Scalability of IEC 61850 Process Bus Solutions

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1. Introduction

Too often solutions are proposed that conceptualize process bus architectures by depicting a single merging unit, or at best a few merging units, and a single or a few relays, interconnected by a "magic cloud" of a Local Area Network (LAN).

Such conceptual sketches are practical and useful in the field of engineering to communicate mature ideas and abstracts in situations when there is a common understanding of the basic principles behind a concept. Common understanding of basic principles may be established by tradition, formal education or on-the-job training of the involved individuals, practical usage and installations, existing products, and common sense. Process bus schemes have not matured enough to yield common understanding that would justify conceptual sketches neglecting the actual physical nature of the problem at hand, and its scale.

It is therefore understandable that prospective process bus users challenge conceptual sketches by asking variety of questions such as: What is a merging unit? What is its function? Where is it located? Does it work with conventional instrument transformers, or only with optical instrument transformers? How about status signals and control commands - do they fit in the merging unit concept? How do I engineer the "magic cloud", interconnecting the devices? How do I know the "magic cloud" will work after adding a new device? How do I test and commission a process bus scheme through the "magic cloud"?

And finally, how does any solution scale up and down to accommodate substations of any size, following a retrofit of any scope and sequence?

A successful IEC 61850 process bus architecture needs to be scalable. Scalability in this context means adding devices to build a coherent system of any size without the need to address size issues along the way. In other words, setting up a process bus consisting of 150 merging units and 100 relays should be as easy as setting up a system with 3 merging units and 1 relay. Moreover, procedures and methods used to isolate, maintain, test and operate a system with 3 merging units and 1 relay should be applicable for larger systems without significant modification.

In contrast, one can consider the characteristics of systems that are not easily scalable. For instance, a system in which the impact of system performance must be re-evaluated each time a device is added cannot be regarded as easily scalable. A system that requires reconfiguration of in-service devices that are responsible for protecting other circuits in the substation in order to add a new device also cannot be regarded as easily scalable.

This paper will explain the need for and benefit of scalability by using a simple breaker-and-a-half substation, and the process bus architecture of the HardFiber system from General Electric [1].

The Hard-Fiber system eliminates custom control wiring within the station and replaces it with rugged field devices, known as Bricks, distributed throughout the switchyard and interconnected with substation IEDs through a standardized optical fiber network.

The fundamental components of the Hard-Fiber system are:

- Bricks – convert analogue copper signals to/from digital optical signals, including CTs, VTs, contact inputs and contact outputs.
- Copper Cables – make the connections between the copper terminals inside the power equipment to the Bricks typically mounted on the outside of the equipment.
- Outdoor Fiber Cables – make the optical connection between the Bricks in the switchyard and the cross connect panels in the control house. Also powers Brick internal electronics.
- Cross Connect Panels – panel where individual fibers of outdoor cables are patch corded to individual fibers of indoor cables, completing the station specific Brick/relay associations. Also DC distribution panel for Bricks.
- IED Process Card – converts Brick optical signals to/from the signal types used by the standard Universal Relay [2-9] elements.
- Indoor Fiber Cables – make the optical connection between the ports of the process card in the UR and the cross connect panel.

