Distributed Dynamic State Estimation and Power Quality Monitoring

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Abstract

This paper describes a proposed substation automation structure that utilizes the advantage of highly redundant substation level data. The proposed substation automation structure is required to deal with several well known limitation of centralized state estimation (SE) and to preemptively address future goals of power system operations. The proposed substation automation structure represents a revolutionary utilization and integration of existing technologies for the design of the substation of the future. The objectives of this project are to increase the functionality of substations and to increase the real-time situational awareness of the power system as a whole.

The proposed substation automation system utilizes a novel device called the universal GPS-synchronized meter (UGPSSM) to digitize and GPS time-stamping all the measurement data at the switch yard equipment. A process bus transmits data between the substation yard and the substation control house. At the control house the digitized data is available for local processing including distributed dynamic SE and power quality monitoring. Power quality monitoring is used to identify power quality issues in the switch yard equipment eg. overexcitation of transformers, DC current into the neutral of the transformer, imbalances, excessive harmonics from customers (from the feeders), excessive zero sequence current, stray voltages, etc.

Distributed dynamic SE is utilized to quantify the accuracy of all measurements and minimize external communication requirements. The first benefit is a result of state estimation measurement accuracy quantification which allows the tracking of the health of the measurement channels utilized for all substation data acquisition. The second benefit realizes minimized external communications with no loss of system visibility by relying on the filtering of highly redundant data to a minimal set of states.

1 Introduction

The technologies involved in the visibility and control infrastructure of the electric power system have evolved to a point where it makes sense to reevaluate the current approach. One glaring issue is the separation of the protection system, the "visibility system" (the infrastructure for identifying the real-time state of the system), and the subsequent control and operation functions. The technology is moving in a direction that there is a need to integrate these systems. This paper describes such integration and discusses one particular application of the integrated system, namely power quality monitoring.

The "visibility system" is traditionally a centralized state estimation (SE) system based solely on supervisory control and data acquisition (SCADA) data. The need for reliable and accurate SE has been emphasized in the recommendations made after significant blackouts including the events on November 9th 1965 and August 14th 2003 [1]. The primary results of SE are to provide a real-time system model and to provide a real-time snapshot of the systems operating condition, i.e. visibility of the system configuration and system operating conditions.

Centralized SE has served the industry with reasonable success; however, the reliability and speed of this approach is not totally satisfactory. Surveys have shown that on average the reliability of the centralized SE is about 95% for US utilities [2]. This means that the model of the system in real time may be unavailable 5% of the time. Because of the required long distance communications and the computational complexity of a centralized state estimator the response time of the centralized version are typically long, on the order of minutes.

A novel substation automation structure to address the above issues utilizing modern technology is proposed. The proposed substation automation structure is required to deal with several well known limitation of centralized SE and to preemptively address future goals of power system operations. It is well known that centralized SE for power system operation and control suffers from several disadvantages: it needs high-fidelity communication channels that are continuously utilized; it is vulnerable to partial loss of the transmitted data that, in extreme cases, can cause significant errors in the real-time results; it requires significant centralized computation resources to analyze all the collected data that generate a bottle-neck in the system; it generates numerous alarms during abnormal events that overwhelm system operators and obscure the root cause of abnormal events; it utilizes complex and vague bad data detection that result in the utilization of erroneous data in computing control actions; and it includes high cost partial failures that result from the systems centralized nature. Improving the functionality of substations will preemptively address future goals of power system operations: improved performance using power infrastructure at or nearing its designed lifespan; increased utilization of distributed energy resources; simplified upgradability using plug-and-play functionality of switch yard equipment; and heightened data security.

The proposed substation automation structure represents a revolutionary utilization and integration of existing technologies for the design of the substation of the future. The proposed substation automation structure is based on the concept of equipping each switch yard data collection point and control actuator: potential transformer (PT), current transformer (CT), circuit breaker, etc., with a universal GPS-synchronized meter (UGPSSM) that will transmit/receive data to/from the control house equipment.

The objectives of this project are to increase the functionality of substations and to increase the real-time situational awareness of the power system as a whole. The remainder of this paper has the following outline. Section 2 describes the physical components of the proposed substation automation structure. Sections 3, 4 and 5 describe three key functions of the proposed substation automation structure: data acquisition, local data processing, and simplified communications with the external system. Section 6 introduces an illustration of the power quality monitoring for overexcitation of transformers. Section 7 ends with a summary of the paper.

2 Proposed Substation Automation Structure

We propose a new structure of substation automation. A block diagram of the switch yard equipment and the control house interface in the proposed substation automation structure is shown in Figure 1. A block diagram of the control house equipment and the switch yard interface in the proposed substation automation structure is shown in Figure 2. The physical component of the proposed substation automation structure will be described in this section.

