Multipoint-to-Multipoint Protective Relaying Signaling Using Digital Communications and Built-In Logic

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Multipoint-to-Multipoint Protective Relaying Signaling Using Digital Communications and Built-In Logic

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Abstract—A state-of-the-art analog microwave system was installed in the Cleveland area in the 1950s and 60s for pilot protection of 138 kV transmission lines as the transmission system was first constructed. Part of this system was documented in a paper, “An Application of Microwave Relaying to Multi-Terminal Lines,” presented at the 1959 Conference for Protective Relay Engineers in Chicago, IL [1]. Four parallel 138 kV lines provided redundancy and load serving capacity. The unique protection problem was the direct tapping of two or more lines to feed 138/36 kV subtransmission stations having low side tied busses while maintaining pilot protection and high-speed reclosing on those “multiterminal” lines. The original solution was a multipoint-to-multipoint analog microwave communications scheme for permissive and transfer trip signals.

When planning retirement of the analog microwave system, no existing digital multipoint-to-multipoint protection communications replacement could be found that would meet teleprotection timing requirements. This paper documents a novel multipoint-to-multipoint solution designed using state-of-the-art communications technology and built-in logic. This paper covers the original logic as well as the new standard digital logic chosen for communications signaling. Improvements were made to the logic for breaker failure direct transfer tripping from the tap substations and the future addition of air break fault isolation switches while maintaining POTT protection. Standard design decisions are described related to communications and equipment redundancy. Finally, included are some challenges discovered after three years of widespread implementation along with mitigating solutions.

Index Terms—Transmission protection, analog microwave, permissive, direct transfer-trip, SONET, C37.94, multi-point, teleprotection

I. INTRODUCTION

ENGINEERS have long been at work implementing contemporaneous technology to solve problems. Many times, fundamental logic had been developed many years previous defining a standard specific to a utility’s system configuration and experience. Understanding this standard and unique configuration is the first task in designing any new technological application. Let’s take a look at these specific factors by way of introduction.

A. Topology

Cleveland, Ohio sits on the southern shore of Lake Erie, presenting challenges to power delivery. Early decisions during the construction of the 138 kV system included a four-circuit double-tower right-of-way that

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circled the city on land in an almost half-circle, terminating at each end in power plants. The four circuits remained independent from one another except at power plants where all four were connected through buses. Other power plants located within the territory were connected via at least double redundancy interior circuits. The load in the suburbs was fed from this 138 kV system primarily through a 36 kV subtransmission system. Transformation was tapped off of the four 138 kV lines, feeding tied 36 kV busses. Radial 36 kV feeds would then provide power to the remote distribution substations. In the city, 11 kV substations were installed with transformation directly off of the 138 kV circuits, again with multiple taps for redundant feeds. Historically the low side 11 kV buses would be tied together through normally closed bus tie breakers. During 138 kV line faults, current flows through these low side buses, back into the fault, necessitating tripping at all such locations. The fault current passing all the way through two tapped transformers is rather weak (by virtue of the impedance of the complete path down to 36 / 11 kV and back up), leading to the designation of such stations as Weak Infeed Tapped Substations (WITS). While considerations are required when designing protective elements for these parallel lines with WITS taps [2], this paper will focus on the communications equipment required for specific implementation in Cleveland.

B. Permissive Overreaching Transfer Trip (POTT)

When designing a communications-based protection scheme, several typical logic options are available including DCB, DCUB, POTT, and DUTT. A complete discussion of these is available in literature [3], but a quick review of POTT here will aid understanding.

Permissive Overreaching Transfer Trip, POTT, is a communication assisted relay tripping scheme where both the local and remote ends look toward the protected line and beyond. If either end sees a fault on the protected line or beyond (forward fault), it sends a “permissive” signal to the other end. If the other end sees a fault on the protected line or beyond and receives a permissive trip signal, that end will trip. Under correct operation, if either end does not see a fault on the protected line, then it will not send a permissive signal and the other end will not trip even if it sees the fault. POTT is also known as POR (Permissive Over Reaching).