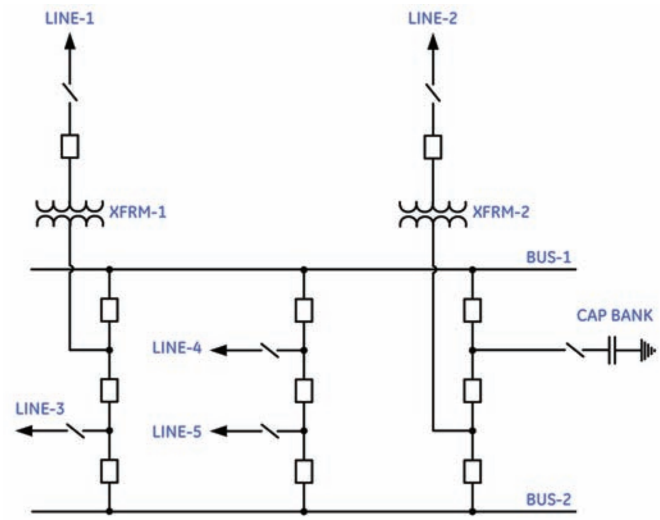

Figure 1.
Sample substation considered

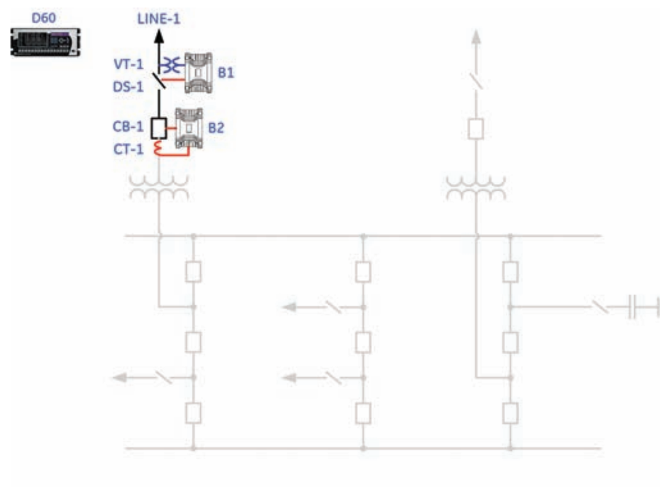

Figure 2.
Line 1 distance protection example

2. Sample station

(Figure 1.)

Figure 1 depicts a sample breaker-and-a-half substation with two transformers and corresponding transmission lines, two buses, several sub-transmission lines, and a capacitor bank terminated on a breaker-and-a-half position.

It is assumed that this station ultimately is to be entirely retrofitted using a process bus system, specifically the HardFiber system [1].

In order to explain and illustrate scalability as it relates to the deployment of a process bus-based protection and control system, the paper will consider the retrofit on a zone-by-zone basis, and progress gradually to cover the entire substation. In the process it will not only become clear that the solution is scalable, but also exceptionally flexible allowing applications in substations of any topology and any practical protection and control practice.

2.1 LINE-1 zone

(Figure 2.)

In order to protect and control LINE-1, a Brick B1 is installed to connect the line potential (VT-1) and possibly interface the line motor-operated disconnect switch (DS-1). A second Brick, B2, is deployed to interface the line breaker (CB-1) and provide the measurement of the zone current (CT-1). These two Bricks can be wired to a variety of other signals associated with the line and breaker apparatus such as breaker position and alarms, position of breaker disconnect switches, and so on. The application is completed by patching the two Bricks to an appropriate line protection relay, the D60 Distance Protection System [2] in this example. The relay is configured to use VT-1 and CT-1 for its fundamental protection functions, and trips CB-1 upon detecting a fault in the LINE-1 zone. A variety of other functions are available in the D60 relay model such as metering, control, an array of backup functions, teleprotection schemes, integrated breaker failure, and embedded Phasor Measurement Unit (PMU).

Note that the LINE-1 P&C refurbishment work can be done in total isolation from the rest of the station, without disrupting other zones of protection or the primary equipment, and without forcing the user to retrofit the entire substation. For commissioning, only LINE-1 needs to be taken out of service.

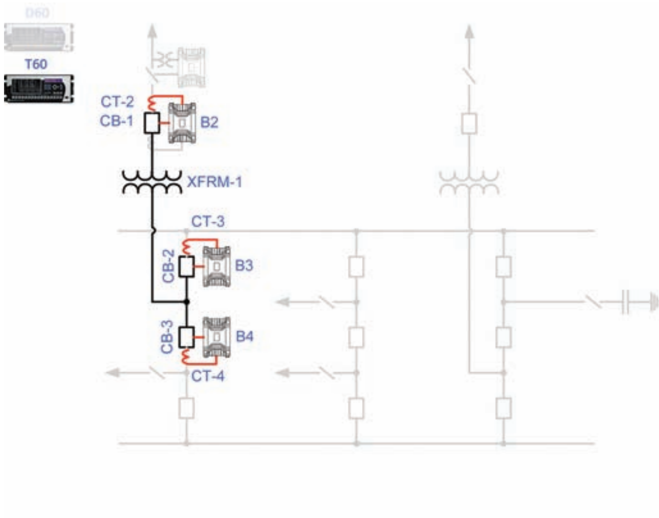

Figure 3.
Transformer 1 protection example

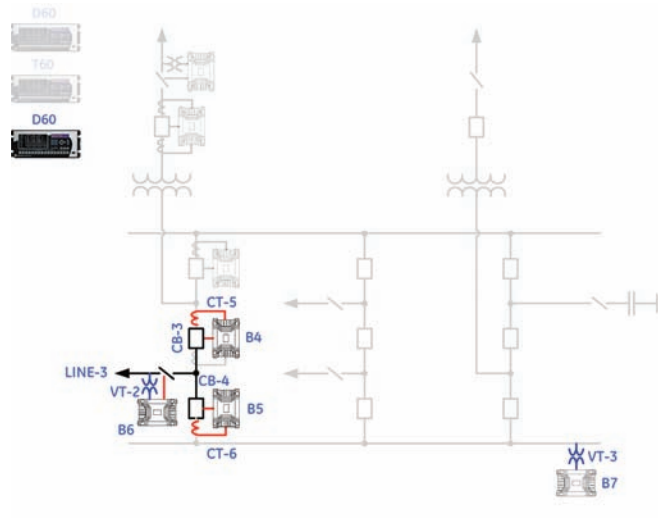

Figure 4.
Line 3 distance protection example

2.2 XFRM-1 zone

(Figure 3.)

