate abnormal events. Cascading detection and mitigation is an application that tries to detect cascading events at an early stage and prevent them from developing into large-scaled blackouts [16]. In the meantime new additions to the grid are taking place. The distributed generation blurred the separation between the generation, transmission and distribution. Smart loads offered an opportunity to smooth out load curve by participating in Demand Side Management (DSM); some loads such as electrical vehicle can also act as a resource to support part of the grid when power supply is interrupted by faults. Intermittent renewables such as wind generator brought in complexity to operation and control along with clean energy requirements. How the EMS evolves under such new developments in the electricity grid expansion remains an important design requirement.

## 3.3 Approach to new EMS design

The new EMS design should be driven by the needs for data by different applications. It should consider the existing infrastructure, as well as the cost and time of re-furbishing and deployment of new infrastructure. We envision the discussion of the future EMS design approach in three stages.

The aim of the first stage is to improve existing applications by providing new data. At this stage the software architecture of EMS remains the same while data from non-traditional sources are merged with SCADA data to provide improved performance of existing EMS functions. At the second stage new applications are implemented. The EMS measurement infrastructure is retrofitted with adequate data transfer and processing capabilities. Also, communication paths between applications and interfaces with “outside” functions are implemented as needed to achieve that. The third stage deals with designing a future EMS with no constraint from current situation, meaning a whole new design of infrastructure for an ideal, next generation EMS.

Due to a limited scope, this paper is further focusing on enhancements in the existing design as a consequence of the data acquisition system technology improvements, which also affects the overall future EMS design paradigm changes.

The next section illustrates the possibilities for enhancing the existing EMS design using the intelligent alarm processor, topology processor and fault location enhancements.

## 4. Enhancing the existing design

To study the requirement for improving today’s EMS we selected three applications: alarm processing, fault analysis and state estimation. Improving such applications will result in closer tying physical systems and electricity markets, faster response to faults, and predictive assessment of system disturbances. The three functions have been identified to demonstrate improved performance of the mentioned applications: intelligent alarm processing [17], automated fault locating [18] and network-topology processing [19].

### 4.1 Introduction of the improved functions

The Intelligent Alarm Processor (IAP) model using fuzzy reasoning Petri nets (FRPN) was proposed in [17]. It can achieve the following goals: suppress multiple alarms from one event, generate a single conclusion through logical cause-effect relationship, automate the process to get answers quickly and make graphical and numerical information concise and easy to follow.

The proposed approach introduces novel techniques for achieving efficiency and speed in alarm processing developed by using SCADA data and additional data obtained from substation intelligent electronic devices (IEDs). IED data refers to the status information from Circuit Breakers (CBs) and relays. Figure 2 is the block diagram of an IAP. The block titled “CB status and relay status” provides new data used for each of the next steps.

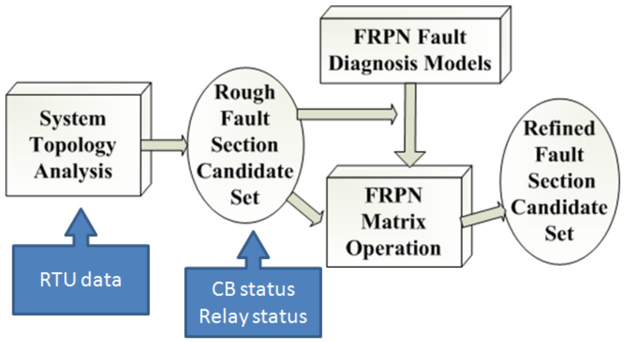


**Figure 2. Intelligent Alarm Processor**

In the fault location method from [18], phasor measurements from different substations located in the region where the fault has occurred are used. The measurements are sparse, i.e. they may come from only some of so many transmission line ends (substations) in the region. This method requires synchronization of the measurements, which may be obtained by using DFRs connected to Global Positioning System (GPS) receivers. Besides the sparse measurements, the technique also uses short circuit program, which is initialized and tuned with SCADA PI Historian, power system model data and measurements associated with the time of the fault occurrence. The method uses waveform matching technique between the current and voltage phasors calculated from the waveforms recorded in a substation (nearby the faulted line) and phasors simulated using short circuit simulation of possible fault locations.

