New concept and solution for monitoring and control system for the 21st century substation

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***Abstract*—Development of Intelligent Electronic Devices (IEDs) brings a leap in the development of substations. Large scale deployment of IEDs creates huge amount of data either recorder continuously or captured when IEDs are triggered by an event such as a fault or disturbance. The power system load increased to the point where the systems operate closer to the limits. The new developments enable much better monitoring to make sure the operation does not bring undesirable consequence. New automated monitoring and signal processing in substation has become a powerful feature necessary to assure the system is reliable and secure. In this paper, the new monitoring and signal processing solution in substation based on synchronized sampling technology and multifunctional IEDs (such as protection, controllers and PMUs) is proposed. To illustrate the above concepts new hardware and software solutions are envisioned. The hardware solution fully supports IEC 61850 protocol and takes cyber security into account. The software solution realizes the automated integration of substation IED data.**

***Index Terms*—Intelligent Electronic Devices (IEDs), signal processing, synchronized sampling, Phasor Measurement Units (PMUs), IEC 61850, cyber security, automated data integration**

I. Nomenclature

CBR — Circuit Breaker Recorder
CBRA — Circuit Breaker Monitor data Analysis
CIP — Critical Infrastructure Protection
COMTRADE — Common Format for Transient Data Exchange
DFR — Digital Fault Recorder
DFRA — Digital Fault Recorder data Analysis
DOD — Department Of Defense
DPR — Digital Protective Relay
DPRA — Digital Protective Relay data Analysis
FAFL — Fault Analysis including Fault Location
GOOSE — Generic Object Oriented Substation Event
GPS — Global Position System
IEDs — Intelligent Electronic Devices
IRIG — Inter Range Instrumentation Group
MMS — Manufacturing Messaging Specification
MTTF— Mean Time To Failure
NERC — North American Reliability Corporation
NTP — Network Time Protocol
PMUs — Phasor Measurement Units
PQMA — Power Quality Meter data Analysis
SCADA — Supervisory Control and Data Acquisition
SV — Sampled Values
SSSV — Substation Switching Sequences Verification
TSSE — Two-Stage State Estimation
VSDB — Verification of Substation DataBase

II. Introduction

The high voltage substation includes the primary equipment (such as circuit breakers, transformer, instrument transformers, etc.) and the secondary equipment (monitoring, control and protection devices), which are installed in the control house. In the legacy substation solutions, all the interfaces between primary and secondary equipment are connected by hard wired cabling. Different length and types cables are bundled, which makes the installation, as well as future maintenance and modification labor intensive [1]. In addition, due to the large number of wires in a highly electromagnetically “polluted” substation switchyard environment, the wiring may experience significant electromagnetic interference (both conducted and radiated) [2].

The sensing and signal processing in existing substation designs is centered on a number of individual sensors being placed in the switchyard and hard wired directly to the control house. The individual monitoring, control and protection devices that are using those signals for their decision-making are located in the control house. This concept is very inefficient in allowing integration of data and signal processing across the substation [2]. Besides, exchanging information among IEDs in the control house is realized by a combination of rigid wiring between devices and low speed serial communications. If a sophisticated inter-IED control scheme is to be realized, a large number of wiring interconnections between multiple IEDs is required. Such wiring approach is complicated to deploy and difficult to check errors. The low speed serial communications is often limited to master/ slave communication mode, so the true peer-to-peer communication between IEDs is not feasible.

The new monitoring and signal processing solution in substation based on synchronized technology and multifunctional IEDs (such as protection, controllers and

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PMUs) is proposed in this paper.

The paper first gives a brief discussion of the criteria considered in the new system design. Then the background technology to be used in the solution is outlined. Next, the hardware and software solution of the new system is explained in more detail. Finally the benefits evaluation of the new solution according to the proposed criteria is provided.

III. Criteria for the New System

Major criteria used in the new system comprise cost, reliability, cyber security, scalability and maintainability, and minimal co-dependencies.

