Trends in power systems protection and substation automation

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Abstract - With the rapid development of the Internet and corporate intranets, and their penetration to technical systems, protection and control system for power systems have evolved. Modern communication technologies including the Internet are used for remote monitoring, setting and retrieval of load and fault data. Smart multi-functional and communicative units have replaced traditional mechanical and static instruments. Next step in substation automation towards totally integrated substations will be applying of the open communication standard IEC61850 which should allow the easy exchange of information between all devices in a power control and management system.

I. INTRODUCTION

In past protective relays have been electromechanical devices whose purpose was only to protect electrical power systems against system failures. Application of microprocessors to power system relaying has increased the functionality of protective relays and brought new concepts, which considers control, protection and monitoring functions integrated together.

In past decade, there is a strong trend in the utility industry to replace electromechanical and static systems for protection, control, monitoring, supervisory, and metering, with integrated, microprocessor-based intelligent electronic devices (IEDs). The advantages of the implementation of systems utilizing IEDs are price, reliability, functionality, and flexibility.

Since microprocessor based, the IEDs can provide a variety of functions traditionally assigned to multi-device systems, such as:
-protection, control and metering,
-condition monitoring and self-diagnostic,
-system monitoring and fault diagnostic,
-oscilography, etc.

With built-in communication port, the implementation of the additional applications that are necessary for a complete system may include:
-multi-component protection,
-remote monitoring and fault diagnostic,
-condition monitoring and diagnostic automated dispatch and control,
-data retrieval,
-site optimization and asset management, etc.

Integrated protection and control first appeared in the mid eighties and has since then matured to full scale substation automation.

The relaying and measurement tasks have been well understood and standardized. On the other hand, the technical methods and operating impact of data communications continue to evolve dramatically. There is a wide variety of incompatible communications protocols, approaches and systems in the marketplace (communication protocol is set of rules that must be obeyed for orderly communication between communicating parties). Competing manufacturers have been following unique approaches when designing the communications interface circuits. Special communications interfaces or gateways must be used to connect any new equipment to an existing data network if a utility wants to expand beyond its proprietary equipment.

Development in substation automation which should led towards totally integrated substations is communication standard IEC61850 which should allow the easy exchange of information between devices made by different manufacturers and should bring a drastic cost reduction.

II. PROTECTION RELAY DEVELOPMENT TRENDS

IEEE generally defines a protective relay as ‘a relay whose function is to detect defective lines or apparatus or other power system conditions of an abnormal or dangerous nature and to initiate appropriate control circuit action’ (IEEE 100-1984).

Traditionally, manufacturers of protective relay devices have produced different designs that are specific to the protection of generation, transmission, distribution and industrial equipment. This approach has its roots from the days of electromechanical and static relay designs, where the widely varying complexities associated with each type of protection had to be implemented in proprietary hardware configurations. For example, there was a significant difference in cost and complexity between an overcurrent relay used for feeder protection and a distance relay used for protection of EHV (extreme high voltage) lines.

A. Universal relay

The number of functions integrated in relays has been expanded parallely with the increasing processing power and storage capacity (relay hardware evolution is shown in Table 1). Only one look at the PC industry is needed to see that the power and performance of microprocessors have increased dramatically while prices have decreased [1].

Table 1: Development of digital relay HW performance

Year	Memory RAM/EPROM	Bus width	Processing power
1986	64k/128k	16	0.5 MIPS
1992	256k/512k	16	1.0 MIPS
1999	512k/4MB (+4MB D-RAM program memory)	32	35.0 MIPS

Also, the technology is now at the point where the performance requirements of a distance relay and the cost/performance requirements of a feeder relay can be met by the same microprocessor and digital technology.

Development of protection relays led to an appearance of a multi-functional device, a universal relay, made of IED (Intelligent Electronic Device) blocks. With ability to performe different protective tasks, there are a lot of other functions integrated in it: metering, monitoring, control, automation incorporated into the design of a relay as functional blocks.

