Southwest Power Pool

ISSUES ASSOCIATED WITH MULTI-TERMINAL TRANSMISSION LINES WHITEPAPER

By System Protection and Control Advisory Group (SPCAG)

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CONTENTS

BACKGROUND & EXECUTIVE SUMMARY

BACKGROUND

During the July 2018 System Protection and Control Working Group (SPCWG) meeting, member Rick Gurley of American Electric Power (AEP), a Southwest Power Pool (SPP) member, brought to the group's attention the fact that the Electric Reliability Council of Texas (ERCOT) is no longer allowing three terminal lines to be designed or constructed in their region. Three terminal lines are created when a sourced tap is directly connected to a transmission line at a location between two main transmission line terminals.

This directive took effect at the end of May 2018. From their perspective, three terminal lines were often built when an Independent Power Producer (IPP) requested a connection and needed it quickly, meaning there was no time to build an interconnection substation.

Rick asked what SPP's stance was on this issue. Doug Bowman from SPP stated that as far as he knew there was no policy as it has not been discussed if SPCWG wanted to pursue a discussion and recommendation, it would need to move through the Transmission Working Group (TWG), Operating Reliability Working Group (ORWG), and Market and Operations Policy Committee (MOPC) for approval.

This paper is designed to provide the following:

1. A general discussion of applicable protection system designs for three terminal lines.
2. A general perspective of some of the justifications for three terminal lines.
3. Provide some protection challenges related to this type of design.
4. Some possible insight and perspective on ERCOT's decision to not allow three terminal lines be built in their region.
5. A recommendation to SPP regarding the status of three terminal lines.

Much of this material was taken from a more rigorous and detailed description of the complexity of protection of three terminal lines from a paper issued September 13, 2006 and sponsored by NERC titled, "The Complexity of Protecting Three-Terminal Transmission Lines". It was prepared by the System Protection and Control Task Force of the NERC Planning Committee of that time. Other publications were also used and provided in the reference section of this paper.

An effort has been made to define the terminology specific to the engineering of protection schemes, some of the terminology still may elude the readers of this paper. A good source to provide missing gaps is the NERC, "Glossary of Terms Used in NERC Reliability Standards" and it can be found on their website.

The goal of this paper is to provide technical information to bring greater insight into the issues with multi-terminal transmission lines without overwhelming the audience with the already unfamiliar technical complexities of the engineering of protection schemes.

EXECUTIVE SUMMARY

If you ask a system protection engineer about the possibility of building a sourced tap onto an existing networked point to point high voltage transmission line, they would advise that you not do it. If you press them as to why not, they would tell you that it is possible to design and build physically but that there are protection issues and increased engineering, maintenance, and material costs to consider before a management decision can be made.

At the heart of the problem of three-terminal sourced lines is the fact that the additional source does not coordinate well with existing methods of transmission line protection schemes that are typically expecting to contend only with two sources of energy flow. Once a third source is introduced into an existing two source protection design, added measures, such as a communication medium between all three sources, often needs to be added into the protection mix. For example, if no communication medium exists, then an additional cost can add up to millions of dollars to install fiber optic (FO) cable between the terminals. This cost is affected by type of FO cable installed and the line lengths between each source. Not only do effective protection designs typically need to be added to the cost of installing a communication medium, but they often need to include the cost of new protection units that can use this communication medium. Then there are the added ongoing costs of testing and maintaining these complicated schemes. Finally, there is the added complexity of the scheme causing a higher risk of misoperations during testing and normal operations.

However, with three terminal lines there are always compromises required in the protection of the lines and equipment the protection schemes are designed to protect. This paper tries to better define these complexities to an audience that may not fully understand the overall problem of designing protection schemes for multi-terminal transmission lines.

INTRODUCTION TO TRANSMISSION LINE RELAY PROTECTION DESIGN

THE PROTECTION ENGINEER’S CHALLENGE

Protection Engineers job is to design protection schemes that:

- Only trip when they are supposed to (reliability).
- Do not trip when they are not supposed to (security).
- Minimize outages so that the least amount of equipment and number of customers are affected. This also ensures that adjacent protective relays are coordinated so that relays outside the zone of protection provide only backup services when the local protection scheme fails to do its job.
- Insure minimal damage to equipment.
- Maximize the safety of company personnel and the public at large.