Network Topology Processor (NTP) is an important function in State Estimation (SE), It determines the status of Circuit Breakers (CB) in real-time to obtain network topology. Traditionally NTP takes CB status data (on/off) to merge electrical nodes that are connected by closed CBs into a bus, and assign nodal injection devices and branches to the proper locations in the bus-branch model. Analog measurement data are used to determine the electrical quantities (voltage and current) directly (bus voltage magnitude measurements, bus power flow injection measurements, branch power flow measurements) or indirectly (nodal voltage magnitude measurements, nodal power flow injection measurements, CB power flow measurements, etc.). The Dynamic Utilization of Substation Measurements (DUSM) from [19] is a method that utilizes currently available measurements in substations to recover network observability to make up for loss of measurements due to topology change.

### 4.2 Integration of IED database and SCADA database

Implementation of the proposed functions requires both traditional operational SCADA data and non-operational IED data. The basic idea of integration of data shown in Figure 3 is to collect all the IED data in a substation database and use it for extracting information automatically.

The data integration and information exchange concept represented in Figure 3 raises a number of practical issues that need to be resolved for the proposed concept to be readily implementable:

- Data from different types of substation IEDs has different data conversion properties resulting from different data sampling rates, approaches to sampling synchronization, and time resolution
- Same of the IED data is scanned at fixed time intervals (RTU), some is captured when an event occurs (DRFs and DPRs) and some is continuously streamed (PMUs)
- Approach to controlling time correlation and time stamping is also quite different with all SCADA data being time stamped at the SCADA database while the

data from IEDs other than RTUs being time-stamped at the source but time correlated differently

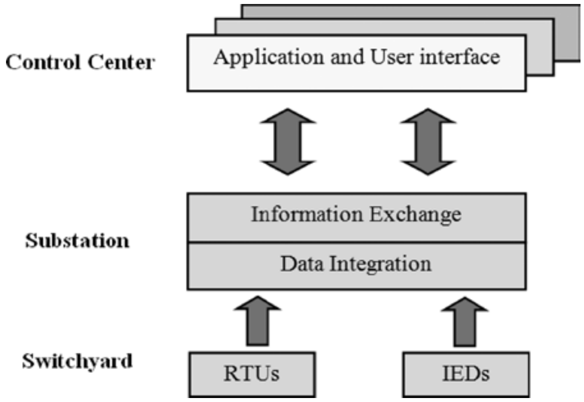


**Figure 3. Integrated data**

## 4.3 Semantics for IED and SCADA database integration

Figure 4 shows the architecture of data integration across the substation and centralized locations used for operating and maintaining the power system.

One big issue is how to convert data provided in different formats into the one that the new applications can use. One requirement is the consistent semantic modeling of IED data. IEC61970 is a standard for integrating number of complex applications developed by different vendors in the same semantic framework using Common Information Model (CIM) to represent the SCADA data [20]. CIM approach mainly focuses on modeling operational data and corresponding substation components. It is object oriented and extensions are possible. Practice shows that the published (CIM) version cannot meet the requirements of some important field device representations for real time applications such as FL. CBM, DFR and some other IEDs that may introduce new functionalities that do not have CIM representation. Extension of CIM such as currently done for PMUs is needed.

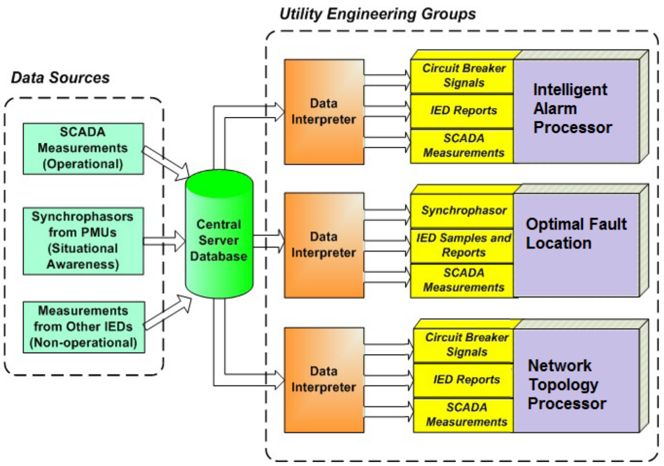


**Figure 4. Architecture for data collection and conversion**

While IEC61970 provides a detailed description of connectivity between various equipment, substations and their static and dynamic information, IEC61850 has the most detailed description of substation equipment and their monitoring and control aspects [21]. IEC61850 defines a tree of objects for modeling IEDs, starting from the server object (representing physical IEDs), and containing a hierarchy of Logical Devices (LDs), Logical Nodes (LNs) ad Data Objects (DOs). The issue of missing IED Model in CIM can be resolved through harmonization of CIM and IEC61850 [22]. Current standardization efforts are under way to allow straight forward implementation of the harmonization between 61850 and 61970.

