Analysis of the unexpected operations of line POTT scheme during remote bus fault isolation

Song Ji, Yujie Irene Lu, Michael Gregg, Daniel Markis & Dylan Dean National Grid USA

Introduction:

In modern society, electricity is indispensible to our daily life. A fault in the power system could result in power quality and stability issues, and even blackouts to a large area. Therefore, power system faults should be isolated by the protection in a timely, effective, and selective manner. Any over-trips of non-faulted sections shall also be avoided. When over-trips occur, the event should be investigated to prevent reoccurrence. Correct and rapid fault clearance and power outage minimization are of great concern to utility companies and regional Independent System Transmission Operators.

The permissive overreaching transfer trip (POTT) scheme is a commonly used communication-aided or pilot schemes for transmission line protections. With the assistance of a communication channel, the scheme provides hi-speed and simultaneous trips from all terminals of the protected transmission line for faults anywhere along the line or within the protected zone.

Base on a disturbance investigation, this paper examines the misoperation of a POTT scheme when the remote bus fault was being isolated. Fault records of digital fault recorders were utilized to determine what happened. The fault records captured by fault and Sequence of Events recording equipment provided valuable information which gave an insight into the nature of this disturbance. The analog and digital data of fault records facilitate an efficient investigation and accurate analysis of these events. Finally, mitigation measures to avoid such misoperation are introduced to the readers.

System Overview:

NS substation, a 345kV bulk power station, is located in Albany, New York and it is one of the key stations in the capital region. Due to its important nature, all the primary equipment at the station is provided with separate and redundant protection elements which are independent. Dual high-speed pilot protection schemes are provided for the associated 345kV transmission lines.

At 7:41:53 AM of 4/19/2021, 345kV bus 77k at NS was correctly tripped by bus protection on the bus fault. All 345kV breakers connected to 77k bus were thus opened. Coincident with the bus trip, the line 2 breaker (R2) at the remote substation A was unexpectedly tripped by POTT scheme. The simplified system diagram is shown in Figure 1.

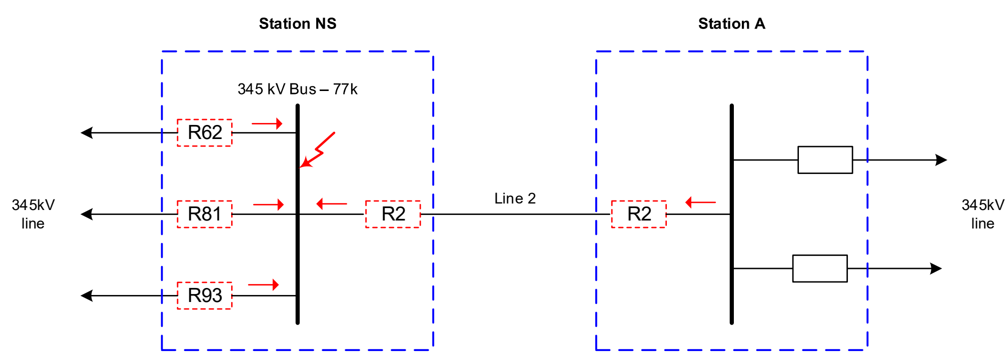

Figure 1: Simplified system one line for 345kV station NS and A

During the event, it was confirmed that the only fault was on 345kV bus 77k at NS and there was no fault on line 2. Line 2 relays at station A saw this forward fault and over-reaching elements would assert. To make a trip by POTT scheme, a trip permissive signal (PT) from NS was required. However, it was verified the line 2 relay at NS detected the bus fault as the reverse direction and no PT from the line relay was sent over to the remote station A. It was also confirmed that no noise or other issue was identified with tele-communication channel and associated equipment. So, why & how was the steady PT signal received at station A during the remote bus fault isolation at NS.

Event & Incident Summary:

By design, 345kV 77k bus differential relay would initiate a digital intermediate relay 94B via its digital input IN101. Once 94B relay receives trip command from bus differential relay, the trip would be duplicated, and its trip contacts would be closed to trip breakers connected to the bus. The functional schematic is shown in Figure 2.