A. *Cost*

Cost includes absolute cost, relative costs of materials and labor, and other cost caused factors. Multifunctional IEDs integrate multiple functions into a single device, which realizes cost savings for protection and control system. This integration results in a considerable degree of cost reduction due to decreased number of individual devices needed to implement required functionalities. It is estimated that total labor savings approaching 50% or more are realizable by deploying IEC 61850 9-2 standard process bus based protection and control system [3, 4].

B. *Reliability*

Reliability (40%) besides cost (35%) is the most dominating consideration in the current substation design [5]. Increasing the number of electronic devices and connections in a system, the system's reliability decreases, which is demonstrated by observing MTTF data and running calculations on hypothetical process bus architecture [6, 7].A properly designed architecture should be achieving compact and simple solution without decreasing the system reliability.

C. *Cyber security*

The process bus solution brings challenges for the cyber security solutions (intrusion detection and/or encryption) due to high data rates of the network traffic and high availability of data. NERC CIP series of standards (CIP-002-1 through CIP-009-1) provide high-level security requirements by [8]. Minimizing the risk of cyber security or human mistakes encourages sound architecture ensuring the benefits of the new technology.

D. *Scalability and maintainability*

Scalability assumes the system should be able to continue expanding as needed. An expansion or modification should not raise any communication network congestion or other related data transfer problems.

Maintainability is defined as the existence of simple, safe and trusted means of performing firmware and setting changes and replacing faulty elements of the system [6]. A sound designed system should consider scalability and maintainability before the solution is deployed.

E. *Minimal co-dependencies*

Minimal co-dependencies requirement assures that when a single zone of protection needs to be taken out of service for upgrades, troubleshooting, or maintenance, the rest of the secondary system should not be impacted and the primary system should not have to be taken out of service. A zone of protection should be deployed with minimal interactions with respect to other secondary systems. Otherwise, a firmware upgrade for a single zone component in the system may have unexpected impact on overall system behavior.

IV. New Substation Technology

The technology of interest used in the new design will be briefly discussed in this section: Synchronized Sampling solutions, optical current and voltage sensors, optical fiber communications, multifunctional IEDs, wireless networks, and communication network devices (routers, switches, etc).

A. *Synchronized Sampling Solution*

The utility industry widely uses GPS for providing a reference time signal, which in turn can be received at each substation through GPS receiver. There are two purposes for using GPS receivers:

- Synchronization of the sampling clock on the input data acquisition systems in IEDs;
- Time-stamping of the data acquired by IEDs.

The two implementations are shown in Fig.1.

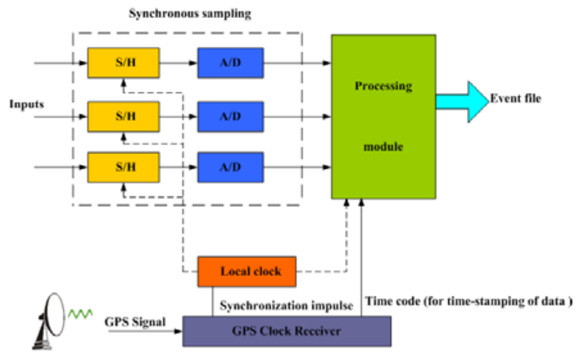

Fig. 1 Synchronized sampling implementation

B. *Optical current and voltage sensors*

Fig.2 shows the new optical current and voltage sensors. The main advantages of using optical sensors are the wide frequency bandwidth, wide dynamic range and high accuracy. Furthermore, these new sensors allow monitoring and control to be implemented with two important application features:

- Single sensor may serve different types of IEDs;
- Single sensor may serve large number of IEDs via process bus.

Those sensors also need GPS synchronization when the output samples are being placed on the process bus.

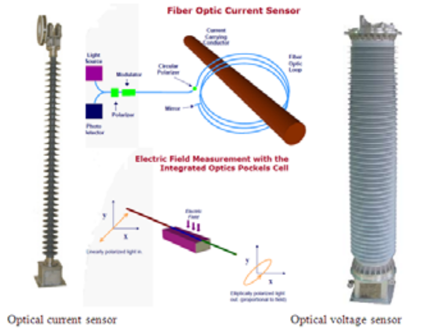

Fig. 2 Optical current and voltage sensors

C. Communication media

Four major communication media options are expected to gain use in a modern power system grid: microwave radio, spread spectrum wireless radio, fiber optic cables and high speed process buses.