Reliability and security typically conflict with each other in meeting the above objectives.

THE CHALLENGES OF PROTECTION OF TRANSMISSION LINES

The Southwest Power Pool has within its territory thousands of miles of transmission lines of various voltage levels, lengths and design topologies. While there are other types of hybrid line designs, the most common line configurations usually include radial, two terminal and multi-terminal designs. Of these configurations, the two terminal is more typical, followed by the radial design. The least common is the multi-terminal design and for the purpose of this paper only the three terminal line configuration will be considered.

From a protection standpoint, a radial line is by far the simplest to protect since it has only one energy source to consider and the direction of the power flow is consistently known to be in only one direction during system disturbances (See Figure 1). Typically, these lines can be protected by simpler overcurrent relays using a set of current transformers associated with a breaker or a power transformer.

Figure 1 - Simple One Source Radial Circuit

The next level in complexity would be a two terminal transmission line with two energy sources to contend with. The main challenge here is that energy can flow in either direction based on changes to the surrounding system (See Figure 2). In this overall protection design, speed, security and reliability each play a very important part. Another factor that also must be considered is the ability to detect the direction of power flow (i.e. knowing quickly if the system disturbance is in front of or behind the protective relay) through the use of potential transformers and current transformers that can accurately portray the primary voltages and current measurements that the relay uses to determine the power flow direction. This gives relays the ability to trip for faults on the protected line and not trip for external faults. As part of the overall design of a specific composite protection system for this type of transmission line design, planners are involved in understanding any system stability concerns that require high speed tripping times to prevent unwanted generator equipment damage or widespread outages to affected customers.

High seep clearing concerns are more elevated at voltage levels above 200kV. Design of a 69kV transmission line composite protection system can usually be considered much simpler than that required for a 345kV line for the simple reason that the amount of energy flowing in the 345kV line is magnitudes higher and the equipment cost is greater at 345kV. Therefore, instantaneous tripping that provides high speed isolation of system disturbances with no intentional time delay becomes much more critical to system stability at the higher voltages.

Often, but not always, this need for high speed isolation is complemented with the installation of Communication Assisted Protection Scheme(s) (CAPS) that can use the transmission line itself to carry a signal to the other end, microwave communication, or use a more modern fiber optic communication path to the other end. Signals sent at one end inform the protection scheme at the other end as to whether it is permissible to trip or not, and thus become part of a more complex design. These signals either inform the other end not to trip (i.e. blocking) or give permission to trip (unblocking). Each communication protocol has its advantages and dis-advantages related to security and reliability but all allow for high speed (instantaneous) tripping for faults along the entire length of the line and enhance the overall high speed protection footprint.

Figure 2 - More Complex Two Source Terminal

A three terminal line design adds more complexity to a protection design through the introduction of an additional source that must be dealt with (See figure 3 below). The CAP for two terminal lines typically will not work as well for three terminal lines. In any protection design, the end goal is to allow the line to carry the needed load, but to detect specific abnormal conditions within the zone of protection and then remove all sources of energy to the disturbance. That action is done using sophisticated protection scheme that open isolation devices such as breakers, circuit switchers, or motor operated switches which are able to withstand these abnormal conditions.

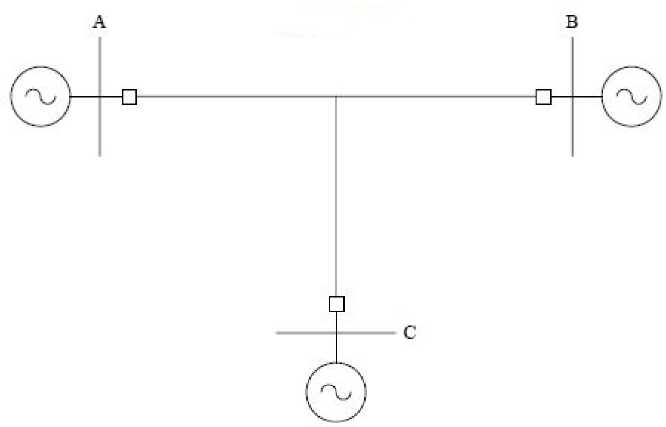

Figure 3 - Three Terminal Line

With three terminal lines, compromises often are made. Generally, a three terminal line presents the following challenges:

- Needed changes to transmission line relay protection elements may limit loadability of the line unless some type of load blinder or load encroachment is used, features that "blind" or block the distance relay from tripping due to load encroachments and are often available in newer digital relay protection packages. Lines with older electromechanical relay technology would need to be replaced with more modern digital relay technology if these features need to be applied.
- Sequential clearing for transmission line faults may fail (discussed below).
- The ability of the composite protection system to detect faults on any one line segment may be compromised by the infusion of energy from another line segment.

