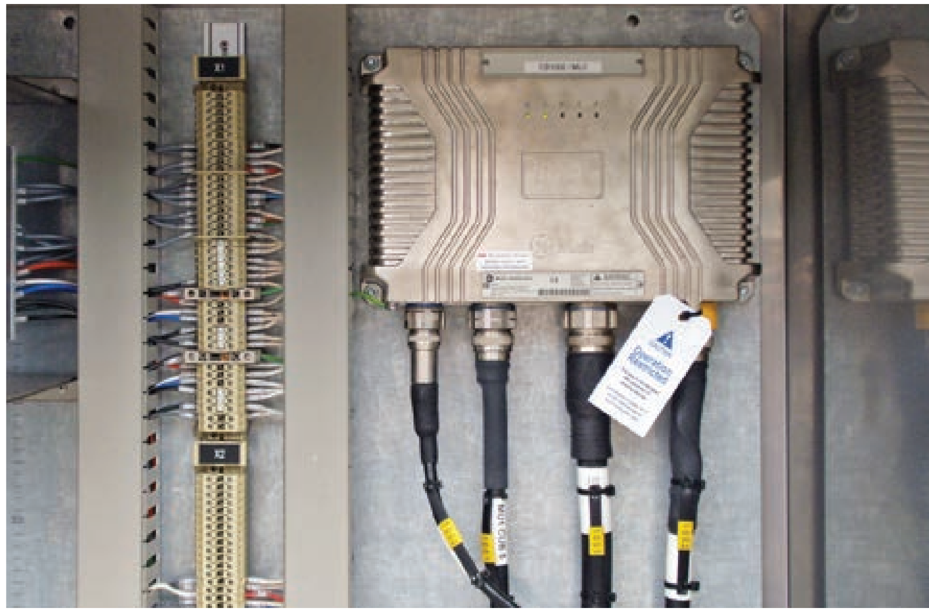

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Distributed bus protection application

in a platform for process bus deployment in the SMART SUBSTATION

Bus protection is typically a station-wide protection function, as it uses the majority of the high voltage (HV) electrical signals available in a substation.

Abstract

Bus protection is typically a station-wide protection function, as it uses the majority of the high voltage (HV) electrical signals available in a substation. All current measurements that define the bus zone of protection are needed. Voltages may be included in bus protection relays, as the number of voltages is relatively low, so little additional investment is not needed to integrate them into the protection system.

This special circumstance, where all HV electrical signals are connected to a single device, allows defining a bus protection scheme as the basic structure for the implementation of a complete Protection, Control and Monitoring System in a HV Substation.

Bus protection is not presently defined as a complete Protection, Control and Monitoring System due to the challenges of data collection. All HV electrical signals, equipment status signals, and equipment control signals, must be physically wired to the bus protection system, and must be further wired to other devices for other zones of protection. Distributed bus protection was developed to partially address this challenge of data collection. Bay units are installed in individual line bays to simplify the field wiring necessary for data collection by collecting the HV electrical signals, equipment status signals, and equipment control signals locally. However, the bay units are still dedicated to a single zone of protection, that of bus protection and the bay units are wired in conjunction with other devices.

This paper presents a new Distributed Bus Protection System that represents a step forward in the concept of a Smart Substation solution. This Distributed Bus Protection System has been conceived not only as a protection system, but as a platform that incorporates the data collection from the HV equipment in an IEC 61850 process bus scheme. This new bus protection system is still a distributed bus protection solution. As opposed to dedicated bay units, this system uses IEC 61850 process interface units (that combine both merging units and contact I/O) for data collection.

The main advantage then, is that as the bus protection is deployed, it is also deploying the platform to do data collection for other protection, control, and monitoring functions needed in the substation, such as line, transformer, and feeder. By installing the data collection pieces, this provides for the simplification of engineering tasks, and substantial savings in wiring, number of components, cabinets, installation, and commissioning. In this way the new bus protection system is the gateway to process bus, as opposed to an add-on to a process bus system. The paper analyzes and describes the new Bus Protection System as a new conceptual design for a Smart Substation, highlighting the advantages in a vision that comprises not only a single element, but the entire installation.

Busbar Protection Operating Principle

Khirchoff's current law states that the sum of the currents entering a given node must be equal to the currents leaving that node. It applies to ac current for instantaneous values. Thus, the sum of the currents in all feeders of a busbar plus any bus fault current must be zero at any instant in time. The sum of the feeder currents alone therefore equals the bus fault current.

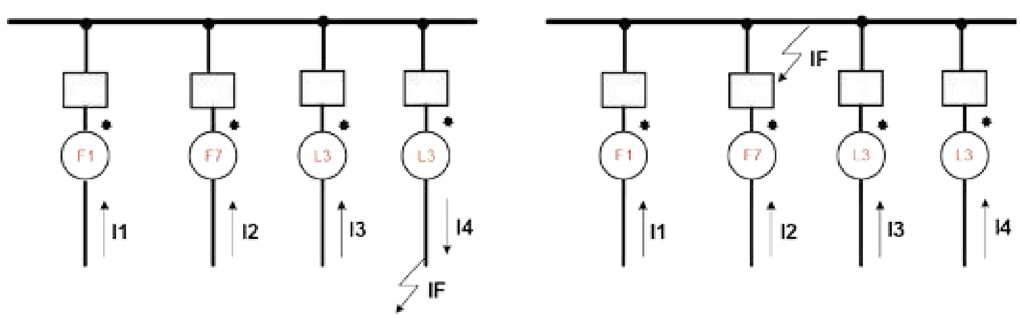
Consider the two situations demonstrated for the simple bus shown in Figure 1.