The new substation design, a hybrid system that integrates fiber optic cable with high speed process bus, is adopted. Fig.3 shows diagram of optical fiber communication solution. There are two options for the optical fiber: single mode and multimode mode. Single mode has one stream of laser-generated light and may be used for long distance up to 3000 meters. Multimode mode has multiple streams of LED-generated light and may be used for medium distance and short distance. The benefits of optical fiber can be summarized as: supporting long distance telecommunication, offering greater data transmission capacity, and providing smaller size, lighter weight, and better electromagnetic isolation.

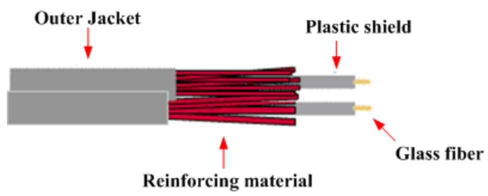

Fig. 3 Optical fiber solution

D. Multifunctional IEDs

Fig.4 shows a sample of the latest multifunctional IEDs from different vendors. Multifunctional IEDs are devices which integrated more functionality into fewer devices, resulting in more compact designs with reduced wiring. The most important advantages of IEDs are communicating through computer networks and hosting multiple applications, hence more information could be made available remotely. As an example, synchronized phasor measurements function is widely used for wide area power system monitoring and control, improving state estimation, archiving improved system monitoring performance, while also enhancing power system model validation and post-event analysis.

Fig. 4 Multifunctional IEDs

E. Wireless network

Fig.5 shows the idea of a substation wireless network. Video surveillance is installed to monitor the condition of the whole substation, which can improve the physical security of the substation. Temperature and motion detection sensors are used to monitoring the conditions of the switchyard. The entire range of sensing received from the switchyard can be transmitted to the control house through the wireless network. The hardened switches in the control house are used to control the data stream and assure security of the wireless network.

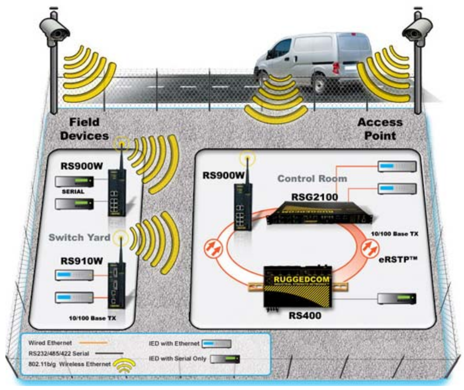

Fig. 5 Wireless network [9]

F. Network device

Ethernet switches which are shown in Fig. 6 maximize the benefits of the process bus. Ethernet switch process the message priority to realize the GOOSE scheme between relays, as well as the secure access, which will be discussed later.

Fig. 6 Ethernet switch

V. Implementation of the New Substation Solution

The solutions proposed in this section utilizes advanced concept for data and information processing. The copper wiring between IEDs and primary devices in conventional substations is replaced with optical fibers. All the multifunctional IEDs in the control house fully support IEC 61850 protocol. The recorded data is synchronized and time stamped utilizing receivers for GPS or computer network synchronization (IEEE PC 37.238). The time reference signal is distributed to downstream devices or IEDs by IRIG-B or IEEE 1588 V2 signal. Hardened Ethernet switches are used to process the message priority to realize the GOOSE messaging scheme between relays and provide security at the local area network level. The software applications include automated analysis of data from CBR, DFR, DPR and other substation IEDs. The new system enables automated collection of field data, extraction of information and sharing of information among different utility groups allowing them to have better view of the system.

A. Hardware implementation

The overall system architecture is show in Fig. 7.