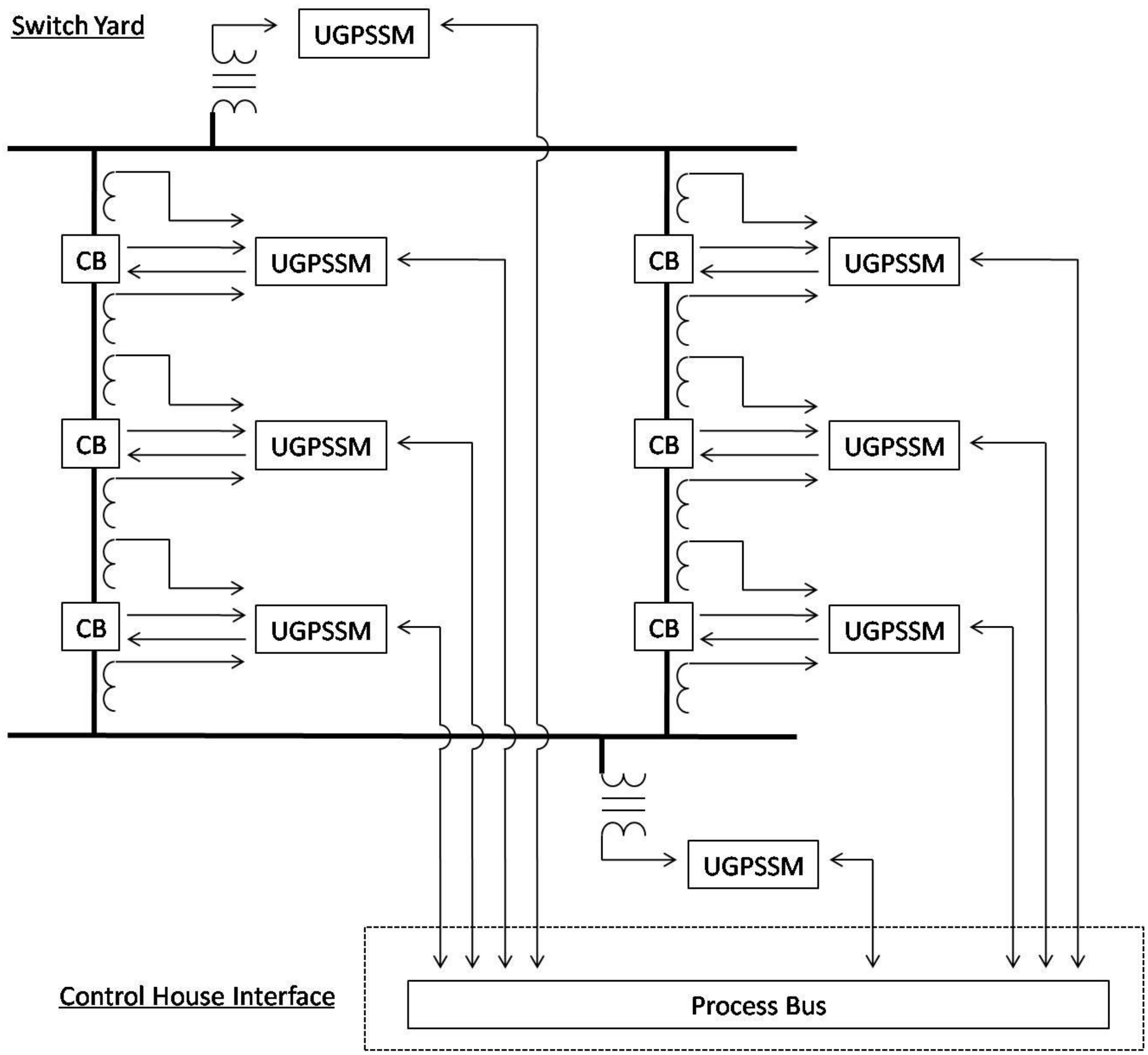

Figure 1: Block diagram of the switch yard equipment and the control house interface in the proposed substation automation structure.

In Figure 1 the switch yard equipment includes PTs, CTs, circuit breakers (CBs), and UGPSSMs. The PTs and CTs provide analog measurements that are conditioned via the UGPSSMs. The CBs provide a digital measurement (auxiliary contacts) and a control connection.

