Testing and Commissioning Protection & Control Systems Based On IEC 61850 Process Bus

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1. Introduction

The Process Bus concept presented by IEC 61850-9-2 [1] is developing considerable interest worldwide in the protection and automation communities. This standard includes detailed guidance on information models, protocol stacks, datasets, VLANs, services, etc. However, little attention is paid to features necessary to engineer process bus based systems with architectures in which effective and safe system testing policies can be developed. Testing in this paper is understood as verification or re-verification of a deployed system during initial commissioning, periodically, or after a major re-work on the system such as protection system expansion, firmware upgrade or replacement of components. As such, testing is an essential part of initial startup and maintenance.

Conventional protection technologies provide for test polices that allow protection relays of a single zone to be isolated, safely modified, re-tested and restored while the protection for other zones remain in-service and unaffected. For the most part, this can be done without having to remove the protected power equipment from service, relying on redundant protection. To gain acceptance, protection systems based on process bus technology will have to provide equivalent or better capability in these areas.

When a process bus-based protection system is first constructed at a station, the protection system can be tested as a whole either before the associated power system equipment is placed in service or, in a retrofit situation, before the new process bus based protection system is integrated with the power system. In this setting, unforeseen interaction of newly added or modified components with other parts of the protection system does not impact the power system. Test signals can be safely injected to simulate fault and other unusual power system conditions, and measurements made of the impact on each part, establishing the performance adequacy of the protection system.

The problem, which is the subject of this paper, is that once a station is in-service using process bus-based protection, modifications or tests that could have unanticipated outcomes are of particular concern. It is not, in general, practical to isolate the entire process bus for the station to retest it in the same manner as was possible during commissioning. Process bus systems must therefore have an architecture that supports the ability to design and perform tests with the same flexibility as existing systems.

A practical IEC 61850-9-2 process bus system is now available for use. This paper reviews key highlights of this process bus architecture which is fully described in referenced works [2], [3] and [4], and outlines a testing policy for it that allows the protection of each zone to be securely isolated from other protections and the power system for testing, for test signals to be injected, and for correct protection system reaction to be verified. The architecture of this system inherently controls process bus traffic such that protection performance is not compromised by system expansion or changes in power system topology, and thus testing issues associated with switched networks such as variable latency and data loss due to congestion are not an issue. The proposed isolation, testing and restoration procedures are well aligned with today's practice, allowing for fast user acceptance and compliance with external regulations.

2. Architecture for a P&C System Based on IEC 61850 Process Bus

Recognizing the driving forces for electric utilities as well as their existing cost structure, a technical solution for protection, control and automation has been developed that is simple and practical with a significant potential for rapid acceptance. The architecture is focused on reducing overall costs and providing a system that is conceptually similar to existing applications, while physically distinct in terms of media used and association of physical interfaces to primary equipment. The solution addresses all major concerns identified in previous work [5], in particular system reliability and testability.

In reference to Figure 1, the system, known as the HardFiber System, includes HardFiber Bricks mounted directly at the primary apparatus, the relay, pre-terminated cables, and cross connect panels for cross-connecting the HardFiber Bricks and relay.

HardFiber Bricks implement the IEC 61850 concept of "merging unit", and are designed to interface with all signals typically used for substation automation and protection as close to the respective origins of the signals 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.

Each HardFiber Brick contains four independent digital cores each composed of a microcontroller with an individual bi-directional fiber link providing dedicated point-to-point communications with a single relay. Sampled value communications conform to IEC 61850-9-2, GOOSE communications conform 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. Improved overall reliability and availability of protection is optionally supported via duplicated HardFiber Bricks. No protection or control algorithms are implemented within the HardFiber Bricks; instead their sole function is to be a high-speed robust IEC 61850 interface to the switchyard.

Cross connect panels are used to land and organize the fiber cables from the HardFiber Bricks and from the relays, and to distribute and individually fuse the dc power to the HardFiber Bricks. Standard patch cords are used to accomplish "hard-fibering", making all the necessary connections between the relays and the HardFiber Bricks as dictated by the station configuration on a one-to-one basis, without the use of switched network communications.

Each relay has eight optical fiber ports, and thus can access directly up to eight HardFiber Bricks. Each relay provides protection for one basic zone, conforming to established protection philosophies. 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 HardFiber Bricks. Due to the completely dedicated communications links between relays and HardFiber Bricks, with a convenient point to "break" this link, traditional testing methods may be used to test both the HardFiber Bricks and the relays much in the same way relays are tested today.

