An Architecture and System for IEC 61850 Process Bus

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1. Introduction

The IEC 61850-9-2 standard [1] focuses on transparency and standardization of data communications. Implementation issues such as suitable architectures, reliability, time synchronization, data sharing, maintainability, testability, and scalability remain outside the scope of the standard.

Process bus architecture is a missing element on the road to implementing the next generation of Protection and Control (P&C) systems. In this paper, architecture refers to the definition and structure of the process interface points, partitioning and allocation of functions to the devices, the underlying structure of time synchronization, settings and firmware management, failure-tolerant communication framework, required data throughputs and latency considerations, data traffic patterns, and other related aspects.

Careful analysis of the rules and symmetries occurring in topologies of high voltage substations allow for identification of process bus data traffic patterns, origins, destinations, and throughput required to accomplish a simple, robust, scalable and flexible IEC 61850 process bus architecture. The primary equipment itself drives a logical and natural architecture for a communication-based protection and control scheme.

This paper presents a practical process bus architecture conforming to IEC 61850-9-2 that fits the task of protection and control of substations by drawing from the universal topology rules of substations.

2. Technical Attributes of A Robust Process Bus Architecture

Successful technical solutions, including a process bus P&C system, are those that address important and well-defined real world problems. Therefore, development of a process bus protection and control system should be approached from the utility enterprise perspective that recognizes and addresses real and present needs of today's utilities – cost reduction and speed of deployment being the chief ones. The proposed 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

- Recognizing copper wiring as a main driver for cost of labour
- Limiting skill set requirements
- Supporting optimum work execution
- Improving system performance and safety
- Using an Interchangeable system conforming to an open standard

With cost, labour and time requirements predominantly associated with copper wiring, the next generation P&C system should replace copper wiring by placing electronic modules throughout the switchyard and using fiber communications for bi-directional exchange of data. On the surface this is yet another remote I/O strategy, practiced for decades in the factory automation field. When applied to protection and control, however, the remote I/O approach faces a level of difficulty far beyond what has been worked out and proven in the realm of factory floor automation.

The following requirements must be factored into the design of a successful architecture. These must not be afterthoughts following an organic development of the concept. Instead, these requirements must be addressed as a part of high-level design before a single printed circuit board is laid out, line of code written, or dataset defined.

Comprehensible and complete architecture

Any component of the system, including field (merging) units, Intelligent Electronic Devices (IEDs), communication infrastructure, datasets, time synchronization, and so on can be designed only after a complete architecture is created demonstrating the ultimate shape of the system. The architecture needs to be simple and intuitive for all affected disciplines in the user's organization. It needs to follow today's proven protection fundamentals and be fit for purpose – addressing the right problem with the right solution. The primary goal is to deliver switchyard data to the P&C devices and to return commands from the latter to the switchyard devices. Not all the process data is needed by all IEDs. The limited data requirements of each IED are clearly and unambiguously dictated by the virtually fixed power equipment arrangement. The process bus network need not be designed to accommodate arbitrary or evolving IED data requirements.

Reliability

When increasing the number of electronic devices and connections in a system, the system's reliability decreases with the increasing device count. This can be easily demonstrated by using typical Mean Time To Failure (MTTF) data and running calculations on hypothetical process bus architectures [2,3]. Each additional element in the system will increase the failure frequency. In a properly designed architecture compensating measures, which often increase system complexity and cost, should not be required to make up for artificially reduced reliability.

Minimal co-dependencies

Today, a single zone of protection can be taken out of service for upgrades, troubleshooting, periodic testing or maintenance without impacting the rest of the secondary system and without an outage in the primary system (for applications where there is a redundant protection system). A zone of protection can be engineered and deployed with minimal interactions with respect to other secondary systems. This separation has proved an indispensable foundation of practical protection engineering, and needs to be retained in the next generation solutions. Without proper consideration, a firmware upgrade for a single digital component of the system may result in unexpected system behaviour and ultimately may trigger a firmware upgrade to adjacent devices. Such domino effects created by co-dependencies are undesirable, may introduce latent failure modes and ultimately would become obstacles in acceptance of the system.

Scalability

A successful system needs to be scalable. One should be able to deploy the system at any initial size (single zone up to an entire substation), and continue expanding one zone at a time as required. An expansion or modification should not raise any network congestion concerns, or other problems. The system must be both feasible and economically attractive in both retrofit and green-field situations.

Testability and maintainability

The system needs to be provisioned to facilitate testing and maintenance. Testing is defined here as verification and re-verification of a complete protection and control system after it has been deployed – initial commissioning, repair, periodically or after a major work such as protection system expansion, firmware upgrade or component replacement. Maintainability is defined as the existence of simple, safe and trusted means of performing firmware and setting changes and replacing faulty elements of the system. Addressing testability and maintainability is possible only by fundamentally engineering these facilities into the system at the beginning, not as afterthoughts in an organically developed solution.

Cyber security

The system needs to be naturally secure from the cyber security point of view. The high data rates of the process bus traffic and the requirement of very high availability of this data create challenges for known cyber security solutions such as intrusion detection or encryption. Cyber security issues, if left unattended, may either slow down adoption of the solution by creating the need to augment it later for compliance, and/or may create extra cost and effort for the user when deploying and running the system. The best solution is to develop an architecture which does not introduce issues related to cyber security in the first place.

This section summarized the key technical requirements for the next generation P&C architecture. It is clear that these requirements need to be factored in early into the architecture development. The next section introduces the rules of substation topologies and explains how these rules lead into a process bus architecture that meets the stated requirements.

3. Observations on Substation Topologies

Power substations are structured following strict rules.

The primary structure of any substation is divided into zones of protection. In order to minimize the size of an outage upon a protection trip, these zones typically span a single network element. Any protection zone is bounded by Current Transformers (CTs) that allow location of a fault, and Circuit Breakers (CBs) that allow isolation of the fault. These measuring and isolation boundaries are close to each other for better selectivity, and overlap in a certain way (the measuring zone is generally slightly larger than the isolating zone).