In case of an external fault, the current leaving the bus is equal to the sum of all of the currents entering the bus, and the total summation is zero. The same would be true when considering load flow. On the other hand, in case of an internal fault, the sum of all of the currents entering the bus is equal to the total fault current (summation of feeder currents is not zero). An ideal differential relaying system takes advantage of the fact that the sum of the feeder currents will be zero for external faults or load flow, whereas the sum will be equal to the total fault current for internal faults. Unfortunately, there are problems introduced wherein the ideal cannot always be obtained, and steps must be taken to insure that the differential relaying system works properly, even under non-ideal conditions.

Low Impedance Current Differential

It is possible to use a low impedance device in the differential circuit if steps are taken to overcome the effects of feeder current measurement errors such as CT saturation. Consider the situation shown in Figure 2, which develops a so called restraint quantity to mitigate against measurement errors.

The currents are shown in oversimplified form and are meant for demonstration purposes only. The CT in Line 2 is assumed to saturate completely every half cycle so that the current Ix will be as shown. As a result of the collapse of the CT in Line 2, the differential current Id will flow. The operating current, Iop, is the absolute value of the differential current Id and the restraining current, Irest. Irest can take various values such as the maximum of all currents entering and leaving the busbar, the sum of the absolute values of all of the currents entering and leaving the busbar, etc. The key point to note in this Figure is that the restraint current is significant during the period of nonsaturation while the operating current at the same time is equal to or very nearly equal to zero.



$$I_F = I4 = I1 + I2 + I3 \qquad \sum i = 0$$

$$I_F = I1 + I2 + I3 + I4 \qquad \sum i \neq 0$$

a) External Fault or Load Flow

b) Internal Fault

Figure 1. Simple Bus Arrangement

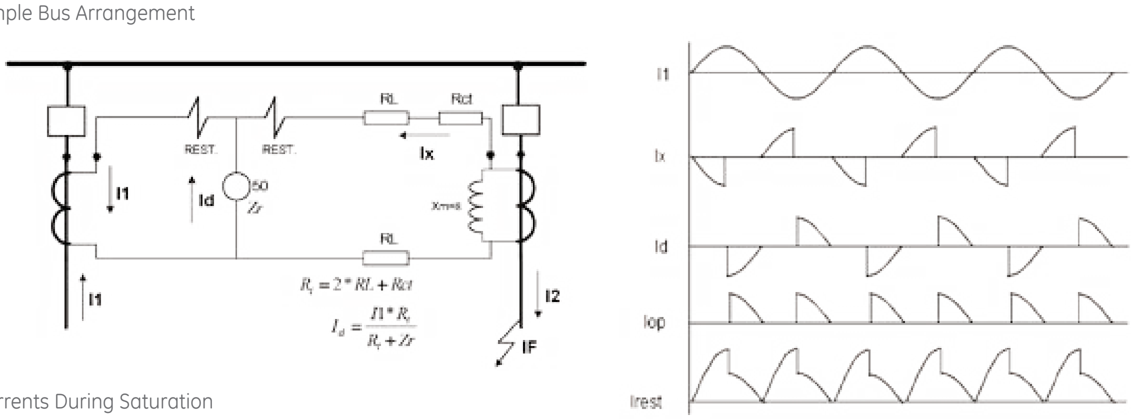


Figure 2. Currents During Saturation

The relay shown in Figure 3 takes advantage of this condition to prevent operation during external faults with significant saturation in the fault CT, but to allow operation during internal faults without any delay. High speed operation, in less than one cycle, can be obtained for heavy faults. The current differential element shown in Figure 3 is in effect a percentage restrained overcurrent relay; i.e., the differential element (4) produces an output when the operating current (Iop) exceeds Kr percent of the restraining current (5).

This relay also requires that all of the CT leads be brought into the relay house for connection to the relay. Additionally there is a directional element (10) that is used to supervise the tripping of the differential unit in case of CT saturation

The directional principle (block 10) checks if the currents of significant magnitudes (as compared with the fault current):

- flow in one direction (internal fault) or,
- one of them flows in the opposite direction as compared with the sum of the remaining currents (external fault).

The directional check should be performed only for the currents that are fault current "contributors" (in contrary to load currents).

Most Common Bus Arrangements

A power system bus is, at the most basic, an interconnection of circuits. Protection of a bus is straightforward, and uses any number of protection methods, including the low impedance differential method as described. The challenge to bus protection is actually in power system operations. Different busbar configurations have been developed to support redirection and reconfiguration of power system flows, to support maintenance activities, to allow efficient use of physical space, and to reduce the amount of capital equipment required. Bus protection on any type must be suitable for all typical bus arrangements.