Most modern numerical, microprocessor based relays are comprised of a core set of next functional blocks[2]:

1. Algorithmic and control logic processing, usually performed by the main 'protection' microprocessor and often referred to as the CPU (central processing unit). Most numerical relays have multiple processors for different functions.
2. Power system current and voltage acquisition, usually performed by a dedicated digital signal processor (DSP) in conjunction with an analog-to-digital data acquisition system and interposing current and voltage transformers.
3. Digital inputs and outputs for control interfaces, usually required to handle a variety of current and voltage ratings as well as actuation speed, actuation thresholds and different output types.
4. Analog inputs and outputs for interfacing to transducer and SCADA (Supervisory Control and Data Acquisition) systems, usually required to sense or output decimal Amper currents.
5. Communications to station computers or SCADA systems, usually requiring a variety of physical interfaces (e.g. RS485, Fiber Optical, etc.) as well as a variety of protocols (e.g. Modbus, DNP, IEC-870-5, UCA 2.0, etc.).
6. Local Human Machine Interface (HMI) for local operator control and device status annunciation.
7. Power supply circuitry for control power, usually required to support a wide range of AC and DC voltage inputs (e.g. 24-300 V DC, 20-265 V AC).

B. Relay architecture

The design of a universal relay requires an architecture that can accommodate all of the above functional blocks in a modular manner and allow for scalability, flexibility, and upgradability in a cost effective manner for all applications. [2, 3]

▪ Modularity

On the hardware side, modularity is achieved through a plug-in card system similar to that found in programmable logic controllers (PLCs) as well as PCs. A key element in the successful performance of such a system is the highspeed parallel bus, which provides the modules with a common power connection, and high-speed data interface to the master processor (CPU) as well as to each other. Modules plug into a high-speed data bus. The high-speed bus should be completely asynchronous, thus allowing modules to transfer data at rates appropriate to their function. This is crucial in order to maintain a simple, low-cost interface for all modules.

One of the key technical requirements of such a system for protective relaying applications is that the modules must be capable of being completely drawn out or inserted without disturbing field wiring which is terminated at the rear of the unit.

▪ Scalability and flexibility

A modular architecture of this type allows for both scalability and flexibility. In particular, scalability is found in the ability to configure the relay from minimum to maximum I/O capability according to the particular requirements. The flexibility lies in the ability to add modules configured with the desired sub-module I/O. This allows for maximum flexibility when interfacing to the variety of control and protection applications in the power system

▪ Upgradability and Enhancements

Another obvious benefit of this architecture is the ability of users to upgrade or enhance their relay simply by replacing or adding modules. For example:

- Upgrading from a twisted pair copper wire communications interface to high-speed fiber optics communications.
- Enhancing a transformer protection application by adding an Analog I/O (ANIO) module with the sub-modules to detect geomagnetic induced currents, sense and adapt to tap-position, perform on-load tapchanger control, or detect partial discharge activity.
- Upgrading the CPU module for more powerful micro-processor technology allowing for more sophisticated and protection algorithms (e.g. 'Fuzzy Logic', 'Neural Networks', 'Adaptive').
- Enhancing the metering capability of the relay by adding a second DSP module with current and voltage transformer sub-modules capable of revenue class metering accuracy.
- Enhancing the control capabilities by adding a Digital I/O (DIGIO) module with customized labeling to customize the reporting of events.
- Enhancing the HMI capabilities by adding an LED module with customized labeling to customize event reporting.

▪ Modular Software

Scalability and flexibility issues are not exclusive to hardware. Software must be able to support the same features. In fact, the software has its own form of modularity based on functionality. These include:

-Protection elements,
-Programmable logic and I/O control,
-Metering,
-Data and Event capture/storage,
-Digital signal processing,
-HMI control,
-Communications.

The key advancement in software engineering that has come to dominate the software industry is Object Oriented Programming and Design (OOP/OOD). This involves the use of 'objects' and 'classes'. By using this concept one can create a protection class and objects of the class such as Time Overcurrent (TOC), Instantaneous Overcurrent (IOC), Current Differential, Under Voltage, Over Voltage, Under Frequency, Distance Mho, Distance Quadrilateral, etc. The same can be done for metering, programmable logic and I/O control functions, HMI and communications or, for that matter, any functional entity in the system. Therefore, the software architecture is able to offer scalability and flexibility: scalability in that the number of objects in an application is scalable (e.g. multiple IOC elements); flexibility in that objects can be combined to create custom combinations to suit the application (e.g. TOC, IOC, Distance Underfrequency and Directional IOC). In combining these attributes - modularity, scalability, flexibility, upgradability and modular software

- the capability is there to run a wide variety of applications on a common platform.

C. Economical aspects

The biggest challenge for relay designers is the 'cost effective manner'. The risk they have faced in the past is creating architecture with all of the above attributes where the base cost of the platform is too high for the more cost sensitive applications such as feeder protection. Today, this has been resolved as a result of cost reductions inherent in the production of a common platform for all applications. Like the PC industry, common components such as power supplies, network cards and disk drives continue to drop in price, while delivering ever-increasing performance levels.