Typical communication channels used for POTT include microwave, fiber optics, and phone line tone. The relays’ zone 2 is used for the pilot scheme and is set to overreach the end of the line. A typical reach could be 120% of the line impedance. POTT is a high-speed pilot relay scheme with operating times as fast as 1 cycle for zone 2 faults.

POTT Schemes are recognized as a more Secure relay scheme as compared to a Directional Comparison Blocking (DCB) Scheme which is recognized as a more Dependable scheme. During a loss of communications, the POTT scheme will be inoperable. The scheme will not overtrip for external faults and not provide high-speed tripping for internal zone 2 faults.

POTT was selected originally as the scheme type for Cleveland 138 kV lines because security was important for multiterminal lines and changing configurations of the early 138 kV system, coupled with the desire to use analog microwave communications.

C. Open Breaker and Terminal Outage

When the transmission line is operated with one terminal open, there is still a desire to utilize the high-speed POTT protection. With the circuit breaker(s) open on the local terminal, the remote terminal will only see forward faults internal to the zone of protection. To accomplish this, since the relay at the local terminal is no longer in the picture, the Permissive signal is permanently keyed to the remote terminal.

A common scenario is when maintenance is being performed on the circuit breaker. It’s bus and line disconnect switches are open and the transmission line remains in service. A control switch, the Breaker Outage Switch (BOS), is utilized as a terminal outage switch. Enabling the BOS switch permanently keys the Permissive Signal to the remote relay allowing the POTT scheme to remain active from the remote terminal.
II. THE ANALOG MICROWAVE SOLUTION

A paper presented at the 1959 Conference for Protective Relay Engineers outlined an analog microwave communications system carrying protective signals for a POTT scheme [1]. Analog microwave technology had been well vetted for teleprotection in the utility setting by this time. A transmitter, when activated, would produce a signal that would be carried on microwave radio links between several stations. Receivers could be located at any of the stations as needed. This allowed one signal transmitted at one location to be received at multiple stations very quickly, a multipoint-to-multipoint property ingeniously leveraged to provide POTT protection for parallel multiterminal lines with WITS.

The focus of the paper was a four-line corridor from substation A to substation D with taps at stations B and C. The tap at C was a WITS while taps at B were radial lines to a WITS. Each line had its own transmitters for permissive signals, one from A, one from D, and one from B. Receivers for the permissive signals were placed at A, B, and D for each other’s reception. The tap at C had receivers for permissive signals only from A. An additional signal, the transfer trip signal, was transmitted from station A, the strongest source, when any line terminating at A was both keying permission and receiving permission from D and B. This transfer trip signal, when activated, would result in tripping at C for the transformer tapped to the line for which the permissive signal from A was also being received. The most terminals on a line implemented with this scheme was five.

The philosophy employed in this corridor was replicated with gradual additions across the entire 138 kV system as it was constructed in Cleveland, making analog microwave ubiquitous. The projected ease of expansions was realized, and several unique protection challenges were solved over the course of the transmission system build out. At some WITS, instead of employing a transfer trip signal in the corridor, permissive receivers for all lines’ main terminals were installed. If permission was received from both main terminals on a line simultaneously, tripping for feed into that line would occur; in later designs, this tripping was qualified by a local fault detector at the WITS, preventing tripping for non-fault conditions. (An example where this is useful is in the case of a switching error – where the permissive signal is keyed through breaker outage switches at both main line terminals and the lack of a local fault detector operation would prevent unintended tripping of the WITS terminal.)

As breaker failure protection became popular, another signal was implemented and transmitted per-terminal for direct transfer tripping of all other line terminals that would block reclosing. This most commonly only originated from main terminal stations, though, as deployment of microwave transmitters at WITS was not deemed a requisite expense.

III. MODERNIZATION

A. Background and Design Requirements

The retirement of the analog microwave equipment had several motivations: expired manufacturer hardware support, equipment aging, waning spare inventory, atmospheric inversion causing variable path losses, some limited spectrum license loss, new relay communications requirements (specifically the desire for digital channels between protective relays), and others. Planning for this retirement started in 2011. Note that design for this replacement was to accommodate existing electromechanical relaying or new relay installations, allowing cost flexibility for transition to the new communications equipment. Several factors were involved in the design for replacement, and some of these are covered here.