The remaining issue is to synchronize all the data sources using common time-synchronization framework. A comprehensive approach to the time-synchronization issues has to be coordinated with the need to differentiate the spatial properties of data. Both issues are discussed in the next section where future EMS design is presented.

## 5. Future EMS Design Requirements

This section points to some key elements of the future EMS design, namely the temporal and spatial correlations, as well as new communication opportunities.

### 5.1 Temporal Considerations

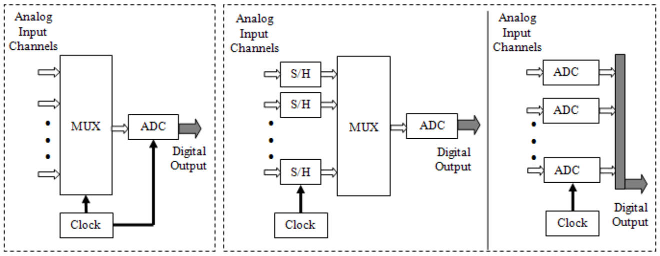
**Relative and absolute time as a reference for correlating power system events.** Monitoring, control, and protection applications require knowledge of the instance of time when a given event has occurred. The relative time may be used to understand the time sequence between the various control actions. As an example, knowing the inception time of a fault, the time it takes relays and breakers to operate can be calculated relative to the event incident time. Besides, an absolute time plays a role when various data related to a given disturbance is collected at multiple locations and such data is used to improve knowledge about the event. As an example, operation of multiple relays and tripping of multiple breakers may be sensed by IEDs located in multiple substations, so absolute time needs to be known to be able to differentiate actions corresponding to the same event from actions caused by other but time-adjacent events.

**Sampling clock time as a reference for synchronous signal sampling vs. scanning.** Various measurements in the power system are performed by IEDs, which convert the measurements to samples by performing analog-to-digital (A/D) conversion at the time the measurement is taken. The samples are taken by a sample and hold (S/H) circuit, and then the A/D converter converts samples into a computer word, known as data. The clock signal used for initiating the S/H circuit operation can be applied simultaneously (synchronously) for all the measured channels or sequentially as each channel is sampled/measured (scanned). Recovery of the information from data samples depends heavily on whether the signals were sampled synchronously or scanned. For example, it is possible to recover the phase angle between different phases in a three phase circuit if synchronous sampling was performed, but it may not be possible to recover it if the signals in the three phases were scanned. The mode of sampling clock control that results in synchronous sampling vs. scanning is widely different in modern IEDs vs. legacy Remote Terminal Units of Supervisory Control and Data Acquisition (SCADA) system.

**Time as a reference for waveform representation in time and frequency domain.** Many of the applications for monitoring, control, and protection require that the analog waveforms of current and/or voltage be analyzed either as time-domain functions or phasors. The time domain representation is important when waveforms experience transient behavior (during faults) while the phasor representation is sufficient for steady state conditions (during normal operating conditions). In both instances, how the time is represented is important, which leads to either an accurate representation of a waveform at any instant in time or an approximation of the waveform with a phasor at a given time.

Typical example of time synchronization between waveform samples is two-ended protection or fault location on transmission line which is implemented using time-domain solutions. A typical example of synchronization of phasor samples is in the two-ended fault location where the measurements from two ends are phasors but may be used either as synchronized or unsynchronized. While the phasors extracted from sample may be used for many applications, taking phasor samples synchronously across all the IEDs is more involved since it requires understanding of how the sample calculation is performed.

**Implementation of the time reference.** To illustrate how various options of time synchronization mentioned above may be implemented, Figure 5 shows various designs of the sample and hold and A/D/ conversion circuits used in legacy and new IED solutions. For ease of implementation of the smart grid solutions in general and in particular the ones discussed in this paper, the sampling synchronization should be controlled by a common reference such as a GPS time synchronization signal [23]. GPS receivers typically provide both the sampling clock signal and absolute time reference as shown in Figure 5, which may be then combined with the design shown in Figure 6 to provide very precise control of all the temporal issues mentioned in this section.