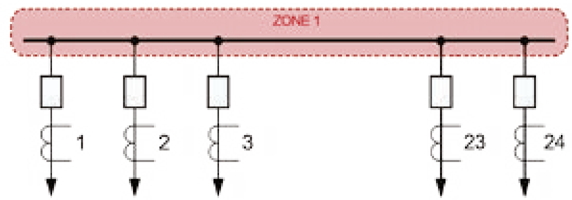


Figure 4. Single Busbar System

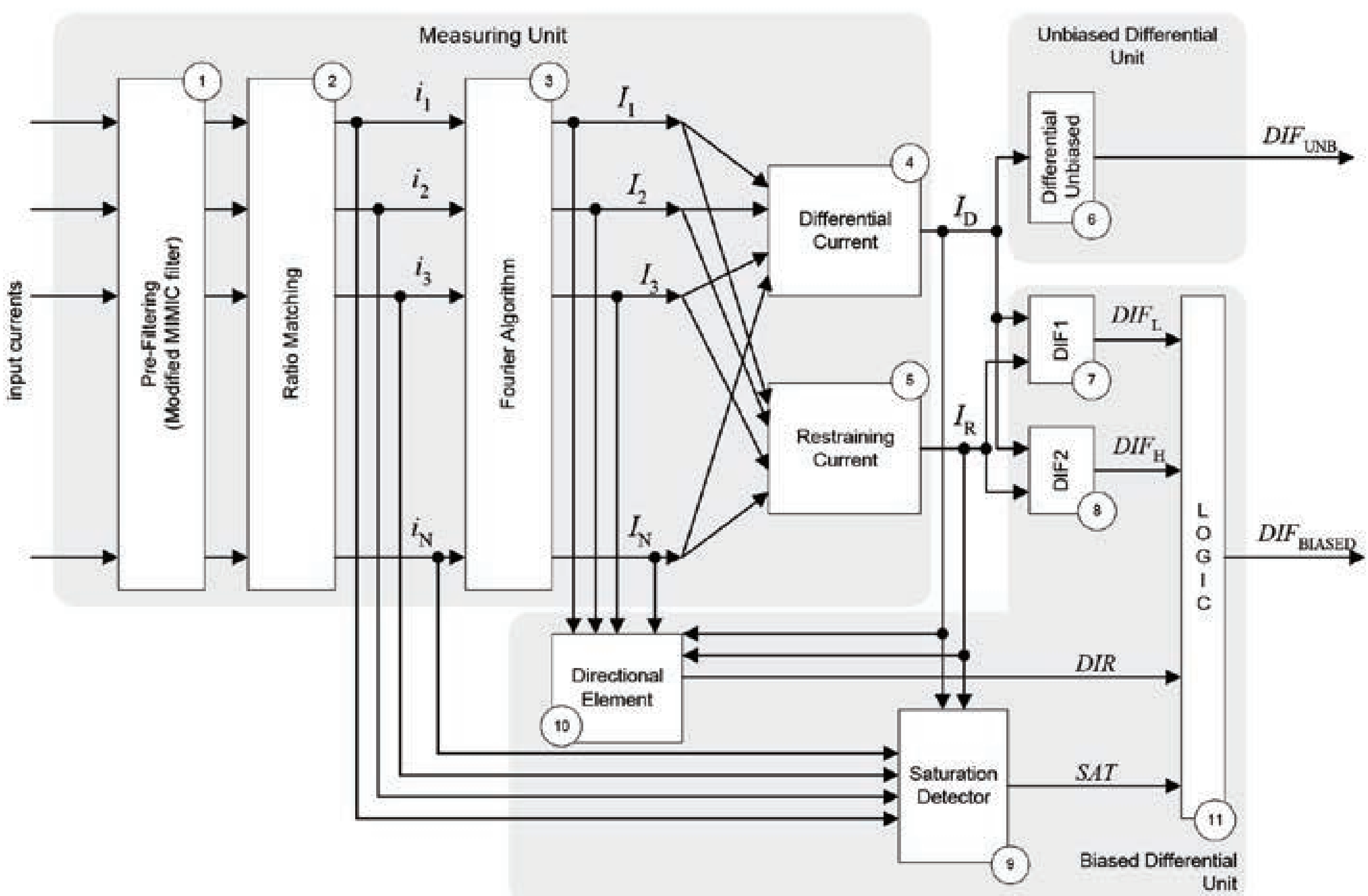


Figure 3. Low Impedance Current Differential with Directional current element as second criteria for ripping and CT Saturation Detection to control the trip logic.

The most common and simple Bus arrangement is the single busbar. See Figure 4.

In some bus arrangements, it is common to switch lines to different buses in the substation to facilitate operation and/or maintenance. The most common in this case is the double busbar system. See Figure 5.

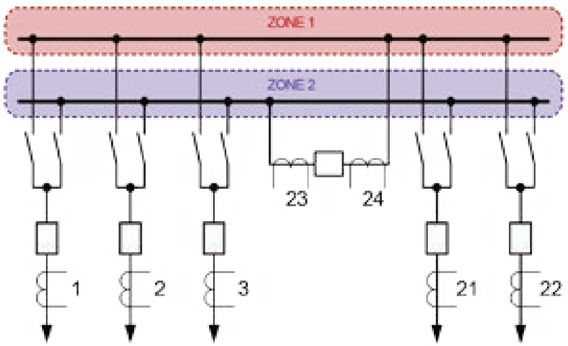


Figure 5. Double Busbar System

There are some variants where a transfer bus is included. A double and transfer bus system is shown in Figure 6. In this arrangement, the tie breaker is connected to one of the lines through the transfer bus while the regular line breaker is removed from service. The switching of the breakers is accomplished via the line switches associated with the breaker to be switched. In the low impedance differential relay described above, auxiliary switches (a and b) associated with the line switches (and certain breakers in some arrangements) are brought into the relay and the state of these switches is used by the relay to determine which breakers are connected to which bus so that the correct differential zones can be established. The CT's in this situation are always connected to the relay, thus CT switching is not required, because the determination of the zone of protection is done via software in the relay. Separate trip outputs are provided for each breaker thus only those breakers associated with the faulted bus will be tripped at the time of a bus fault (one relay can protect multiple buses).

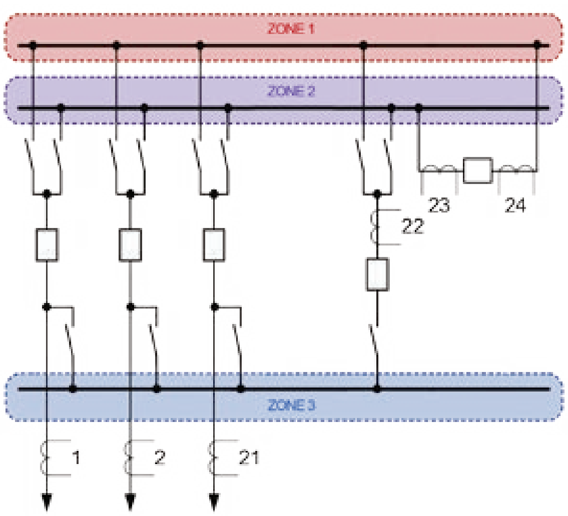


Figure 6. Double and Transfer Bus System

Another version of the double busbar arrangement is shown in Figure 7, where each busbar segment is split into 2 segments through the use of a tie breaker.

