Future requirements for digital substation control and protection systems

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Abstract:
This paper is aimed at describing some new developments in the area of substation monitoring, control and protection. The developments are related to new implementations of the existing functions, as well as, new applications. The application, design and implementation requirements for the future substation systems are defined as a consequence of the features introduced by the new developments.

1. Introduction

The history of digital Substation Control and Protection Systems has been quite interesting and development path somewhat controversial. One of the first projects in this area in the world has promoted a high level of integration between control and protection functions, where a custom designed high speed local area network was used to connect different parts of the system [1]. Due to the design complexity, the development cycle of this project was almost 10 years long. At the end, this solution was quite attractive from the performance standpoint but the cost was pretty high due to the custom communication solution for integration and outdated technology. Even though the field demonstrations of this system were indeed successful, this solution did not gain a wide acceptance by the users and vendors alike.

In the mid eighties, an argument against the integrated solution was introduced. The need to keep the control and protection segregated so that the common failure modes between the two systems are avoided was cited as the main reason. This argument has led to development of digital substation systems that were more coordinated than integrated. The final result of the development was that each major vendor had developed its own coordinated system that was implemented using custom solutions. The outcome seen by the end users was the same, in both cases: custom solutions allowing only the use of the equipment from the same vendor. This solution was not very attractive in the case the user wanted to mix the equipment from different vendors.

The next generation of the substation systems was aimed at an open-system design where the equipment from different vendors can be combined in a common solution. The most obvious approach was to develop dedicated interface modules that will allow various types of equipment to be connected to a common local area communication network representing a backbone of the substation system design. This solution did meet the requirement of an open system but the cost was still pretty high due to the need to have the custom interfaces implemented.

The present developments are aimed at selecting a common local area network communication protocol that will be accepted as a standard solution for all of the substation equipment regardless of the vendor origin. The effort to standardize the substation communication protocols is quite extensive. A number of utilities and vendors as well as research and standardization organizations are presently involved [2]. Once the standard is agreed upon and formalized, it will allow for cost effective mixing of the equipment from different vendors in the same digital substation system design.

This paper goes beyond the requirements considered today. Several new implementations of existing functions and new applications are discussed to illustrate the new requirements that may be placed on the substation system designs in the future. It will be argued that if the new requirements are satisfied, the substation system solution can be implemented either as an integrated or coordinated design. Compliance with the new requirements will also enable mixing of the equipment from different vendors as well as a modular design that can be expanded and upgraded as needed.

2. New developments

This section will summarize basic characteristics of some new developments recently introduced by the author and others. These developments relate to the new implementation of existing functions and introduction of new functions as well as the new approach to the substation system testing and instrument transformer interfacing. Each of these developments is introduced briefly with an intent to emphasize the new requirements that may affect future substation system designs.

2.1 New implementation of existing functions

The following three new implementations are discussed:

- Distributed bas-bar protection
- Accurate transmission line fault location
- Neural net transmission line relaying

New distributed bas-bar protection implementation has been recently described by the author and other developers [3,4]. The main emphasis in this solution is on a high-speed communication system that will allow for distributed bay units to communicate to a centralized unit the sampled data required for the final trip decision. In addition, the centralized unit needs to inform the bay units if a trip action is to take place. One additional property of this implementation maybe the ability of each of the bay units to also act as a back-up unit for the line protection relays. The distributed bus-bar protection may be implemented using different communication protocols. One option maybe a master slave communication for both the transmission of the sampled data about line currents to the centralized location as well as for distribution of the trip signal from the centralized location to the bay units. Another option is to use broadcast modes where each bay unit provides all other bay units with its measurement of the currents. In this case each bay unit may carry a parallel decision making for the trip action. A trip signal initiated by any of the bay units can be broadcasted to all other bay units.

An accurate fault location using data synchronously taken from both ends of a transmission line has been recently introduced by the author and his colleagues. [5]. This implementation requires that data sampling is controlled via a reference time signal provided by the Global Positioning System (GPS) of satellites. Therefore, a GPS receiver interface to the data acquisition front end is needed. In addition, high speed communication between two ends of the line may be needed if the fault location determination is to be provided in real time. Finally, this implementation can benefit from a relatively high data sampling rate in the range of 1-5 KHz.

The neural net transmission line applications for high speed fault detection, classification and directional discrimination have been studied by the author and others. Some initial results are recently published [6-8]. In all of these applications, it became essential that a training procedure for the neural net learning algorithms be implemented in a versatile and automated way. In addition, data sampling rate somewhat higher than what is presently used in digital relays may be desirable.