3. Testing Strategy for Traditional P&C Systems

Protection and control systems need to be tested to verify that they are capable of correctly performing their intended functions when initially placed in-service and when modifications are made. They need to be tested periodically in order to detect any hidden failures that may develop. Testing is required to isolate an operational problem to a specific component, and to verify system performance following repair. Tests must cover the entire protection and control system, not just the relay. The "test zones" as they apply to traditional P&C systems are summarized in Table 1.

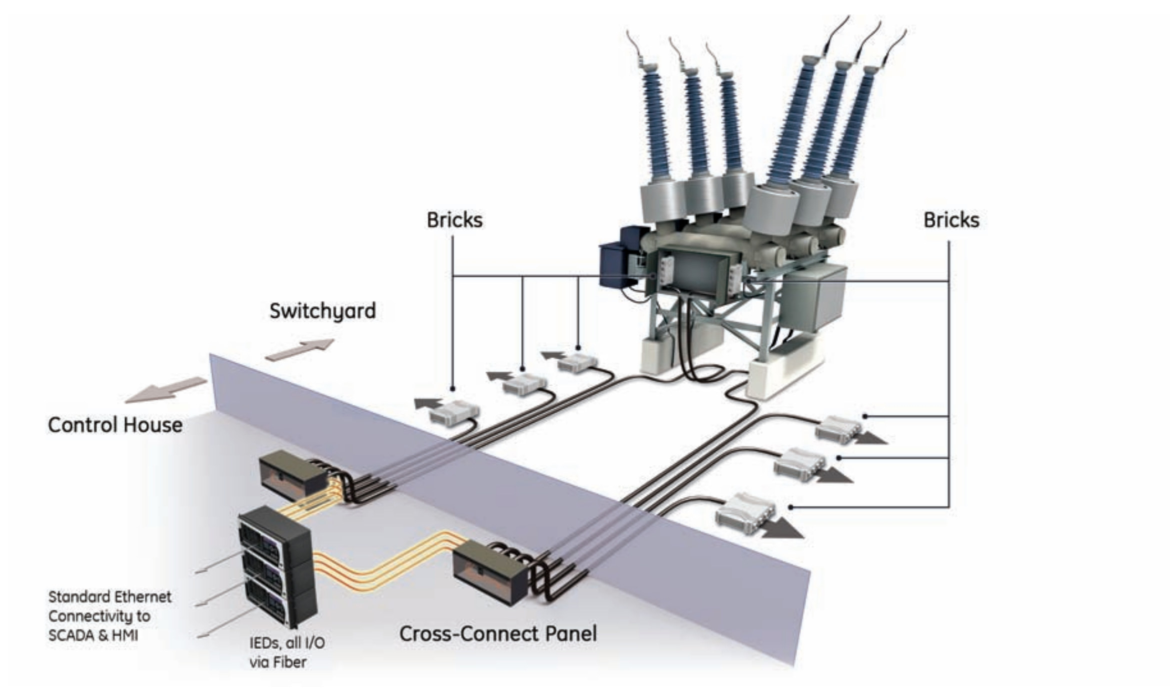

Figure 1.
HardFiber process bus architecture

Test Zone	Purpose	Methodology
Relay	• Device, including I/O • Firmware • Settings	• Isolate • Secondary ac injection (5A, 115/66.4V) • Short contact inputs • Monitor output contact closures
Instrument Transformers, Position Sensors, Condition Monitors, Control (e.g. Trip/ Close) Circuits	• IT ratios and location • Primary sensor/monitor functionality • Control circuit functionality	• Excitation check • Ratio check • Functional test of position sensors and condition monitors • Control circuit operational tests
Relay/Switchyard interconnection	• Verify cables and connections	• Ring-out wiring • On load metering checks • Trip tests from relay panel

Table 1.
Traditional P&C Testing Strategy

It is worth noting up-front that traditional protection test procedures are based on the use of test switches (e.g. FT switches) at the relay location, but that such test switches are impractical with HardFiber applications as all copper wiring is terminated at HardFiber Bricks located at primary equipment in the switchyard. Instead, the HardFiber System is designed for the ability to isolate trip outputs and analog signals by disconnecting the fiber optic cabling between the relay and the HardFiber Bricks. This method provides the same functionality as traditional test switches, and does so in a simpler and more error-proof manner.