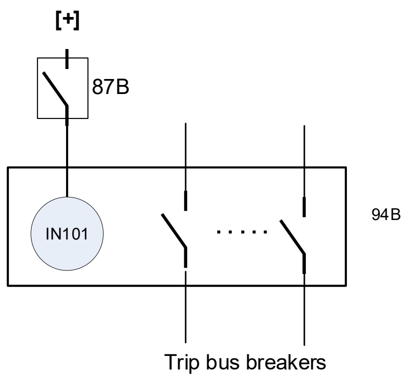

Figure 2: the functional depiction of bus 94B trip relay

From the fault inception, it took 0.42 cycle for differential relay to identify the fault and send the trip command to 94B trip relay, then trip command was repeated in 1.1-cycle in 94B relay.

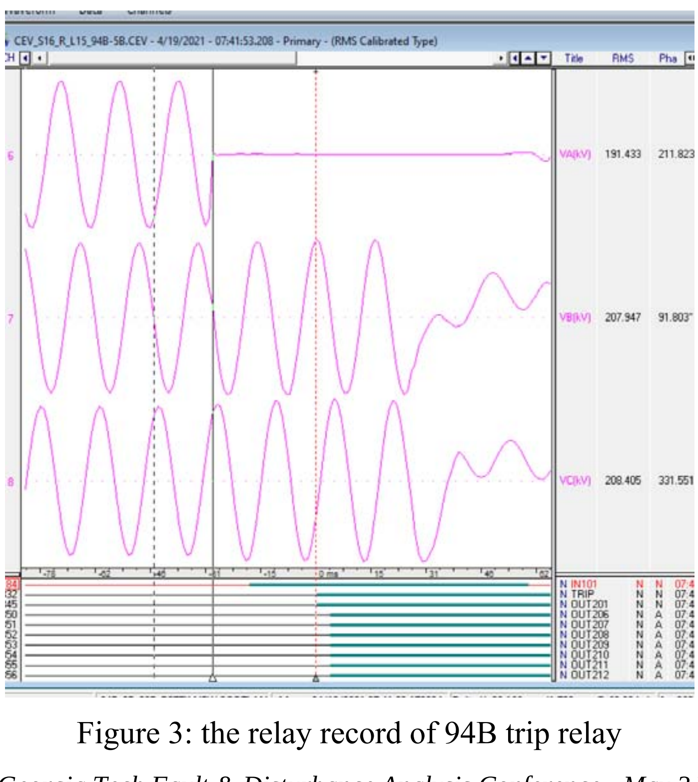

Figure 3: the relay record of 94B trip relay

According to the bus differential relay record in Figure 4, A-phase fault occurred on 77k bus. Breaker R2 and R93 were the last breakers to extinguish the fault current. It took approximately 5-cycle, including bus differential relay operation time, 94B relay time, trip circuit time and breaker interrupting time, for the final fault isolation from the system. It should be noted that intermediate 94B relay introduced approximately 1.1-cycle delay, which was relay internal processing time as shown in Figure 3.