Table I. The requirements for new implementation of the existing substation functions

New Implementation	**New requirements**			
	Data Acquisition Communication	Inter-Station Comm.	Intra-Station Comm.	Special Interfaces
Distributed Bas-bar Protection	Applicable for both line and bus functions	N/A	High speed	Back-up for the line protection units
Accurate Line Fault Location	High sampling rate, interface to GPS receiver	High speed	N/A	Communication between two line ends
Neural Net Line Protection	High sampling rates	N/A	N/A	NN training

2.2 Development of new applications

The following new applications are considered as an example of the new trends in enhancing the substation system performance:

- Automated analysis of faults and power quali disturbances.
- Automated monitoring and diagnostics of the powe apparatus operation .
- Automated switching sequences for substatio reconfiguration and stability control.

Automated analysis of faults and power quali disturbances requires that samples of all analog and conta signals be taken synchronously throughout the substatic [9,10]. In addition, all the samples need to be brought in i "raw" form into a common substation data base. It beneficial if the data sampling is in the order of sever kilohertz. It is also beneficial if an interface is provided import data from dedicated "outside" instruments such digital fault recorders (DFRs), sequence of event recorde (SERs) and power quality monitors (PQ nodes). For th transmission line fault and disturbance analysis, data fro the other end of the line may be quite useful in carrying o a comprehensive analysis. Data sampling synchronizatic to the GPS receiver is desirable.

Monitoring and diagnostics of the power apparat operation requires continuos processing of the sampl data coming from the analog and contact inputs. Tl sampling rate may have to be quite high (5KHz and abov to be able to capture high frequency transients used f some of the diagnostic techniques. In addition, speci interfaces for various temperature, pressure, conta position, and other sensors need to be provided. Finally, the data has to be readily accessible in the substation da base for the substation-wide coverage and processin Again, it may be required that all the data be sampl synchronously throughout the substation.

The automated switching sequence may require centralized substation decision-making and decentraliz coordinated execution of control actions. Automat execution of the control actions may also require a hi speed communication of a trip message in the case wh several breakers need to be operated simultaneously as consequence of one of the breakers getting stuck during protective relaying trip action (breaker failure initiate). It assumed that most of the operator-initiated automat switching actions will be issued from the Control Cent hence an adequate communication with the Control Cen is required. In a broader sense, the control decision m require local and remote analog measurement to processed prior to the control action. Typical examples the synchronization of the breaker closing as well as wide area measurement system (WAMS) of phasors for stability control. In this case adequate local and/or rem analog measurements have to be provided.

A summary of the requirements imposed by the n developments is given in Table II.

Table II. The requirements of the new developments

New Developments	New Requirements			
	Data Acquisition Communi-cations	Inter-station Communi-cations	Intra-station Communi-cations	Special Inter-faces
Automated Event Analysis	Synchronized sampling, high sampling rate	Data from adjacent substations	Transfer of samples to the data base	DFRs, SERs, PQ Nodes
Automated monitoring & diagnostics	Synchronized sampling, high sampling rate	N/A	Transfer of samples to the data base	Various sensors
Automated switching sequences	Synchronized sampling	Data from other sub-stations	Data acq. from, and tripping to all equip.	WAMS

2.3 Substation system testing and instrument transformer interfacing

Recent developments of cost effective digital simulators for relay testing and optical transformers provide a new possibility of interfacing of this equipment to the substation system [11,12]. This means that the new substation equipment should have low energy analog or digital inputs that can take the signals from the simulators and from the new optical sensors. The mentioned equipment could still be interfaced through the standard auxiliary transformer interfaces. However, the low-energy input interfaces are allowing direct input of the low level analog and digital signals into the rest of the filtering and/or processing input circuitry of the substation system.

3. Future digital substation system requirements

This section provides a discussion of some of the most important requirements that may be imposed on the new digital substation systems in the future. These requirements are related to the application, design and implementation issues [13,14].

3.1 Application Requirements

Advanced applications, as presented through a few examples discussed in Section 2 (New Developments), impose the following requirements:

- Higher data acquisition performance
- More elaborate inter-station communications
- Higher speed for intra-station communications
- Special interfaces

An analysis of the existing digital algorithms for control, protection, and monitoring indicates that further improvements in the classical functions maybe possible if the data acquisition system has higher performance. An increase in the sampling rate to several KHz and ability to provide GPS synchronization throughout a substation, and between adjacent substations, is a highly desirable feature. This enables the use of this data directly in various electrical circuit equations, which in turn allows for direct solution of these equations providing more accurate characterization of faults, power quality disturbances and stability issues. In addition, data synchronization enables appropriate time correlation between various analog and contact signals in a substation providing for an ability to automate the analysis of the substation and system-wide events.