4. Testing Strategy Overview

As shown in Figure 2, the high-level test strategy is to divide the protection into three test zones:

1) The relay

2) The primary equipment and associated HardFiber Brick(s)

3) The relay/switchyard interconnections

Each of these three zones are tested independently, with testing properly overlapped to establish correct inter-zone interaction, and thus correct operation of the system as a whole. To emphasise an important and novel point here, HardFiber Bricks are blended into primary equipment in the same way the wires they replace are blended by traditional test strategies. As one would for instance, initiate a test trip from the control house to check that both the copper cabling conducts the trip signal to the breaker's trip coil, and at the same time check that the breaker actually opens when trip is applied to the coil. Here a test trip from the control house checks that the fiber cabling and HardFiber Brick combination conducts the trip signal to the breaker's trip coil and at the same time checks that the breaker actually opens.

The overlapping "test zones", as they apply to the process bus implementation, are summarized in Table 2.

Test Zone	Purpose	Methodology
Relay	• Device, including I/O • Firmware • Settings	• Isolate • Injection of AC input sampled values • Force contact input signals on optical fiber ports • Monitor contact outputs on optical fiber ports
HardFiber Brick & Instrument Transformers, Position Sensors, Condition Monitors, Control (e.g. Trip/ Close) Circuits	• IT ratios and location • Primary sensor/monitor functionality • Control circuit functionality • HardFiber Brick functionality	• Excitation check • Digital ratio check (primary input to sampled values) • Functional test of position sensors and condition monitors (primary state to signal on optical fiber) • Control circuit operational tests digitally forced from optical fiber link
Relay/Switchyard Interconnection	• Verify cables and connections	• Continuous self-checking • On-load metering checks • Trip tests from relay

Table 2.
HardFiber Testing Strategy

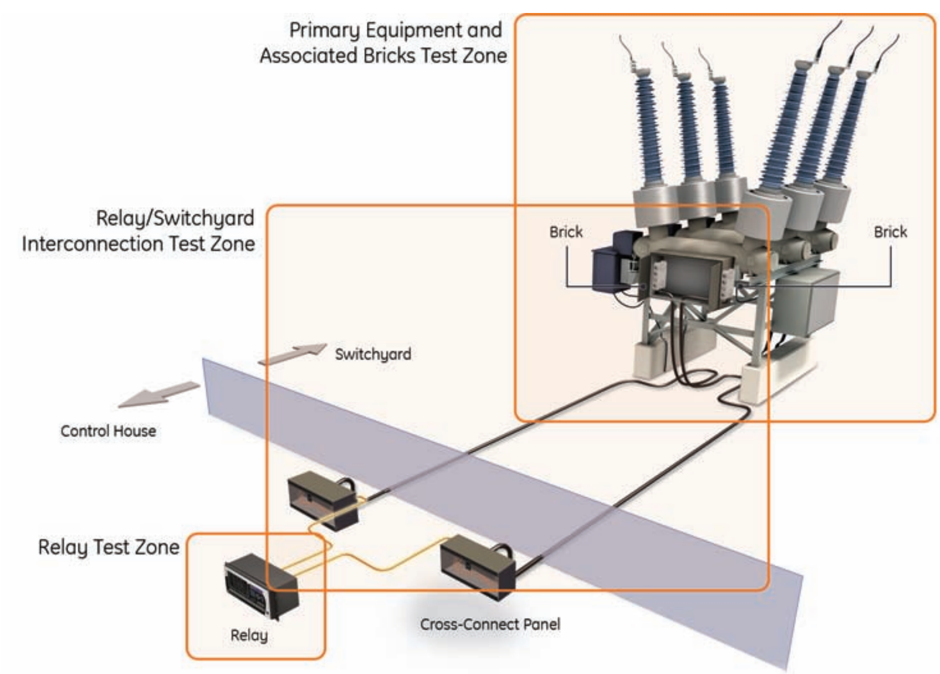

Figure 2.
Test Zones

It is important to note that when Table 1 is compared with Table 2, the total coverage remains the same between the traditional and process bus-based systems, although the methodology is different.

5. Test Procedure for Relays

In overview, the procedure for testing a Universal Relay (UR) in a HardFiber process bus system is the same as testing a Universal Relay in a conventional system, and consists of isolating the relay test zone, doing any required work such as hardware replacement, settings or firmware changes, followed by the actual testing, and then finally restoring the relay test zone to service. The difference is in the physical methods used to isolate the zone, and the means to inject and monitor relay signals. The test zone for this procedure is the UR and any process bus fiber cabling between the relay and the point where the relay is physically disconnected to isolate the relay from the remaining in-service protection system. The test zone may also include some station LAN components and conventional copper I/O beyond the scope of this paper.