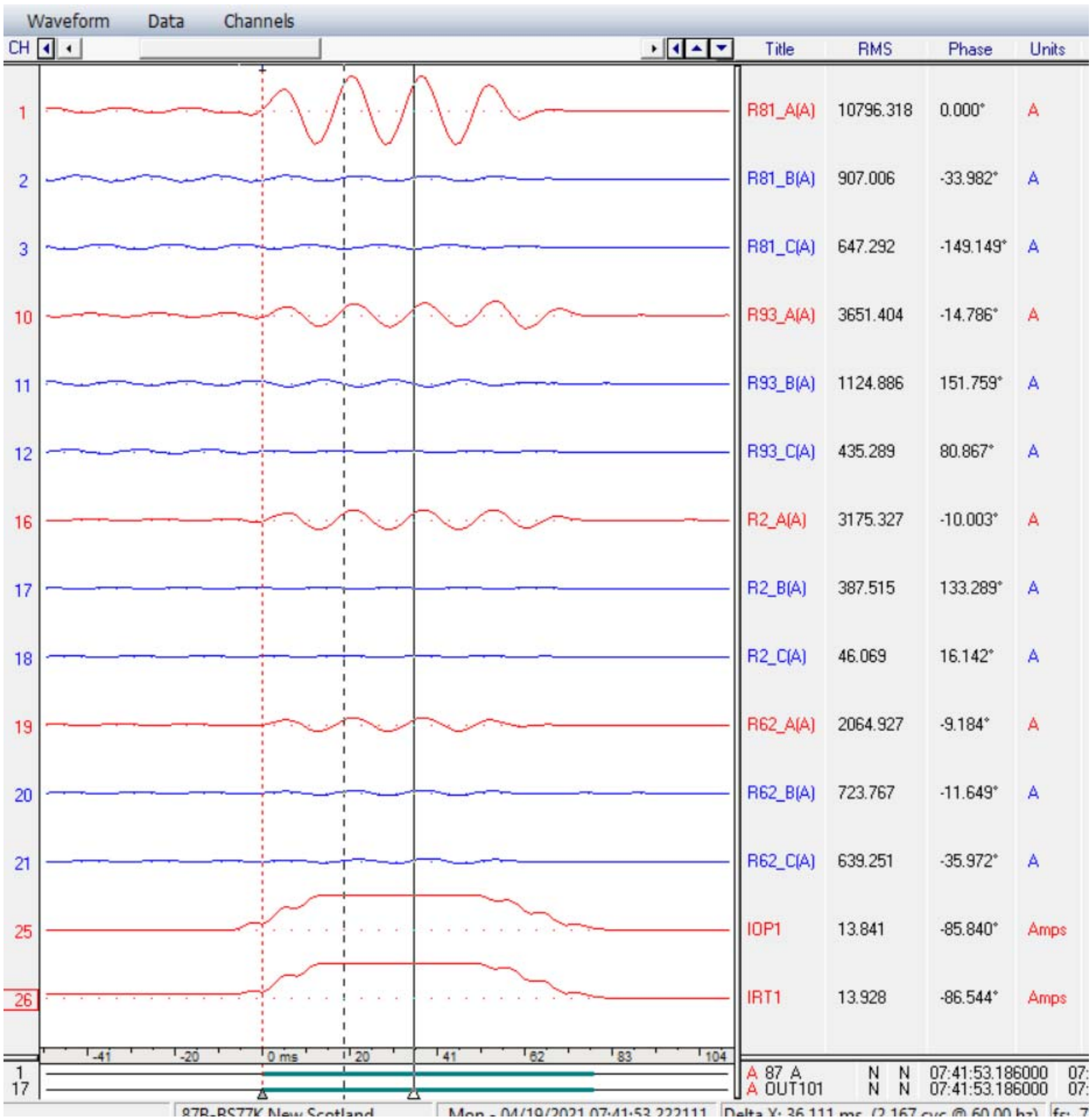

Figure 4: 345kV 77k bus differential relay record from station NS

It also can be seen that 3175A fault current on A-phase was contributed from remote station A through the line 2. 345kV line 2 between station NS and A is provided with high-speed POTT scheme. For 77k bus fault at NS, it would be considered as out of zone fault for line 2 relay at station A and line 2 breaker R2 should not have been tripped by POTT scheme. Let's look at line 2 relay records from station A to see why & how POTT scheme made an unwanted false trip.

