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Application of synchronized monitoring for
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Monitoring Power System Dynamic Performance Using Synchronized Sampling

Mladen Kezunovic, Zheng Ce
Texas A&M University
College Station, U.S.A.
kezunov@ece.tamu.edu

Abstract: The use of synchronized sampling technology is currently under rapid development in various areas of power systems. This paper reports on the latest development, demonstration and deployment efforts related to the uses of synchronized sampling technology and associated applications to improve power system monitoring during switching sequences, faults, cascading disturbances and other types of alert or emergency situations that may jeopardize power system reliability or security. The proposed efforts are aimed at improving verification of switching sequences, interpretation of alarms, reduction of state estimation errors, assessment of equipment status, etc. The new developments are illustrated using examples of improved existing, as well as new applications.

Keywords: Faults, Synchronized Sampling, Dynamics, Wide-area disturbances, Data Processing

I. Introduction

Simultaneous measurements across the power system can be obtained by synchronized sampling technique, which uses state-of-art Intelligent Electronic Devices (IEDs) to obtain samples of different signals at various locations, at exactly the same time [1~4]. In power system, synchronized sampling and synchronized phasor measurement have become a practical proposition since 1980s. However, their potential use in power system applications has not yet been fully realized.

Comparing to the other methods, Global Positioning System (GPS) of satellites can provide time-synchronization signal with higher precision, and is capable of maintaining high degree of reliability. GPS-based synchronized sampling technology, enabled by satellites and Intelligent Electronic Devices and GPS receivers in substations, has been widely used for providing accurate time reference and global clock. Using these sources, power system signals such as voltages, currents and contacts could be sampled at a high sampling rate, which will then be recorded and processed by extracting features such as phasor, frequency and amplitude. All these features are essential indicators for assessment of the power system dynamic performance.

Phasor Measurement Units (PMUs) are the most accurate and advanced synchronization technology devices available to power system engineers and system operators for monitoring, control, and protection applications. This technology has been made possible by advancements in computer and data processing technologies and availability of GPS synchronization signals. Each PMU has a receiver tied to GPS clock, which enables synchronized measurements by offering both high precision pulse per second (PPS) signal for time synchronization of the local clocks, as well as highly accurate time tag for each sample [5~7].

The paper starts with a background about the difference between synchronized samples and synchronized phasors. It has been pointed out that distinction is also made between operational and non-operational data, which with the new synchronized sampling technology can be all integrated and made transparent to the user as to what the source of data is. The new approaches for data processing are discussed next, as well as new power system applications including the use of synchronized sampling technique in topology processing, state estimation, alarm processing, fault location and condition-based maintenance assessment. Finally, the paper discusses the strategy for future implementation of applications relying on synchronized sampling technique.

II. Background

2.1 Synchronized Samples and Phasors

Currently, most measurement devices in power system sample data at sampling rates varying between $4f_0$ and $40f_0$ (f_0: power system nominal frequency). The sampling rate of $12f_0$ is widely deployed in many relays and phasor measurement systems in recent years. Sampled data are used to extract phasors, utilizing techniques such as Fourier transform method. Phasors are basic tools of AC circuit analysis. Conventionally, they are introduced as a means of representing steady state sinusoidal waveforms of fundamental power frequency. Recent research reveals that the phasor analysis is also applicable under dynamic conditions such as power swings, in which the waveforms of voltages and currents are not in steady state, and the frequency of the power system is not at its nominal value [1], [2]. Under such conditions, the calculations can be made to compute dynamic state phasors. Thus the phasor analysis is critical in describing the power system performance in both steady state and dynamic process. As the monitoring and analysis functions are stepping from static state to system dynamics, higher precision of synchronized samples and synchronized phasors is required.

The necessity of synchronizing sampling clocks in various substations had been recognized almost 30 years ago. Introduction of microprocessors into substations made it possible to measure critical real time phasors such as positive sequence voltage and current. The major benefit is to gain the capability of putting the phasors onto a common time reference and thus making full use of the phasors measured at different locations [7], [8]. To reduce errors and improve synchronization accuracy, advanced communication approach is needed.