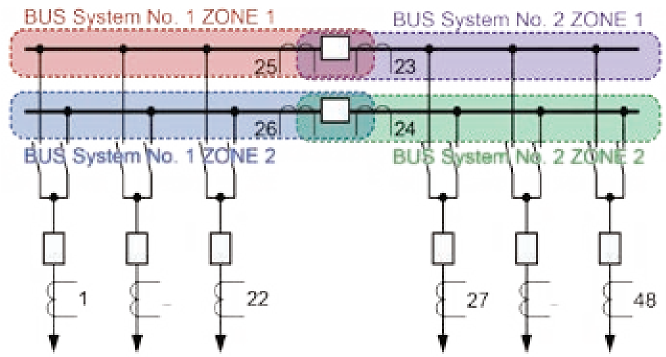


Figure 7. Two Double BusBar System

A configuration that is very popular for HV substations is the breaker-and-a-half arrangement. Breaker-and-a-half provides similar operating advantages to double busbar, but requires fewer circuit breakers and isolator switches. For busbar protection purposes the breaker-and-a-half is equivalent to a two single busbar systems.

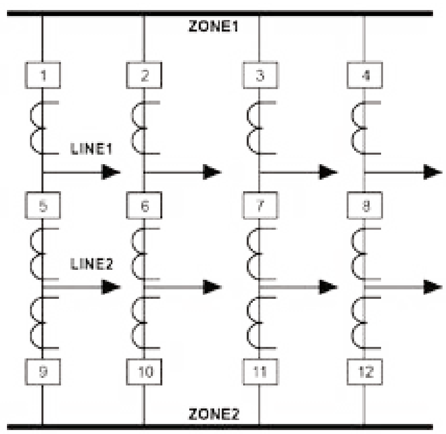


Figure 8. Breaker-and-a-half arrangement

Another configuration very popular in the USA is the double busbar with by-pass. In this mode the operation is in single bus. The other bus is used for a line where the feeder is bypassed for maintenance, and the bus coupler breaker becomes the line breaker. See Figure 9.

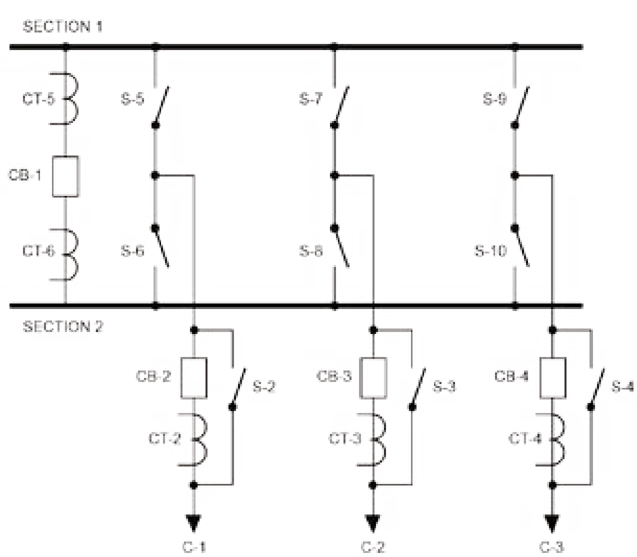


Figure 9. Double Busbar with Bypass

Bus Protection Systems

Bus protection systems must be suitable for application on any of the busbar arrangements as described. Beyond the standard protection requirements of reliability (both dependability and security for all fault events) and high speed (to limit the impact of a bus fault on the power system), bus protection systems need to be selective. This requires that a bus protection system only trip the feeder breakers that are actually connected to a faulted bus. For a single busbar system or a breakerand-a-half busbar system, this requirement is easily met, as all breakers can only connect to one bus. However, for more complex arrangements, such as the double busbar system, this requirement for selectivity is more difficult to meet. This sets the following requirements for bus protection systems:

- Providing independent protection zones with independent protection settings for each bus segment.
- Monitoring which bus segment each feeder or source to the bus is connected to.
- Tripping only the breakers connected to a faulted bus segment.
- Dynamically change each bus protection zone based on which feeders are connected.

THE CHALLENGE FOR TRADITIONAL SOLUTIONS IS THAT FIELD WIRING IS COMPLEX AND TIME CONSUMING, AND THAT THE BUS PROTECTION SYSTEM AND FIELD WIRING IS COMPLETELY DEDICATED TO BUS PROTECTION.

The first requirement is straightforward to meet for numerical bus protection systems. The second and third requirements are essentially wiring and I/O point count requirements. The status of each circuit breaker and each isolator switch (that determines which bus segment the feeder is connected to) must be brought to the bus protection system. Trip contacts for each circuit breaker must be supplied by the bus protection system. A typical feeder connected to the double busbar system of Figure 5 is going to require at least 6 status inputs (2 for the circuit breaker, 2 each for the isolator switches) and 1 contact output. Many more I/O points may be required based on actual arrangements and individual utility practices.

The fourth requirement is for a dynamic bus replica, that tracks which feeder is connected to which bus protection zone, through the status of isolators and circuit breakers, and issues trip commands to only the circuit breakers connected to a faulted bus.

Such a bus protection system is necessarily complex, and must provide for large numbers of contact inputs and outputs. There are 2 architectures in common use today.