5.1 Relay isolation

A critical testing step in the in-service environment is the isolating (blocking) of relay outputs from external circuits to prevent unintentional operation of those circuits (e.g. tripping). Failure to perform this step properly can result in the testing effort causing much more harm than it could potentially do good. For this reason the UR relay firmware provides a manual command that puts the relay in a "Test-Isolated" mode, wherein all process bus command outputs from the relay are disabled. This is equivalent to opening the output test switches in a conventional copper connected protection, except that all of the command outputs are blocked with a single user action – there is no chance that wiring or personnel error can result in one output being overlooked and left operational. When in this mode, a front panel "In-Service" indicator is turned off, a "Test Mode" indicator is turned on, and the critical failure contact put in the alarm position, so that there is little chance of even one output of the relay being inadvertently left in this blocked state when work is complete. This mode is non-volatile; the only way to return to the normal in-service mode is by specific user command action.

In the testing methodology state diagram of Figure 3, the state transition resulting from this step is labelled "Command Test-Isolated Mode".

With conventional copper connected protection schemes, external circuits connected to the relay inputs must also be safely isolated from test conditions harmful to the external circuits (e.g. opening a CT circuit), and test actions (e.g. AC injection) with an adverse effect on other users of the signals. There is no equivalent concern with the HardFiber process bus implementation. There is no equipment harm in opening the fibers, and the fibers associated with the relay under test have no other client, due to the point-to-point process bus architecture.