2.2 Operational and Non-operational Data

Before the appearance of GPS-based technique, because of the limited synchronization precision, power system phasors were extracted from sampled data recorded by non-synchronized or poorly-synchronized devices such as Remote Terminal Units (RTUs) of Supervisory Control and Data Acquisition (SCADA) systems. The extracted phasors are always the approximation of their real values, and less accurate versions may be used in some particular situations. Today, the phasors are obtained from high precision dedicated phasor measurement units used for monitoring of operational states. The non-operational data describing power system performance during power quality distortions, faults, cascading disturbances and other types of system transients and dynamics may also be used as operational data if processed automatically.

Now in substations, the GPS-based Intelligent Electronic Devices have two properties:

1) Synchronization of the sampling clock used for the input data acquisition systems;
2) Time-stamping of the acquired data.

The sampled data with above characteristics have much more value in operation, and could be used in monitoring power system transient process as well as dynamic performance. The uses of non-operational data for operational purposes are demonstrated in Figure 1. Merging operational and non-operational data gives more redundant and comprehensive view of the power system dynamics [9].

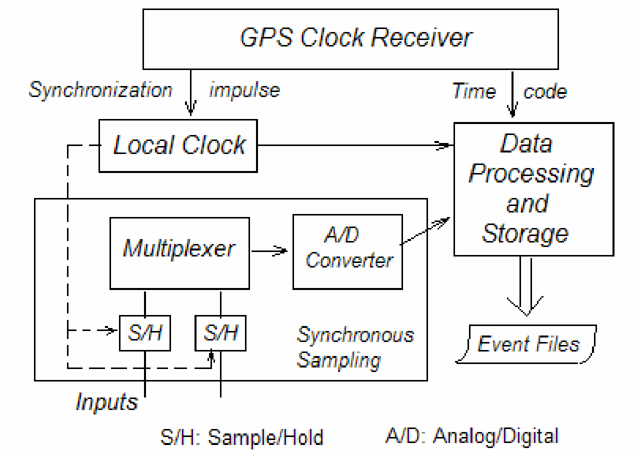

Figure 1: Synchronized Non-operational Data

III. Improved Data Processing

3.1 Automated Data Collection and Integration

From the time the Intelligent Electronic Devices were introduced close to 30 years ago, the amount and type of data collected in substations have dramatically increased.

Since the data is acquired with high sampling rates, transmitting the IED data to centralized location represents a huge burden on the communication channels. Related research in substation automation reveals that, in order to reduce communication congestions and make full use of the synchronized sampled data, the data collection and integration process could be accomplished at substation level [10]. An example of such architecture is given in Section VI.

3.2 Automated Information Extraction and Exchange

Recent efforts have been focused on turning the synchronized sampling data into useful information automatically. This is done by developing software for automation of local substation information extraction and exchange. New client/server architecture has been developed [9] to demonstrate the phasor extraction from IEDs and information exchange between substations, control center and remote users, which is shown in Figure 2.