The transformer is terminated on a breaker-and-a-half diameter. Bricks B2, B3 and B4 are used to provide tripping capabilities toward the associated breakers CB-1, CB-2 and CB-3, respectively; as well as to measure all the currents of the transformer protection zone: CT-2, CT-3 and CT-4, respectively.

Note that the B2 Brick is already deployed as a part of the LINE-1 zone. To support the XFRM-1 zone, this Brick is wired to the CT-2 set of currents, and communicate with the transformer relay on its second digital core [1]. In this way the B2 Brick is shared between line and transformer relays. A stand-alone Breaker Failure (BF) relay may de deployed for the CB-1 breaker, such as the C60 Breaker Protection System [3], being the third relay connected to the B2 Brick. Note that although the B2 Brick is shared by several relays, there are no shared subsystems that introduce inter-dependencies between protection applications.

The transformer zone application is completed by patching the B2, B3 and B4 Bricks to a transformer protection relay, a T60 Transformer Protection System [4] in this case.

The considered transformer protection zone spans the associated breakers. Alternatively, its zone can be deployed from the transformer's bushing CTs with Bricks installed at the transformer, rather than at the associated breakers. In such a case, the transformer Bricks will pickup alarms and status signals for the transformer, tap changer status and control, and other signals naturally related to a power transformer, while the breaker Bricks will still be connected to execute the trip commands.

Neutral point currents required for Restricted Earth Fault (REF) protection of wye-connected windings can be wired to transformer Bricks if installed, or to the nearest Brick associated with any of the transformer breakers. Quite often a dedicated Brick will be installed at the transformer regardless of the protection measurement and tripping Bricks to pick up additional trip signals like Bucholtz relays or tap changer gas relays.

The T60 relay deployed in this example supports a multitude of functions such as overcurrent and distance backup, harmonic and power measurement, and so on [4].

2.3 LINE-3 zone

(Figure 4.)

LINE-3 is terminated as a breaker-and-a-half power element, and therefore Bricks B4 and B5 are used to interface the associated breakers (CB-3 and CB-4), as well as to measure the zone currents (CT-5 and CT-6). Note that the B4 Brick is already installed as a part of the XFRM-1 zone, and needs to measure the second set of currents, CT-5, at that breaker to support the LINE-3 zone. The third Brick, B6, is required to interface the line potential, VT-2, and possibly the line disconnect switch. It is assumed a synchrocheck function is incorporated for the CB-4 breaker therefore B7 Brick is deployed to measure the bus voltage via VT-3 potential source.

A line protection relay, D60 Distance Protection System [2] is connected to the B4, B5, B6 and B7 Bricks to complete the application for the LINE-3 zone. Having five zones of distance protection, the D60 can be used to provide time-coordinated reverse-looking backup for the substation and associated circuits.