While protective relay production is nowhere near the volume of PCs, a next generation relay platform based on a modular architecture which can accommodate all applications will yield significant development and manufacturing cost reductions.

III. SUBSTATION AUTOMATION - STATE OF THE ART AND TRENDS FOR THE FUTURE

Substation automation is, by definition, the use of the IED data within the substation and control commands from remote users to control the power system devices within the substation. The universal relay is the engine for substation automation.

A. Comunication protocols

The IEEE defines communications protocol as: a formal set of conventions governing the format and relative timing of message exchange between two communications terminals. A strict procedure required to initiate and maintain communication. This regulates the order and arrangement of information, transfer speed or baud rate and error checking.

In general, power system communication networks support four basic operations: establish communications, terminate communications, write data, and read data. The write data function can be used to tell an IED to perform a control action, change settings, or send data to the requesting device. Error checking is done by each device to determine if the message data was corrupted during transmission. The type of protocol, message format, and transfer speed are parameters that are configured during installation. Communications schemes are polled, scheduled or unsolicited. In a polled situation, one IED acts as the host and initiates almost all data exchange. The other IED acts as a slave and does only what it is told. The slave rarely initiates data exchange, it simply reacts to requests for data from the host. The exception is an unsolicited message from a slave which sends data to the host without the host requesting it. Often, this is a result of an unexpected change.

B. Most popular protocols

To see just how important standards-based communication systems are, we can consider the example of a large Germany electric utility. At present, this utility has more than 200 different protocols running on intelligent devices within its distribution network [4]. The most popular communication protocols around the world are [5, 6]:

- ASCII - Protocol that is easily converted to human-readable characters and numbers. This protocol is simple but generally slow.
- Modbus - A popular master-.slave protocol with industrial users, which has also become popular in substations. It issues simple READ/WRITE commands to addresses inside an IED.
- Modbus Plus - A medium speed network built with proprietary network interfaces using an extension of Modbus protocol.
- DNP 3.0 - An ever increasingly popular SCADA master-slave protocol, governed by a standards committee and users group, that was designed to optimize efficiency through report by exception, remote modem connections, and multidrop capabilities. DNP can run over multiple media, such as RS-232 and RS-485 and can issue multiple types of READ/WRITE messages to an IED. Predominantly popular in North America.
- IEC 60850-5-101 - This protocole is considered as the European partner to DNP. It differentiates itself from DNP with its slightly different messaging structure and the ability to access object information from the IED.
- UCA/MMS - Utility Communications Architecture, currently being designed by North American utilities, vendors, and consultants to satisfy most requirements in substation feeder equipment and eventually all power system equipment.
- Proprietary - Protocols created by the product vendors to communicate with their devices. These are generally unique for each vendor and are not inter-operable. Some vendors design their own protocol because existing protocols lack necessary robustness and efficiency.
- Interleaved - Interleaved data streams is a simple way that multiple communications messages can occur on a single communications connection. Data acquisition, control, configuration, and time-synchronization communications can occur at the same time.

The international effort for standardised communication protocol has begun at 1990s and resulted in:

- IEC61850 - designed to satisfy every possible requirement in substation equipment.

C. Communications media

Many different types of communications media can be used to conduct the data between IEDs in a power system. They include copper communications cables, power line carrier (PLC), land line telephone, fiber and wireless. Wireless includes FM and microwave radio as well as cellular telephone and satellite communications.

- Direct copper - A copper communication cable dedicated to power system communications between two devices.
- Land line telephone - Conventional dial-up or leased lines dedicated to power system communications.
- Power line carrier (PLC) - A method of passing data on the power line conductor at high frequency.
- Fiber - Fiber applications communicate data in the form of light conducted over a single direct connection or multiple direct connections bundled together.
- Wireless - Where available, cellular telephone can be used as a dial-up connection. Radios supporting FM and microwave are installed as a dedicated connection for power system communications.

D. Communication tehnology development

A functional comparison of different generations of enabling communication technology is now discussed to point the development trend. Table 2 describes the characteristics of enabling technologies for conventional substations and modern automated substations using today's technology and tomorrow's technology. [7]