**Scanning** **Synchronous Sampling**

**Figure 5. Synchronous Sampling vs. Scanning**

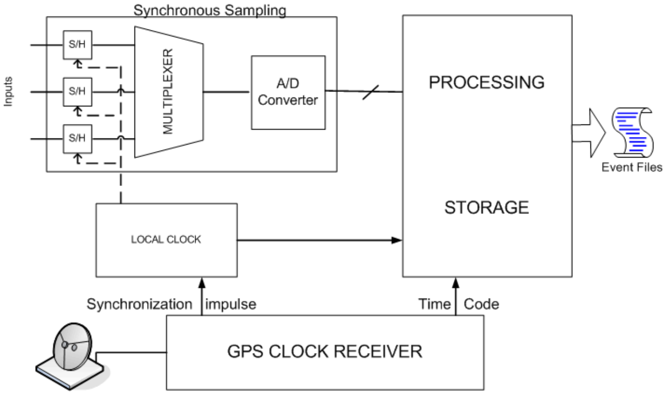


**Figure 6. GPS Synchronization**

## 5.2 Spatial Considerations

**Location as a reference for data processing and information extraction.** For various events in power system such as faults only specific power system components are involved in the event and only local data from IEDs are used in the process of information extraction. For example, transmission line protection relay uses only local data to analyze faults on the line. On the other hand, System Integrity Protection Scheme

(SIPS) monitors large area and requires wide-area data. Due to huge diversity in IEDs, their technologies and communication infrastructure it is challenging sometimes to achieve good spatial considerations. There are some innovative ways that could be used to improve presentation of spatial data obtained by substation IEDs: precise satellite images similar to Google Earth [24], National lightning Detection Network (NLDN) [25], and Geographic Information System (GIS) technology [26].

**Location as a reference for model representation.** In the approach to create new knowledge the extracted information needs to be supplemented by a predefined model. Choices of models vary depending which type of information is utilized to create them. As an example, the model can represent power system network, like in case with the Optimal Fault Location applications [18], or it can represent cause-effect relationship in control equipment operations like in the case of Petri-Net logic used in Intelligent Alarm Processor [17], or it can represent pattern space for resulting vectors in the Neural Network based Fault Detection [3].

**Location as a reference for applications.** Given that there may not be a clear divide between the applications at a substation and the applications at a central EMS, an application may reside at either the control center or a substation or even be split between the two. For example, those applications that are specifically meant for the human operator (monitoring, alarming, supervisory control, etc.) must be resident at the control center where the operator consoles are. Similarly, those applications like local control and protection will be resident at the substation. However, the wide-area control and protection that requires data from several substations can be resident on any computer to which communication of this data is possible. Similarly, some applications can now be distributed between several substations and/or the central EMS given that each substation will have significant computational capability to do a lot of pre-processing before sending information to the EMS (e.g. a lot of the topology and state estimation calculation can be done at the local substation before sending to the control center [27,28].

### 5.3 Challenge to communications

The biggest issue for communication is how to handle the huge amount of data.

- Bandwidth: Most of the communications networks being deployed today are based on lower-bandwidth, lower-cost technologies. As new data is being collected and transferred to control center, extra bandwidth is needed to accommodate the large volume of IED data. For example bandwidth over 100Mbyte/sec is most likely to be the lower boundary with the upper boundary reaching 1Gbyte/sec.
- Latency: As some of the selected applications are implemented to support system control and operation, latency becomes the most important issue in the data transfer, which is decided by the transfer rate and the number of switches the data transverses. The most stringent requirement for the latency comes from the cascading event detection where the local substation data such as fault location may have to be transferred to the control center and an automatic command issued within a few seconds.
- Data compression: It is a solution to improve the efficiency of data flow and hence reduce latency. For the events that do not show much change in the waveforms or measurements lossy or lossless compression may be performed. Data compression may be used to facilitate timely transfer of information.
- Congestion management: It is another solution to reduce latency under the condition of heavy traffic. Data classification and prioritized communication channel are the key issue in congestion management since special high priority data transfer may be implemented for emergency situations.

Figure 7 shows a generic communication infrastructure that connects all substations in an information network [29]. The communication infrastructure is shown as a three-level hierarchy. Each substation has its own high speed local area network (LAN) which ties all the measurements and local applications together. Each substation also has a server that connects to the higher level communication network through a router. LAN within control center receives data and sends it to different applications (after pre-processing, if necessary). Thus all applications requiring data from more than one substation, i.e., applications that are not local, have to use this higher level network for gathering input and sending output.

The main requirement for the communication system that will serve the future EMS is its ability to transmit the right data from the location where it is produced to the location where it is needed for an application. The data can be the measurements at a substation or processed data at some server. Different sets of data are needed by different applications at different time scales. The communication middleware must be able to handle this data transmission with a high level of quality of service (QoS). This kind of a publisher-subscriber communication system with the ability to monitor proper QoS is described in [28,30,31].