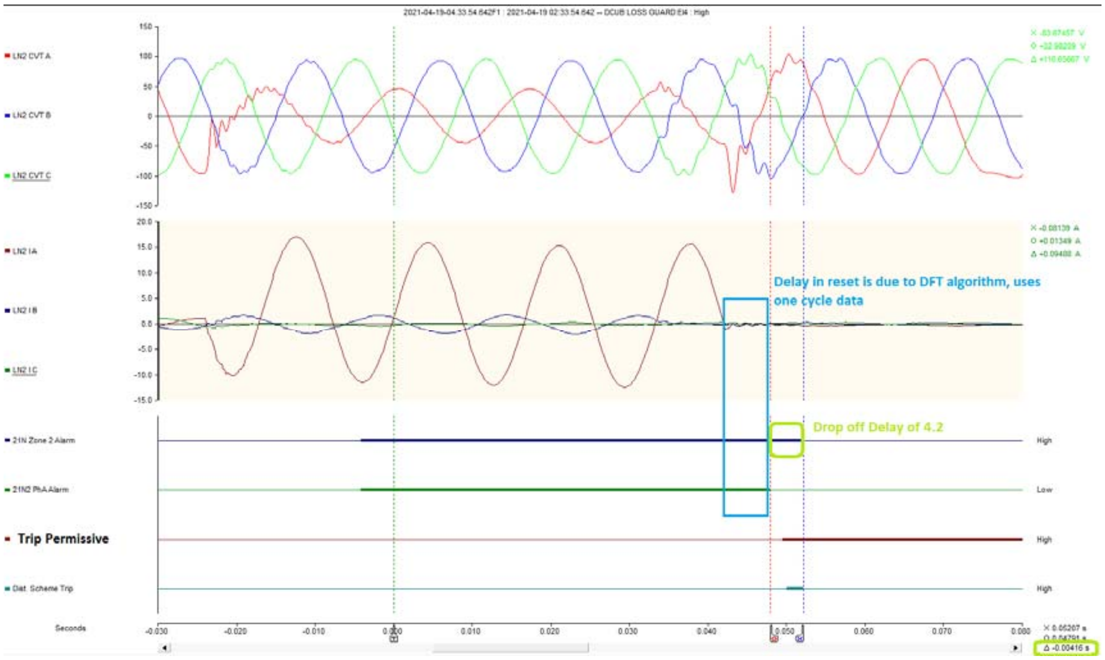

Figure 5: 345kV line 2 relay record from station A showing POTT scheme operation#

In one cycle after 77k bus fault inception, the overreaching zone 2 element of the relay asserted to declare a forward fault. Since the fault was behind of line 2 protection at NS, line 2 relay at NS detected the fault as a reverse direction and trip permissive (PT) was not sent over to station A, which is also confirmed by the status of PT signal in Figure 5. Once line breaker R2 at NS was tripped by 87B and 94B relay, the fault was isolated from station NS in 4-cycle and then the asserted zone 2 element (21N Zone 2 Alarm) started to reset. However, a momentary pilot trip with duration of 2ms was issued when a 3ms time overlap happened between the asserted zone 2 and received trip permissive signal which was initiated by open breaker keying from NS line 2 POTT scheme following the opening of line 2 breaker R2 at NS. After reviewing the DC schematics for the POTT scheme and tele-protection equipment, it was confirmed that normally closed auxiliary contact (52b) of the breaker was directly wired to the input of tele-protection device for remote trip permissive signal (PT) initiation. Now let's review the basics of POTT scheme and function of open breaker keying.

Basic Principles of POTT Schemes:

The permissive overreaching transfer trip (POTT) scheme is one of the commonly used communication-aided or pilot schemes for transmission line protections. With the assistance of a communication channel, the scheme is secure and provides hi-speed and simultaneous trips from all terminals of the protected transmission line for faults anywhere along the line.

In the minimum, a POTT scheme requires the phase & ground forward-overreaching elements at each terminal of the line. This is typically achieved by Zone 2 elements. If each relay detects the fault in the forward direction, then the fault is determined to be internal to the protected line.

In Figure 7, the relay at bus A will key permission if it sees the fault (F1) in a forward direction. Then the relay at bus B will be allowed to trip if it sees the fault (F1) in a forward direction AND it receives trip permissive signal from the remote relay. It is important that the local reverse Zone 3 element be set overreaching the remote forward overreaching zone 2 element. The underreaching Zone 1 elements are typically set to trip for non-end-zone faults and be independent of POTT scheme.