Table 2: Characteristics of enabling technologies

Function	Conventional Technology	Today's Technology	Tomorrow's Technology
SCADA	Hardwired logic, data acquisition via transducers	Logic in software, direct analogue-to-digital conversion for data, some use of IEDs for data collection and control	Distributed system with multifunction IEDs for control, monitoring, and data acquisition
Protection	Discrete electro-mechanical or static analogue relays	Mixture of conventional and microprocessor-based multifunction relays	Multifunction relays with inter-relay commu-nication via substation LAN
Wiring between primary and secondary equipment	Multi-conductor copper cables	Multi-conductor copper cables	LAN-based commu-nication between IEDs for control, protection, and monito-ring extended LAN or process bus commu-nication to switchgear IEDs
Commu-nication protocols within the substation	None	Serial connection of secondary equipment to station unit with commonly used protocols for control and protection (IEC 60850-5-101, Modbus, DNP3)	LAN and process bus connection with standard protocols (IEC 61850)
Commu-nication between substation and control centres	Serial multidrop connection using predominately proprietary protocols	Migration to standard protocols (IEC 60850-5-101, DNP)	Continued migration to standard protocols, including the use of WAN-based commu-nication (DNP3, IEC 60850-5-104, IEC 61968, and 61970)

E. Standardisation development

Power providers are focused on increasing productivity and making electric power safer, more reliable and more economical by providing innovative, simple to use, robust technologies for power system protection, automation, control, monitoring. Development of appropriate communications technologies and protocols is at the heart of this strategy. When relays and IEDs are integrated together, they form a powerful, economical Instrumentation and Control (I&C) system to support all aspects of electric power protection, automation, control, monitoring, and analysis. Figure 1 shows how typical IEDs and relays can be interconnected together to form a protection of power system. Such a system also supports the substation in terms of the monitoring, analysis, and automation aspects.

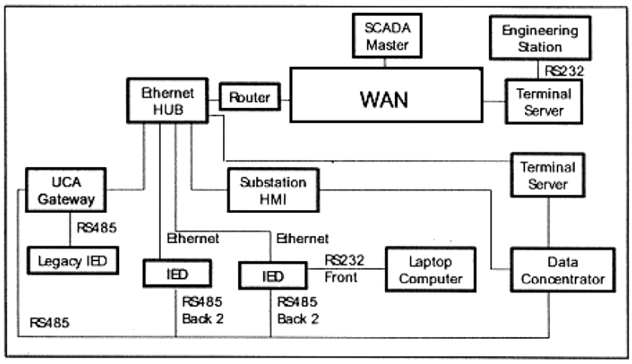

Figure 1: Typical integrated substation protection and control system [8]

A non-proprietary, standard, high-speed protocol offering sufficient services is required to enable a robust, integrated substation communications network without protocol converters. The introduction of IEC 61850 and the Utility Communications Architecture (UCA) has made it possible and justifiable to integrate station IEDs through standardization. Using the standardized high-speed communications between IEDs, the utility engineers can eliminate, many expensive stand-alone devices and use the sophisticated functionality and the available data to their full extend.

F. IEC 61850 project [5, 9, 10, 11]

The development of the IEDs has given new communication capability for the implementation of the single communication protocol, that is high speed, networkable, peer-to-peer architecture using as many 'existing' protocols as possible.

The Standard IEC 61850/UCA is developed in an international co-operation with broad vendor and utility participation. The primary target is the electrical substation automation (switchyards and transformers in the medium and high voltage transport and distribution). Most major utilities (e.g. AEP, EDF, EON, ENEL, RWE, ...) and system suppliers (ABB, Alstom, General Electric, SAT, Siemens, ...) contribute to the development of the standard.

IEC 61850 makes use of existing standards and commonly accepted communication principles, which allows for the free exchange of information between IEDs. It considers the operational requirements since any communication standard must consider the substation operations functions. However the communication protocol standard IEC 61850 focuses on neither standardising the functions involved in substation operation nor their allocation within the substation automation systems. Identifying and describing the operational functions used define the impact of the operational functions on the communication protocol requirements.

IEC 61850 identifies all the known functions in a substation automation system and splits them into sub-functions or so called logical nodes. A logical node is a sub-function located in a physical node, which exchanges data with other separate logical entities. In IEC 61850, all logical nodes have been grouped according to their most common application area, a short textual description of the functionality, a device function number if applicable and the relationship between logical nodes and functions. IEC 61850 decouples applications to design them independent from communication so they are able to communicate by use of different communication protocols. This is due to the fact that the vendors and utilities have maintained application functions that are optimized to meet specific requirements and that have reached a high degree of maturity and quality. Therefore IEC 61850 provides a neutral interface between application objects and the related application services allowing a compatible exchange of data among components of a substation automation system.

One of the most important features of IEC 61850 is that it covers not only communication, but also qualitative properties of engineering tools, measures for quality management, and configuration management. This is necessary since when the utilities are planning to build a substation automation system with the intention of combining IEDs from different vendors, they expect not only interoperability of functions and devices, but also a homogenous system handling.