Traditionally, a single multi-function relay is used to provide protection for any given zone. Such a device needs access to all CTs surrounding the zone for a given principle of protection, and needs to control all CBs around such zone. Any given relay therefore, has well-defined data origins – there is no need to make all possible signals available to all possible relays. By the same logic, any given relay has well-defined signal destinations. These destinations (CBs) are generally coincident with the origins (CTs) as the measuring and isolation boundaries of protection zones are physically close to each other.

From the perspective of a relay there is a need for a bi-directional data exchange with points that bound its zone of protection. This creates a consistent one-to-many data traffic pattern. With the exception of a bus relay that may have a considerable number of CT/CB points surrounding its zone, all other known types of protection require access to just few points – typically all local three-phase conductors to the protected network element (CT/CB combination), and voltage from within the zone as needed.

Zones of protection are normally engineered to overlap in order to eliminate blind spots. Ideally this overlap should occur at the breakers, or at least within close proximity of the breakers. Engineering a precise fault measurement scheme without a corresponding means for fault isolation does not make economic sense (with a few exceptions such as transformer leads), therefore the situation depicted in Figure 1 is typical. In this arrangement zone 1 protection measures CT-1 (among others) and trips the breaker, while zone 2 protection measures CT-2 and trips the same breaker. Breaker Failure (BF) protection may be integrated with either or both of the protection relays, or implemented as a stand-alone device. In any case, the BF device will measure the same currents as the two protection zones.

A field (merging) unit is defined as a device interfacing with both CTs and the CB at the intersection of the two zones of protection in Figure 1. From that point of view such a unit needs to communicate with only 2 or 3 relays: the zone 1 and 2 relays, and potentially a stand-alone BF relay. This creates a universal one-to-many pattern for the bi-directional data traffic between the merging unit and its relays.

Detailed analysis of typical substation arrangements proves that the ability to feed four relays from a single merging unit covers all typical applications. For the few exceptions where more relays need to be fed from the same point, a second merging unit can be added and wired to the same signals.

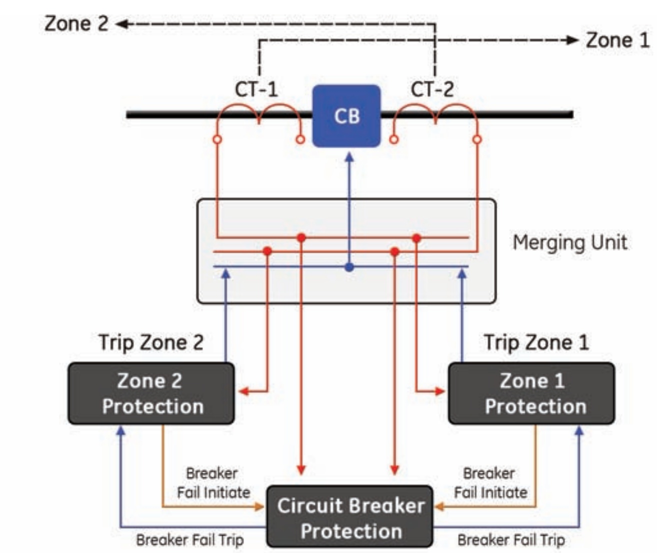

Figure 1.
Intersecting zones of protection map into a process bus architecture.

Zones of protection span and overlap breakers and network elements throughout the entire substation. This means that if a single merging unit is used for a given point of interest in the switchyard, the following domino effect takes place (Figure 2): IED-1 may need data from merging unit MU-1; MU-1 may feed IED-2; which in turn will connect to MU-2 to perform its function; etc. This means that the one-to-many data patterns of IEDs intersect with the one-to-many data patterns of merging units, seemingly putting all IEDs and merging units in the same communication network, and leading to a LAN spanning the entire substation. This would introduce maintenance and reliability problems, but can be avoided by observing that only four logical connections from a merging unit are required, which can easily be provided on a dedicated point-to-point basis.

Consider further a Breaker Failure application. With reference to Figure 1, when initiated from zone 1, the BF function should use CT-1 or CT-2 for the measurement, and upon breaker failure, it should issue a trip to all breakers surrounding zone 2, initiating their BF functions at the same time. Symmetrically, when initiated from zone 2, the BF function trips and initiates BF for all breakers of zone 1. This is a universal rule that holds true for all standard substation topologies.

Note that from this perspective, a merging unit that monitors CT-1 and CT-2 while controlling the breaker in between, is a suitable data exchange point (a "mailbox") for all involved IEDs. In order to function and issue a zone 1 trip, IED-1 needs to communicate with this merging unit, so it can also send a Breaker Fail Initiate (BFI) signal to the merging unit. In order to measure breaker current / position to perform its BF function, BF IED needs to communicate with the said merging unit, thus it can also receive a BFI from this merging unit. By the same logic, the BF IED can send the BF trip command to the said merging unit. This signal can be then forwarded by the merging unit to IED-2 and there executed as a trip and BFI for all breakers of zone 2.

The above observation shows how one could take advantage of the constraints imposed by switchyard topology to avoid challenges associated with passing BFI signals over station bus (isolation, testing, determinism) by building a fit for purpose architecture. From this perspective Figure 2 does not illustrate a problem anymore, but an opportunity. Station topology requires that any pair of IEDs that need to exchange protection signals typically both communicate with a common merging unit that may be used as a mailbox to forward the signals.

This section explained some of the rules and symmetries used to arrange primary equipment in a typical substation. When understood, these rules allow structuring a robust and simple process bus architecture as detailed out in the following section.

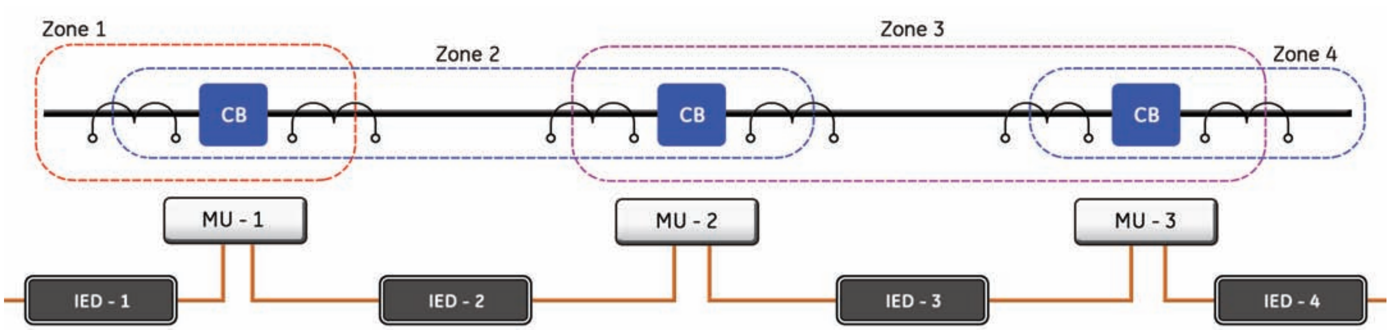

Figure 2.
One-to-many data traffic patterns.