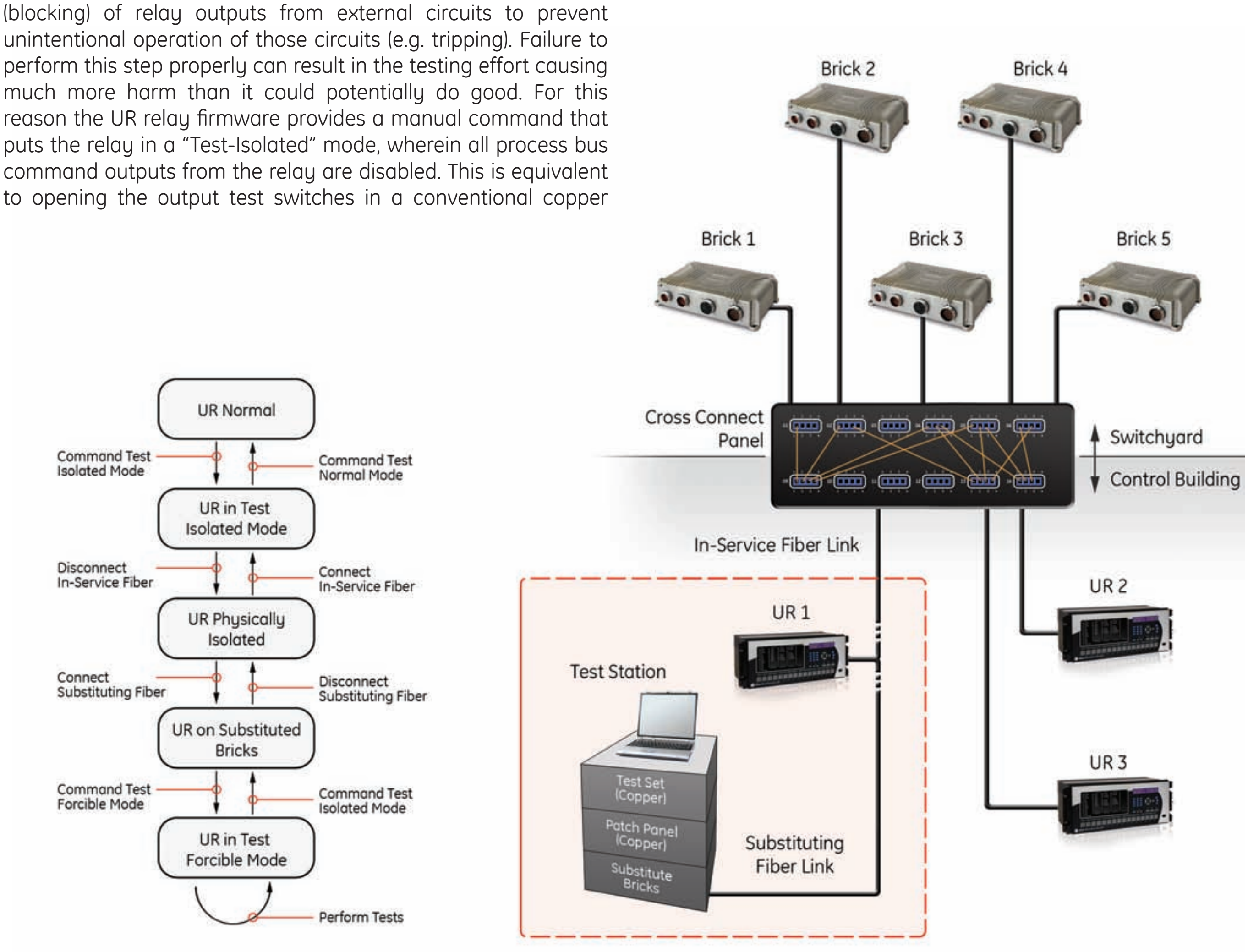

Figure 3.
Relay test methodology and facilities

5.2 Relay injection testing

Traditionally, relays are tested by injecting signals, to check their current, voltage and contact input hardware, to check that the measuring elements and scheme logic are operating correctly, to check that their settings are correct (e.g. that the technician or settings engineer did not accidentally type 15.0 instead of 1.50 for a pickup value), and to check the contact output hardware. Now with process bus, the relay has no physical current, voltage or contact inputs, so there is no corresponding hardware to check. The hardware performing a somewhat analogous function, the optical transceivers, PHY chip, etc., are continuously self-tested with signal level margin detectors and with data security codes (i.e. CRC), so there is little, if any, value in further testing the relay's process bus input/output hardware. The firmware that implements the measuring elements and scheme logic is continuously checked again by CRC, and the processors by watchdog timers. A strong argument can be made that injection testing for checking the settings is of little value, that there are other less complex and more secure means of verifying the settings [6]. There seems to be little value for using injection testing on the relays. Never-the-less, simulating power system faults and observing relay reaction has value as a method for checking the settings in a way that does not involve a human understanding of how the relay interprets its settings, and thus can be done by personnel with a different perspective than the settings engineers, and thus less likely to make the same mistake. This makes it advisable to have the ability to do injection testing with process bus.

Traditionally, injection testing uses a relay test set connecting to the relay under test via test switches (e.g. FT switches). With the HardFiber process bus architecture a conventional relay test set is still used, but is connected to the relay's optical fiber ports through test or "substitute" HardFiber Bricks, identical to the permanent HardFiber Bricks. The substitute HardFiber Bricks and the relay test set together form a "test station", which can be thought of as a process bus relay test set. It injects inputs and monitors outputs from the relay's process bus ports analogous to the way a conventional relay test set injects and monitors conventional current/voltage/contact ports.

The HardFiber Bricks have no "personality"; except for their serial number and order code, the permanent HardFiber Bricks are fully interchangeable with substitute test HardFiber Bricks. HardFiber Bricks have no settings, which would otherwise differentiate them, and the initial HardFiber Brick firmware version is irrelevant as the relay's version is automatically downloaded. The connection between the relay and the substituted/permanent HardFiber Bricks are both direct point-to-point hard-fibered links, and need no settings to setup. Therefore one may be confident that the test signals delivered to the relay by the substituted HardFiber Bricks are the same as those from the permanent HardFiber Bricks, and vice versa.

This hardware substitution test strategy tests outputs by checking the output signals using the test station as a measuring device. The assumption is made that a signal that made an output of the substituted HardFiber Brick operate would have made the permanent HardFiber Brick operate. Traditional relay test strategy for checking outputs is by measuring voltage signal levels at a break in the signal path made by an FT test switch, using a multimeter or a relay test set. The assumption is made that if the FT switch were instead closed, the connected breaker would trip. Thus it can be seen that the hardware substitution strategy is more realistic than the traditional test strategy; to be comparable the traditional strategy would have to use a "test breaker" to confirm outputs are capable of supplying breaker trip level currents.

To use this technique, after putting the relay in the test-isolated mode, the user disconnects the in-service process bus fiber connections either at the relay itself or at the cross connect panel, and connects instead substituting fiber to the test station. Proper fiber handling practices need to be observed while disconnecting and reconnecting the fiber.