- For the relays that protect the three terminal lines, the ability to set these relays to coordinate with other external relays one or two buses away will always be difficult.
- Increased complexity of associated communication systems tied into new composite protection system.
- Increased susceptibility to false tripping for heavy loading conditions and for stable power swings due to the compromised settings mentioned above.
- Three terminal lines need more sensitive protection settings to account for infeed effects mentioned below.

Two terminal lines are superior to three terminal lines from a protection perspective because they:

- Provide faster backup clearing times without risking miscoordination.
- Reduce the risk of overtripping caused by ground miscoordination.
- Eliminate the risk of miscoordination caused by one of the terminals being open.
- Eliminate the need for sequential clearing which may not be acceptable from a stability perspective.

POSSIBLE JUSTIFICATIONS TO THREE TERMINAL LINES

The decision as to whether to build a three terminal transmission line usually requires tradeoffs between economics, protection complexities, and compromises in reliability and security.

Justifications for building a three terminal line center on four factors:

- Economic benefits in the lower cost of construction through the avoidance of additional substation equipment and transmission line miles.
- Potential reduced lead time in addressing system needs.
- Less impact on changes to right of way and property acquisition due to availability and/or regulatory push back that can also impact factor #1.
- Mitigation of some overloads due to single contingency events, depending of transmission topology.

THREE TERMINAL LINE PROTECTION CHALLENGES

Generally, protection systems are designed to detect abnormal conditions and initiate tripping to isolate the problem, to protect equipment and help assure the overall reliability of the electrical system. A protection system typically consists of protective relays, associated communication systems, voltage and current sensing devices, station batteries and DC control circuitry. A protection system element mis-operates when it either fails to operate as designed, or operates unintentionally.

Presented above are some of the compromises that must be considered in designing a three terminal line protection scheme. This section provides more details to better define the implications of each of those compromises. To better understand some of the protection challenges, we need to provide some additional background on how lines are generally protected.

DISTANCE RELAYS

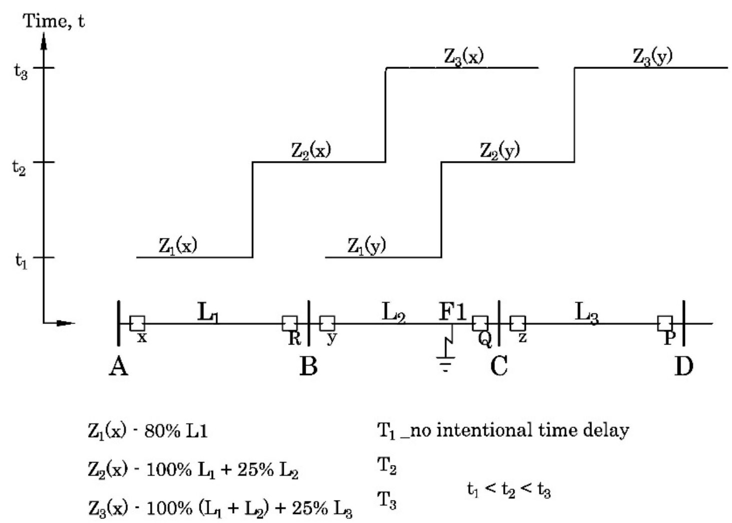

Figure 4 - Step Distance Relay Protection Scheme (Tripping Zones)