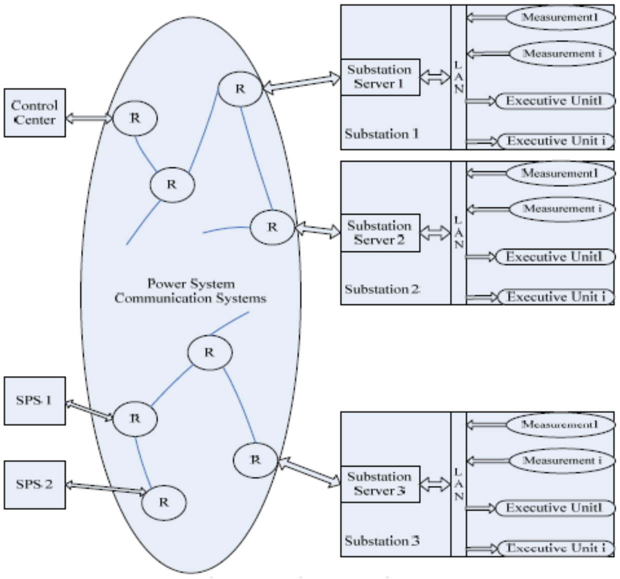


**Figure7. Real-time information infrastructure**

## 6. New Functionalities

The purpose of this section is to illustrate how the proposed EMS design enhancements may lead to development of new functionalities and operator support tools that are not feasible with the legacy solutions. This discussion reinforces the reasons and benefits of pursuing the proposed changes in the EMS design requirements.

### 6.1. Detection and mitigation of cascading events

An illustration of such a solution is given in Figure 8 [32]. This figure points out to the need to: a) monitor system conditions using synchronized phasor measurements to assess system disturbances that may result in major system contingency, and b) monitor protective relay operation using synchronized samples from two (all) ends of a transmission line to assess whether the lines switched out are actually faulted or now. The consequence is that that it is feasible to anticipate unfolding contingencies and monitor the impact that they may have on the system. As a result, the operators would be able to establish the fact that a cascade has been initiated and react accordingly to arrest cascade, which is not possible today.

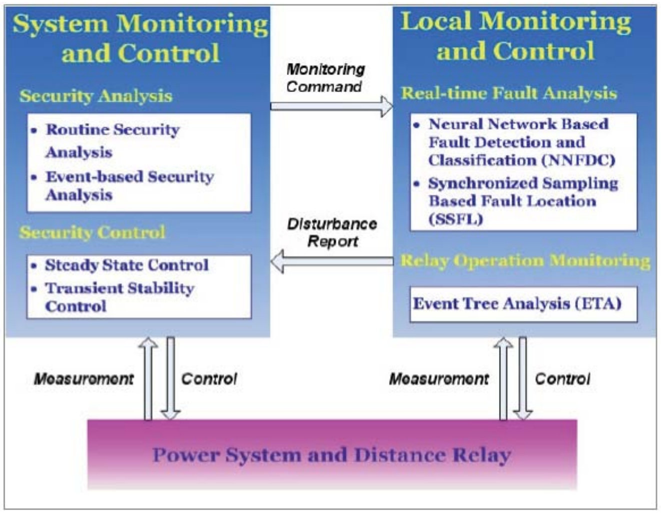


**Figure 8. Detection and mitigation of cacscades**

## 6.2 Enhancing the view of the power system

Based on the mentioned improvements in the alarm processor, topology processor, and fault location, and taking into account the new capability to detect and mitigate cascading events, a new set of monitoring capabilities may be offered to the EMS operators as illustrated in Figure 9.