At this point if required, the relay can be swapped out, new firmware loaded, and/or new settings applied. The user then issues a command to the relay causing it to switch from the test-isolated mode to the "test-substituted" mode, wherein the commands are again enabled onto the process bus, which now connects only to the test station. In addition, the configuration locking mechanism that normally prevents communications between a relay and a HardFiber Brick with other than the set serial number is bypassed, to allow the relay under test to communicate with substituted HardFiber Bricks. The front panel indicators and critical fail output continue to show that the relay is not in-service.

Refer to the correspondingly labelled steps in the state diagram in Figure 3. Once in this test-substituted mode, the conventional relay test set may be used to perform any functional tests that could have been performed on a non-process bus system. The nature of these tests, and how they accommodate station bus or conventional contact I/O, is beyond the scope of this paper.

5.3 Relay restoration to service

Once the testing is complete, it is necessary to restore the relay to service in a safe and secure way. One needs to avoid the trap of closing a switch, making a connection, or restoring a mode that results in undesired action such as tripping a circuit breaker. Without due care, such could occur for instance due to the seal-in of a protection scheme or the response to having some but not yet all live inputs restored. This can be accomplished by reversing the actions of the previous steps, moving up in the Figure 3 state diagram. First the user commands the test isolated mode so that when the permanent HardFiber Bricks are re-connected, no process bus commands can result in undesired action such as tripping. The substituted HardFiber Brick fiber links are disconnected, and the permanent HardFiber Bricks re-connected. Just before commanding the switch to the normal in-service mode and going live, the user should check the actual values of the relay's process bus outputs, that they are in a state that will not cause problems when re-enabled. At this time the user should check that the relay has not raised any alarms resulting from missing or misconnected permanent HardFiber Bricks, or unacceptable signal margins. One may also check that the data being received from the permanent HardFiber Bricks is reasonable, internally consistent, and matches indications from other equipment. However, as neither the permanent HardFiber Bricks nor their connections to the power equipment have been disturbed by this test procedure, and as the relay annunciates any problem communicating with the HardFiber Bricks, this crosschecking may not be worth the effort.

6. HardFiber Brick/Primary Equipment Testing

6.1 Initial installation/major rework

The proposed high level test strategy combines the HardFiber Brick testing with the testing of the associated primary equipment functions. For a particular function, such as a breaker trip command, the checking of the HardFiber Brick, the primary equipment and the interface between the two is efficiently verified with one test. This strategy also eliminates the need for test switches between the HardFiber Brick and the primary equipment.

Testing of functions using HardFiber Brick contact inputs is accomplished by forcing a change of state in the primary equipment and observing the result on the signal transmitted by the HardFiber Brick. For instance, breaker position status contact inputs are tested by opening or closing the breaker and observing the signal change on the HardFiber Brick fiber port. The transmitted signal may be observed either using the permanent relays, or with a substitute relay used in a way similar to how substitute HardFiber Bricks were used in testing the permanent relays. A substitute relay may be more convenient than a permanent relay, as the substitute may be made portable and used adjacent to the HardFiber Brick/primary equipment. A substitute may also be used when the permanent relay or fiber cabling is not available such as at the primary equipment factory, during initial on-site installation before the fiber cable and/or permanent relay is installed, or while the relays are in-service and cannot yet be configured for the new incoming HardFiber Brick/primary equipment.

Testing of functions using HardFiber Brick contact outputs is by activating that output from the substitute or permanent relay and observing the correct primary equipment response (e.g. tripping).

CT and VT functions are checked by observing the analogue values transmitted by the HardFiber Brick with primary voltage or current present. The observed magnitude and phase indication is compared with other devices metering the same primary quantity. In the case of initial testing before the primary equipment can be energized, the checks may be either by primary injection using the appropriate injection test equipment, or by separately testing the HardFiber Brick (with secondary injection) and the instrument transformer (with conventional techniques). Test cables are required with a plug to inject secondary signals to the HardFiber Brick and a receptacle to breakout the secondary signals from the instrument transformer. Where this separate testing technique is used, the comparison technique should also be used immediately after the primary equipment is energized to verify the correct connection between the instrument transformers and the HardFiber Brick.