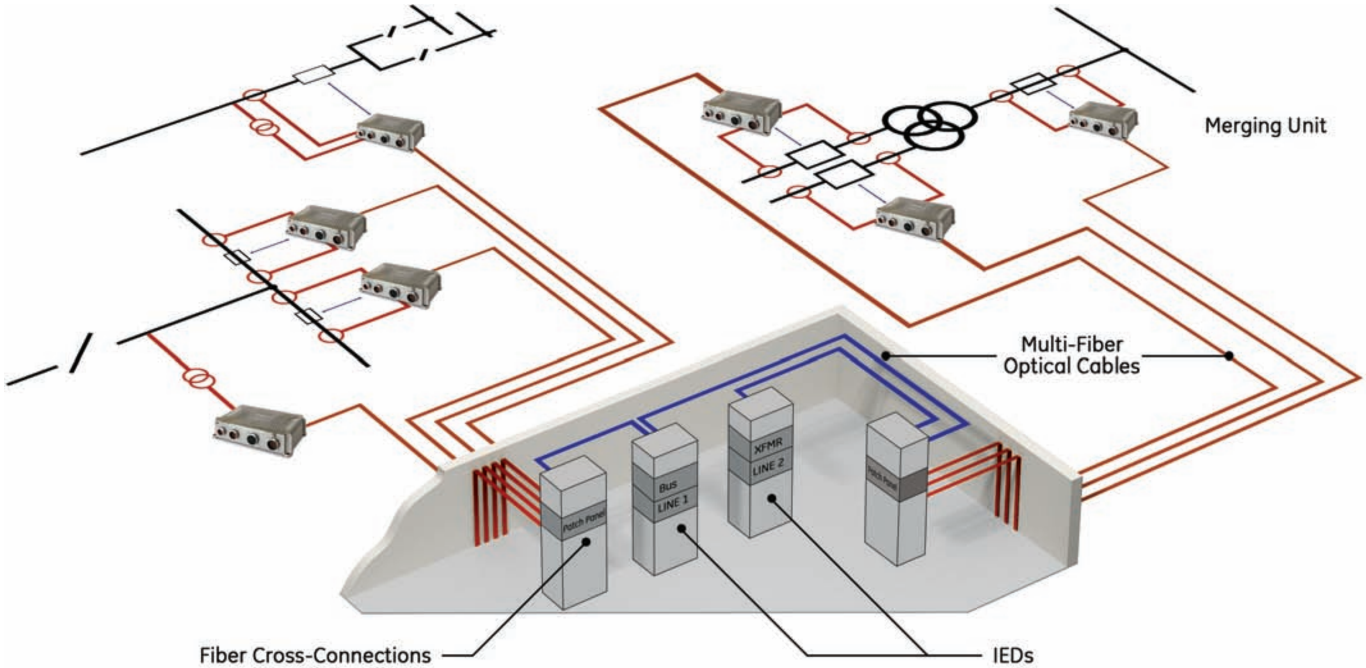

Figure 3.
Proposed Process Bus architecture

Figure 4.
Rugged outdoor merging unit

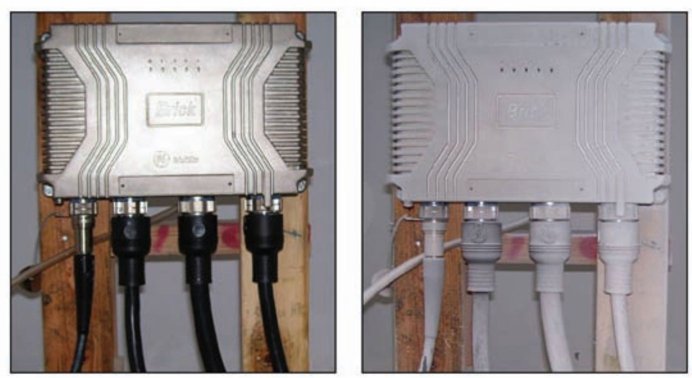

Figure 5.
HardFiber Brick merging units tested for dust: pre-dust inspection (left) and post-dust inspection (right)

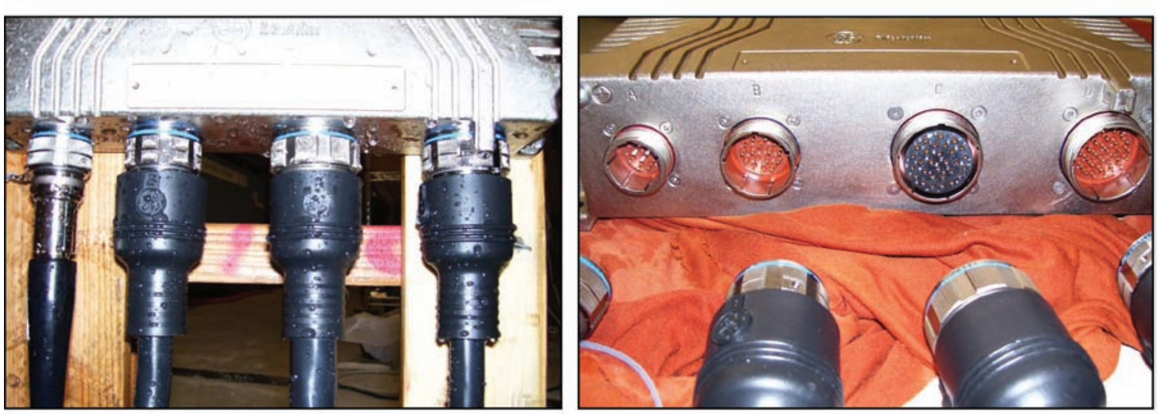

Figure 6.
HardFiber Brick merging units tested for water ingress (pressure washing): post water inspection

4. Proposed Architecture For A Distributed IEC 61850 P&C System

The proposed architecture incorporates all the stated utility driven requirements in performance, maintainability, expandability and reliability through using merging units to collect CT/VT signals and CB/process control and status signals. The IEC 61850-9-2 output of each merging unit is connected via pre-terminated fiber cable to a patch panel that directs the appropriate signals to each relay.