Two types of UGPSSMs are shown in Figure 1. The first type is connected to two three-phase CTs and one circuit breaker; requiring 6 analog inputs (one for each phase current), one digital input (circuit breaker auxiliary contact), and one output (control connection for the CB trip signal). The second type is connected to a single three-phase PT; requiring 3 analog inputs (one for each phase voltage).

Note that, the interface between all the control house equipment and all of the switch yard equipment is a single device, the UGPSSM, suggesting an interoperable environment for multivendor equipment. Further description of the UGPSSM is provided in the description of the data acquisition function of the proposed substation automation structure.

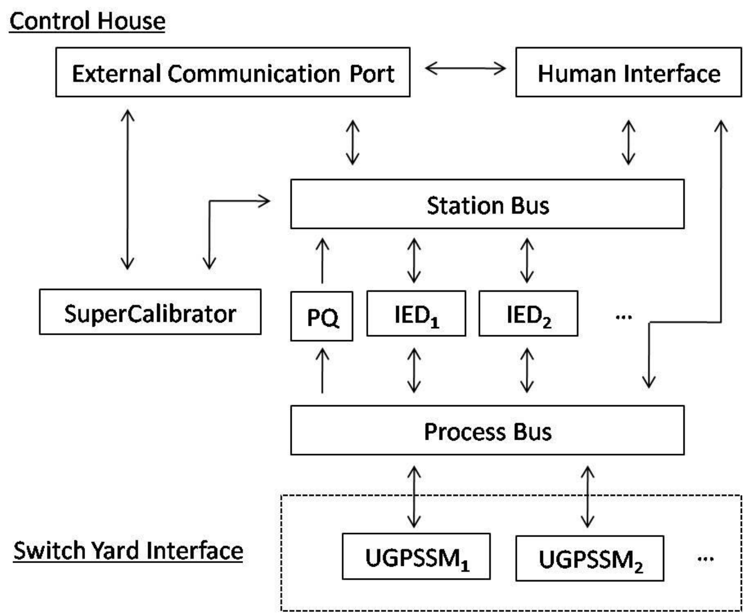

Figure 2: Block diagram of the control house equipment and the switch yard interface in the proposed substation automation structure.

In Figure 2 the control house equipment includes process bus, SuperCalibrator [5] – [9] equipment, power quality (PQ) monitoring equipment, intelligent electronic devices (IEDs), station bus, external communication port, and human interface equipment. The process bus is a data communication network used to communicate between the switch yard equipment and the control house equipment. The data within the process bus is high frequency, high redundancy, and possibly corrupted. The PQ monitoring equipment provides harmonic spectrum and transient event monitoring. The SuperCalibrator equipment consists of a high end personal computer and performs local state estimation; measurement channel error quantification; bad data identification and removal; and alarm processing and root cause identification. The control house IEDs generate station bus data, including phasors, RMS, magnitudes, phase angles, sequence quantities, etc. utilizing the sampled and time-stamped data from the process bus. Protection is performed by the control house IEDs using the data within the station bus. The station bus network is a data communication network used to communicate all substation data between the control house IEDs, the SuperCalibrator equipment, the external communication port, and the human interface equipment. The external communication port provides a single port for all external communications. The human interface equipment provides a local terminal for an operator to access all available substation data and functions.

Now that the physical components of the proposed substation automation structure have been defined three key functions of the substation automation structure will be described: data acquisition, local data processing, and simplified communications with the external system.

3 Data Acquisition

The first step in the proposed substation automation structure is to collect all of the available data at the substation. The data acquisition function in the proposed substation automation system is characterized by digitizing all the measurement data at the switch yard equipment by the use of the UGPSSMs and then transmitting the digitized data to a process bus. At the process bus the digitized data is available for power quality analysis to identify power quality issues in the switch yard equipment, eg. overexcitation of transformers, DC current into the neutral of the transformer, imbalances, excessive harmonics from customers (from the feeders), excessive zero sequence current, stray voltages, etc. IEDs connected to the process bus and use the digitized data to extract phasors, magnitudes, phase angles, sequence quantities, etc. Once this processed data is within the station bus it is available for all other devices connected to the station bus. The overall approach is illustrated in Figures 1 and 2. The remainder of this section describes the design and functionality of the UGPSSM.

3.1 Universal GPS-Synchronized Meter (UGPSSM)

The UGPSSMs provide a common interface for all input and output data, between the switch yard equipment and the control house equipment, in the proposed substation automation structure. In general, the UGPSSM is similar to the IEC 61850 merging unit [3]. The UGPSSMs process all analog measurements, digital measurements, and control signals. This processing for analog measurements includes sampling, digitizing, and GPS time-stamping. This processing for digital measurements includes appropriate sampling rate compression/upsampling and GPS time-stamping. A block diagram of the analog measurement channel within the proposed UGPSSM hardware is shown in Figure 3. The digital measurement channels include optical isolation, microprocessor (μP), phase lock loop (PLL), and GPS clock signal. The control channels include optical isolation and μP only.