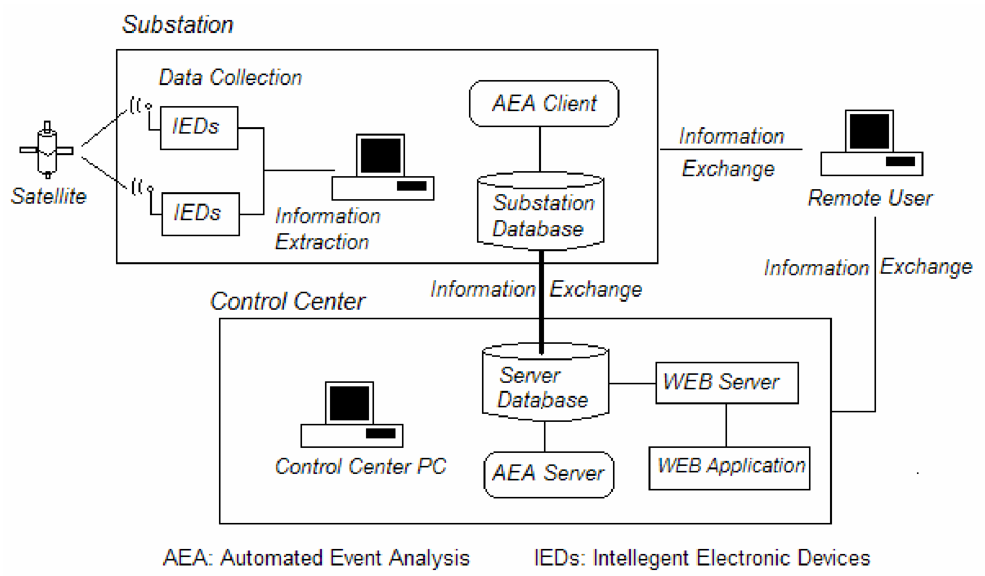

Figure 2: Automated Data Processing Architecture

IV. Improved Applications

4.1 Topology Processing

The GPS-based synchronization system provides high-quality synchronized samples at the substation level. New approaches have been proposed to use these sampled data for the topology processing. Traditional topology processor uses the status of breakers and switches at the substations collected by the RTUs and converted the much simpler bus-branch model of the system. This conversion may not produce the true system model when the information on the breaker status is wrong. Such topology errors are difficult to detect and correct using the current state estimators. Several investigations provide possible solutions to detect the topology error, based on state estimation technique [10], [11].

The development of synchronized sampling technique has enabled a new approach [11], [12], which implements a topology tracking system at the substation and gives the central state estimator access to tracking system outputs when necessary. The proposed tracking system will monitor the status of circuit breakers and analog measurements within the substation and perform various consistency checks based on circuit laws and connectivity logic. This will cost less effort because the problem is solved at the substation level before it is allowed to corrupt the central state estimator database.

4.2 State Estimation

The theory of power system state estimation appeared and evolved since 1960s. Now the steady state estimation has become universal in power system operation and control centers as a fundamental tool for on-line system security monitoring. The development of GPS based synchronized sampling may greatly improve current state estimation technique. It introduces the possibility of directly measuring state during system dynamic changes.

It is well known that the basic system model used in all state estimation algorithms is the positive sequence network representation. Therefore the positive sequence voltage and current are two essential quantities to be measured for state estimation purposes. If the sampling instants could be synchronized at all substations [10], [13], we will be able to put positive sequence phasor measurements on a common frame of reference.

It has been revealed that if clocks are synchronized to within about 10 microseconds, the phase angles of the phasors will be within about 0.2 degree of their correct value on a 60 Hz basis, which is acceptable in power system control analysis [13]. In practice, the synchronization theory stayed on paper until the appearance and development of Global Positioning System. With the essential positive sequence phasors available and having been synchronized at all buses, the GPS technique has greatly boosted the applications of power system state estimation. Now, the time-synchronized IEDs, such as PMUs, make it possible to measure the system state directly, instead of estimating it using system models and telemetry data. Using the advanced synchronization technique, a new state estimator has been proposed implementing a bilevel hierarchical scheme: individual areas represent the lower level and the coordinator represents the top level [10].

4.3 Alarm Processing

Alarms are typically generated in power system control centers any time when one of the following two broad categories of events happen [14]:

- An analog value recorded by measurement devices passes a limit;
- A digital (status) value changes state.

The implementation of alarm processing requires high-quality sampled data to be fed into the centralized computer system for further analysis and interpretation of alarms. Traditionally, the research focus is on the improvement of hardware and software of alarm processing to guarantee that no alarms are lost when an event triggers a series of alarms within a short period of time. If the transient data are not synchronized with high precision, or they are improperly organized, it is always possible for control center computers to not make right judgments and false alarm signals could be issued.

Now that the synchronized sampling technique is gradually developing, it is possible to have high precision assessment of the alarm occurrence and sequences leading to a possibility for automated cause-effect analysis at the substation level. Several new alarm processor approaches built upon the GPS technique are proposed to handle local processing of alarms supported by advanced analysis software in control center [15~17]. Accurate alarm interpretations could be made by computers in a very short time after an event happens, without the intervention of control center operators.

4.4 Fault Location

The synchronized sampling applications to improve the protective relaying functions were introduced long time ago. Observing the real-time data provided by synchronized PMUs and other IEDs could help detect the onset of a power swing. The relay could sense the extreme values of the apparent impedance change, using the corresponding voltage and current phasors [3]. In another application [5], a new GPS-based fault location system is proposed in Figure 3.