In reference to Figure 3 the system includes merging units mounted at the primary apparatus, relay, pre-terminated cables, and fiber patch panels for cross-connecting the merging units and relays [4].

The merging units are designed to interface with all signals typically used for substation automation and protection as close to their respective origins as practical, including AC currents and voltages from instrument transformers, breaker status and alarms, breaker control, disconnect switch status and control, temperature and pressure readings, etc (Figure 4). The merging units are designed for harsh environments including temperature extremes, shock and vibration, electromagnetic compatibility, sun load effect, pressure washing and exposure to salt and other harsh chemicals (Figures 5 and 6).

Each merging unit contains four independent digital cores each composed of a microcontroller with individual bi-directional (bi-di) fiber links providing dedicated point-to-point communications with a single relay. Sampled value communications used conform to IEC 61850-9-2, and GOOSE communications to IEC 61850-8-1. These cores share common input/output hardware, implementing a fail-safe design strategy that ensures total isolation and independence of the digital cores.

Enhanced security and availability of protection is optionally supported via duplicated merging units. No protection or control algorithms are implemented within the merging units; instead their sole function is to be a high-speed robust IEC 61850 interface to the switchyard.

All cables are connectorized and pre-terminated for ease of deployment and replacement (Figure 7), using standard military/avionic grade components. The outdoor fiber cables contain a pair of DC supply wires to provide control power to the merging units including the internal wetting voltage for field contact sensing (e.g. auxiliary switches, gas alarms, etc.) within the switchgear associated with each merging unit, independent from the control power in the field.

Patch panels (Figure 8) are used to land and organize the outdoor cables, and to distribute and individually fuse the DC power to the merging units. Standard patch cords are used to accomplish “hard-fibering”, making all the necessary IEC 61850 connections between the relays and the merging units as dictated by the station configuration on a one-to-one basis, without the use of switched network communications as detailed in Figure 8.

Each relay has eight optical fiber ports, and thus can access directly up to eight merging units (Figure 9). These maximum connectivity numbers have been selected upon careful analysis of substation topologies and required data traffic patterns as explained in the previous section. As such the 8/4 connectivity covers almost all typical applications. Each relay provides protection for one basic zone, conforming to established protection philosophies.

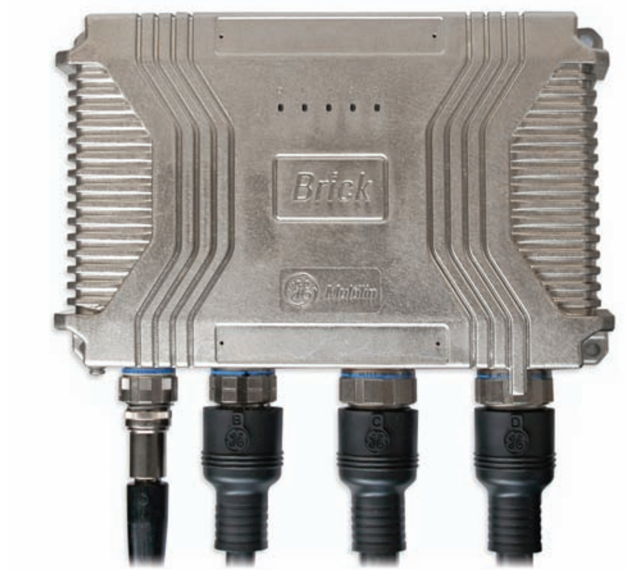

Figure 7.
GE Brick merging units is fully pre-connectorized.

It receives the signals to perform its function over a secure and dedicated network consisting of direct hard-fibered links to each of the associated IEC 61850 merging units. Due to the completely deterministic data traffic on these dedicated links, a simple and robust method is used for synchronization whereby each relay controls the sample timing of the connected merging unit cores over the link without relying on an external clock for process bus data synchronisation.

All architectural decisions have been made based on recognizing present technology and its current momentum as well as making practical tradeoffs. For example, the cost of implementing four independent cores in a merging unit is negligible compared with the gain of simplicity and independency of relays in the system. Similarly, the cost of point-to-point connectivity is comparable to implementing redundant switched networks with the added advantages of avoiding active network devices and supporting the ability to perform system maintenance and isolation.

All system components conform to the best industry standards:

- Communications between merging units and IEDs conforms to IEC 61850-9-2 and IEC 61850-8-1
- Bi-directional Ethernet conforms to IEEE 802.3 100Base-BX
- Merging unit connectors conform to MIL-DTL-38999
- Patchable fiber connectors are standard LC type [per TIA/EIA-568-B.1].

The system can be implemented on existing relay platforms supporting all typically required applications. Owing to the built-in supervision and optional redundancy of inputs and outputs, the new system is more reliable when compared with today’s solutions.

The following sections provide examples of system topologies, and elaborate more on key technical challenges and solutions.