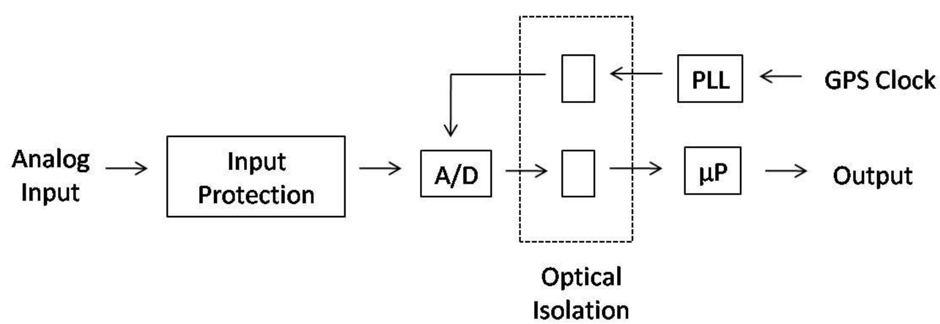

Figure 3: Block diagram of the analog input channel within the proposed UGPSSM.

The blocks in Figure 3 provide the operation of the UGPSSM. Input protection is provided in similar fashion as in [4]. Digitization (A/D) is provided by a 16 bit sigma/delta modulated analog to digital converter. GPS time-stamping is added to each measurement using a GPS clock signal. UGPSSMs also provide optical isolation between all low voltage hardware and the switch yard equipment. In general, the UGPSSMs are placed physically close to the switch yard equipment which they monitor to minimize any low energy analog signal corruption.

It is conjectured that a SuperCalibrator feedback signal could be utilized by the UGPSSMs to automatically calibrate the measurement channels; leading to a self correcting measurement channel within the proposed substation automation structure. The SuperCalibrator provides measurement channel error quantification, monitoring the variance of the measurement channels leads to the quantification of the health of the measurement channels. This quantification could be utilized, in the future, to derive a feedback signal to automatically increase the accuracy of all measurement channels. Increasing the accuracy of the measurements from the UGPSSMs would result in higher accuracy local processing within the substation. The variance of the measurements, the measurement channel error quantification, provides quantified feedback on the ongoing health of all the measurement channels and can be utilized as an indication of when service is required.

4 Local Data Processing

The proposed substation automation structure utilizes local processing: protection, power quality monitoring, and the SuperCalibrator. The focus of this paper will be on the power quality monitoring and the use of the SuperCalibrator in the proposed substation automation structure.

Electric power quality is loosely defined as the ability of the system to deliver electric power service of sufficiently high quality so that the end-use equipment will operate within their design specifications and of sufficient reliability so that the operation of end-use equipment will be continuous. The first requirement implies that the electric power service should be provided with near sinusoidal voltage waveforms at near rated magnitude and at near rated frequency. The second requirement refers to continuity of service. From this loose definition, it must be apparent that power quality is very much dependent upon the characteristics of end-use equipment and their design characteristics in terms of tolerances for voltage and frequency deviations.

The sources of disturbances are multiple and with varying parameters. For example in many places of the world, the most frequent disturbances originate from lightning activity near electrical installations. Lightning may result in flashover causing voltage sags to some portion of the distribution system, voltage swell to other areas, as well as interruption of power. The number of customers affected depends on the design of the system and placement of interruption devices, while the level of voltage sags or swells may depend on the grounding system, size of neutral, etc.

We have mentioned lightning as one of the causes of reduced power quality. Additional types of temporary disturbances include switching, power faults, feeder energization inrush currents, motor start transients, load imbalance, harmonics and resonance, electromagnetic interference (EMI), etc. The effects of these disturbances on the end user are voltage distortion, voltage sags, voltage swells, outages, voltage imbalance, etc. These effects may have different levels of impact, depending on the susceptibility of the end-user equipment. As end-user equipment becomes more sensitive, these effects are labeled as power quality problems. The impact of these temporary disturbances can be mitigated by modifications of circuit layout, grounding system design, overvoltage protection, filters, steel conduit, additional transformers, etc.

Another source of power quality problems can be end-use equipment or certain power system apparatus. Specifically, recent advances in power electronics resulted in a large number of switching devices, which are directly connected to the power system. These devices may be end-use equipment (electric motor drives, air-conditioning units, etc.) or power apparatus, which perform a specific control function (static VAR compensators, transformer tap controllers, etc.). A subclass of these devices controls the power quality and they affect system performance. These devices interact with the power system, may distort the voltage waveform (thus generating harmonics) and also are subjected to all transients, which are generated by the power system.