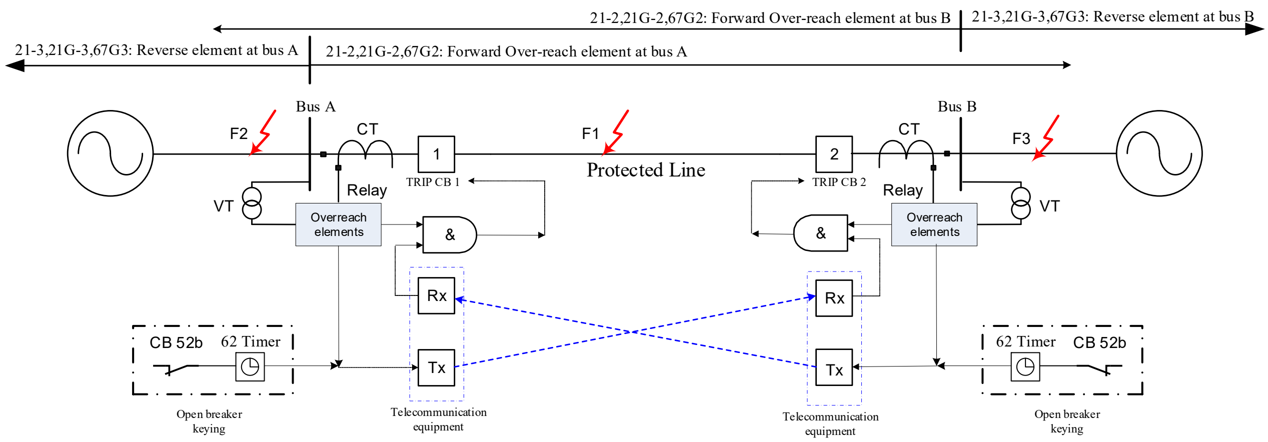

Figure 7: Overreaching zones and direction in a POTT scheme

In order for POTT scheme to work properly under some system conditions, other logic is required in addition to the simple "AND" logic shown in Figure 7. The reverse zone 3 is designed for current reversals during the fault clearing in parallel transmission lines, which could result in the unwanted trip on the healthy line. Current reversal and the corresponding logic in POTT schemes for the double-circuit parallel line applications will not be discussed in the paper; the interested parties can find the details from the paper "Analysis of POTT Scheme Misoperation for a Parallel Line Fault at National Grid" published at 22nd Annual Georgia Tech Fault and Disturbance Analysis Conference in 2019.

Open breaker keying logic:

When the remote terminal of the line is open and the line is still energized from local terminal, the relay at remote terminal will not see the fault; therefore, it can't transmit trip permissive signal to the remote end.

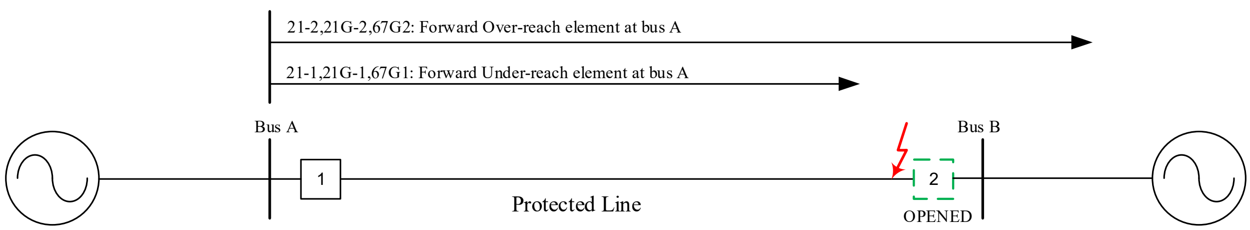

Figure 8: End of line fault with remote terminal open

For the fault on the end of the line close to Bus B in Figure 8, the local under-reach zone 1 element of the relay at Bus A is unable to assert, and the fault will have to be isolated by the time delayed overreaching protective element(s). To speed-up fault clearing, the trip permissive signal can be continuously sent when the breaker 2 at Bus B terminal is open, which is called open breaker keying function.

The simplest way of implementing this is to use a 52b contact of the open breaker to key a constant permissive signal. To avoid the over-trip mentioned in this paper, a short time delay should be provided for 52b after its status change to initiate the open breaker keying. The time delay shall be coordinated with the time interval of the reclosing following a protection trip (especially hi-speed reclosing). However, the open breaker keying method for POTT scheme is not suitable for all application scenarios. Let's look at an in-line breaker case in Figure 9 where lines are protected by POTT scheme and open breaker keying is used at all three stations L, M & R.