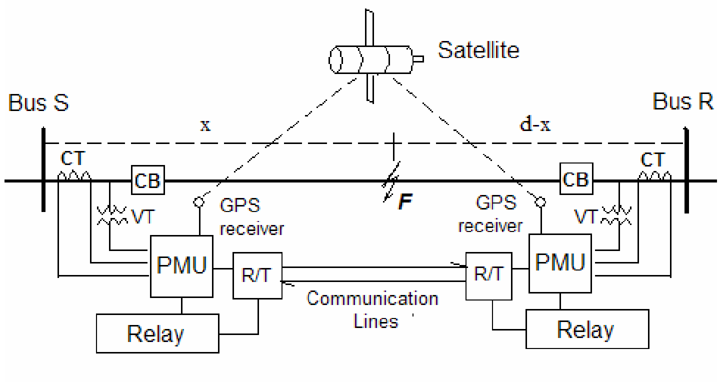

Figure 3: GPS-based Fault Location System

In Figure 3, CB represents circuit breaker, R/T represents receive terminal or transmit terminal, CT and VT represent current and voltage transformer. It can be observed that the sampling devices at both ends of the line need to be precisely synchronized. The sampled data could accurately describe the system performance when fault occurs.

Previous work has developed many algorithms which use synchronized sampling techniques to implement fault location. The synchronized sampling techniques used in fault location area are reported in [3]. A new two-end fault location algorithm using Digital Fault Recorders and GPS is discussed in [3] and [18]. A method to use only the voltage PMU sampled phasors in fault location is presented in [19]. A method for designing a new high-speed PMU-based protection scheme for EHV transmission lines is reported in [20].

4.5 Condition-based Maintenance Scheduling

Recently, the subject of condition-based maintenance has been investigated. Its objective is to optimize the frequency of inspection and repair according to the condition of the equipment being maintained. Several investigations are focusing on the automatic monitoring of circuit breakers' (CBs) conditions, based on advanced synchronized measurement techniques. Low cost circuit breaker monitors along with signal processing modules and expert system modules have been designed to monitor the circuit breaker control circuit signals [21]. A model for quantifying the effect of circuit breaker maintenance using the on-line condition data has been presented. This model can be used in developing system level maintenance strategies [22]. Efforts for this new monitoring approach are gradually moving the power system practice from scheduled to just-in-time maintenance [23].

V. Implementation Considerations

5.1 Temporal and Spatial Considerations

In this section, we will discuss how the temporal and spatial considerations affect synchronized sampling implementations.

5.1.1 Temporal Considerations

As mentioned before, monitoring, control and protection functions require knowledge of the instant of time when a given event has occurred [10]. The interpretation of the event may require different lengths of time such as minutes, seconds, milliseconds and even microseconds. To meet such requirements, different applications have different temporal requirements as shown in Table 1.

Table 1: Typical Applications of the Temporal Consideration

Time Frame	Applications	Devices Used	Synchronization Method
Seconds	State Estimation	RTUs	Local/Central time stamp
100s of ms	Fault Location	Fault Locators	Two ends of a Line
Milliseconds	Relaying	DPRs	Local clock
Microseconds	Phasor Measurements	PMUs	GPS receiver

5.1.2 Spatial Considerations

As we implement monitoring, control, and protection functions, we target specific areas of a system, selected region, entire system or the areas surrounding the system. The spatial considerations include:

- Space as a reference for power apparatus locations;
- Space as a reference for location of decision-making equipment;
- Space as a reference for data processing and information extraction;
- Space as a reference for execution of a command.

5.1.3 New Infrastructure

Traditional infrastructure invariably uses SCADA system for monitoring and control functions. Although SCADA provides a broad spatial view of the overall system, it could only give a limited temporal view of the system dynamic performance. PMUs and some other IEDs (such as Digital Fault Recorders-DFRs and Digital Protective Relays-DPRs) could provide much better time resolution of the signal and status changes with higher precision. Figure 4 shows a new infrastructure proposed for future monitoring and control in power systems where the data from PMUs and other IEDs is merged for more precise time resolution in recorded data.

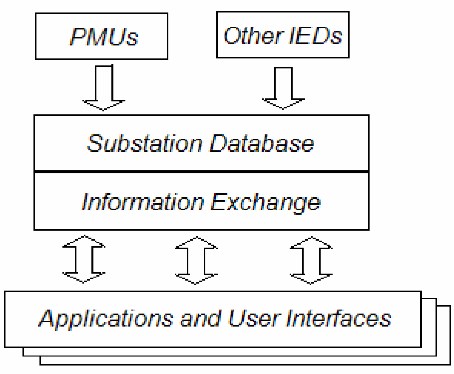

Figure 4: Infrastructure for Monitoring and Control Using Synchronized Sampling

In this infrastructure, all the IEDs (including PMUs) are synchronized to the GPS clock, which in turn could be tied to the absolute time. The temporal benefits of doing this are:

- All the events would be correlated to the same time reference and could be interpreted using an absolute time;
- All the waveforms would be sampled synchronously, allowing more accurate applications based on synchronized samples and phasors, such as system dynamic monitoring, assessment of disturbances, and phasor extraction;
- All the commands could be synchronized using the GPS clock.