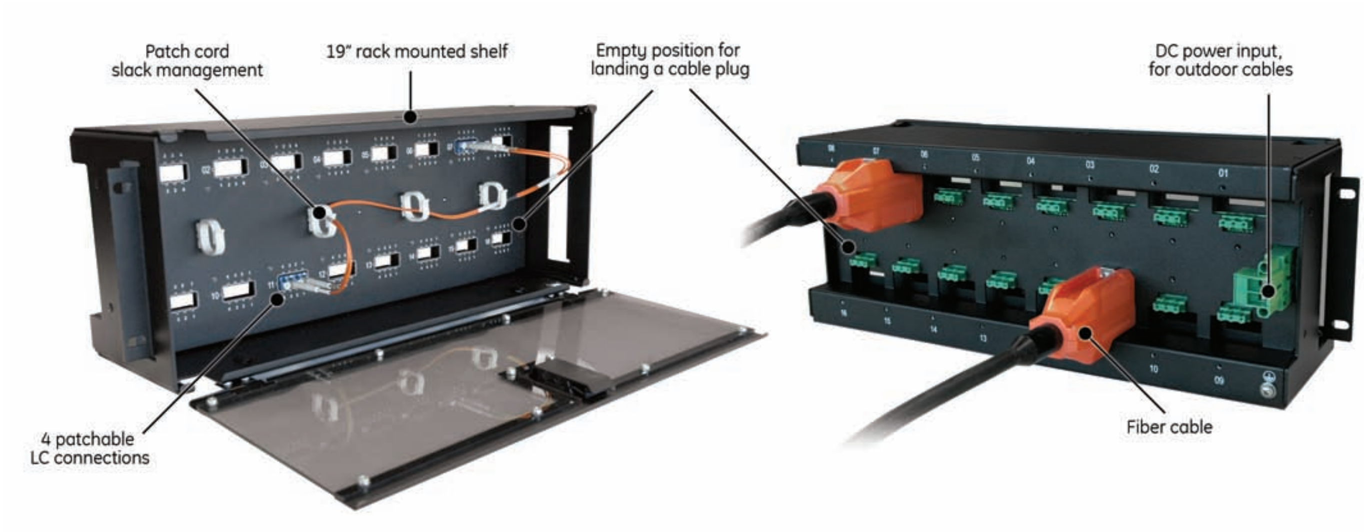

Figure 8.
HardFiber Cross-Connect patch panel

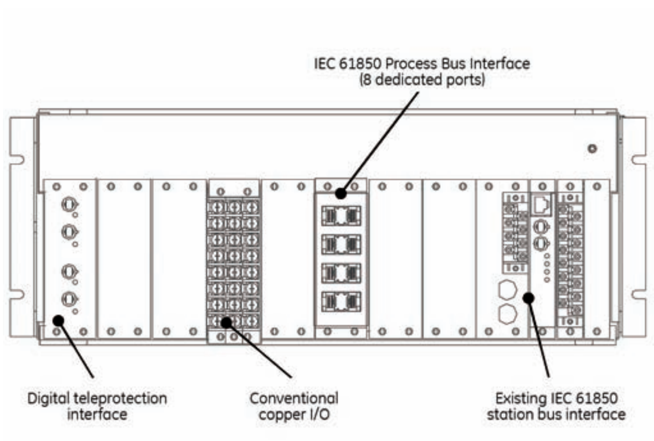

Figure 9a.
IED's means of connectivity

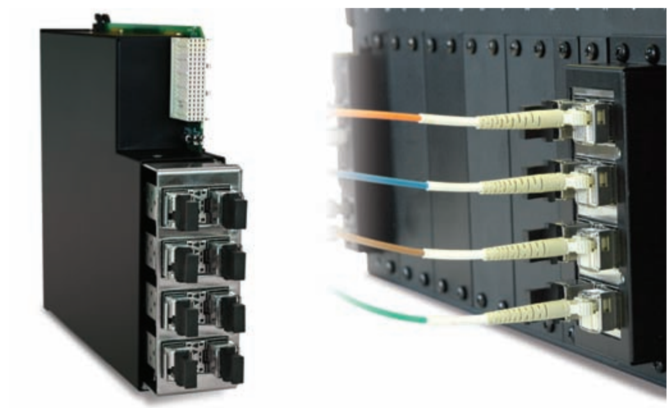

Figure 9b.
Rear view of the GE Universal Relay (right) incorporating 61850 Process Card (left).

5. Example 1

In reference [3] a benchmark substation topology has been proposed for the purpose of illustrating applications for IEC 61850 process bus architectures.

This station is a 10-breaker, arbitrary combination of a ring bus and breaker-and-a-half arrangements with two transformer banks that will be used to illustrate the proposed solution. Only one system is shown (main 1 or main 2), the merging units are deployed non-redundantly, and auto-reclose control is integrated within the line relays. Breaker Failure protection may be done in a number of ways in this architecture, and is not addressed in this example for simplicity.

Figure 10 presents the station topology, while Table 1 lists the IEDs and explains their associations.

Note that the count of IEDs is identical to a traditional solution. The second transformer bank is protected via bushing CTs, and two extra relays are used to provide differential protection for the HV and LV leads. Alternatively a single two-zone differential relay can be used to protect the HV and LV leads, reducing the number of IEDs to 10.

The IEDs do not carry the overhead of physical I/O. Instead the I/O interface is provided via a total of 16 merging units, marked B1 through B16. These units make available a total of 128 single-phase AC inputs. Almost 80% of them are utilized in this benchmark case. A total of more than 250 digital inputs are available on the 16 merging units allowing to interface breaker and disconnect positions and alarms. On average each merging unit feeds 2.625 IEDs. Two 16-position patch panels are required, 16 outdoor fiber cables, 14 indoor fiber cables, and 42 patch cords are needed to cross-connect IEDs and merging units.