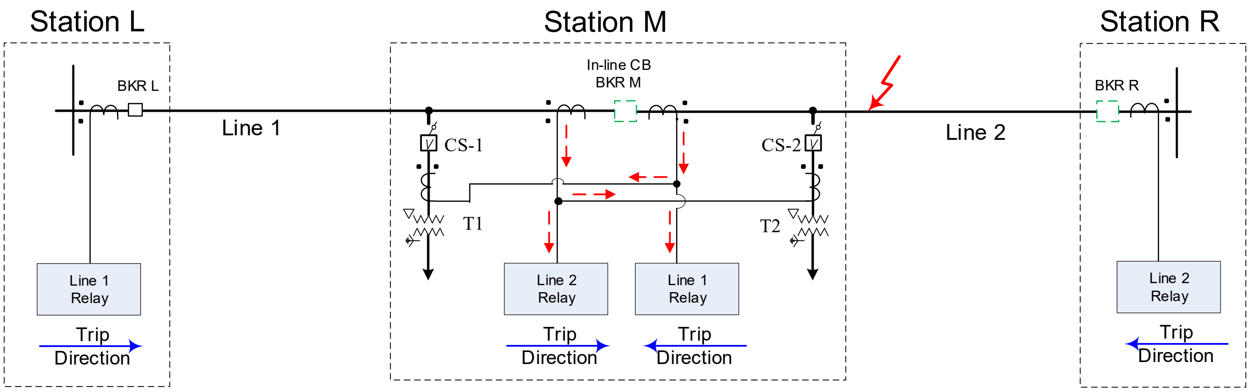

Figure 8: In-line breaker station & open breaker keying for POTT scheme

In this simplified system, line 1 & 2 are provided with a POTT scheme. Transformers T1 & T2 at station M are tapped to line 1 & 2 respectively. The current of the tapped transformer is subtracted from other side of in-line breaker CT so that the corresponding line relay would see "pure" line current flowing to the remote station. Therefore, the line relays at station M are unable to see the transformer related fault. When in-line breaker BKR M is open, the transformer T1 & T2 can still be picked up if the line(s) is energized from the remote. In the meantime, trip permissive signals (PT) are continuously transmitted to station L & M.

Assume there is a permanent fault on line 2 close to station M and over-reach element zone 2 of line 1 relay at station L also see this fault. After the fault inception, line breakers M & R at station M & R are tripped by POTT scheme to isolate the fault. At station M, transformer T2 lost the power as line 2 is "dead". Transformer T1 at station M is still energized from station L via line 1; line breaker BKR L remain closed as the fault is out of its protection zone and line 1 relay/POTT scheme would not operate. The open breaker keying for trip permissive signal is sent to station L after in-line breaker M is open with short time delay. The set of time delay for opening breaker keying is typically short than the time interval of reclosing trial shot.

After a time interval, in-line breaker M starts its first unsuccessful reclosing trial and is reclosed onto the permanent fault on line 2. In the meantime, over-reach element zone 2 of line 1 relay at station L also asserts once breaker M is reclosed. The presence of zone 2 assertion and received open breaker keying PT signal would result in the unwanted trip of line breaker L by POTT scheme at station L, which results in the blackout at station M as transformer T1 lost the power from line 1. Even though breaker L at station L can be reclosed back, the quality of service at station M is compromised due to the short time of unnecessary interruption. Now we can see the open breaker keying is the culprit for the over-trip of line 1 from station L.

For some analog communication channels, to avoid the random noise, a certain amount of duration time for the guard is required to qualify the valid received PT signal. If the communication signal is interrupted or weakened momentarily before the PT arrived, the POTT scheme is unable to work. In addition, the communication channel could be locked-up after the normal communication is restored. This is because the guard signal would never be back as the channel is overwhelmed by the continuous remote open breaker PT signal. It should be noted that guard signal is not required for digital unit with fiber optical channel. For analog unit with audio tone, it is guard before first POTT trip.

There could be other scenarios where constant PT keying signal is not desirable from both line terminals after the breakers are open. Therefore, the echo logic in POTT scheme is developed to overcome the deficiency of open breaker keying PT function.

Echo Logic of POTT Scheme:

The echo logic is like the open breaker keying logic in the way that the received trip permissive signal (PT) at the open breaker terminal is echoed back to the initiating terminal which detects the line fault. To qualify the echo back, the following conditions must be met at the local relay:

- The reverse Zone 3 elements don't assert for the reverse fault, this is to ensure the fault is within the protected zone and the forward elements would assert with adequate quantities.
- The forward looking Zone 2 elements don't pick-up for the forward fault, this is to ensure either the terminal is open or a true weak source is sitting behind.
- The received PT signal lasts for certain duration to avoid the communication channel noise.

The typical echo logic in digital relay is shown in Figure 9.