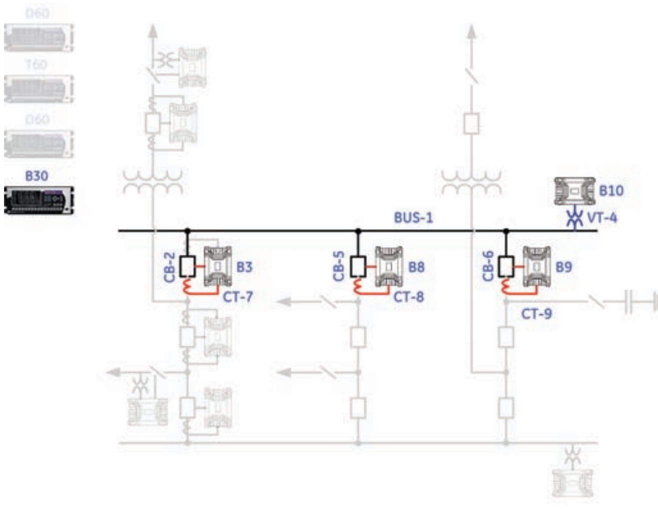

Figure 5.
Bus 1 differential protection example

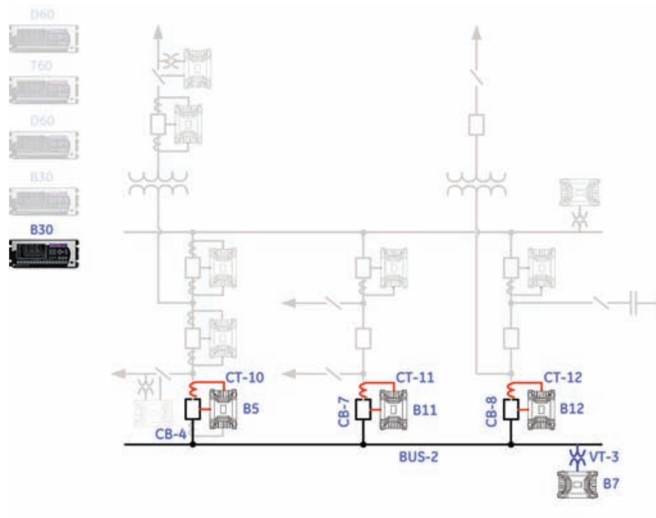

Figure 6.
Bus 2 differential protection example

2.4 BUS-1 zone

(Figure 5.)

A bus differential relay, a B30 Bus Protection System [5] in this example, is deployed to protect BUS-1. The relay is patched to Bricks B3, B8 and B9 to measure the bus zone currents, CT-7, CT-8 and CT-9; and to execute the trip command toward breakers CB-2, CB-5 and CB-6. Optionally, it may connect to the B10 Brick for the voltage signal, VT-4 in order to provide for under-voltage trip supervision or power metering.

Note that the B3 Brick is shared between the B30 and T60 relays. Additionally, a stand-alone BF relay, such as the C60 [3] can be deployed for each of the CB-2, CB-5 and CB-6 breakers. In such a case, the C60 relays are patched to Bricks B3, B8 and B9, respectively.

2.5 BUS-2 zone

(Figure 6.)

Similarly, a bus differential relay, B30 Bus Protection System [5] in this example, is deployed to protect BUS-2. The relay is patched to Bricks B5 (already installed for the LINE-3 protection), B11 and B12 to measure the bus zone currents, CT-10, CT-11 and CT-12; and to execute the trip command toward breakers CB-4, CB-7 and CB-8. Optionally, it may connect to the B7 Brick for the voltage signal, VT-3 in order to provide for under-voltage trip supervision or power metering.

2.6 CAP BANK zone

(Figure 7.)

Consider the capacitor zone next. A capacitor bank relay, the C70 Capacitor Bank Protection and Control System [6] in this example, is connected to Bricks B9 and B13 in order to interface currents CT-13 and CT-14 for short circuit protection and metering, as well as to trip the dual-breaker connection via CB-6 and CB-9. In addition The B14 Brick is installed to provide for sensitive voltage-based bank unbalance protection such as voltage differential, or neutral voltage unbalance by measuring the VT-5 and VT-6 potentials. This Brick may interface with the shown disconnect switch and other signals associated with the installation as required.

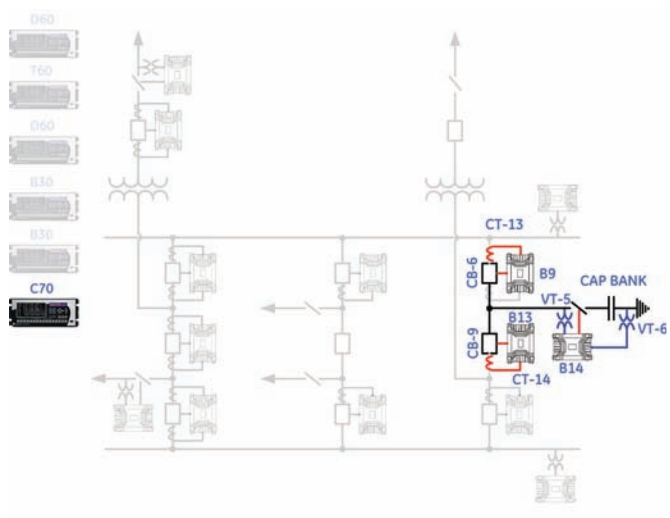

Figure 7.
Capacitor bank protection example

The capacitor bank application is a good example of scalability within a given zone of protection. Imagine a very complex cap bank arrangement with parallel banks, multiple current and voltage measurement points, multiple protection principles deployed such as phase current unbalance, neutral current unbalance, voltage differential, neutral voltage unbalance or multiple coordinated controllers for multiple capacitors or banks. In such a case a number of Bricks can be installed to interface all required signals, and more than one C70 can be used to provide all required functions.

Additionally, capacitor banks tend to be added long after a station has been built, usually in remote areas of the switchyard. The long distances to the control house makes a process bus solution a natural choice for elimination of copper wires.