1) MPLS vs. SONET

SONET (Synchronous Optical Networking) and MPLS (Multiprotocol Label Switching) are two common digital communications transport protocols utilized by power utilities for substation-to-substation communications.
SONET is an older technology, originally designed for carrying digitized voice traffic over fiber optic based networks. SONET networks are circuit switched, meaning that individual point-to-point communications circuits are created. SONET facilitates the creation of many individual point-to-point circuits over a common communications medium, or fiber optic cables as the SONET name suggests. This is accomplished by allocating equal fixed time increments for each circuit to communicate. Once all circuits have been given their time, the process starts over. This type of multiplexing is called TDM (Time Division Multiplexing). Because TDM establishes circuits in the time domain, in a repeated fashion, the delivery of traffic is deterministic in nature. This means that the time required to communicate from one point to another is always the same, except during path failures. As more communications applications demanded data transmission rather than voice, SONET has also evolved to support data transmission. Because SONET is independent to the communications protocol of the data being transported, it is widely used to carry many sources and types of data. This has expanded the use cases of SONET and as a result also includes power utility applications. These applications can include both IT (Information Technology) and OT (Operational Technology) data. Due to the deterministic handling of data, SONET is well suited for OT applications.

Another critical feature of SONET is the ability to employ automatic protection switching methods. SONET utilizes network topologies, like rings, to form backup paths in the event of a failure. In the event of a fiber break or port failure traffic is switched to different paths to “heal” the network and minimize loss of traffic. UPSR (Unidirectional Path Switch Ring) is a commonly used method. With UPSR traffic flows around a ring topology network over separate parallel rings (ring 1 and ring 2), in opposite directions. In the event of the fiber break, the egress node can detect the failure and switch between the rings to maintain traffic. Detection and switching time are not to exceed 60ms total and is often significantly less using specialized techniques.

Relative to SONET, MPLS is a newer technology and is a packet switched type network. Packet switched networking is a multiplexing method that routes packets from source to destination using addressing information. In contrast to circuit switched networks, packets are only sent as needed. This is a more efficient use of bandwidth since data may be variable in nature and not necessarily constant. The tradeoff is that this requires queuing as only one packet can be served at a time. So subsequent packets will have to wait their turn until the previous packet is served. Packet switched networks often employ QOS (Quality of Service) and traffic engineering methods to prioritize important packets and optimize the flow of traffic to mitigate excessive delays during network congestion.

The intent of MPLS is to route packets based on packet labels rather than addressing. To speed up routing of packets, these labels identify virtual paths between network nodes rather than using large lookup tables to identify the appropriate network path. Like SONET, MPLS is protocol independent and can carry many types of data protocols. Due to the adaptability of MPLS and the differing nature of data and each unique need, MPLS is well suited for carrying both IT and OT data simultaneously.

MPLS paths are termed LSP (Label Switched Path). LSPs are defined for each point-to-point circuit and may be unique for each application of data entering the network, facilitating traffic engineering. LSPs may also be assigned for primary and backup purposes to provide redundant paths in the case of a failure. MPLS Fast Reroute (FRR) is another method used to provide SONET like network healing time in the event of port or node failure.

2) Device to Multiplexer Connections

Several standards exist for digital signaling between station devices. Communications multiplexers include many of these standards as options for digital interfaces. Common choices include RS-232, G.703, RS-422, and C37.94. C37.94 is unique: it is a standard written for communication between multiplexers and substation equipment over fiber optic cable. This optical medium improves isolation, is electromagnetic noise immune, and eliminates concern about ground potential rise present with the other metallic-based standards.
3) Substation Digital Hardware

Hardware in a substation environment can be subject to demanding electrical and environmental hazards including electrical transients, surges, and extreme temperature variation. These require critical power system digital devices to be constructed with extra features not typically present in standard commercial or even industrial equipment. Numerous standard type tests exist, such as IEEE 1613 and IEC 60834-1 for communications equipment and IEEE C37.90 and IEC 61000-4-5 Class 4 for protective relays, to allow selection of equipment properly designed and manufactured for installation in the substation. Selection of communications equipment designed for office or data center usage may result in unexpected failures during the very event most critical for protection and communication system performance.