The two power quality issues introduced in this paper include harmonics and transients. Here harmonics are defined as, voltage and current deviations from the sinusoidal waveform with a specific pattern that is repeatable each cycle of the base frequency of the system. Here transients are defined as, oscillatory voltage or current deviations from the sinusoidal waveform of relatively high frequency.

The proposed substation automation structure will process all the substation data utilizing the SuperCalibrator methodology. The SuperCalibrator methodology is a distributed dynamic state estimator. The SuperCalibrator performs SE within a substation utilizing all available data and, with appropriate communication infrastructure, can transmit the results from each SuperCalibrator enabled substation to a centralized location where the results can be pieced together to so that the entire state of the system can be visualized with no additional processing. The static SuperCalibrator has performed in multiple field installations [6] – [8], and has more recently been improved into a dynamic SE methodology [9].

The SuperCalibrator performs local state estimation; measurement channel error quantification; bad data identification and removal; and alarm processing and root cause identification. The proposed substation automation structure utilizes the SuperCalibrator to quantify the accuracy of the measurement channels to provide indication of improper connections during substation commissioning and ongoing tracking of the health of the measurement channels. This section will introduce the local data processing functions harmonic spectrum monitoring, transient event monitoring, and the SuperCalibrator.

4.1 Harmonic Spectrum Monitoring

The electric power system is comprises of devices that have the potential of generating harmonics, for example synchronous generators generate harmonics, transformers, if overexcited, will generate harmonics, etc. Recently we have witnessed the introduction of many grid connected power electronic devices. These devices operate by switching circuits at relatively high frequencies. The switching operation of these devices generates harmonics at level that can be potentially high and may affect the performance of the power system. Grid connected power electronic devices are proliferating and it is expected that eventually the majority of end use devices will include some type of power electronic circuitry.

As it has been mentioned, there are numerous sources of harmonics. Under normal operating conditions these devices produce a moderate level of harmonics; however, under abnormal conditions these devices have the potential of producing high levels of harmonics. For example, an overexcited transformer will saturate and depending on the saturation level it will generate a substantial level of harmonics that may damage the transformer itself.

The effects of the harmonics can be classified into the following categories insulation stress, thermal stress, and load disruption. Insulation stress occurs because of overvoltages that result from harmonics. Harmonic currents can increase the operating temperatures (thermal stress) of many devices because of one or more of the following phenomena: copper losses, iron core losses, and dielectric losses. Load disruption occurs whenever the harmonics interact with control and protection systems and disconnect the power apparatus. The control and protection systems are designed to operate in a certain way. Harmonics may interfere with this operation and may cause the disconnection of the apparatus.

Harmonic spectrum monitoring provides a continuous record of the harmonic spectrum content within the substation. We assume that the highest harmonic of interest is the 30^{th} harmonic.

4.2 Transient Event Monitoring

Transient events are caused by internal and external events. Internal transients are all disturbances that originate from normal operations of electric power systems: switching of circuits, switching of capacitors, transformers, motors, etc. These operations cause temporary transients that may or may not lead to problems. Typical internal transients include power frequency overvoltages, ferroresonance, switching transients, inrush transients, motor start transients, and transient recovery voltages. External transients are caused by external causes: faults, lightning, and equipment failures.

Transient event monitoring provides a continuous record of any high frequency voltage events within the substation. We assume that the highest frequency transient event of interest is a 5,000 Hz signal, using this assumption and the Nyquist criterion results in a minimum sampling frequency of measurements is 10,000 Hz; this sampling rate accommodates monitoring of the 30^{th} harmonic.

4.3 SuperCalibrator

Within the proposed substation automation structure the SuperCalibrator procedure is illustrated in Figure 4.

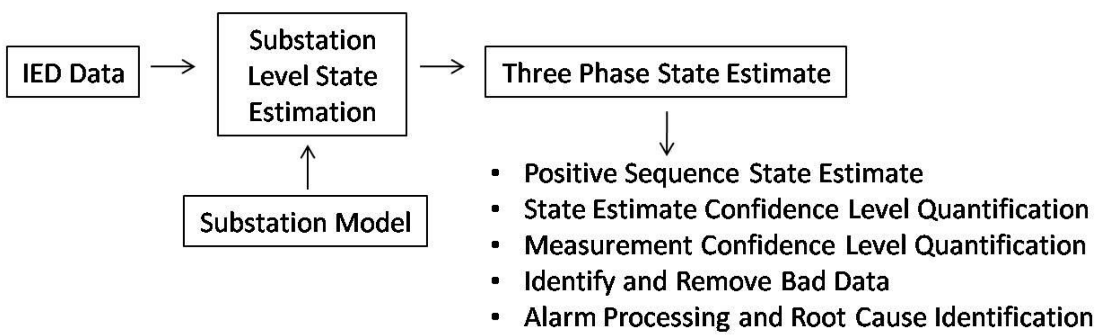

Figure 4: Block diagram of the SuperCalibrator procedure within the proposed substation automation structure.