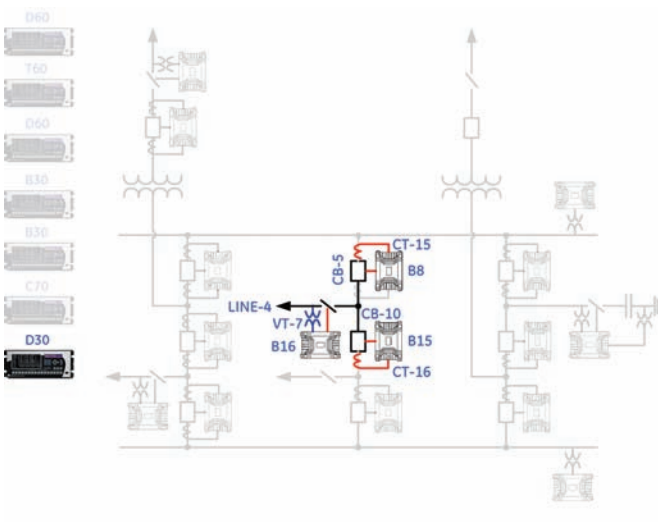

Figure 8.
Line 4 distance protection example

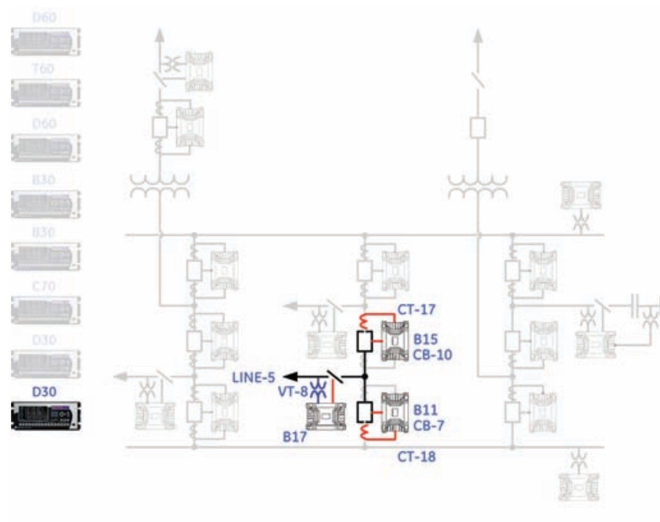

Figure 9.
Line 5 distance protection example

2.7 LINE-4 zone

(Figure 8.)

Three Bricks (B8, B15 and B16) are connected to a line relay, D30 Distance Protection System [7] in this example, in order to interface the zone currents (CT-15 and CT-16) and voltages (VT-7). The B16 Brick may interface the line disconnect switch if appropriate, and Bricks B8 and B15 execute trip commands upon relay operation toward the associated breakers CB-5 and CB10.

Again, the B8 Brick was already in place as a part of the BUS-1 protection.

2.8 LINE-5 zone

(Figure 9.)

Three Bricks (B15, B11 and B17) are connected to a line relay, D30 Distance Protection System [7] in this example, in order to interface the zone currents (CT-17 and CT-18) and voltages (VT-8). The B17 Brick may interface the line disconnect switch if appropriate, and Bricks B15 and B11 execute trip commands upon relay operation toward the associated breakers CB-10 and CB7.

Again, the B15 and B11 Bricks were already in place as a part of the LINE-4 and BUS-2 protection.

2.9 XFRM-2 zone

(Figure 10.)

Similarly to XFRM-1, the second transformer protection employs the T60 Transformer Protection System [4] connected to Bricks B12, B13 and B18 with the application of tripping breakers CB-8, CB-9 and CB-11, accordingly; and for the measurement of current signals CT-20, CT-19 and CT-21, respectively.

Again, the transformer zone can be stretched from bushing CTs calling for extra Bricks at the transformer. Yet another Brick may be connected to interface voltage for power metering.

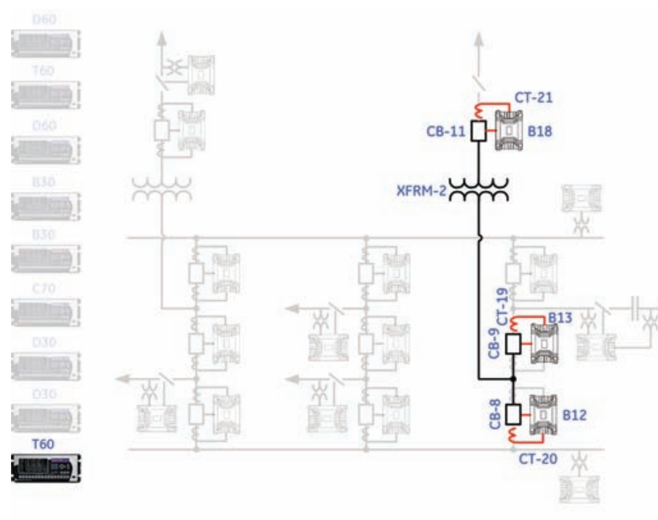

Figure 10.
Transformer 2 differential protection example

2.10 LINE-2 zone

(Figure 11.)