4) Redundancy

The nature of the protection system reliance upon the communications-based protection scheme to achieve coordination and maintain power system reliability determines the required reliability of the communications infrastructure. A point-to-point dedicated communications link has almost trivial failure mode analysis. One power supply fails, or one fiber strand breaks, and the link goes down. An increase in reliability here is achieved simply with redundancy in the form of duplication: two power supplies, a hot standby fiber strand. Failure analysis in multiplexed systems can be far more complicated, owing to some level of redundancy integrated in the chosen architecture.

The original analog microwave system as implemented in Cleveland included one main baseband amplifier per radio path termination. If this amplifier ever underwent complete failure, all signals on that path were simply lost until repair could be made. Enough backup protection and good enough coordination provided the flexibility for this low-probability contingency.

Equipment interfacing protection to the communications system has its own redundancy considerations. For the purposes of this paper, a piece of equipment that translates contact closure to some other medium will be called a communications unit. Since parallel lines exist between multiple substations, is one communications unit installed to carry all needed signals for all parallel lines simultaneously? Or does each line terminal have its own separate communications unit? Original implementation in the analog microwave involved separate transmitter/receiver units for each channel, requiring multiple units per line.

5) Logic Realization

For many years digital logic has been implemented directly in DC circuitry. ANDs are realized with series contacts and ORs with parallel contacts. Transmission of one signal to many terminals could be accomplished through one contact driving many inputs on communications units. Receipt of many signals from many terminals could be accomplished through many outputs on communications units driving one relay input. This type of construction depends upon the integrity of wiring between inputs and outputs. It has no inherent ability to monitor or log. Post-event analysis of the operation of such logic relies heavily upon assumptions of health and standard time delays.

6) User Interface

Logic realization in DC circuitry lends itself to light indicators for status. A set of simple light bulbs indicate clearly when certain inputs, outputs, or alarms are active. When logic is realized digitally, a method of indication is still required for field users to know the actual state of equipment and communications links. The use of multi-colored LED packages can even simplify status checking, as only a single point can indicate status at a glance. This type of indication in DC circuitry was previously only possible in more intricate annunciator displays. Now they are being included as standard features in many microprocessor-based devices.
7) Sequence of Events

Forensic analysis after tripping events has become a highly-scrutinized activity with regulatory bodies requiring analysis of every event and specific follow up for every mis-operation. While dispensation is made for cases where data are not available, reliability of the system is not benefitted from any promulgation of previously less-monitored schemes. The ability to track the exact time (as synchronized to a GPS clock) a point in logic changes state can provide information critical to discerning the real cause of a mis-operation.

B. Challenge: Multipoint-to-multipoint

The biggest challenge in modernizing this communications system was the need to communicate a signal from one substation to many while also receiving signals from them as well. The analog microwave solution was elegant in that multiple receivers could be placed at microwave terminals in tapped substations, simply listening in and reacting to the signals passing through. At the time, some limited multidrop SCADA applications of RS-232 were identified, but those have far too much latency from a protection perspective. Other options existed involving many sets of paired transmitter/receiver units, one for each communications link, but this would involve extensive parallel DC wiring and maintenance of many more pieces of equipment.

Another requirement was to have communications links from each main source terminal to all WITS terminals but no need for communications links between WITS directly. This was to limit the number of required communications circuits/interfaces to be purchased and reduce complexity.

C. Design

The decision for overall communications architecture between MPLS and SONET was made in the 2013/2014 timeframe. The lack of widespread implementation of MPLS teleprotection versus the well-known and widely-deployed SONET drove the selection of SONET. The deterministic nature of SONET and the desire to use 87L protection without dependence upon external clock source further influenced this selection, considering proper configuration constraints on the SONET switching behavior. The selected SONET platform also included proven failure switching times of 5 ms or less, a very attractive feature when considering the rare occasion of simultaneous power system and fiber failures.