In Figure 4 all available substation data (measurement set) is provided via IEDs. This measurement set is augmented with pseudo-measurements [8]. In Figure 4 the substation model block represents a detailed substation model (three-phase breaker-oriented, instrumentation channel inclusive substation model) to perform state estimation. The results of the state estimation include a set of three phase state estimates which can be easily converted to positive sequence estimates using the symmetrical component transform [10]. Additional results of the state estimation include quantification of the accuracy of the state estimates and of the measurements. This quantification can be utilized within a hypothesis testing procedure to identify and remove bad data. Finally, the SuperCalibrator performs alarm processing and root cause identification.

Instrumentation channels are designed to provide a scaled version of the input at the output. It is well known that all instrumentation channels have many sources of error. In the proposed substation automation structure the analog instrumentation channels consists of CT or PT, UGPSSM, and IED. Each component within the instrumentation channel generates small random error under normal operating conditions; whereas, harmonic content and transient events can cause significant errors. The instrumentation channels models are described in detail in [11]. In general, CT and PT devices are prone to saturation; coupling capacitor voltage transformer (CCVT) include complex circuitry which is prone to problems involving resonate circuits and parameter drifting; UGPSSMs will induce sampling error due to the finite number of digital bits; and IEDs include numeric errors due to finite bit length floating point arithmetic.

The accuracy of the SuperCalibrator results are highly accurate for two reasons; first the high level of redundancy in a substation and, second, the use of hypothesis testing to identify and remove bad data. The data availability at the substation level is highly redundant. The use of this redundancy within the local processing allows highly accurate state estimation calculations. By fitting the measured data to the system model using a weighted least squares algorithm, highly accurate results can be derived for potentially error prone input data. The accuracy of the estimated state results is further improved because of the limited size of an average substation allows for the use of powerful hypothesis testing to identify and remove bad data and can be performed without significant computational delays.

5 Simplified Communications with the External System

The proposed substation automation structure simplifies the required communication, between the substation and the external system, in a number of ways. The simplified communication with the external system represents the second of two key improvements of the proposed substation automation structure. In general, the proposed scheme provides for a single port of communications with the external world, the data to be communicated from the substation is filtered, and additional flexibility in substation information rates can be tailored to the requirements of specific information seeking functions.

The first communication simplification the proposed substation automation structure provides is a single port of communications with the external world as opposed to each relay or each intelligent electronic device having the capability of external communications. By reducing the number of communication ports the proposed substation automation structure provides a single point of contact with all external stakeholders for both monitoring and control.

The second communication simplification the proposed substation automation structure provides is that the data to be communicated from the substation is filtered. The data set within the substation contains a high level of redundancy. Typically, there are many more measurements then states. This leads to accurate state estimation results. The state estimation results are improved further through the use of hypothesis testing to identify and remove bad data. Filtering the highly redundant measurements into accurate state results minimizes the amount of data needed to be communicated. Further, the alarm processing and root cause identification provides information regarding the root cause of an abnormal event. As opposed to the current practice where numerous alarms are generated, which overwhelm system operators and blur the root cause of a system event.

The third communication simplification the proposed substation automation structure provides is additional flexibility in modifying substation information poling rates. The amount of data to be transmitted between the substation and the control center and its frequency of transmission are fixed today. The proposed scheme can make this completely flexible with the data amount and frequency adjusted to the particular control center application, which can also be made to run more or less often depending on the state of the system. At present, control centers use a round-robin polling of all the remote terminal units (RTUs) at the substations at relatively slow rates. If the RTU is replaced with a new platform that has all the possible substation data available, the paradigm changes completely. All of the data from every substation is not needed; in fact, the data amount and frequency can be selected according to the application at the control center. If it is for monitoring or for contingency analysis or for automatic generation control, the data reaching the control center can be customized for each. Although the need for this data in operation and control is very sensitive to latency, a much larger set of engineering and business functions need this data not as urgently. Thus, this data needs to be stored in a historical data base that can be accessed by many functions and people inside and outside the enterprise.