During a fault on a transmission line, distance relays are used to measure the impedance of the fault using current and voltage inputs at the relay location. Since there is a one to one correspondence between impedance and the measured distance to the fault, often these protective elements are called "distance" relays. These devices can discriminate whether the fault is in front of the relay or behind it and typically act to isolate faults they detect in front of them. Prudent protection philosophy provides for up to three distance relay "Zones" of protection set to detect faults at preset distances and operation times. Referring to figure 4 at Bus A, Zone 1 for breaker x is usually set to recognize faults on the line segment starting at the breaker and going 80-90% of line L1 toward the next bus (Bus B in the above diagram) and the relay will trip instantaneously or without any intentional delay within this zone. Zone 2 for breaker x is usually set to 120-125% of L1 with a delay of around 15-30 cycles. Note that Zone 2 will pick up at the same time as Zone 1 if the fault is within Z1 distance reach, but Zone 2 is set to wait longer to trip breaker x and therefore both are considered time coordinated. If the fault is beyond Z1 reach, then Z2 will eventually time out as long as the fault is within its "reach" zone of protection. Zone 3 at breaker x is set to be a backup to Zone 2 and is often set about 150% or greater of the line L1 impedance but trip delay times can vary by company (typically around 60-90 cycles). Also note the overlap between Z3(x) and Z2(y) and the time coordination between each of these zones. Both may detect the same fault and pick up at the same time but time delays are staggered so that the local zone will trip first and if for any reason the fault condition is not removed by the time Z3(x) time delay expires, then Z3(x) will operate and trip its own local breaker.

As an overall example of primary and backup relay coordination, given a transmission line fault at F1 in the above diagram, both set of relays at terminals A and B can potentially detect the fault and recognize the fault condition but terminal B relays at breaker y would normally trip and isolate the fault first in that relay's Zone 1, 2 or 3 protective elements. If the fault was in Z2(y) areas, then Zone 2 would pick up and send a 'trip' signal to the breaker at y to clear the fault. If for some reason the breaker at y were unable to open prior to the 15-30 cycle delay period, then possibly Z2(x) or more probably Z3(x) would detect the same fault and after a set time delay the breaker at x would be sent a 'trip' signal from the x relay to operate and clear the fault. This overlapping of protective zones in distance and time is intentional and its purpose is to provide overlapping back-up protection in the case of a slow, stuck, on inoperative primary breaker or issue with the protection schemes(s). In this case, the primary breaker would be y and the backup breaker would be x.

Note that this standard design is for a two terminal transmission line. If a third source is inserted into this design then there are several added issues that must be contended with.

INFEED

Referring to the Figure 5 below, if a distance relay is at Terminal A and energy is leaving terminal C onto the line at the Tee point and flowing towards a fault at F2 at 90% of the line towards terminal B, a phenomenon called infeed skews how the distance relay at A measures the voltage drop to the fault and the fault current at the other end due to the added source at Terminal C. Because impedance measured is defined as the ratio between the voltage drop and the available fault current, the affected relay impedance measurement at A will therefore be skewed higher than the actual impedance due to the added source of the line. This phenomena is called the apparent impedance.

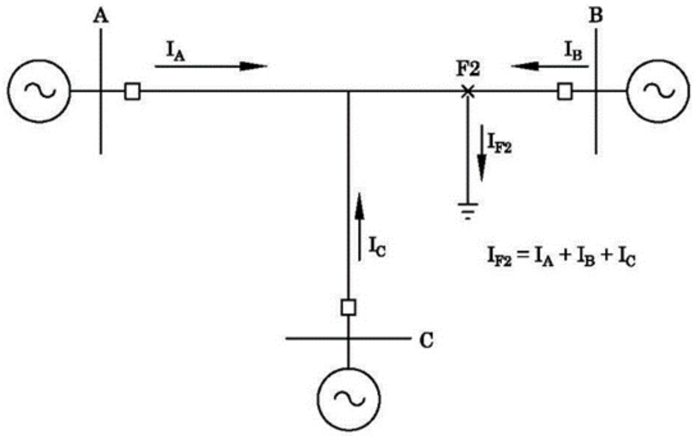

Figure 5 - Fault on a three terminal line causing infeed condition

Therefore, if the relay at Bus A is to be set for 80% of the natural line impedance to Bus B (typical), this relay will now have a tendency to inaccurately measure and detect where the fault actually is and will not trip within its set zone of protection. This is because the relay is detecting and measuring the higher apparent fault impedance, this higher apparent impedance causes this measurement to now be beyond its set zone of protection. In this case the distance relay must be set higher than the natural line impedance to reach the intended 80% reach point to maintain the needed instantaneous zone of protection.