The second transmission line protection employs the L90 Line Current Differential Protection System [8] connected to Bricks B18 and B19 to obtain the zone current (CT-22 from B18), voltage (VT-9 from B19), and executing the trip command toward CB11 via B18.

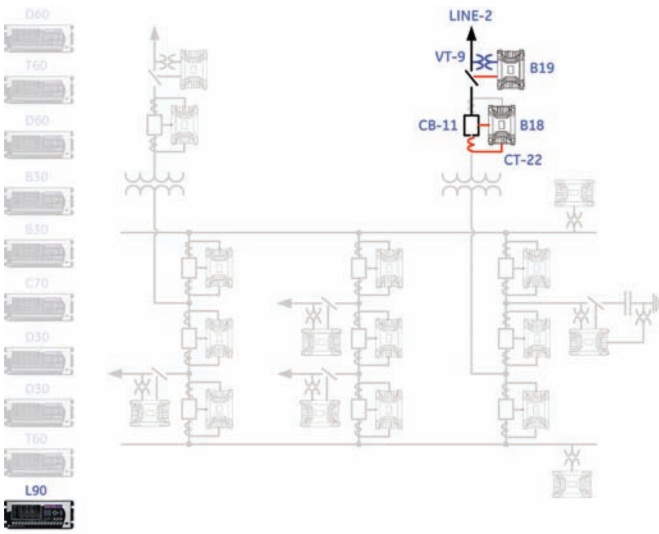

Figure 11.
Line 2 differential protection example

3. Summary of Zone Protection Applications

The presented example substation uses 10 relays. This is natural as the presented substation incorporates 10 tripping zones given the number and position of the breakers. Extra relays may be deployed to accommodate stand-alone breaker failure (C60 [3]) or provide protection for transformers spanning their tanks rather than breakers (T60 [4] or T35 [9]), or alternatively one may provide separate protection for transformer leads (B30 [5]). These extra relays may be patched toward the existing Bricks to get their signals and execute commands as required.

The application involves 19 Bricks to cover the major signal clusters in the switchyard. In practice more Bricks may be needed if some of the CTs are free-standing CTs and cannot be wired back to the breaker Bricks, if stand-alone Bricks are deployed to interface disconnect switches, or when more potential points are available and metering is required for the transformer windings.

At minimum two Cross Connect Panels are needed to land and organize the Brick and relay cables, and to make associations between relays and Bricks.

Table 1 below summarizes the cross connections between relays and Bricks.

Zone	IED	Merging Units (Bricks)																			Comments
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	
Line 1	D60	×	×																		CT-1, VT-1 for protection, trip and reclose for CB-10
Line 2	L90																		×	×	CT-22, VT-9 for protection, trip and reclose for CB-11
Line 3	D60				×	×	×														CT-5, CT-6, VT-2 for protection, trip and reclose for CB-3 & CB-4
Line 4	D30								×							×	×				CT-15, CT-16, VT-7 for protection, trip and reclose for CB-5 & CB-10
Line 5	D30											×				×		×			CT-17, CT-18, VT-8 for protection, trip and reclose for CB-7 & CB-10
XFRM 1	T60		×	×	×																CT-2, CT-3, CT-4 for protection, trip CB-1, CB-2 & CB-3
XFRM 2	T60												×	×					×		CT-19, CT-20, CT-21 for protection, trip CB-8, CB-9 & CB-11
Cap Bank	C70									×				×	×						CT-13, CT-14, VT-5 for protection, trip for CB-6 & CB-9
Bus 1	B30			×					×	×	×										CT-7, CT-8, CT-9, VT-4 for protection, trip for CB-2, CB-5 & CB-6
Bus 2	B30					×		×				×	×								CT-10, CT-11, CT-12, VT-3 for protection, trip for CB-4, CB-7 & CB-8
Total	10	1	2	2	2	2	1	1	2	2	1	2	2	2	1	2	1	1	2	1	An average each Brick feeds 1.58 IEDs. With stand alone BF, 11 more BF IEDs (C60) are needed – in such a case each Brick feeds 2.16 IEDs on average.

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

4. Breaker Failure Protection

Once the wiring between the relays and switchyard equipment has been eliminated, the Breaker Failure function remains as the last major application wherein extensive wiring is required to exchange critical signals.