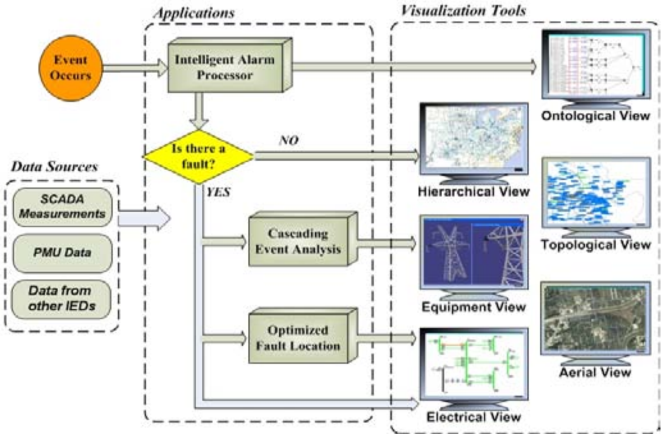


**Figure 9. Enhanced view for EMS operators**

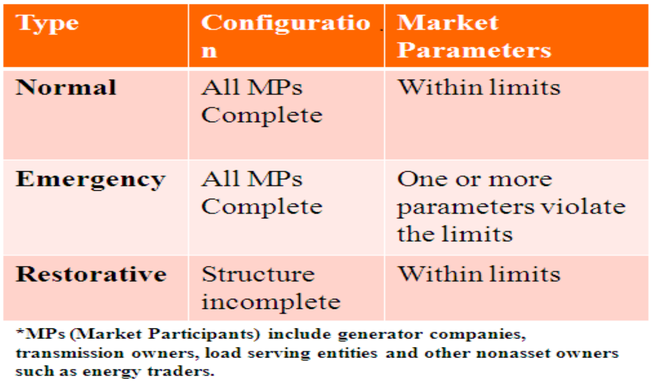
The EMS operator view concept illustrated Figure 9 reflects some new EMS design features not available in legacy EMS designs but certainly expected in the next generation designs:

- Underlying GPS time synchronization and stamping allows spatiotemporal correlation between field data and power system models assuring correct assessments of the dynamic states and transitions
- Improved data acquisition system allows detailed monitoring of the evolving system dynamics using synchrophasors and abrupt transient changes using time domain samples
- Improved functionalities allow quick understanding of the cause effect relationship among the alarms and accurate location of faults leading to detection and mitigation of cascades
- Improved hierarchical views of the equipment, electrical circuits, geospatial displacement, and network topology allows full understanding of the system conditions and targeted control action

If one compares the new capabilities illustrated in Figure 9 with the capabilities of the original EMS design one can certainly note improvements in operator's ability to view an operate power system.

## 6.3. Tying physical and electricity market states

With the proposed changes in the EMS design requirements, one can expect further improvements in operator's ability to correlate status in the electricity market operation and operation of the physical power system. An illustration of the market states that correspond to the power system states shown in Figure 1 is given in Figure 10.



| Type | Configuration | Market Parameters |
|---|---|---|
| **Normal** | All MPs Complete | Within limits |
| **Emergency** | All MPs Complete | One or more parameters violate the limits |
| **Restorative** | Structure incomplete | Within limits |

*MPs (Market Participants) include generator companies, transmission owners, load serving entities and other nonasset owners such as energy traders.

**Figure 10. The Electricity market states**

As an extension of the proposed correlation, one can develop new concepts in operating the system by tying together the high fidelity alarms with the economic constraints. A recently proposed concept of "Economic Alarms" allows this correlation to be established and explored to for the benefits of market and system operators [32]. The new economic alarm EMS functionality is shown in Figure 11.

As illustrated, this new EMS functionality ties together a cause-effect capability of the intelligent alarm processor enhanced with spatiotemporal measurements from all IEDs with the capability to better control and mitigate electricity market consequences caused by major physical disturbances in the system. Using this example, the new EMS design requirements can be summarized as follows:

- Improved data acquisition infrastructure provides better monitoring of the power system states

- As a consequence, operators are able better track and control changes in the power system operating states
- This creates ability to better match system and market conditions under major disturbances
- It also creates an ability to better respond to cascading events by arresting cascades early on