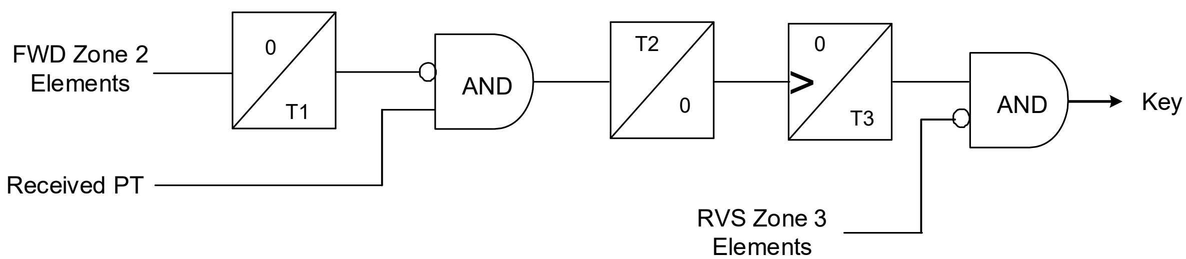

Figure 9. Typical echo logic

The purpose of timer T1 is to prevent echoing of received PT signal for the delay after dropout of local Zone 2 elements, in other words, the echo transmit function is temporarily blocked for T1 time after the forward Zone 2 fault is detected. The dropout time delay of T1 is typically be set greater than the total summation of the following time delays:

- The pickup time of local Zone 2 elements (it depends on the relay operational time, 1-1.5 cycles)
- The local breaker interruption time (two or three cycles)
- Channel reset time (1 to 1.5 cycles)

The typical T1 setting is 10-cycle.

The echo time-delay pickup timer (T2) setting determines the minimum time requirement for received PT signal before echo starts. A typical setting is two cycles.

Once the echoed PT signal is "bounced" back to the remote initiating terminal, the duration must be limited to prevent the channel lockup due to too long duration or constant "ON" status. It is desirable to keep the echoed PT signal for the remote breaker to finally isolate the fault. Therefore, T3 is typically set greater than the communication propagating time, telecommunication device operation time and the remote breaker interrupting time (2 to 3 cycles). The typical set for T3 is 4-cycle.

Summary:

1) Open breaker keying logic is simple & straightforward, a short time delay to initiate the trip permissive signal to the remote is required after the line terminal breaker is open.

2) Open breaker keying logic has its constraints for some application scenarios. Echo logic can be utilized if open breaker keying is not suitable.

3) It's not recommended applying open breaker keying and echo logic at the same time.

4) All relays including digital type have hysteresis. The relay would not reset instantly after the input signals are removed.

References:

1. Analysis of POTT Scheme Misoperation for a Parallel Line Fault at National Grid, *YIL*

2. Applying the SEL-421 Relay to Permissive Overreaching Transfer Trip Schemes, SEL Application Guide AG2010-01

Authors:

Song Ji is a principal engineer in the Department of Protection Policy and Support of National Grid. Song has more than 25 years' experience in the power system studies, substation & power plant design, protection and control for utility and industrial systems ranging from 4.16 kV to 500 kV.

Yujie Irene Lu received a BSEE degree in Power Systems Engineering from Huazhong University of Science & Technology in China, and a MSEE in Electrical Engineering from Virginia Polytechnic Institute in Blacksburg, VA. She is a senior member of IEEE and a registered professional engineer in the Commonwealth of Massachusetts. She received the 2010 Annual Outstanding Engineer Award from the Boston Chapter of the IEEE Power and Energy Society in November 2010. Irene has been employed in Protection Engineering at National Grid since 1990. She is a consulting engineer in the Department of Protection Policy and Support, where she analyzes system disturbances, performs system analysis for short circuit conditions, develops protection and control system standards, designs protection systems and determines protection settings and logics. She has over 20 year's experiences as a lead protection engineer on projects.

Michael Gregg is a field protection relay supervisor for National Grid in Albany, New York. Mr. Gregg has been employed at National Grid for 34 years and has held a variety of engineering and operating positions. He works closely with protection engineers to decide, test, commission, and troubleshoot substation and transmission protection schemes. He received his BS engineering science degree from Clarkson University in 1986.

Dan Markis is an Engineering Manager at National Grid. He received his M.S. degree 2007 and B.S degree in 2005 in electrical engineering from Clarkson University. Dan analyzes system disturbances, performs system analysis for short circuit conditions, develops protection and control system standards, designs protection systems on a conceptual basis, specifies equipment and determines protection schemes, settings and logics. He is a member of IEEE and a registered professional engineer in the state of New York.

Dylan Dean is a senior engineer in the Department of Protection Policy and Support of National Grid. Dylan been employed at National Grid for 5 years. He received his MS engineering science degree from Clarkson University in 2016 and B.S. degree in 2014. Dylan analyzes system disturbances, performs system analysis for short circuit conditions, and develops standards for protection and control systems.