The inter-station communications have been constrained in the past to the transfer of various logic states used in the protective relaying schemes (blocking, transfer trip, etc.) for transmission lines. In some special occasions, pre-processed analog quantities were communicated for the purpose of transmission line relaying (current differential, phase comparison). The new applications can be envisioned (accurate fault location, automated event analysis, enhanced stability monitoring) if more elaborate inter-station communications are available. The most desirable performance is an increased speed so that data samples can be transmitted. However, reliable transmission of preprocessed data, such as the phasor magnitude and angle for selected analog signals, are also useful.

The data transfer speed and mode for intra-station communications are essential for some new applications. It is recognized that data transfers for the monitoring purposes do not require high communication speed, and that data is transferred mostly from various distributed bay devices to the centralized substation computer. However, a certain small number of applications requires high speed communication to transfer data samples from several protection/control devices to the centralized one (distributed bus protection data collection) or from the centralized device to many other devices (breaker failure initiate, bus tripping, automatic switching sequences).

The special interfaces introduce an extremely important set of requirements, since they may have a far reaching impact on the new functionality of the substation systems. One set of interface requirements is related to the data acquisition front end (low energy inputs for system testing and new transducers). Yet another set of special interfaces is required for high speed inter station communications to support the new media (fiber-optics, digital radio) and communication technology (digital back-bone data networks). The special interfaces that are probably most desirable are the ones enabling communication with existing substation equipment (DFRs, SERs) that initially may not be a part of the substation system design as well as the supervisory control and data acquisition (SCADA) interface for the control center Energy Management System (EMS). This paper did not explore the new opportunities that the substation systems offer as substitutes for the Remote Terminal Units (RTUs) of the SCADA systems. However, discussion of the new automated fault and disturbance analysis, automated power apparatus monitoring, as well as automated switching sequences and system state monitoring are very good examples of the substation systems serving as a location for distributed processing of some of the control and monitoring EMS functions.

3.2 Design requirements

This set of requirements leads to the following design choices:

- Flexible system interfaces
- Versatile communication protocols
- Extensive substation data base and processing power
- Advanced testing equipment and related test software

Flexible system interfaces are related to improvement of the existing and introduction of new interfaces. The existing front-end data acquisition for sampling of analog and contact inputs from the switchyard needs to be redesigned to allow for higher sampling rates and GPS synchronization. The existing protection and control algorithms should not be affected since proper decimation and filtering of the data sampled at a higher sampling frequency can be accommodated. At least a 16-bit A/D conversion should also be provided. A special provision shall be made for interfaces to the optical current transformer (CT) and potential transformer (PT) as well as for the secondary injection test points. The new interfaces for inter-station communications, SCADA and special sensors shall be provided on a dedicated device that can be configured to support a designated interface function.

The communication protocols are well known issue that is still somewhat controversial. In any case, a versatile protocol for intra-station communications is needed so that both master-slave and peer to peer communication modes are supported. The local area network (LAN) configuration with 100 MB/sec data rate may be required where both token-passing and Ethernet-type protocols can be selected as needed. A special purpose option may have to be provided on an independent LAN where high speed transfer of a burst of short messages can be accommodated. In addition, standard protocols for point-to-point as well as wide-area communications are needed. The existing efforts in standardization of the protocols are well intended but may not be detailed enough to provide the required level of data description for an unambiguous definition of all the application data transfers [15].

The role of a digital substation system is to allow for implementation of both the standard monitoring, control and protection functions as well as the new substation wide applications. The substation-wide applications may be related to the local substation functions or may be a part of the distributed EMS applications. In any case, an overall substation data base is needed for most of the new substation-wide applications. This data base should contain samples of both analog and contact data acquired throughout the substation switchyard. Since most of this data is sampled by the protection devices, it is required that this data can be uploaded into a common data base. Since it is assumed that this data is taken synchronously throughout the substation, and data sampling front ends of all the devices have the same characteristics, this data base is going to be "consistent". Such a data base can be utilized to perform automated substation wide fault and power quality disturbance analysis, automatic switching sequences and automatic power apparatus monitoring. The system stability monitoring can also be enhanced through the wide area measurement system that can be implemented using this data base as well. In addition to the data base, the substation system needs to have a dedicated powerful computer for implementation of the substation-wide applications.