Quality assurance for system life cycles is one of the important aspects covered by the IEC 61850, which defines the responsibilities of utilities and vendors. Guidelines for environmental conditions and auxiliary services with recommendations of the relevance of specific requirements from other standards and specifications are also defined. With the plug and play capabilities embedded in the standard and the immediate prove of concept in pilot projects, IEC 61850 promises to be a great step forward in the development and acceptance of substation automation systems world-wide. This will finally bring the real benefits of automation and integration to utilities that were originally promised years ago.

Most parts of the IEC 61850 are finalized or were already issued as standards, while others were in final phase at the end of 2003 [12]. Some prominent device vendors have already announced first compatible devices for 2004. [10]

a) Primary application of the standard IEC 61850

Figure 2 shows a typical example of a substation automation system with its common three levels. At process level there are the process interfaces hard-wired in the past and serially linked by the process bus in the future. Protection and control at bay level may reside commonly in one device or in dedicated ones.

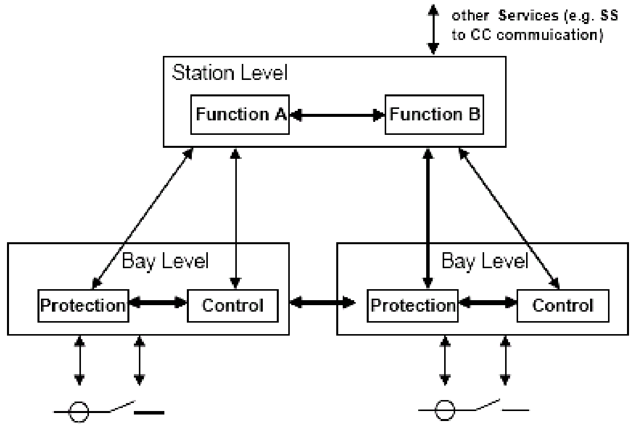

Figure 2: Typical substation automation system

These devices are connected in between and with the station level by the interbay/station bus. At station level, there is very often a station computer with HMI (human machine interface) and a gateway to the control at the higher network level. There exist a lot of variations of this example but all substation automation systems have to provide all or at least a subset of the following functions with some domain specific performance, heterogeneity and life-time conditions.

Important function groups and functions are:

- System management (self-supervision, communication management, time synchronization);
- Operation and control (access security management, switchgear operation, measurement, event and alarm handling);
- Parameter (data/disturbance records retrieval, logging and archiving);
- Local and distributed automation (protection and busbar protection (remote phasors).

G. Internet technology

The latest trend goes to using Internet technology in an Intranet or the Internet itself. [13]

Several vendors already offer substation automation systems with integrated Internet server. In this way, the acquired data can be exchanged in a cost saving way in an Intranet and distributed to a wider circle of users. Classic workstations can be replaced by normal Internet browsers. Maintenance work, for example implementation of new functions, must then only be performed at the central application server.

An American vendor offers a monitoring system where space and administration of data is provided on the vendor's own server [1]. The user must only install the Internet enabled relays and devices in his substation and connect them to the Internet via the local service provider. Safety against foreign access is claimed to be guaranteed by passwords, authentication procedures and firewalls. The offer aims at small users where an own SCADA system is too expensive or not yet installed.

IV. CONCLUSIONS

The protection subsystem of today adopts digital technology for high reliability and performance. Utilities worldwide have been clamoring for a standard that will allow different devices from different manufacturers to communicate with a common protocol and to interoperate. Modern digital protection relays that can accommodate the requirements of any substation automation proposal have this main features: consistent design concepts applied to hardware and software for different relays; modular software; standardization; tools for analysis and coordination; user-friendly interface; relay parameters set remotely and/or locally; data backup and storage for later analysis; standard communication protocols; a serial interface for connection to personal computers.

This relay architecture, a universal relay with IED blocks, is the engine for substation automation. At this area, trends point towards standardisation of communication protocols, since there are few hundred different protocols for communication beetwen substation devices, and development of one uniqe protocol. The new incoming standard IEC 61850 is based on the need and the opportunity for developing standard communication protocols to permit interoperability of IEDs from different manufacturers. Utilities also require IED interchangeability, which is the ability to replace a device supplied by one manufacturer with a device supplied by another manufacturer, without making changes to other elements in the system.

The trend of system integration will continue, driven by the cost pressure of competition and technological progress. The ongoing development towards totally integrated substations is expected to pick up speed with the approval of the open communication standard IEC61850 in the next years.

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