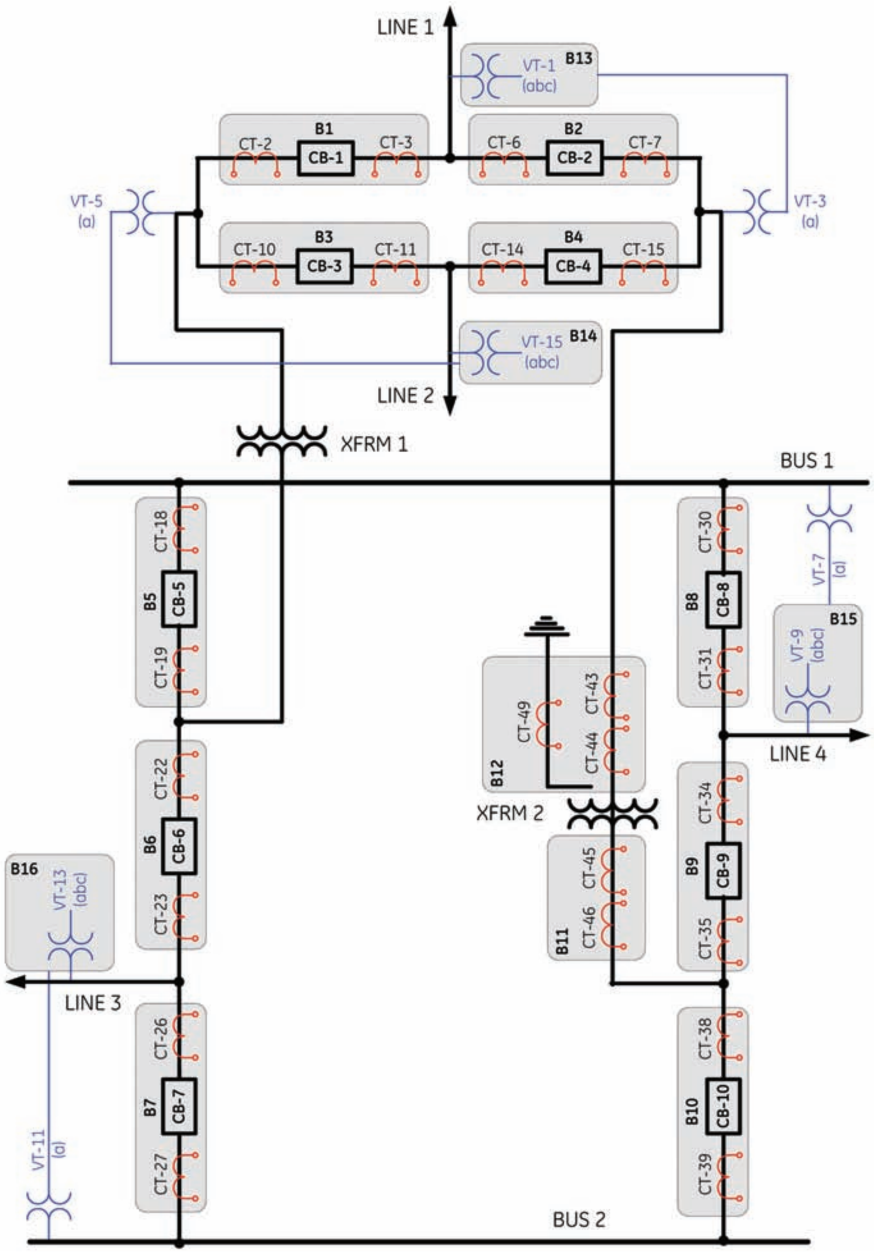

Figure 10.
Sample benchmark case [3].

6. Example 2

Figure 11 presents another application example of the system. In this sample breaker-and-half diameter all merging units are deployed in a fully redundant configuration. CB-2 is a live-tank breaker with free-standing CTs (CT-3/4); there are no CTs on the L-1 line side of the breaker. CT column ground fault protection will use CT-5. The merging units interface with key signals as shown in the Figure. In addition, disconnect position/control can be interfaced via nearby merging units as well (not shown).

Table 2 associates the IEDs and their function with the merging units and their I/Os.

7. Key Technical Challenges

The two top technical challenges for the next generation P&C architecture are data sharing and sampling synchronization for AC inputs. A number of other technical issues such as firmware management simplify themselves once these two fundamental problems are solved. Note that neither of the two challenges is encountered in today's hard-wired protection applications: analogue signals are delivered via wires to each individual relay.

Zone (IED)	Merging Units																Comments
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
Line 1	×	×											×	×			CT-2, CT-7, VT-1 for protection and metering, Tripping CB-1 and CB-2,VT-3 and VT-5 for synchrocheck
Line 2			×	×									×	×			CT-10, CT-15, VT-15 for protection and metering, Tripping CB-3 and CB-4, VT-3 and VT-5 for synchrocheck
Line 3						×	×							×		×	CT-22, CT-27, VT-13 for protection and metering, Tripping CB-6 and CB-7, VT-5 and VT-11 for synchrocheck
Line 4								×	×				×		×		CT-30, CT-35, VT-9 for protection and metering, Tripping CB-8 and CB-9, VT-3 and VT-7 for synchrocheck
XFRM 1	×		×		×	×								×			CT-3, CT-11, CT-18, CT-23 for protection, CT-2, CT-11 and VT-5 for metering, Tripping CB-1, CB-3, CB-5, CB-6
XFRM 2		×		×					×	×	×	×	×				CT-43, CT-46, CT-49 for protection, CT 43 and VT-3 for metering, Tripping CB-2, CB-4, CB-9, CB-10
XFRM 2 HV leads		×		×					×	×		×					CT-6, CT-14, CT-44 for protection, Tripping CB-2, CB-4, CB-9, CB-10
XFRM 2 LV leads		×		×					×	×	×						CT-45, CT-34, CT-39 for protection, Tripping CB-2, CB-4, CB-9, CB-10
Bus 1					×			×									CT-19, CT-31 for protection, Tripping CB-5, CB-8
Bus 2							×			×							CT-26, CT-38 for protection, Tripping CB-7, CB-10
Total	2	4	2	4	2	2	2	2	4	4	2	2	4	4	1	1	On average each merging unit feeds 2.625 IEDs; 42 patch cords required

Table 1.
List of IEDs and association of functions for the case of Figure 10

The proposed approach is best understood with reference to Figure 12. In this system each merging unit contains a common I/O structure and four digital cores. The I/O structure is controlled independently of the relays and digital cores by low-level hardware. The control circuitry is exceptionally basic and future-proof. The concept of a common I/O structure allows for a single compact field device and its associated wiring. That I/O structure is isolated from the digital cores using appropriately deployed hardware buffering. In this way it is impossible under reasonable failure conditions for the digital cores to interfere with the common I/O hardware or one another.

The cores are totally isolated on the hardware level and are comprised of independent microcontrollers running independent firmware instances, and communicating with IEDs via independent fiber transceivers. The interface to the common I/O structure and the power supply circuitry is engineered to ensure total independence of the digital cores. Each digital core is associated with a specific IED, and each core runs as if it were the only core in the merging unit. For example, core number 1 may be working with a line current differential relay model A running firmware rev.5.61, while core number 2 may be in the process of upgrading its firmware to rev. 5.80, while core number 3 may be running firmware rev. 2.22 of a bus differential relay model B.