This infeed effect can limit the ability to provide a remote backup function on adjacent circuits. The actual adjustment to Terminal A relay must also account for where the Tee is located on the circuit and possible contingencies such that its maximum source impedance is understood. The longest Tee length from A will determine the worst case fault location and the highest infeed factor. High infeed conditions can sometimes cause Zone 2 relay elements to be set so high that the affected relay can miscoordinate with Zone 2 or Zone 3 settings of the remote and adjacent line relays.

OUTFEED

The opposite can also be true if energy is being received into terminal C (e.g. an autotransformer connecting two HV transmission systems). Using the same relay configuration and fault location as the above example with infeed, outfeed causes the distance relay A to measure a smaller impedance and can cause the distance relay to trip for faults beyond its intended 80% of the line impedance. Through the use of fault models, this outfeed condition can be estimated and a calculation can be made to actually shorten the distance relay reach to compensate for this lower apparent impedance seen by the relay at terminal A.

LINE LOADABILITY

Usually where a three terminal line exists, infeed is the dominant issue and therefore distance relay settings have to be set higher than those needed for a two terminal line. Depending on how much infeed is created, distance relay settings can be in the order of several magnitudes of actual line impedances. For distance relays, the higher the set impedance, the longer the reach and potentially the greater the risk in picking up for high load conditions, thus effectively limiting how much load can be transmitted through the line. As mentioned before, this issue can be addressed by some type of load blinder or load encroachment as measured as an impedance to the distance relay. These features can be used to "blind" or block the distance relay from tripping as the measured impedance encroaches into its zone of protection. This type of added security is often available in newer digital relay protection packages. However, transmission lines with older electromechanical relay technology would need to be replaced with more modern digital relay technology if these features are needing to be applied.

For a more detailed discussion on correlation between line loadability and distance relay settings, refer to the NERC guide titled, "The Complexity of Protecting Three-Terminal Transmission Lines" under "Decrease in Line Loadability". It also provides a couple of other methods that can be used to mitigate this issue.

GROUND OVERCURRENT PROTECTION

Since distance relays are sensitive to the loading of the transmission line, another relay that is much less sensitive to load can be used to detect ground faults. The directional ground overcurrent relay (i.e. it can discriminate between faults in front of it or behind it) typically provides two protection elements. One element provides an inverse characteristic that can be pickup and time coordinated against other type units internal and external to the protected transmission line. A second element is provided that provides an instantaneous protection to about 80% of the line it protects. The ground overcurrent relay therefore becomes an integral part of the complete line protection package. Even though phase distance relays can pick up for ground faults, there is often no coordination issue between distance relays and ground time overcurrent relays due to the fact that pickups for these ground overcurrent relays can be set at 10-15% of maximum loading of a line. Studies are conducted to determine what the maximum ground fault current is for system changes so as not to trip outside its zone of protection. Distance relays Zone 1 instantaneous settings from each terminal must not operate for a fault external to its zone of protection. Overcurrent Instantaneous units work opposite of distance relays in that the further out on a transmission line you are, the higher the apparent impedance of the line and the lower the ground fault measured by the unit. So for an overcurrent instantaneous unit on a two terminal line, the further away from the relay the ground fault location is, the lower the measured fault current. Therefore, it will only operate if the measured current exceeds a threshold value and eventually drops out the closer the ground fault is to the opposite end. Typically, ground faults on transmission lines represent about two thirds of all faults experienced on a company's system during a given year. For two terminal lines, ground instantaneous relays are normally set at or about 80% of the maximum ground fault experienced at its given line terminal for changes on the system around it. However, for three terminal lines, this instantaneous protection must always be set just short of each terminal tee connection which limits the degree of instantaneous ground protection provided compared to two terminal lines. With the additional source, the relay engineer has another ground instantaneous relay to coordinate against. Since instantaneous means without any intentional delay, the engineer cannot coordinate instantaneous trips through use of a time delay. Instead, the setting is now limited so that ground fault detection and coverage is now shared by all three terminals up to the Tee point with no overlap. Therefore, the Tee point determines the reach of the ground overcurrent instantaneous unit for all three terminals. This issue created by the additional third terminal results in the need to now rely on ground time overcurrent (TOC) relays at each terminal for faults beyond the Tee location and therefore creates longer trip times that what instantaneous protection can provide. That is, for a ground fault on one end of a three terminal line, while one terminal can now trip by a ground instantaneous, the other two terminals can only rely on the slower ground TOC to detect and isolate the fault. Again, the issue is that normally with two terminal lines, ground TOC settings usually only need to cover the remaining 20% of a two terminal line that the ground IOC does not cover, allowing for greater instantaneous ground fault protection.