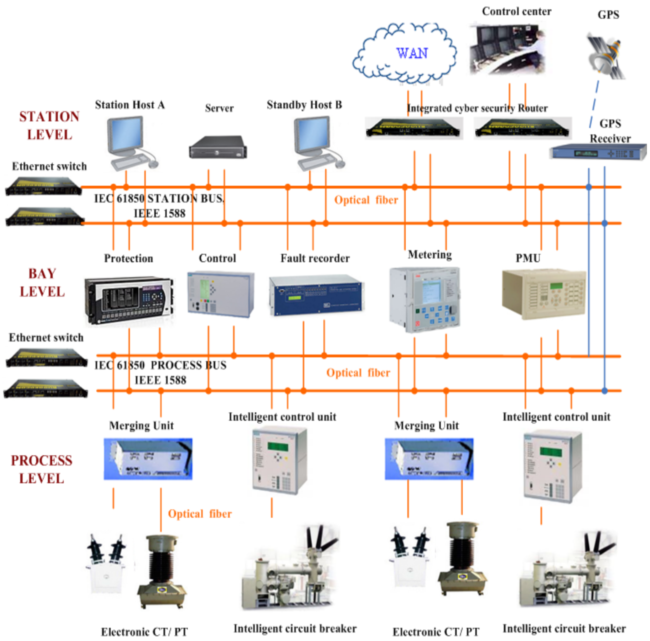

Fig. 7 Hardware implementation architecture

1) Process level solution

Optical current and voltage sensors are used instead of conventional transformers. The voltage and current signals are captured at the primary side, converted to the optic signals by merging unit and transferred to the protection and control devices in the control house via optical fibers. This can lower the requirement of transformer insulation and reduce the interference present in the analog signal transmission. Intelligent control units are used as an intermediate link for circuit breaker interfacing. The intelligent control unit converts analog signals from primary devices (such as circuit breaker and switches) into digital signals and sends it to the protection and control devices via process bus. At the same time, the tripping and reclosing commands issued by protection and control devices will be converted into analog signals and sent to the switchyard to control the primary equipment. Large amount of copper wiring between IEDs and primary devices in conventional substations is replaced by optical fibers.

2) Bay level solution

All the IEDs in the control house fully support IEC 61850 protocol. Synchronous phasor measurements are realized by PMUs. PMUs are used for wide area power system monitoring and control. The interoperation between IEDs is realized by using GOOSE massage network. The Ethernet switch is used to process the message priority to realize the GOOSE data exchange scheme between relays.

3) Station level solution

MMS network which is the communication link between SCADA, control center and IEDs at bay level is used in the station bus. Redundant networks are used for high reliability.

4) Cyber security issues

Since the Ethernet switches and routers are used in the network, the major concern is the cyber security. Hardened routers are used to specifically provide an electronic security perimeter for the protection of critical cyber assets. The hardened switches are used to provide security at the local area network level.

Besides the hardened routers and switches, secured access control device is used in the new design to further protect the security of the substation. The main function of such control device is shown in Fig.8.

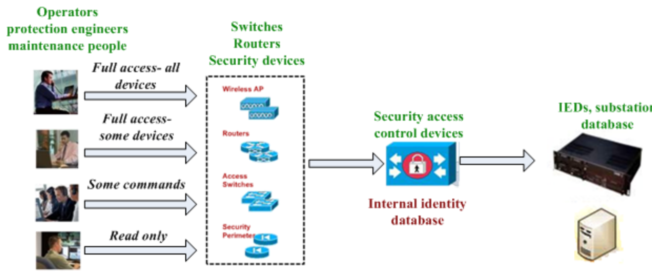

Fig. 8 Function of security access control device

There are four levels of access to the substation database. Operators are allowed a selected access (includes read and write) to all the devices (relays, meters and controllers). Protection engineers have the full access to some devices (protective relays). Maintenance people can only have the partial access to the devices. Customers or utilities can only read the substation data. According to the different access level, the different passwords or secured access methods are specified [8, 9].