The independent cores combined with the concept of point-to-point connectivity allow solving the two key technical challenges.

Each relay operates in its own "time zone", developing its own explicit sample and hold signal (S&H) internally to match the needs

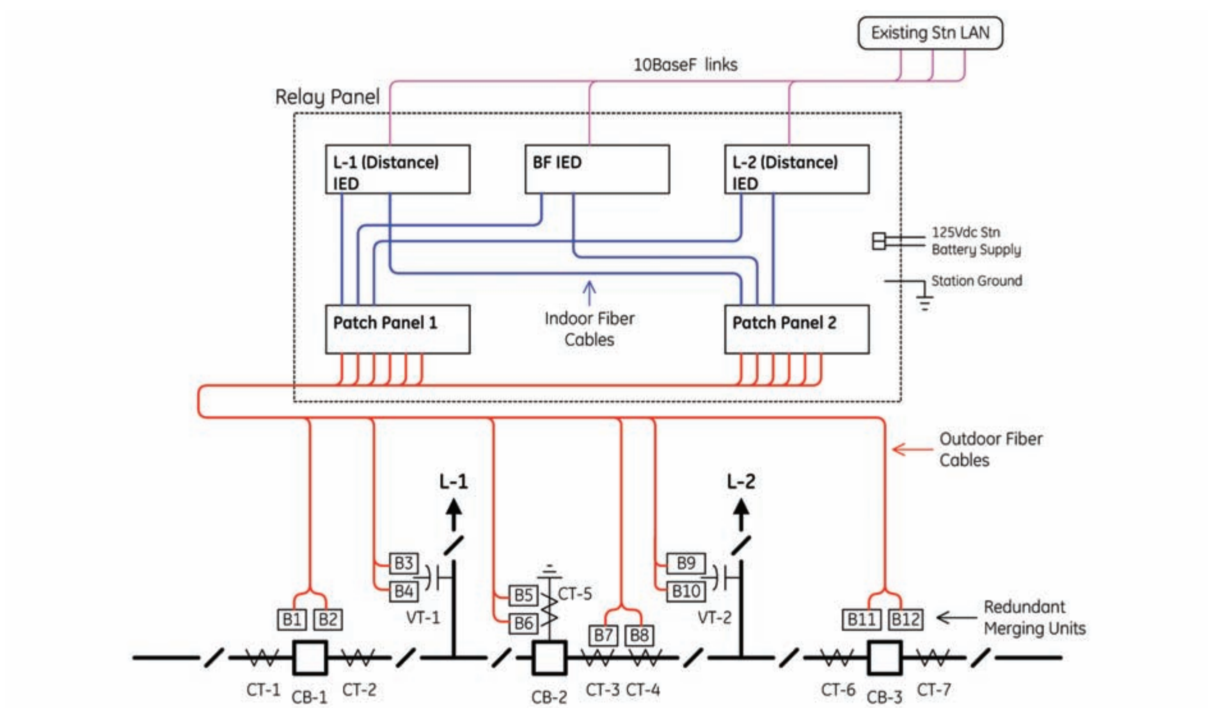

Figure 11.
Example of application to a breaker-and-a-half diameter

Zone (IED)	Merging Units												Comments
	1	2	3	4	5	6	7	8	9	10	11	12	
Line 1	×	×	×	×	×	×	×	×					CT-1, CT-4, VT-1 for protection, Tripping CB-1 and CB-2
Line 2					×	×	×	×	×	×	×	X	CT-3, CT-7, VT-2 for protection, Tripping CB-2 and CB-3
BF	×	×			×	×	×	×			×	×	CT-3/4 for BF protection, CT-5 for CT column ground protection, Tripping CB-1 and CB-3
Total	2	2	1	1	3	3	3	3	1	1	2	2	On average each merging unit feeds 2 IEDs; 24 patch cords required

Table 2.
List of IEDs and association of functions for the case of Figure 11

of its specific application algorithms. This S&H signal is sent using IEC 61850 GOOSE messages to all merging units connected to the relay (up to 8 in the proposed architecture). Owing to the point-to-point connectivity, any foreign data traffic is prevented, and the GOOSE messages are delivered to the merging units in a short and very consistent time. In this implementation the S&H jitter is kept below 1 microsecond, with no need to run phase locked loops to average out random jitter. The payload of the GOOSE messages is a dataset controlling the local sampling and the outputs of the merging units (trip, close, interlock).

The common I/O structure of the merging unit collects AC samples based on its own free-running S&H clock at a relatively high rate. Individual copies of such physical samples are presented via independent digital links inside the merging units to each of the four digital cores. These cores, upon receiving their virtual S&H signals in the form of GOOSE messages, re-sample their own stream of physical samples to obtain and return virtual samples in precise synch with the requesting IEDs. In this way each merging unit supports 5 time references: one local and one for each of the 4 relays, all running asynchronous to each other.

Each relay receives its samples synchronized with its own S&H clock. The high physical sampling rate allows high accuracy of re-sampling required for metering and sensitive protection functions.

In this IEC 61850 architecture each relay can sample following its own frequency tracking scheme and different relays can apply different sampling rates. None of the sampling or protection functions are dependant on a central clock or on a large number of complicated distributed phase lock loops either within an open standard or proprietary that need to synchronize before the system can start producing and consuming data.

The concept of independent digital cores in the merging units facilitates not only independent timing zones, but also independent “firmware zones”. Upon start up each relay checks the firmware revision on all connected merging unit cores. If the revision does not match the firmware on the relay, the relay automatically loads the appropriate firmware to the connected core, while the other cores continue normal operations unaffected and unaware of the changes occurring in their neighbour. This operation lasts only milliseconds and is entirely transparent to both the user and the system.

The merging units do not have inherent firmware or settings – all is controlled from each connected relay. In this way the user is not exposed to the problem of permutations of firmware and settings among the relays and merging units (the domino effect). No software tools are required to deal with the merging units. A traditional relay setup program – as understood today – is sufficient to setup the system.