The main issue is three terminal lines cause IOC zones to be shortened and makes the TOC zones cover more of the line creating longer trip times than for two terminal lines. Some cases the TOC’s cannot be coordinated for all internal and external line ground faults.

SEQUENTIAL TRIPPING

What happens if ground distance or ground overcurrent relays cannot detect faults at the other end or ground relays cannot be coordinated properly due to the third source being added? The protection engineer must do his best to set the relays as sensitively and as fast as possible at two of the ends and must rely on sequential tripping to do the rest. IEEE Standard 100-2000 (The Authoritative Dictionary of Standard Terms) defines sequential tripping as “A situation where one or more relay terminals of a line cannot detect an internal line fault, typically because of infeed, until one or more terminals has already opened and removed the infeed”. This condition is considered a viable alternative. However, it is a much slower process and must be studied to determine if there are other concerns with the fault clearing speed such as system stability. Also note that remote backup protection is non-existent with sequential tripping so the protection system must rely only on local tripping protection schemes within the three terminal line itself. Often, CAPS are used with or instead of the sequential tripping technique to add additional instantaneous coverage as needed. These added communication schemes however, can increase the cost of protection substantially. Sequential trip may work for ground faults but will not work for phase to phase faults.

OTHER ISSUES WITH THREE TERMINAL LINES

Three terminal lines may create other issues based on how a given protection scheme is designed to work. For example, due to the directional relay's extended Zone 2 setting to compensate for infeed conditions, it is possible that a stable power swing may encroach onto a typical distance relay phase characteristic used to detect a fault condition, possibly resulting in a false trip. This same issue can cause more frequent false tripping, even when CAPS are used.

COMMUNICATION ASSISTED PROTECTION SCHEMES (CAPS)

For some companies, step distance protection with ground relay protection is the normal design and a CAPS is added to compliment as needed. For many protection engineers, the main purposes of adding CAPS is to solve a problem with coordination with remote backup relays, extend instantaneous backup protection for breaker failure protection at the local bus or to more effectively and reliably extend instantaneous protection on a transmission line. However, keep in mind that all CAPS are still susceptible to increased risk of misoperating from system power swings on three terminal lines since all Zone 1 or Zone 2 settings must still be increased to accommodate the effects of infeed.

While there are other ways for relays to communicate with each other (e.g. microwave), today there are typically two ways to accomplish CAPS: 1) by using the existing protected transmission line as the carrier of a transmitted signal to the other end or, 2) by use of a fiber optic (FO) cable.

In the case of a carrier signal, additional substation equipment is required. Transceivers and tuners are necessary to send and receive the high frequency signals. Voltage transformers are used to couple the high frequency signal onto the transmission line and low pass frequency filters called wave traps are needed at each terminal to allow the 60Hz power to pass through to the substation bus and equipment while stopping the high frequency signal from passing into the bus and into other transmission lines. These signals are used to communicate to the other end whether it is permissible to trip (unblocking) or whether tripping is not permitted (blocking).

A line differential CAPS works entirely differently in that it passes to two or more relays, usually using a point-to-point FO cable, the real time phasor measurements from the other ends and sums them at each end to securely and reliably determine whether the fault is internal or external to the relay terminals. While effective, secure, and reliable, line differential protection can be expensive to design, install, and maintain, due to the needed fiber optic equipment.

Each of these CAPS is discussed below and how a three terminal line affects them. Each of these CAPS has its advantages and disadvantages in a composite protection system.

DIRECT UNDER-REACHING TRANSFER TRIPPING (DUTT) (UNBLOCKING)

DUTT has a lower risk of tripping due to stable power swings simply because it uses Zone 1 to detect faults and these Zone 1 reaches are not increased to account for infeed effects. For this scheme, a fault within the protected line will be detected by at least one Zone 1 relay terminal. A transfer tripping signal will then be issued to the other end(s) to trip the remote ends. However, this design requires a dependable communication channel so dual and redundant channels are often used in case one fails. Keep in mind that for two terminal lines, DUTT Zone 1's can overlap each other but for three terminal lines with high infeed, Zone 1's are usually limited to reach to the Tee point of the three terminal line with no apparent overlap.