In the spatial aspect, the above infrastructure expands the monitoring, control, and protection application to the following major cases:

- Decentralized (local) data processing and decision making;
- Centralized (EMS) data processing and decision making;
- Distributed (substations) data processing and decision making with a coordination capability that may be centralized.

5.2 Processing of Data from Individual IEDs

Generally, the processing of data from individual IEDs is completed at the substation level. At this level, the processing scheme includes two parts [9]. The first part relates to automated analysis of data coming from substation IEDs such as Digital Fault Recorders (DFRs), Digital Protective Relays (DPRs), Circuit Breaker Monitors (CBMs), Power Quality Meters (PQMs), etc. The second part serves multiple purposes: Verification of the Substation Database (VSDB), Two-stage State Estimation (TSSE), Fault Analysis and Fault Location (FAFL), and Substation Switching Sequences Verification (SSSV). Between the two parts, the substation data is analyzed for a variety of needs, some related to individual tasks of interest to various utility groups and some for automated analysis of events and disturbances. The result of local data processing is the extracted information that is sent to the centralized location.

5.3 Processing of Integrated IED Data and Information

The processing of integrated IED data is mostly done at the substation while the processing of integrated information is done at the centralized location. After the preprocessing of sampled data in substations, the control center will now have two distinct differences 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 two 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 frequent;
- The local information is extracted close to the source using abundance of data coming from IEDs. If a coordination of local conclusions is needed, this can be accomplished at a centralized location through further exchange of information.

The overall system scheme is shown in Figure 5.

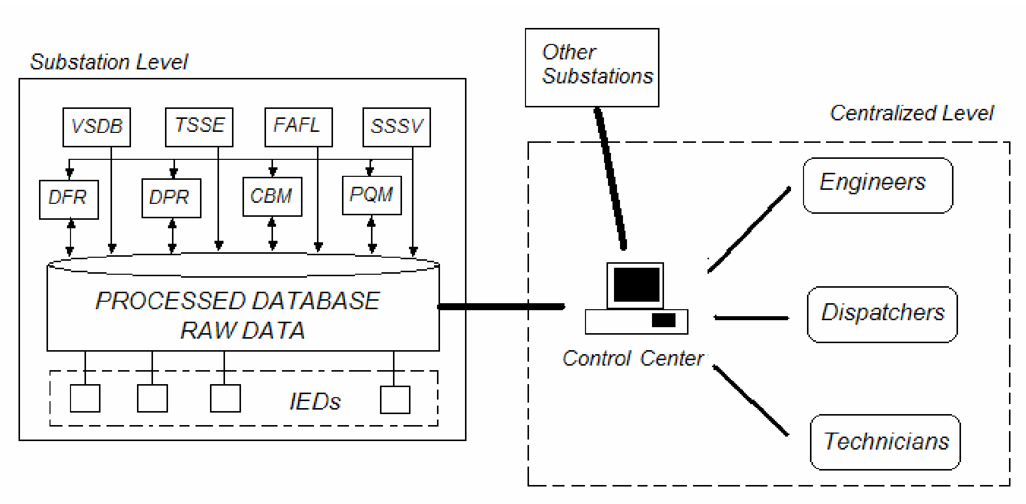

Figure 5: Two-level Data Processing and Information Extraction Deployment Scheme

VI. Conclusion

GPS-based Synchronized sampling technology provides data with high precision and reliability, which can be used in various fields, such as power system monitoring, control and protection. In the past 30 years, many new applications have been investigated and realized deploying the synchronized sampling technique, which have greatly improved the traditional power system methods in topology processing, state estimation, fault location, alarm processing, phasor extraction and information exchange, etc. All of these have inspired the development of the new applications for monitoring of power system dynamic performance. Meanwhile, new designs of system architecture, as well as deployment strategy of the GPS-based IEDs have been proposed, applying both the temporal and spatial considerations.

In power systems, time synchronization is not a new concept but its potential benefits and future applications for power grid monitoring, protection and control are not fully explored. As the synchronized phasor technology is deployed and as users gain experience and additional tools are developed, new applications of synchronized samples will continue to be identified.

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