Centralized Busbar Protection

In a centralized busbar protection system, all field wiring is brought directly to the bus protection relay. This requires massive amounts of field wiring connected to a single relay panel. The relay panel wiring, and field wiring, is complicated and time-consuming to design and install.

Distributed Busbar Protection

In a distributed system, field wiring for each feeder or bay is connected to a bay unit. Each bay unit is then tied to a central processing unit by digital communications. In most existing designs, the bay units are actually relays that send current measurements to, send equipment status to, and accept trip commands from the central unit via a proprietary communications method. Ideally, all field wiring ends in the feeder bay by connecting to the bay unit, but in many applications, the bay units are actually installed in the control house in panels adjacent to the central unit.

Busbar protection systems using both methods meet the protection requirements for complex bus arrangements. The challenge for traditional solutions is that field wiring is complex and time consuming, and that the bus protection system and field wiring is completely dedicated to bus protection.

Process Bus as Part of the Smart Substation

One possible definition of a "Smart Substation" is a substation that supports the ability to acquire the data necessary to support intelligent applications, and the ability to rapidly deploy intelligent applications as they are developed. A Smart Substation then supports more robust data acquisition, improved communications between access levels inside the substation, and more robust application platforms. Some goals and proposed solutions for the Smart Substation can be described as follows:

1. Reduce the use of copper wiring and the project execution time to a minimum by moving field labour to the factory.
2. Reduce the time of data collection to SCADA from the current typical time of 1 second to 1 power cycle, providing an effective real time system.
3. Implement one communication protocol for access levels.
4. Facilitate the data access for an easy asset management implementation.

"Process bus" is nothing more than the ability to communicate currents, voltages, equipment status, and equipment control commands between primary system equipment (the "process level") and application devices at the bay or station level. It is clear that process bus is a key piece of the Smart Substation. A process interface unit (PIU), installed at primary equipment at the switchyard, publishes sampled values of currents and voltages along with equipment status, and subscribes to equipment control commands via IEC 61850 message formats. This clearly replaces much field wiring, and makes data from the primary equipment available for all applications.

More formally, the design of new substations shall not only have the objective of reducing the initial investments and application suitability of devices but also minimizing the cost of long term maintenance and future refurbishments. The amount of corrective maintenance actions on the secondary copper wiring between the primary apparatus and protection and control IEDs as well on all copper connections at IEDs I/O boards can be significantly reduced. Therefore the concept of process bus permits the lifecycle view of design of electrical substations. Standardization of interfaces between primary equipment and secondary systems, reduction of the number of copper cables and the use of pre-connected cables permits the refurbishment to be done with less effort.

Furthermore, process bus supports the development of a protection, control and monitoring system (PC&M) approached from the utility enterprise perspective that recognizes and addresses needs, such as cost reduction and speed of deployment, while remaining at the same time reliable and secure. The process bus system originates from the following enterprise objectives:

- Achieving cost savings
- Reducing project duration and outage windows
- Shifting cost from labour to pre-fabricated material
- Targeting copper wiring as main area for cost optimization
- Limiting skill set requirements
- Supporting optimum work execution
- Improving system performance and safety
- Using open standard communications

Bus Protection Using Process Bus

A typical process bus architecture involves process interface units (PIUs) distributed throughout the substation switchyard to acquire signals at primary equipment. To implement bus protection, a bus protection system simply needs to connect to, and acquire data from, PIUs located at the appropriate current transformers, circuit breakers, and isolators. It is intuitive, then, that bus protection using process bus uses a distributed architecture, using PIUs as opposed to bay units. All protection and control functions will be implemented in a central relaying unit that connects to the appropriate PIUs.

In fact, bus protection is a good first use for process bus. The concept of a station-wide distributed architecture, with remote acquisition of data, is a well-established architecture for bus protection. Process bus simply changes the nature of the bay units by using PIUs, and uses an industry standard communications method, IEC 61850, as opposed to proprietary methods. The capital cost of a bus protection system using process bus and PIUs should compare to a traditional distributed bus protection architecture using bay units. The advantage to the process bus system is twofold: wiring costs should be reduced over traditional bus protection using process bus, and the PIUs installed for bus protection can also supply the same data to other relays for other zones of protection via process bus communications. Therefore, bus protection provides a built-in expansion and upgrade path for protection and control systems in the substation.

THE NEW DISTRIBUTED BUS PROTECTION SYSTEM CHANGES THE FOCUS OF BUS PROTECTION TO THAT OF APPLICATION BY REPLACING MOST OF THE FIELD WIRING WITH DISTRIBUTED I/O AND FIBER OPTIC CABLES.

New Distributed Bus Protection System Using Process Bus

This paper describes a new Distributed Bus Protection System using process bus. The goal of this new system is to start to meet the needs of the Smart Substation. The new system uses a central relaying unit for all protection and control functions, uses PIUs to acquire all signals from and provide control of primary equipment, and uses IEC 61850 communications between the central relaying unit and the PIU. The central relaying unit, in addition, collects all related and necessary data in one device. So this new Distributed Bus Protection System addresses the Smart Substation goals of reducing field wiring, implementing one communications protocol for all access levels, and starts on facilitating easy data access. In addition, this system can be a future platform for further applications for station-wide data.