Two signaling paths are required for Breaker Failure protection: initiation by relays tripping a given breaker, and tripping surrounding breakers should the associated breaker fail. The latter task may be seen as cumbersome, involving a variable number of breakers depending on the application. The task of BF tripping, however, can be unified by observing that all zones of protection that normally trip a given breaker contain all of the breakers that need to be tripped upon breaker failure.

In general, the BF initiation and tripping can be accomplished in three ways:

1. By using traditional copper wiring. This solution is practiced today, and may be a requirement during a retrofit when some of the protection zones are implemented utilizing the process bus solution, while the remaining portion is hard-wired. Naturally, this approach is scalable and poses low risk as the existing workforce is more than familiar with the approach. The drawback is in lower savings due to keeping some copper wiring in the control house.

2. By using peer-to-peer signaling between digital relays over the station LAN (GOOSE). This approach is used today and is maturing relatively quickly with configuration and test tools emerging, and with fundamental issues being worked out, such as isolation and testing.

3. By using merging units as natural "mailboxes" to exchange the BF related signals. The reminder of this section describes this novel but simple concept.

The HardFiber system provides a fast, deterministic means for peer to peer messaging which is based on a fundamental premise of protective relaying: that critical signals need to be exchanged primarily between IEDs within the same zone or adjacent zones. The Shared I/O feature [1] uses the Brick itself as a "mailbox" to exchange these messages and can support several types of messaging: one-to-one, one-to-many, many-to-one and many-to-many. By design, Shared I/O signals are confined to the zones in which they operate. The benefit of this approach is that these signals can never be compromised due to activities (configuration, testing) occurring in other parts of the substation, supporting the concept of scalability – additions or modifications to other zone would not call for re-engineering, re-configuration or re-testing of other zones.

Refer once again to the example system and focus on the CB-1 breaker. A C60 relay has been added to implement Breaker Failure protection for CB-1 (Figure 12). According to the principles of protective relaying, any protections that trip CB-1 will also initiate breaker failure; in this case the D60 and the T60 must send breaker failure initiate to the C60. If the C60 relay subsequently detects that CB-1 has failed, all breakers in the zones adjacent to CB-1 must be opened. Note that these breakers are under the direct control of the D60 and T60 relays.

With reference to Figure 12, the D60 and T60 relays are connected to the B2 Brick. They will send a BFI flag to this Brick. This flag will arrive simultaneously with the trip command for CB-1, and will be reflected back to the all the relays connected to the B2 Brick before the breaker even starts to open. At this point in time the initiating relay (assume the D60), the other relay for the zone that overlaps at the breaker (T60), and the stand-alone BF relay (C60) have been informed a BFI had been issued for CB-1.

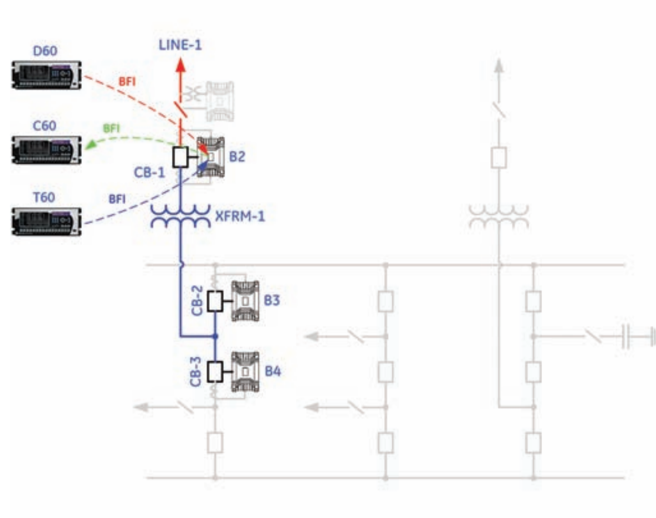

Figure 12.
BF initiate scenario for CB-1

At least one of these relays (the C60 in this example) has the BF function enabled and starts monitoring the CB-1 breaker. Assume now that the breaker fails to open. With reference to Figure 13 the C60 relay issues a BF Trip command, communicated via the B2 Brick to both the D60 and T60 relays. The relays are configured to execute the breaker fail trip command by tripping all breakers surrounding their zones and – possibly depending on the protection philosophy – initiating BF for those breakers. Therefore, the T60 relay will trip and lockout CB-2 and CB-3 via the B3 and B4 Bricks, respectively. A non-volatile, latching output contact is provided within each Brick for the purpose of providing a breaker lockout. The D60 relay, in turn, will send a Direct Transfer Trip (DTT) to the other end(-s) of the line.