C37.94 was chosen as the default protocol for all protection communication with the multiplexer. This eliminated the need to support varied interface types in the relay and multiplexer hardware.

One communications unit per line, per line terminal was chosen as a balance between simplicity, communications efficiency, and redundancy. Digital logic realization was required, eliminating from consideration any solution that involved one unit per point-to-point path.

Selection of a substation-hardened communications unit for interface with the relaying involved finding equipment that could communicate over C37.94 interfaces in a multipoint-to-multipoint configuration for up to six terminals (one additional terminal allowing for expansion). A model was identified that provided this capability directly, without C37.94 converters, while also internally realizing custom digital logic, providing clear user indication with multi-color LED lights, and recording GPS-synchronized time sequence of events.

Input and output functions were standardized to enable the standardization of developed custom logic shown in figures. The logic is divided into two types: source shown in Figure 1 and Figure 2 and tap shown in Figure 3 and Figure 4. Source logic is for main line terminals, while the tap logic is for any WITS. Both permissive and direct transfer trip signaling were implemented, along with a function called slave trip to be covered in another section.
Figure 1: Source Input / Transmit Logic
Figure 2: Source Output / Receive Logic
Figure 3: Tap Input / Transmit Logic
Figure 4: Tap Output / Receive Logic
Input 1 on all units is the send permission input. The permission signal is sent to all active communications interfaces. Most times this permission is only sent from main source terminals where the POTT fault detectors are located, though future use at WITS for line switches will be discussed in a later section. Output 1 is dedicated to the permissive scheme. For source logic, this output asserts any time permission is received from any communications interface. This signal would normally come from the first interface, connected to the other main terminal on a line with two main source terminals (nearly all cases in practice). If a line has three main terminals, all three use the tap logic type, and no WITS are permitted. The tap logic only asserts Output 1 if permission is received from both main source terminals on the first two communications interfaces. This output can be used to directly trip the breaker(s) at the WITS to isolate the fault while also initiating the reclosing scheme. As mentioned previously sometimes local fault detectors also supervise this function. The output has a 9-cycle dropout timer implemented in the communications unit logic to help prevent interruption of trip current by any contact other than the breaker auxiliary. For the line with three main source terminals, the permission received signal is only sent to the local relay if permission is received from both remote main source terminals. Because this POTT logic is kept in the communications unit, standard relay panel design wiring and relay logic can be used without modification for even this three main source terminal case.

Input 2 on all units is the breaker failure direct transfer trip input. Assertion of this input transmits direct transfer trip to all connected communications interfaces. WITS communications units only need to communicate with the two main source terminals. When the signal arrives at the source terminal communications unit, this signal is repeated to all communications interfaces to taps, ensuring the signal will make it to all WITS. Output 2 is the breaker failure direct transfer trip received output, asserted any time the direct transfer trip signal is received on any communications interface. This output is used to trip the terminal and cancel any reclosing scheme.

LEDs are configured to indicate status of each communication link’s health, permissive and direct transfer trip signaling. Technicians and engineers can tell at a glance if a link is up and if permission or direct transfer trip are being received.

D. Implementation
In the lab, a small number of SONET nodes and communications units were configured and installed to simulate the substation A to substation D topology. Performance testing focused on source/tap logic validation and delay and also included some basic SONET failover validation.

Extensive testing on the SONET system was completed with factory acceptance testing and post-deployment system acceptance testing comparison with factory results.

After the SONET ring was deployed, the first installations of this new scheme were installed successfully. Some additions to the logic were made over time for duplication of outputs enabling external DFR digital point recording. Another logic addition was made when direct tripping point-to-point was needed, as described in a later section.

IV. LESSONS LEARNED
A. Terminal Outage
During routine switching the wrong terminal outage switch was turned. Because the remote terminal was actually already switched out on other maintenance, when the local switch was turned, WITS on the line received permission from both main source terminals and tripped connection to that line. While this did not outage any customers because the low side bus remained tied, it emphasized the benefit of local fault detector supervision. Contrastingly, this also illuminated the feature of automatic backfeed removal. If one main source line terminal is out for maintenance and the other main source terminal is tripped for whatever reason, say a bus fault, previously the WITS on the line would feed any other tapped distribution station loads through their low side but ties. At times this can actually be a good thing in maintaining service to
customers, but when voltage supplied to customers drops excessively in traveling through two extra transformers, and perhaps even starts to overload the first feeding transformer, the WITS tripping without fault detector supervision can be considered a beneficial automatic backfeed removal scheme.