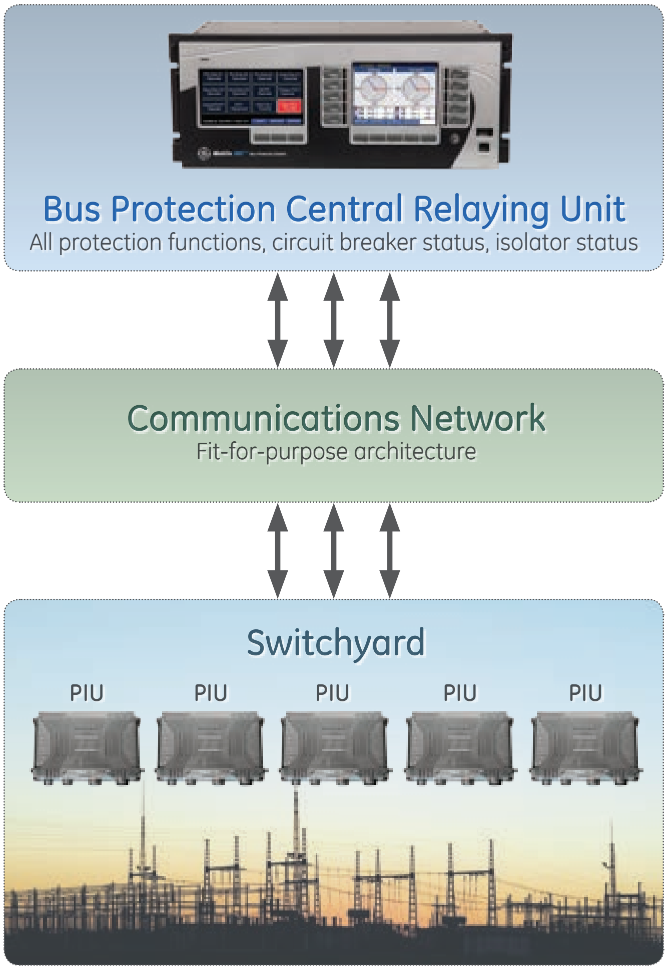


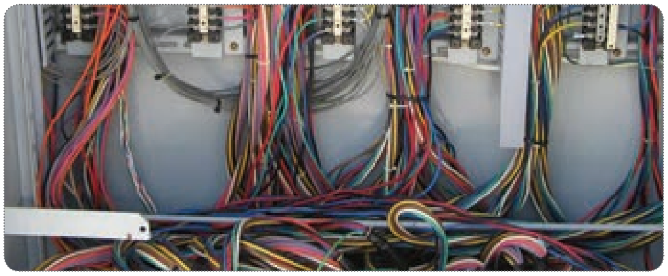
Figure 10. Overall Scheme of the Process Bus based Bus Protection System

Solving the Cost of Field Wiring

As previously described, bus protection for large bus architectures is costly due to the time to design, install and commission all of the associated field wiring. Every source in a bus protection zone requires extensive field wiring for the relay to acquire the current measurements and equipment status, and to issue control commands. Every signal used by bus protection requires a pair of copper wires. Every one of these wires between the primary equipment and the relay, and the terminations of these wires, must be designed, installed and commissioned for the specific project. Every one of these wires will be wired in series or parallel to protective relays associated with the zones of protection for the source, so this effort will be duplicated. This process is exceedingly labor-intensive, with most of the labor requirements being on-site manual labor. The end result is a very intensive and error-prone process that adds significant time and cost to every project and makes long term maintenance costly, and changes difficult to implement. This effort is very much the same if the project is installing a new bus protection system, or simply adding an additional source to an existing system.

The new Distributed Bus Protection System changes the focus of bus protection to that of application by replacing most of the field wiring with distributed I/O and fiber optic cables. The protection system consists of a distributed process interface (data acquisition and tripping) architecture using PIUs as bay units, with centralized processing performed by a single IED.

Extensive amounts of copper cables need to be distributed from each switchyard apparatus back to the control house



Many connections need to be made in each apparatus in the high voltage equipment switchyard

- All copper field wiring is between primary equipment in the switchyard and PIUs, which ideally should be located at the primary equipment in the switchyard. Fiber optic cables connect PIUs to the central bus protection unit.
- For all applications, the installation is then identical: the physical interface consists of PIUs connected to a fiber optic cable. A single IED is mounted in a relay cabinet, with the process cards in the unit patched to the fiber optic cables coming from the PIUs. The size of the IED, and the fact that there only fiber optic connections to the IED (with no field wiring) simplifies the relay panel, Therefore the relay panel design for all busbar arrangements and bus protection schemes is identical: one central relaying unit mounted in a relay panel, along with fiber optic patch panels.

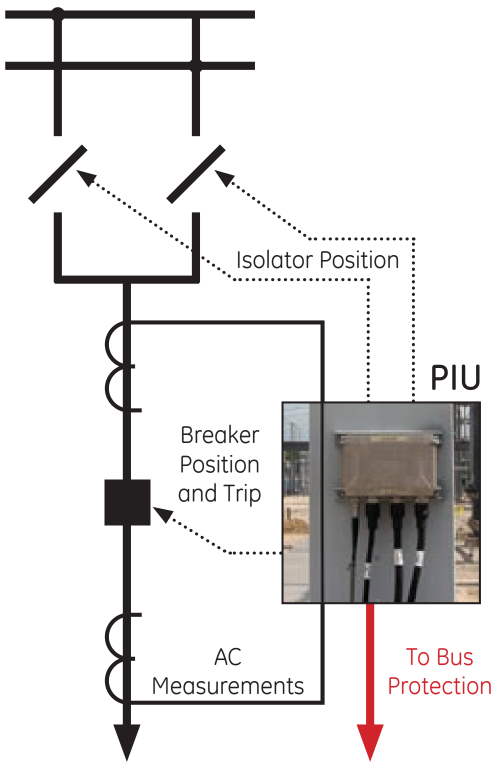


Figure 11. PIU Field Wiring

As previously described, the new Distributed Bus Protection system uses PIUs as bay units, that both samples currents and voltages, and provides contact I/O for equipment status and control. Once a PIU is installed in a Bus Protection system, the PIU can interface with any other device that supports sampled value messages as per the IEC 61850 standard implemented with the correct profile. Rather than duplicate field wiring from the bus source for a feeder zone of protection, simply patch any compliant family to the fiber optic cable from the PIU to add acquire the same signals.