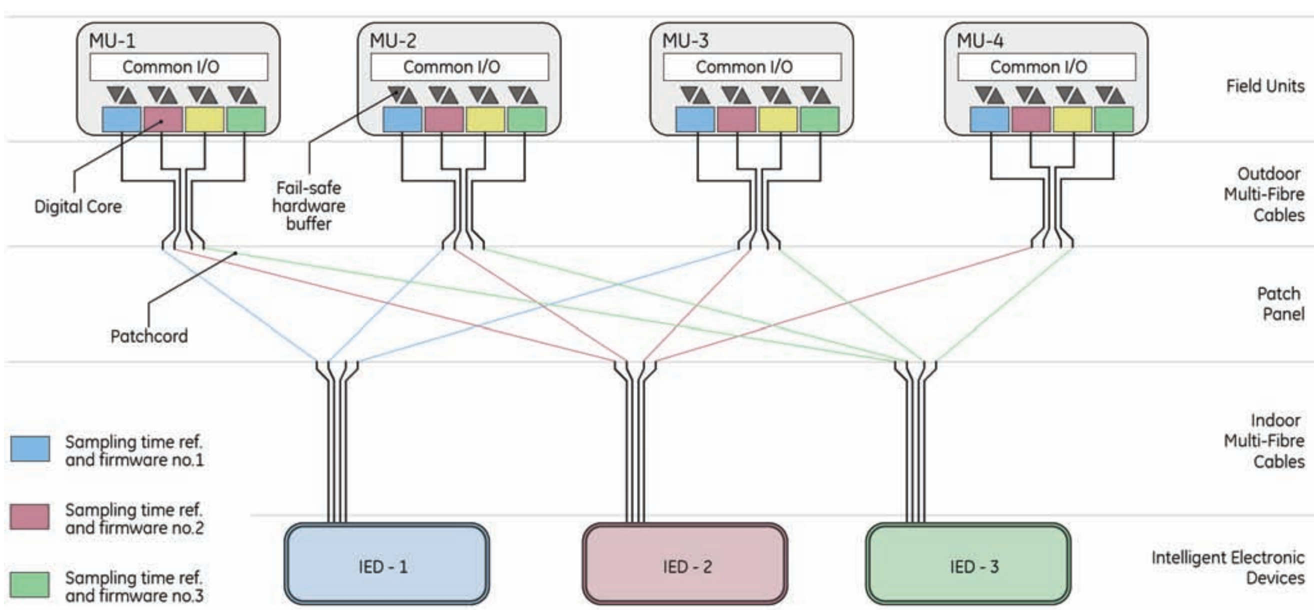

Figure 12.
Independence of sampling clocks and firmware between devices in the system

The second issue of data sharing is solved via point-to-point connections. This is a very simple and robust solution, eliminating a whole array of problems associated with switched networks. On the surface this point-to-point scheme might seem to carry a cost overhead and reliability degradation associated with the number of transceiver ports and fiber terminations. This is not actually the case.

In a switched network architecture, two ports are required to integrate each merging unit (one in a switch and one in the merging unit). The same applies to each of the main 1 and main 2 relays to switch links. This makes the total number of ports in a system equal to the number of merging units times two plus the number of relays times four. Assume each relay works with 6 merging units on average (two CB/CT points and one voltage point, each with redundant merging units). Also, assume each merging unit feeds 3 relays on average (zone 1, zone 2, stand-alone BF). This implies there are two merging units for each relay. Thus the number of ports in such a system is on average 8 per relay. In practice some extra ports are used up to build a LAN out of switches with a finite port count. Assume an overhead of 1 extra port per relay, bringing the total in this example to 9 ports per relay.

In the point-to-point architecture presented in this paper, a total of 12 ports are required per relay to connect 3 merging units and 3 redundant merging units (6 in the relay and 6 in the merging units). However due to the fixed port count in relays and merging units of 8 and 4 respectively, the actual total is 16 ports per relay in this example. The 9:12 proportion for reliability considerations, and 9:16 proportion for hardware considerations are acceptable given the gain of simplicity, maintainability and reliability of the proposed architecture.

Moreover, this architecture uses bi-directional fiber (using wavelength division multiplexing per IEEE 802.3 100Base-BX), cutting the number of fiber terminations by half, improving both cost and reliability.

This architecture has an additional advantage in that signal routing is completely defined in hardware at the patch panel. No software configuration or active components are required.

This section explained how the proposed architecture solves the key technical challenges for the IEC 61850-9-2 P&C system: time synchronization and data sharing.

8. Summary

The paper presents a robust IEC 61850-9-2 process bus architecture for distributed protection, metering and control. In particular the solution:

- Targets copper wiring as a major cost, labour and time factor, and replaces copper wiring for protection and control purposes in the switchyard and the control room with fiber-based communication.
- Introduces rugged merging units that solve practical problems such as outdoor fiber cabling and connectivity in harsh conditions, weatherproofing, commissioning, maintenance, and expandability.
- Uses merging units designed to interface all process interface measuring and control points at a given switchyard location using a common device conforming to IEC 61850 and working with a standard I/O structure: status inputs, binary output commands, transducers and sensors, and instrument transformers.
- Uses an optimized communication framework that mirrors the topology of the primary equipment and recognizes the exact data flow patterns, origins and destinations required to accomplish a practical zone-based approach to protection.
- Solves the data synchronization problem without reliance on external clocks, and their associated communication-based or hard-wired distribution.
- Solves the data-sharing bottleneck for substations of any size without relying on impractical throughputs, in a simple, robust, scalable and maintainable communication framework.
- Increases reliability by a novel concept of redundancy and optimized communication architecture.
- Eliminates cyber security concerns by using a non-routed communication scheme.
- Eliminates the need for extra software tools for setting up the process bus data.
- Preserves all major protection principles successfully practiced for decades:
  - separation of protection zones,
  - determinism,
  - independence of devices,
  - simplicity,
  - ability to augment a single protection zone without the danger of affecting adjacent zones, and other potentially problematic aspects.

The work presented in this paper reflects the actual development of a complete system encompassing all major protection application types [4].

9. References

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