5) Time Synchronization Methods

Modern protection, monitoring and control systems rely on the availability of high accuracy time signal. Time synchronization eliminates or reduces the effort involved in correlating event information from distributed intelligent disturbance recording devices. Accurate time signal is required for disturbance analysis in order to correlate individual device event reports and is also essential for synchronized system control and synchrophasor utilization. Moreover, time synchronization is also required when integrating data from different IEDs in different locations. GPS is the most common source to provide high accuracy time signal in current substations. Hence, the GPS becomes the single point of failures caused for example by solar activity, intentional or unintentional jamming, or U.S DOD modifying GPS accuracy or turning off the satellite system [11].

IEC 61850 recommends the NTP as the primary synchronization method, but NTP time accuracy is insufficient for SV applications (< 1us). IEEE 1588 Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems will be adopted to distributed the 1 us accuracy timing required. IEEE 1588 uses the LAN cables to distributed high accuracy time, eliminating the need for the additional IRIG cabling compared to separate IRIG time reference distribution. Clocks that support the IEEE 1588 standard will have more options for alternate time sources which will provide time source redundancy.

RuggedCom devices (RSG 2288 and RS 416 [13]) suggested in the new design are capable of receiving 1588 V2 through their Ethernet ports and distributing 1588 V2 or generating synchronized IRIG-B signal for legacy devices. Those devices used in the design make implementation of the IEC 61850-9-2 "Process Bus" more economical, more practical and easier to deploy by providing reliable and precise time synchronization over the substation Ethernet network. Besides, the new design facilitates the migration path from legacy solutions and paves the way towards IEC 61850 Edition 2.

B. *Software implementation*

In order to integrate data from multiple substation IEDs and extract information for different utility group purpose, a software package, which can combine bulk of data recorded by individual substation IEDs such as DPRs, DFRs, PMUs and CBMs and streamline it to provide a more relevant and versatile source of information to serve control center applications is used.

Fig.9 shows different levels of software-based analysis. The substation level analysis provides information to serve control center applications such as fault location, topology processor for state estimator and alarm processor. This analysis together with power system component models can provide system with wide level disturbance monitoring and analysis.

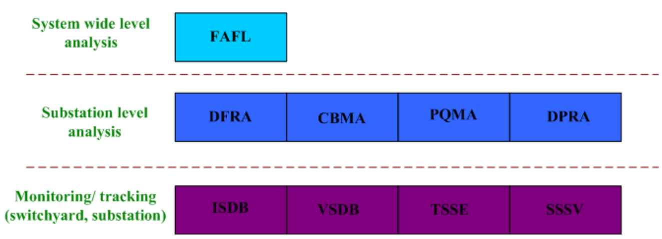

Fig. 9 Software implementation architecture

The substation data is divided into two categories: non-operational and operational data [14]. The software discussed here is adding the nonoperational data from relays, recorders and PMUs to SCADA data, because redundancy of data is very important in data analyzing and decision-making process. The new data processing uses standardized data and communication formats.

Fig.10 shows a simplified diagram of the substation level integration of data. Data is collected from IEDs in COMTRADE file format, and if not, the native format is changed to COMTRADE first, and then the data is processed at the substation level and populated into the database together with the automated analysis reports and recording system configuration information.

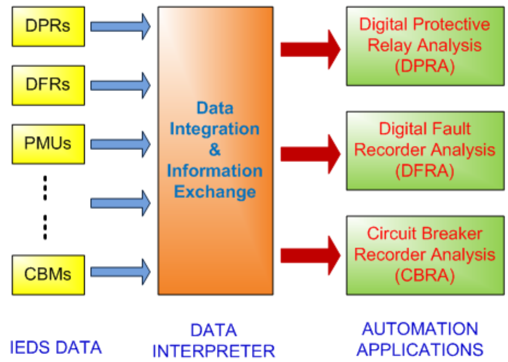

Fig. 10 Substation level data integration

Three types of the automated analysis applications: CBMA, DPRA, and DFRA will be discussed briefly here. IEDs are synchronized to the GPS reference clock and time-stamped data makes integration of data from different IEDs much easier.