6 Typical Results

Power quality monitoring with the proposed system may provide information about a number of issues that may develop in a substation. Examples of substation power quality events are overexcitation of transformers, DC current into the neutral of the transformer, imbalances, excessive harmonics from customers (from the feeders), excessive zero sequence current, stray voltages, etc. Future work involves illustrating the use of the proposed structure to identify the power quality concerns introduced in this paper.

An example of transformer overexcitation is shown in Figures 5 and 6. Figure 5 illustrates a set of waveforms captured at the low voltage side of a transformer. Figure 6 illustrates the harmonic analysis of the phase A voltage. This analysis indicates that the transformer is in an overexcitation state indicated by the harmonic signature of the voltage. Similar analysis of the data at the process bus can provide useful information about the power quality of the system.

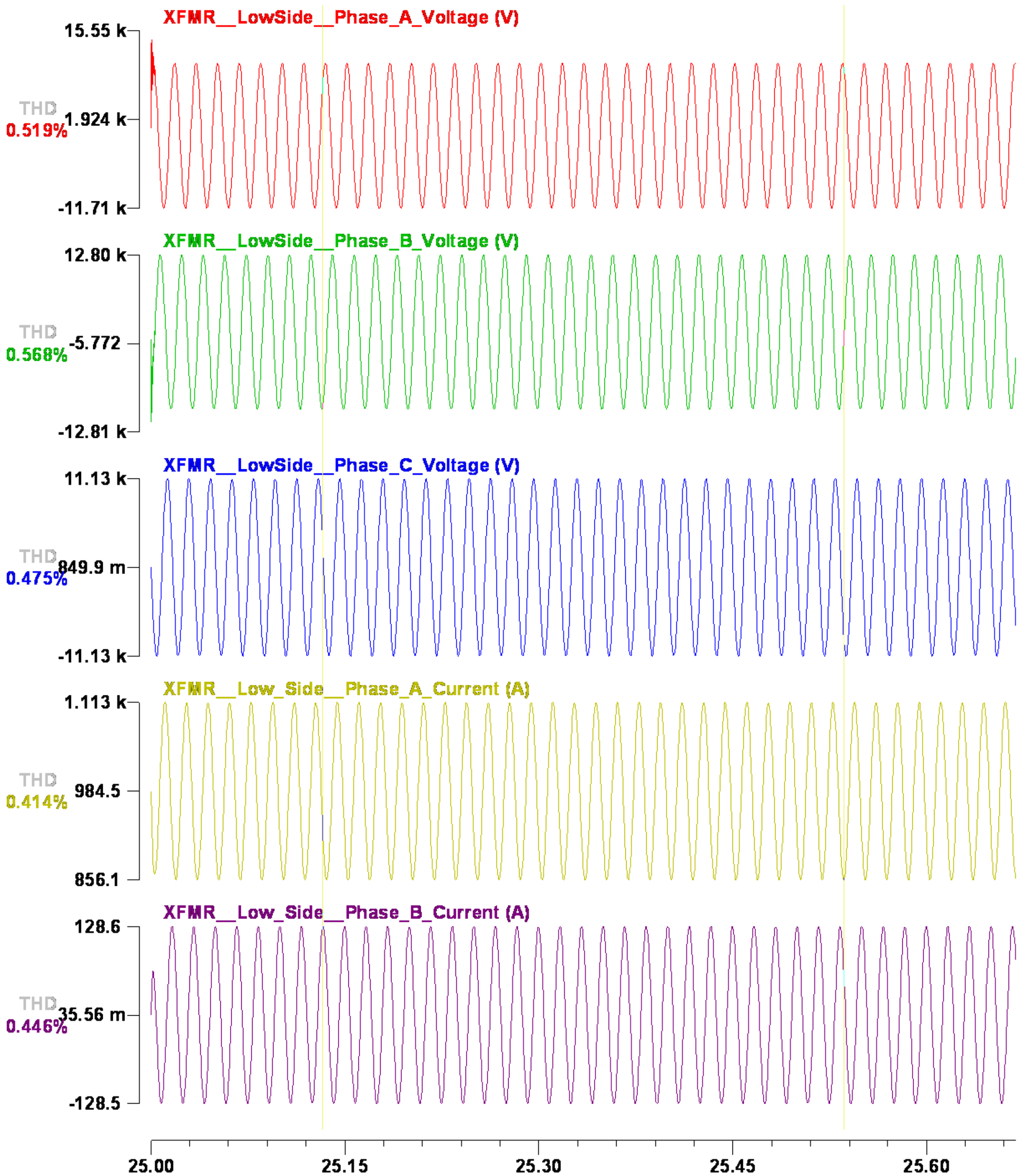

Figure 5: Captured data at the low voltage side of a transformer.