B. DTT Transmit Initiate Relay
During work at a customer-owned WITS, vibration caused the activation of an ice cube relay in the breaker failure scheme. This caused input 2 of the WITS terminal to assert, tripping all electrically adjacent terminals. While this was a great proof that the logic design was correct and SERs could be retrieved and easily analyzed, it was a reminder that ice cube relays are not ideal for use in such potent schemes.

C. Rodents
A 138 kV line upgraded to the new scheme tripped off at all terminals. Investigation found a direct transfer trip signal was sporadically originating from a specific WITS. Upon arrival at the WITS the technician found input 2 to the unit was not being asserted. Instead a rodent nest was found directly on top of the communications units, with contamination causing corrosion on internal boards. See Figure 5 and Figure 6 for photographs of the damage to the circuit boards.

![Figure 5: Damage caused by rodents](image_url)

![Figure 6: More damage caused by rodents](image_url)
V. UPDATES & FUTURE DESIGN OPTIONS

A. Point-to-point Slave Tripping

A need was identified to be able to send a "slave" tripping signal from a WITS to one main source terminal to cause a trip with reclose initiation. The availability of extra inputs and outputs on the communications unit allowed this logic to be easily implemented in a generic fashion for future use. Inputs 3-7 when activated send a slave trip signal directly to communications interfaces 1-4, respectively, to be used in any needed function. When received, the auxiliary signal asserts output 3-7 as per which interface 1-4, respectively, received this signal. This logic is included in the overall logic diagrams in Figure 1, Figure 2, Figure 3, and Figure 4.

B. Midline Sectionalizing Switches

Midline sectionalizing switches are switches located in the line that allow line sections to be isolated when permanently faulted or for maintenance, allowing taps to continue to be fed from main terminal source(s). When a midline switch is open on a line protected with POTT, the main line terminal POTT fault detectors will never both simultaneously see a fault, rendering the POTT scheme inoperative. Midline switches have never been installed in this area because of this limitation. One possible solution is to limit the installation of new midline switches to WITS locations. Install good status auxiliary contacts on these switches to provide 89a auxiliary contacts that follow the status of the switch. Use an inverting auxiliary relay to assert Input 1 on the communications unit at the WITS as soon as the switch contacts begin to open. Built into the tap logic is the provision to send a permissive signal to both main source terminals when Input 1 is asserted. This will then allow the main source terminal POTT fault detector to issue a trip as soon as a fault occurs on either isolated line section. One identified drawback is non-POTT protection will be required to isolate the WITS, as retransmission of this midline switch permissive signal to all other WITS would result in receiving permission from both sources, immediately resulting in the POTT tripping signal output simply for the opening of the midline switch.

C. Implementation in 61850 GOOSE

While the focus of this paper has been on SONET and single communications unit implementation, technology continues to change. A future implementation of these scheme would likely fit well with inter-substation virtual private LANs (one per line) and GOOSE messaging broadcasts on those networks. This type of communication would be natively packet-based, lending itself to straightforward transmission over packet-switched networks. In the event of a packet-based network being used, the communications terminal equipment may be upgraded to native Ethernet communications without the need for data packetization methods. In addition, the line relays and overall design can remain untouched.

VI. CONCLUSION

A multipoint-to-multipoint communications scheme for POTT has been presented for lines having up to six terminals with a single substation-hardened communications unit per terminal, standard digital logic, sequence of events recording having GPS-synchronized time stamps, LED status indication, flexible auxiliary signaling, and C37.94 interfaces. The overall communications architecture type selected was SONET. Implementation of this new system has resulted in good performance, continued flexibility, and better redundancy than the system it replaced.

VII. ACKNOWLEDGEMENT

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VIII. REFERENCES


IX. BIOGRAPHIES

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