Protection

The central relaying unit of new Distributed Bus Protection system provides robust and reliable protection for all bus protection applications. Highlights of the protection functions related to bus protection include:

- Multi-zone differential protection with both restrained (dual-slope percent or biased) and unrestrained (unbiased or instantaneous) functions incorporated. Differential protection is fast (typical response time: 1 power system cycle) and secure. Security is achieved by using a fast and reliable CT saturation detection algorithm and a phase comparison operating principle. Security is further enhanced by support for redundant process interface units (Bricks). Supports both three-phase tripping and individual phase tripping.
- Dynamic bus replica functionality and multi-zone protection (up to 6 zones) is supported allowing application of the Bus Protection to multi-section reconfigurable buses. A zone expansion/contraction to an open breaker feature is included. Isolator position monitoring for up to 96 isolators.
- Check-zone functionality configured by programming one of the differential zones to enclose the entire bus.
- Additional bus protection functions including end fault protection, breaker fail and overcurrent protection for each bus source, with CT trouble monitoring for each bus zone

All protection and control functions are implemented in the central relaying unit, including breaker failure. The PIU is intended to be a device located at primary equipment in the switchyard, and as such, is only a simple I/O device, and has no sophisticated processing. Sophisticated processing and application functions are best utilized in the central relaying unit.

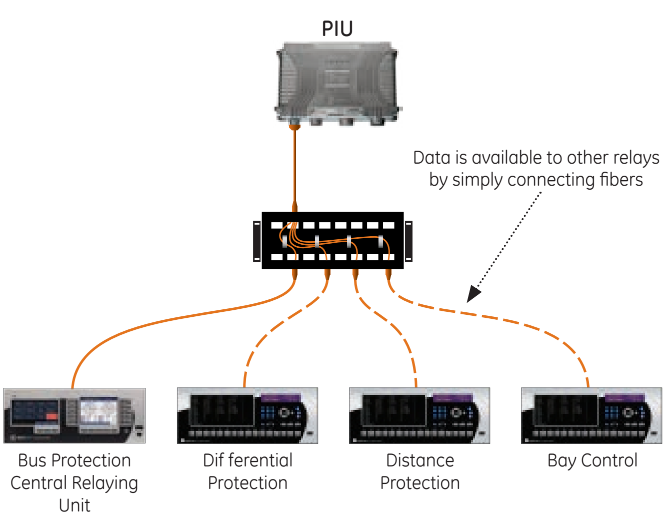


Figure 12. Process Bus and Expansion

Applying the New System

The new Distributed Busbar Protection System can be applied on all of common busbar arrangements previously described in this paper. Because all data is acquired through PIUs and IEC 61850 communications, configuration can be made using common object-oriented programming techniques.

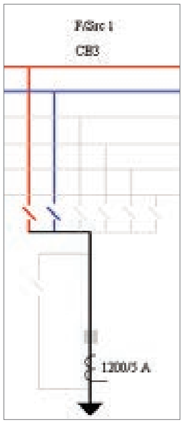


Figure 13. Bus Source Concept

The central relaying unit of the new System includes specific functions such as circuit breaker status, isolator switch status, and current transformer connections and ratios. The System also defines the concept of the "bus source", which, at heart, is a function block that ties together the status and connection functions for one individual bus feeder or circuit. Therefore, the bus source is responsible for determining which bus segment and bus differential zone a specific feeder or circuit is connected, and is responsible for issuing the appropriate trip command to the circuit breaker.

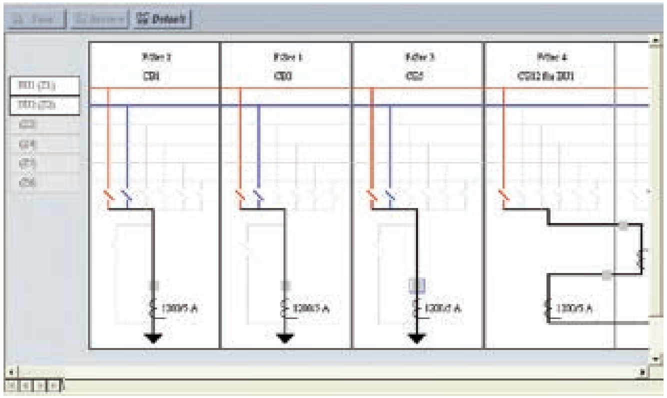


Figure 14. Dynamic Bus Replica Concept

The bus protection carries the object-oriented modeling even farther. The dynamic bus replica, to ensure protection zones match the actual power system conditions, is another function block. The dynamic bus replica is simply multiple bus sources connected together through configuration.

Quickly Expand the Protection System Through Process Bus

The Bus Protection System is intended to operate as a standalone, distributed bus protection system. The bay units for this system are PIUs, part of an IEC 61850 process bus solution. Once the PIUs for the Bus Protection are installed, process bus data is available for use for any other zone of protection. The PIUs, then, are a distributed I/O interface for all protection functions and zones, not just the Bus Protection

With the Bus Protection in place, installing line protection or feeder protection is a simple process: mount the relays in a panel, and patch to the fiber optic cable from the appropriate PIUs. The only requirement is the relays must implement the appropriate IEC 61850 profile to interface successfully with the PIUs.