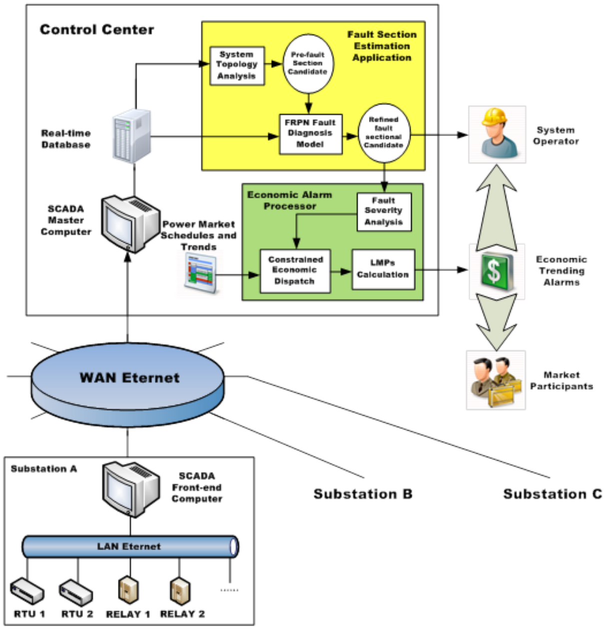


**Figure 11. Intelligent Economic Alarm Processor**

## 7. Conclusion

The continuing changes in sensing, measurements, communications and computation have now reached a stage where the digital data acquisition architecture that has served the monitoring and control of the power grid for over half a century requires a fundamental change to fully utilize the new technologies and realize the promise of a new generation of applications. Although the new applications will evolve over time, they are dependent on this new architecture requirement and the various considerations that will influence this design are discussed in this paper.

The time stamping and increased frequency (fidelity) of the measurements are fundamental differences in the data acquisition. So is the ability to process the data locally at the substation instead of all data processing centralized at the control center. This changes the communication requirements and points to a more networked high-bandwidth architecture rather than a star configuration. This further indicates that a decentralized database and applications that could be distributed may be considered going forward, but such approaches need much more elaborate set of application requirements that are outside the scope of this paper.

The purpose of this paper was not to propose a specific new configuration of the next generation EMS but to raise the various trends that will surely affect the new architecture that will evolve. In support of the new trends the paper has clearly indicated limitations of the data acquisition infrastructure in use today and illustrated how the new design features may affect existing EMS functionality and offer opportunities for development of new functionalities.

## 8. Acknowledgments

The authors wish to express thanks to the industry members of the NSF I/UCRC Power Systems Engineering Research Centers (PSerc), as well as to Electric Power Research Institute and Department of Energy who have supported PSerc’s Future Grid Initiative for funding that allowed continued exploration of the future EMS design issues over the years.

## 9. Reference

[1] CIGRE WG D2.24 report, “ EMS for the 21st Century-System Requirements,” CIGRE Technical Brochure 452, CIGRE, Paris, 2011.
[2] Wu Xingping, Zhang Yang, Wang Xiwei, "A New Generation EMS," Power System Technology, 2002. Proceedings. PowerCon 2002. International Conference on, vol.1, no., pp. 190- 194 vol.1, 13-17 Oct 2002.
[3] M. Kezunovic, "Translational Knowledge: From Collecting Data to Making Decisions in a Smart Grid," IEEE Proceedings, 2011 Vol. 99, No. 6, pp 977-997, June 2011.
[4] M. Kezunovic, J. McCalley, T.J. Overbye, “Smart Grids and Beyond: Achieving the Full Potential of Electricity Systems,” Proceedings of the IEEE, Vol.100, Special Centennial Issue, pp.1329-1341, May 13 2012.
[5] J. Giri, M. Parashar, J. Trehern and V. Madani, “The situation room,” IEEE Power and Energy Magazine, Vol.10, No.5, pp.58-69, September 2012.
[6] M. Kezunovic, A, Abur, “Merging the Temporal and Spatial Aspects of Data and Information for Improved Power System Monitoring Applications,” IEEE Proceedings, 2005 Vol. 93, No. 11, pp 1909-1919, November 2005.
[7] Van Gorp, J.C., "Enterprising Energy Management," Power and Energy Magazine, IEEE, vol.2, no.1, pp. 59- 63, Jan-Feb 2004.
[8] E. Vaahedi, A. Y. Chang, S. Mokhtari, N. Muller, G. Irisarri, "A Future Application Environment for BC Hydro's EMS," Power Systems, IEEE Transactions on, vol.16, no.1, pp.9-14, Feb 2001.
[9] B. Zhang, H. Sun and W. Wu, "A new generation of EMS implemented in Chinese electric power control centers," Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, vol., no., pp.1-3, 20-24 July 2008.
[10] F.F. Wu, K. Moslehi and A. Bose, “Power System Control Centers: Past, Present and Future,” Proceedings of the IEEE, vol. 93, No. 11, pp. 1890-1908, November 2005.
[11] K. Tomsovic, D.E. Bakken, V. Venkatasubramanian and A. Bose, “Designing the Next Generation of Real-Time Control, Communication, and Computations for Large Power Systems,” Invited Paper, Proceedings of the IEEE, vol. 93, No. 5, pp. 965-979, May 2005.
[12] Salehi, V., Mazloomzadeh, A., Fernandez, J.F., Mohammed, O.A., "Real-time power system analysis and security monitoring by WAMPAC systems," Innovative Smart Grid Technologies (ISGT), 2012 IEEE PES, vol., no., pp.1-8, 16-20 Jan. 2012.