IEDs from various vendors have different data files formats, so it is necessary to standardize file format before data integration.

1) CBMA

CBMA analyzes waveform records taken from CBR, explains event, and suggests repair actions [15]. CBMA uses advanced signal processing and expert system techniques to enhance speed and provide timely results that are consistent. The main function of CBMA is shown in Fig. 11.

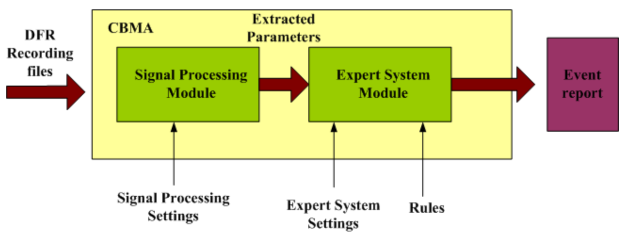

Fig. 11 CBMA function diagram

2) DPRA

DPRA is expert system based analysis software which automates validation and diagnosis of relay operation [16]. The main function of DPRA is shown in Fig.12.

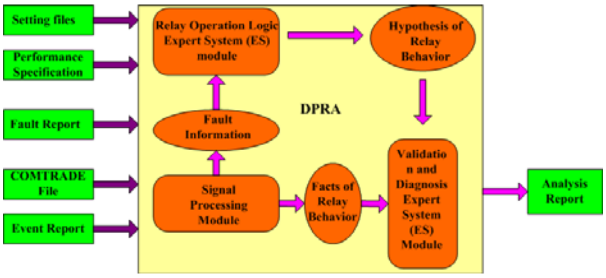

Fig. 12 DPRA function diagram

3) DFRA

DFRA provides automated data analysis and integration of DFR event records [17]. It provides conversion from different DFR file formats to COMTRADE. Besides, DFRA performs signal processing to identify pre- and post- fault analog values, statuses of the digital channels, fault type, and faulted phases. The main function of DFRA is shown in Fig. 13.

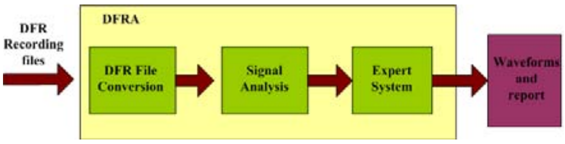

Fig. 13 DFRA function diagram

VI. Benefits of the New System

According to the criteria mentioned in section III, the benefits of the proposed architecture are as follows:

- Cost: Optical fiber replaces costly copper wires, which saves investment money, and reduces the construction labor and maintenance cost;
- Reliability: Redundant design improves the reliability of the whole system, and some level of self-healing can be realized by automatic transfer scheme between different IEDs which could be done by GOOSE messaging;
- Data sharing: Automatic data analysis software used in the control house allows data sharing among different utility groups improving their understanding of the events;
- Cyber security: hardened switches and routers provide the first level security and the secured access control devices provide further protection.

VII. Conclusion

In this paper, the new monitoring and control system based on IEC 61850 standard and implemented using existing technology and advanced software solutions is proposed. The hardware implementation considers the cost, flexibility, reliability and cyber security issues, and the software package implementation makes the data transparent and meaningful to different utilities groups.

The conclusions based on the new solution discussed in this paper are:

- The new design merges the existing technology and new design criteria;
- Process bus replaces the cooper cables at the process level and realizes the peer-to-peer communication where the IEDs can communication by using GOOSE messages.
- The new synchronization method based on the IEEE 1588 V2 communication profile is used in the new design, which paves the way for the future time reference;
- Cyber security issues in the new design are considered and double level protection is proposed;
- Automated integration of IED data allows more comprehensive view of the fault events and related consequences;
- The new design makes the data access transparent, so the substation and control center applications can access data in the same manner;
- The new design benefits multiple utility groups: protection, maintenance and asset management, and operations;
- The substation level analysis combines the system components configuration to make an accurate system for wide monitoring possible.

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IX. BIOGRAPHIES

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