6.2 HardFiber Brick replacement

Although HardFiber Brick design is such that failures will be rare, a strategy for handling such cases in a cost effective manner is still required. The design should be such that HardFiber Bricks can be replaced without undue worker safety risk, and ideally without outage to the associated power system element. Isolating means are therefore built into the HardFiber Brick itself that do not consume additional space or field labour for installation. The HardFiber Brick has all electrical and optical fiber connections

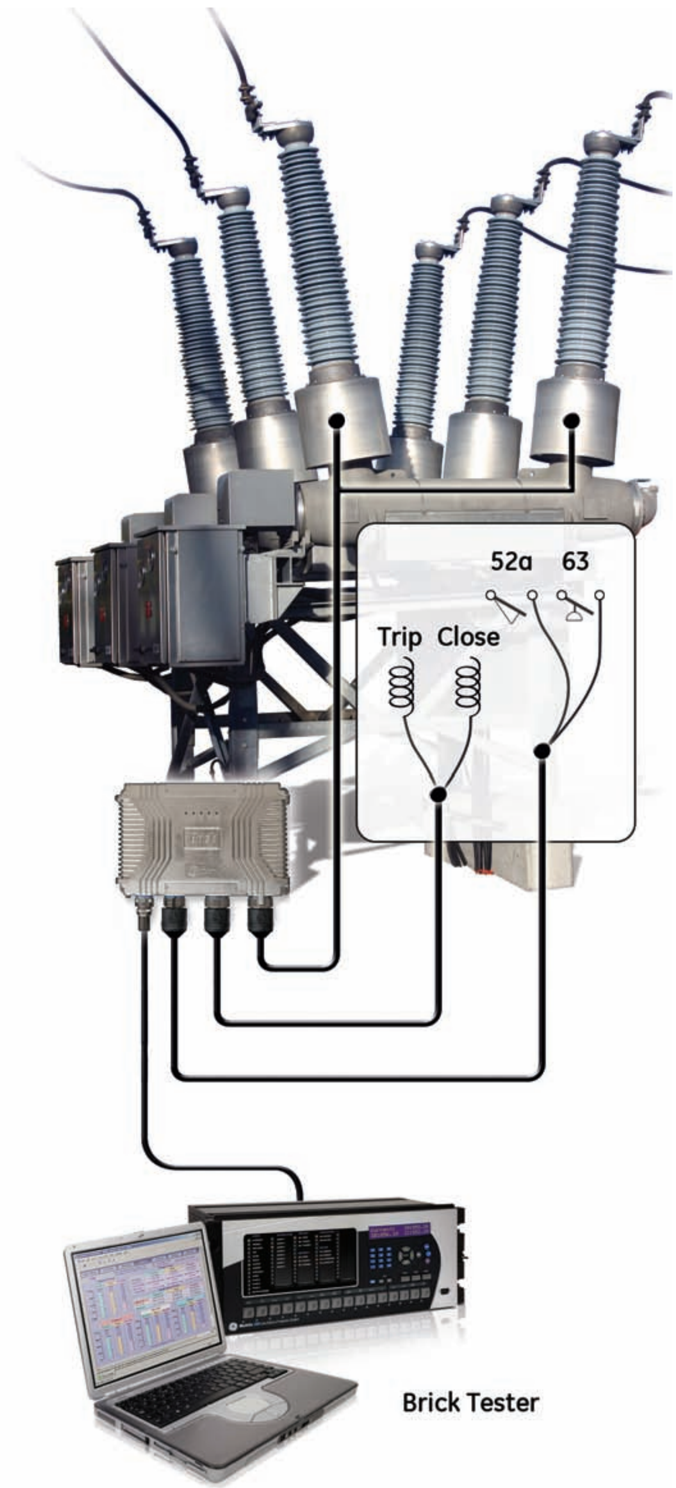

Figure 4.
HardFiber Brick/Primary Device testing

equipped with highly reliable quick mating connectors in the proven MIL-DTL-38999 series. However, with this particular series of connector, if one wishes to have the ability to replace a HardFiber Brick with the CT circuit live, additional facilities are required to bypass live CT current loops. Careful consideration should be made on whether the ability to replace a HardFiber Brick without primary equipment outage is worth the addition cost, complication and safety risk involved with working on live CT circuits.

Prior to connecting the new HardFiber Brick, it can be fully tested in a safe environment using the HardFiber Brick tester and a conventional relay test set. Once the fiber cable plug-in connections to the in-service relays are made, the communications system testing described below is executed. Typically the replacement activity would conclude with a check that the controls are operational (i.e. trip and close breaker, which can be done via SCADA if it uses the same hardware), a check that the currents' and voltages' magnitude and phase are reasonable and consistent with other sources, and that breaker and alarm status is correct.