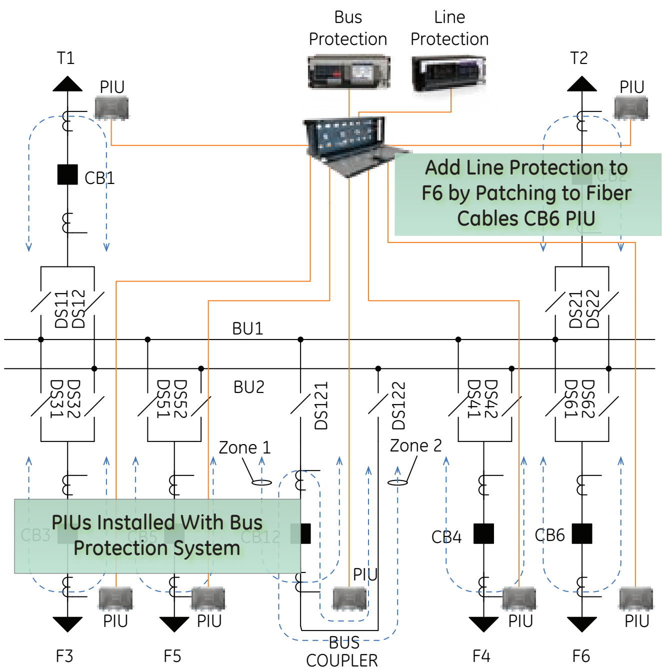


Figure 15. Easy Protection Expansion

Use the Distributed Bus Protection System as a Centralized DFR

In keeping with one of the requirements of the Smart Substation, the new Distributed Bus Protection System can be used to supply additional functions to provide better access to data. With access to data across the entire substation, the new System also has the capability to function as a basic centralized Digital Fault Recorder (DFR). While not as full-featured as dedicated DFRs, the unit includes specific transient recorder settings and digital triggers to initiate recording. The Distribute Bus Protection System can capture up to 50 individual oscillography records at sampling rates of up to 128 samples per cycle. Oscillographic data will include AC waveform channels from every enabled bus source and every enabled protection zone differential and restraint current. The oscillographic data can also include up to 384 digital channels. In addition, the System provides an event recorder that records the last 8,192 events time tagged to 1 microsecond.

The Distributed Bus Protection System as Component in the Smart Substation

The new Distributed Bus Protection System described in this paper starts to meet the goals of the Smart Substation. The use of process bus and process interface units (PIUs) as bay units reduces the use of copper wiring and project execution time to a minimum. Communications between the central relaying unit and PIUs uses the common communications protocol of IEC 61850. The system also facilitates the acquisition of data from across the substation for presentation to other devices, station control, and traditional SCADA services. The new system supports the rapid development of other station-wide functions, and has started the implementation of a station-wide fault recorder. And finally, installing this system is a low-risk and cost-effective way to start the installation of process bus protection systems. For the same cost as a traditional distributed bus protection system, easy expansion of other protection systems is nothing more than an add-on function.

Cyber Security and Process Bus

Process bus systems can introduce challenges related to cyber security, especially in North America. NERC Critical Infrastructure Protection rules will define merging units or PIUs as critical cyber assets, and subject to implementing appropriate cyber security protection. This new Distributed Bus Protection System is designed specifically to address the cyber security problem. The communications architecture is a point-to-point architecture, with no remote access to the communications between the Protection central unit and the PIUs. The messaging between the relay and the PIUs is completely, physically sealed from the outside world, so there are no special concerns with regards to cyber security.

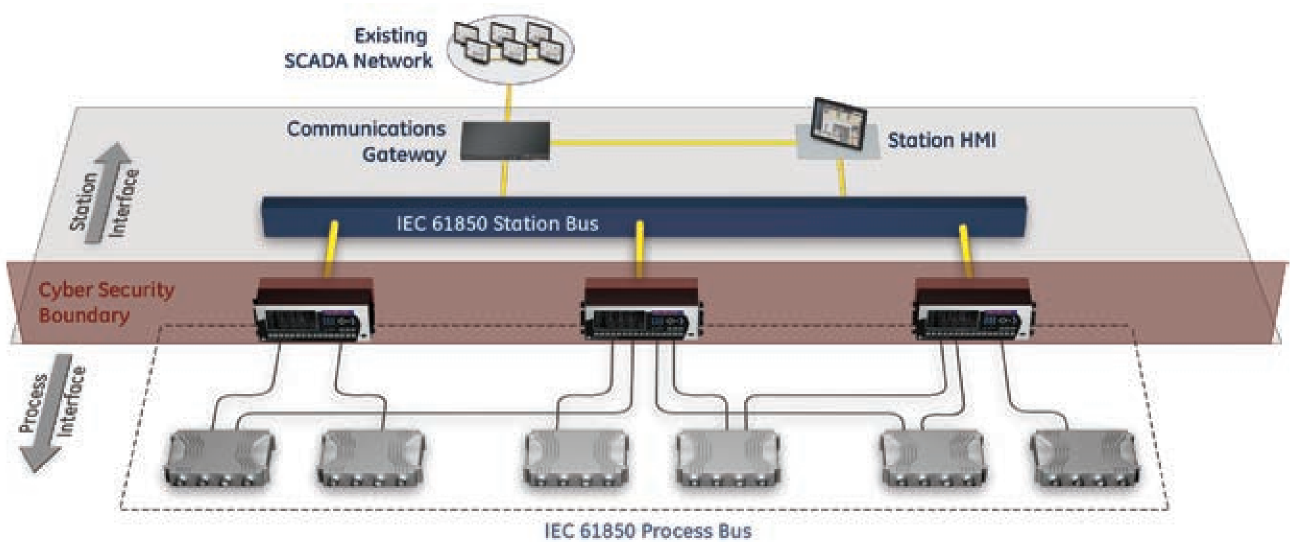


Figure 16. Natural Cyber-security Barrier

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