One area that has not received much attention in the past was development of digital simulators for substation system testing. The individual devices that constitute the substation system can be tested separately, and this has been done to a great extent in the past. However, some of the new applications that are related to the overall substation operation need to be tested by providing test signals to all inputs of the substation system, simultaneously. This practice was not known in the past due to the fact that the new substation-wide applications were not commonly used. With new developments in the digital simulator technology it is straight forward to develop multi-terminal configurations that will allow for simulation and generation of a number of test wave forms and contact changes, simultaneously [16]. This will resemble a full substation front-end connection and can be used to exercise substation system operation under a huge number of application scenarios. Any interaction between various parts of the substation system can be fully tested using this methodology. This system test can be performed at the factory when the system is assembled, and pre-wired. In addition, field version of such a test system can also be developed and used for maintenance and filed commissioning. If the low power inputs to the substation system are utilized, the test system can be made portable and readily available for the field use.

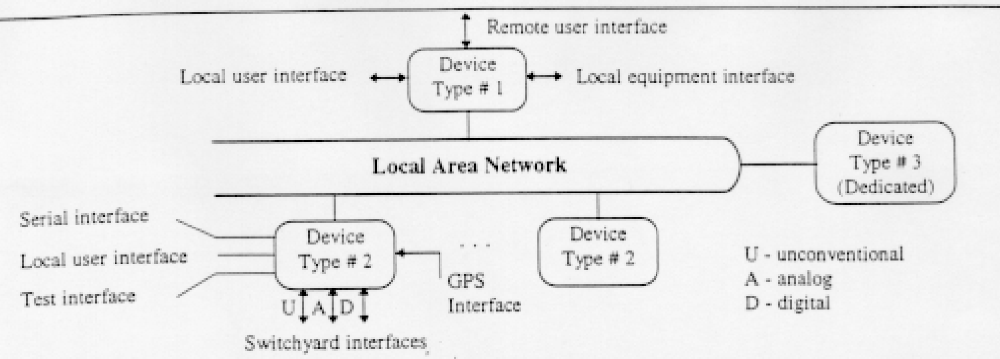

Figure 1. Substation System Design

3.3 Implementation requirements

Implementation requirements may become quite complex if one seeks to accommodate the new application and design features discussed in this paper. The complexity justification depends on the market needs in the future, and those are not the same throughout the world. To illustrate the major differences in the market needs, one can look at the developing countries' markets where the entire substation may be built by a given vendor and the digital substation system may be installed as the only secondary equipment in the substation. In this case the vendor may have an opportunity to provide the total substation design where all the devices constituting the system are selected to fit the best the overall system design. Another extreme are the developed countries' markets that may require that the existing substation equipment is gradually phased out and the new digital design is brought in and expanded over certain number of years. A combination of the equipment retrofitting and substation refurbishing may take place during this process. The following requirements are considered essential if a full flexibility of the substation system implementation is to be provided:

- Versatile device platform design
- System design modularity
- Advanced tools for application algorithm allocation
- New methodology for substation design testing

The first implementation step is to define the requirements of the future devices that will be the major building blocks of the substation system. A block diagram of the substation system is shown in Figure 1.

In most of the applications, three major categories of the devices can be envisioned. The device type #1 can be used for interfacing of the entire substation system to the users, local devices that are not part of the system and the rest of the devices that are a part of the system. This device will have to have a substantial data base capability, increased processing power performance and high-speed communication facilities for system-wide communications. This device should also be capable of acting as a master in communicating with the rest of the devices. The other communication modes such as the broadcasting, peer-to-peer, and point-to-point should also be available. The device type #1 computer platform would need to accommodate a multitasking, multi-user operating system and double buffering communication interface to be able to decouple its operation between the rest of the system devices and the outside "world".

The device type #2 is the most critical implementation component of the substation system. It should be capable of interfacing to the standard switchyard analog and digital signal as well as to the unconventional transducers. A number of communication interfaces such as a high-speed serial interface for communication with other local and remote devices, local user interfaces, and special test interfaces are needed to provide for the required flexibility in using these devices. A GPS interface for substation and system wide data sampling synchronization is also required. This device type needs a powerful operating system that will allow (in addition to the application algorithm processing) for high speed transfer of the "raw" samples as well as the control messages that may come from the substation system or external devices.

The device type #3 is a special purpose device that may be customized to some dedicated functions peculiar to the given substation system and its application. Typical example may be the interfacing to other existing digital equipment in the substation.

The modularity of the substation design is a feature that assumes that the system can be assembled by using a variety of devices coming from different vendors. In addition, the modularity assumes that the substation system can be configured to perform a number of functions that