By examining Figures 12 and 13 four important observations can be made:

1. The BF configuration is very simple. Almost no settings are required if one uses properly prepared setting templates.

2. The scheme is universal and will work for any type of station and for any zone of protection, with integrated or stand-alone BF function. As the Shared I/O points are programmable, exceptions can easily be handled.

3. The BF initiate and BF trip signaling paths are locally contained. These signals are not published across the entire station potentially causing false operations, or burdening the network.

4. The scheme is inherently robust. To issue a trip in the first place the tripping relay needs to communicate with the breaker Brick – as such it is always capable of sending the BFI to that Brick. To perform a BF function the BF relay needs to communicate with the breaker Brick to obtain the current data – as such it is always able to receive the BFI and send the BF Trip signals back.

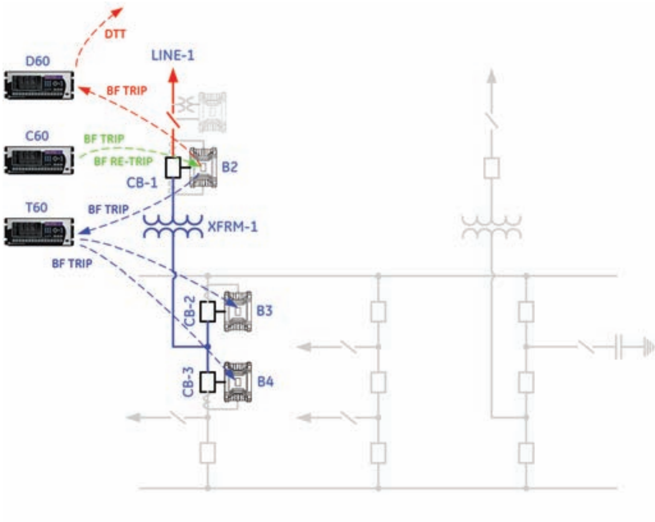

Figure 13.
BF trip scenario for CB-1

There may be a concern about using Brick B2 to route the breaker failure signals due to its proximity to the failed breaker. This represents a very low, albeit non-zero risk. However an alternate Brick could be chosen to eliminate this risk. For instance the breaker failure signals could as easily be routed via Brick B1 (associated with the VT). This would require that a digital core from this Brick be assigned to the C60 – entailing the placement of one additional patch cord at the cross connect panel.

5. Conclusions

This paper has explains the meaning of scalability as it relates to process bus solutions, and identifies the need for scalability for such systems.

Practical process bus solutions should be free from the problems of scale: systems with 10, 100 or 1000 devices should be equally robust and manageable. Unrealistic solutions may appear reasonable when sketched for a few devices. The ability to scale up, be deployed gradually, and remain naturally aligned with traditional protection principles, is what differentiates practical solutions from conceptual sketches.

The paper demonstrates natural scalability and flexibility of one particular solution, the HardFiber system [1].

The analyzed solution scales naturally owing to the following:

- Rational definition of the merging unit.
- Dedicated point-to-point connectivity.
- Simple and robust time synchronization.
- Separation and independence of the Brick's digital cores when interfacing with multiple relays.

The sample substation described in this paper uses a variety of relay models to cover all of the protection zones. No process bus solution can be considered complete and scalable unless it addresses every practical protection application (distance, line current differential, bus, transformer, capacitor bank, feeder, breaker failure, etc.).

This paper also illustrated that the HardFiber system is scalable because it does not depart from the proven signal routing topologies that have been employed within substations for decades. HardFiber merely integrates and standardizes the interface between the relays and the primary equipment resulting in protection systems that are simpler to design, install, and maintain. The HardFiber process bus solution can be implemented for any one zone of protection in the substation, or all zones of protection. Each zone of protection can be converted to process bus independent of any other zones, as work resources and equipment outages can be scheduled.

6. References

[1] HardFiber System Instruction Manual, GE Publication GEK-113500.

[2] D60 Line Distance Protection System, Instruction Manual, GE Publication GEK-113482.

[3] C60 Breaker Protection System, Instruction Manual, GE Publication GEK-113479.

[4] T60 Transformer Protection System, Instruction Manual, GE Publication GEK-113492.

[5] B30 Bus Differential System, Instruction Manual, GE Publication GEK-113476.

[6] C70 Capacitor Bank Protection and Control System, Instruction Manual, GE Publication GEK-113480.

[7] D30 Line Distance Protection System, Instruction Manual, GE Publication GEK-113481.

[8] L90 Current Differential Protection System, Instruction Manual, GE Publication GEK-113488.

[9] T35 Transformer Protection System, Instruction Manual, GE Publication GEK-113491.