6.3 Routine periodic testing

Regulations in some jurisdictions mandate that protection systems be periodically re-tested to verify that it is capable of performing its intended protection function. Most requirements of such regulations are satisfied by the continuous self-testing and event recording the process bus system provides. For instance, the optical signal is continuously monitored in the system and degradations that may affect signal adequacy are alarmed. Event reports can be used to locate and verify the correctness of recent breaker operations, usually avoiding the need for trip tests. Any individual items not covered by either of these can be accomplished using the techniques described in the above sections.

7. Relay/Switchyard Interconnections Testing

The objective of the relay/switchyard interconnections testing is to check those process bus functions not covered either by the relay injection testing or by the HardFiber Brick/primary equipment testing. Relay injection testing using substituted hardware establishes that the relay properly consumes data streams presented to its process bus optical fiber ports, and properly generates control data streams on these same ports. HardFiber Brick/primary equipment testing establishes that the HardFiber Brick and primary equipment working together generate a data stream that properly encodes the primary quantities and properly executes commands received. What remains in checking the protection system as a whole is to establish that with the protection system fully in-service, the data streams generated by the relays and the HardFiber Bricks are reaching the correct destinations with adequate signal levels.

With the HardFiber process bus implementation, the "hard-fibered" approach eliminates interconnection testing issues such as LAN congestion, correctness of LAN configuration settings required to automatically re-route around failed switches, non-deterministic latency, etc.; issues that make thorough testing very difficult in a packet switched network. Use of single bi-directional fiber technology eliminates the concern present with double simplex fiber links and with multi-conductor copper cabling that the link is only partially correct – correct communications of any bit of data in either direction establishes that all data on that link is communicated correctly. All that is necessary is to establish that there is a continuous optical path from each port of the relay to/from the correct HardFiber Brick, and that path losses leave adequate signal margin.

Excessive optical path losses can result from manufacturing problems or damage occurring during shipment or installation, though the more likely the cause is contamination in the optical fiber connectors introduced during installation or maintenance. Establishing the value of path losses (and thus operating margin) is easily done in the system, as the optical transceivers at both ends are equipped with diagnostics that continuously measure the send and receive light levels even while the link is in normal operation. The relay then generates alarms should any level fall out of tolerance. Establishing the correct operation of these alarms should be part of the relay injection testing and the HardFiber Brick/primary equipment testing.

The "hard-fibered" architecture means that incorrect interconnection between relays and HardFiber Bricks can only result from incorrect installation of the fiber cables or patch cords. There are no settings that result in cross-connections. Correct interconnection can be established in any of several ways:

- Physically tracing the cable and patch cord routing from the back of the relay to the HardFiber Brick.
- Observing the data received by the relay over the link is reasonable and matches other indicators. For example indicated current/voltage magnitude and phase matches other indicators of these same quantities.
- Causing some change of state and observing its correct communication over the link. For example, observe the reported effects of initiating a breaker operation or a tap change. Initiation may be from the operator's HMI where it uses the same fiber link.
- The relays are designed such that when normally in-service, they alarm and reject data on a port when the HardFiber Brick serial number that is included with the data fails to match the relay setting for that that HardFiber Brick's serial number. The relay serial number value is included with outgoing commands, and the HardFiber Bricks are designed to accept commands only when the accompanying serial number matches its own serial number. Thus, once the HardFiber Brick serial numbers are correctly entered into the relay settings, the fact of normal communications establishes that the link is correct. The serial number setting in the relay can be manually checked against the serial number on the HardFiber Brick's nameplate.

Thus it can be seen that testing of the passive interconnection system is quite simple, and that after commissioning is complete, it can be entirely automatic.

8. Conclusions

This paper presented a complete and simple testing procedure for the HardFiber process bus architecture. In particular the following important advantages are provided:

- Opportunities for inadvertent operations due to employee error are reduced due to easy comprehension on the part of test personnel of the simple architecture.
- Improved safety for test personnel as all relay testing work is done in the safety of the control house, separated from the hazards present in the switchyard, and isolated from high energy CT and VT circuits by fiber optics.
- The comprehensiveness of the relay test method proposed is assured though use of the traditional strategy of isolating the relay's outputs, injecting signals simulating power system conditions such as faults to the relay's inputs, and monitoring the relay's response. Traditional methods are also used to test the complete protection system.
- Training of test personnel is minimal as conventional relay test sets are used in familiar ways, with additional HardFiber Bricks adapting the conventional test set to the optical fiber format used by the relay.
- The system is self-monitored. Most or all of routine re-verification and much of commissioning testing can be accomplished without disturbing the in-service system.

9. References

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