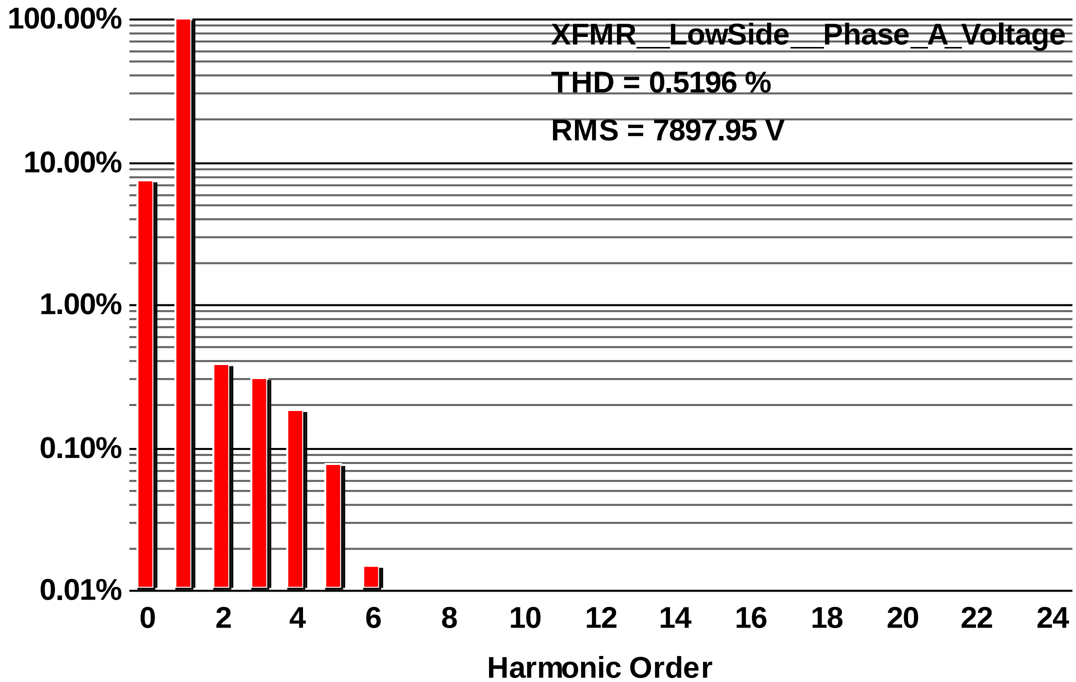

Figure 6: Harmonic analysis of the phase A voltage of Figure 5.

7 Conclusion

This paper outlines the motivation for redesigning the existing substation automation paradigm, describes the proposed substation automation structure, and illustrates the use of the proposed substation automation structure for power quality monitoring. Three key functions of the substation automation structure are data acquisition, local data processing, and simplified communications with the external system. The data acquisition function in the proposed substation automation system is characterized by digitizing all measurements at the switch yard equipment via UGPSSMs and then transmitting the digitized data to a process bus. The local processing includes power quality monitoring and the use of the SuperCalibrator. The simplified communications with the external system consists of a single port of communications, the data to be communicated from the substation is the minimum set required for full visibility, and additional flexibility in substation poling rates.

The proposed substation automation structure utilizes the measurement accuracy quantification and state estimation filtering functions of the SuperCalibrator to assist with the commissioning of the substation, to provide ongoing monitoring of the health of the substation measurement channels, and to minimize all external communication requirements. These improvements lead to system wide improvements including increased speed and accuracy of system wide real-time situational awareness.

The measurement accuracy quantification function of the SuperCalibrator provides quantified feedback of the substation measurement channels. This quantification can be utilized during substation commissioning to indicate where improper connections were made. This quantification can also provide ongoing measurement channel health monitoring. Future work will utilized the accuracy quantification to derive a feedback signal from which a calibration signal can be provided to the UGPSSMs to periodically improve the accuracy of the individual measurement channels.

The state estimation filtering function of the SuperCalibrator provides minimal external communications with full system visibility. By reducing the number of communication ports the proposed substation automation structure provides a single point of contact with all external stakeholders for both monitoring and control. Filtering the highly redundant measurements into accurate state results minimizes the amount of data needed to be communicated. The amount of data to be transmitted between the substation and the control center and its frequency of transmission are fixed today but the proposed scheme can make this completely flexible with the data amount and frequency adjusted to the particular control center application, which can also be made to run more or less often depending on the state of the system.

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