[13] Johnson, A.; Jun Wen; Jia Wang; Liu, E.; Yi Hu; , "Integrated system architecture and technology roadmap toward WAMPAC," Innovative Smart Grid Technologies (ISGT), 2011 IEEE PES , vol., no., pp.1-5, 17-19 Jan. 2011.

[14] M. Kezunovic, "Smart Fault Location for Smart Grids," IEEE Transactions on Smart Grid Vol. 2, No. 1, pp 11-22, March 2011.

[15] S. Natti, M. Kezunovic, "Assessing circuit breaker performance using condition-based data and Bayesian approach, "Electric Power Systems Research, Volume 81, Issue 9, pp. 1796-1804, September 2011.

[16] H. Song, M. Kezunovic, "A New Analysis Method for Early Detection and Prevention of Cascading Events," Electric Power Systems Research, Vol. 77, Issue 8, Pages 1132-1142, June 2007.

[17] Y. Guan, M. Kezunovic, "Implementing Intelligent Techniques for the Advanced Alarm Processing," the 15th International conference on Intelligent System Applications to Power Systems , Curitiba, Brazil, November, 2009.

[18] M. Kezunovic, P. Dutta "Fault Location Using Sparse Wide Area Measurement," CIGRE Study Committee B5 Annual Meeting and Colloquium , Jeju, October 2009.

[19] M. Kezunovic, T. Djokic, T. Kostic, "Robust Topology Determination Based on Additional Substation Data from IEDs," PowerTech 2005, St. Petersburg, Russia, June 2005.

[20] “IEC 61970 Energy management system application program interface (EMS-API) – Part 301: Common Information Model (CIM) Base”, IEC, Edition 1.0, 2003-11.

[21] “IEC 61850 Communication networks and system in substations”, IEC, Edition 2.0, 2012.

[22] Project final report, “Harmonizing the IEC Common Information Model (CIM) and 61850 - Key to Achieve Smart Grid Interoperability Objectives”, Electric Power Research Institute (EPRI), May 2010.

[23] W. Lewandowski, J. Azoubib, W.J. Klepczinski, “GPS: primary tool for time transfer”, Proceedings of the IEEE, January 1999.

[24] Google Earth [Online]. Available: http://www. google. com/ earth/index.html.

[25] K. L. Cummins, J. A. Cramer, C. J. Biagi, E. P. Krider, J. Jerauld, M. A. Uman, V. A. Rakov, “The U.S. National Lightning Detection Network: Post-Upgrade Status”, Second Conference on Meteorological Applications of Lightning Data, January 2006.

[26] D. J. Maguire, M. Batty, and M. F.Goodchild,” GIS, spatial analysis, and modeling”, 1st edition, Redlands, California: ESRI Press, 2005.

[27] D.E. Bakken, C.H. Hauser, D.E. Whitehead, G.C. Zweigle and A. Bose, “Smart Generation and Transmission with Coherent, Real-Time Data,” Proceedings of the IEEE, vol. 99, No. 6, pp. 928-951, June 2011.

[28] H. Gjermundrod, D.E. Bakken, C.H. Hauser and A. Bose, “Gridstat: A Flexible QoS-Managed Data Dissemination Framework for the Power Grid,” IEEE Transactions on Power Delivery, vol. 24, No. 1, pp. 136-143, January 2009.

[29] A. Bose, "Smart Transmission Grid Applications and their Supporting Infrastructure," IEEE Trans. Smart Grid, vol. 1, pp. 11-19, June 2010.

[30] C.H. Hauser, D.E. Bakken, A. Bose, I. Dionysiou, K.H. Gjermundrød, V.S. Irava and J. Helkey “Security, Trust and QoS in Next-Generation Control and Communication for Large Power Systems,” International Journal of Critical Infrastructures (Interscience), vol. 4, Nos. 1/2, 2008.

[31] C.H. Hauser, D.E. Bakken and A. Bose, “A Failure to Communicate – Next-Generation Communication Requirements, Technologies, and Architecture for the Electric Power Grid,” IEEE Power & Energy Magazine, vol.3, No. 2, pp. 47-55, Mar/Apr 2005.

[32] Y. Guan and M. Kezunovic, "Grid Monitoring and Market Risk Management using Intelligent Economic Alarm Processor,“ IEEE Intelligent Systems, vol.26, no.2, pp.18-21, March-April 2011.