With a leg of a three terminal line that is closer to one end than the other, some overlap can exist but it can cause an issue with the longer branch creating a section of unprotected line. Therefore, for this case, Zone 2 can also be set and used to augment CAPS with a POTT or a DCB scheme discussed below.

PERMISSIVE OVERREACHING TRANSFER TRIP SCHEMES (POTT) (UNBLOCKING)

POTT CAPS use Zone 2 to detect faults and are therefore more susceptible to stable power swing misoperations as discussed above. However, this design can create some overlap not necessarily available in a DUTT scheme on a three terminal line. It is a very secure scheme requiring all terminals to detect a fault before allowing the other end(s) to trip. This means that each end must be able to detect the fault at the remote ends and issue a permissive trip signal to the other ends.

A modified scheme can be used, such that if a local breaker opens, an echo permissive signal can be sent to the other two ends to give permission to high speed trip, but it still requires the ability for all Zone 2 elements to be set sensitive enough to extend beyond the remote terminals. For situations where Zone 2's cannot see the other ends due to very high infeed, because of loading restrictions or coordination issues with adjacent lines, the DCB scheme below might be the next better choice. It is critical that at least one Zone element be able to see and trip for a fault up to the end of a line terminal. This communication scheme is very dependent on communications channels.

DIRECTIONAL COMPARISON BLOCKING SCHEMES (DCB) (BLOCKING)

A DCB CAPS is a more reliable scheme in that if a blocking signal is not received from the other ends, the local relay will trip anyway so it is the least communication channel dependent. However, it is less secure and more susceptible to misoperations. It requires the use of a forward

Zone 2 and a reverse zone relay. The reverse relay quickly determines if the fault is behind the relay and if it is, a blocking signal is sent to the other ends to keep them from tripping. Tripping is initiated by the Zone 2 over-reaching element or a ground instantaneous element unless either receives a blocking signal from the remote relay. Because this scheme uses a Zone 2 forward looking element, it is susceptible to the same issues at the POTT scheme above with the exception of communication channel dependency.

Depending on the system configuration DCB and POTT schemes can be problematic on three terminal lines. If one of the three terminals is strong and any one of the other two are weak it may not be possible to develop ground overcurrent settings with the required sensitivity to properly restrain tripping for all external faults. For example: If a fault were placed behind the strong terminal of a three terminal line the weak terminal 67N2 (forward tripping) settings are going to be set very sensitively to detect all faults on the line. The strong source 67N3 or (reverse blocking) element will be set per utility practice but this is typically 1.5-2 times more sensitive than the forward looking 67N2 settings for 2 terminal line. It should be set more sensitive on three terminal than it is for two terminal line because one of the terminals could be open. This usually causes 67N3 to be set to 3-4 times the forward looking 67N2. Setting the strong source 67N3 sensitivity may not be possible because of the setting capabilities of the relay itself.

PILOT LINE DIFFERENTIAL

A line differential relay works under Kirchhoff's Current Law which states that all currents entering a node must sum to zero. Therefore a differential relay is actually a summation relay that sums all phasors from each measured phase at each terminal. As long as the summation results in a nearly zero value, the relay takes no action. If there is a resulting summation value above a set threshold value, the relay initiates a trip action.

Modern microprocessor relays and digital communications, typically using FO cable(s), make the protection more versatile. Using only current information, each phasor measurement is sent to the other end of the line for the relay to make a high speed, reliable and secure real time calculation to determine if elevated fault current is internal or external to the differential zone of protection. This type of pilot protection eliminates any infeed error. It is also less immune to load, phase unbalance, power swings, mutual coupling between transmission lines and a phenomenon called voltage inversion. There is usually redundancy between the relay communication channels in that each relay always uses two channels and if one channel is lost, the relay can compensate through the other channel. If a fault is detected at one end or if backup breaker failure is required, a high speed direct transfer trip signal can be sent along each channel to trip the other ends immediately. This scheme is channel dependent and any channel failure disables this protection. However, but because it uses a FO cable, the cable itself must be broken for channel failure to occur. Therefore, depending on stability issues, a redundant scheme and channel path(s) are typically required and designed into this type of protection scheme. Coordination of backup elements may not be possible when using line differential relays.

REMOTE BACKUP PROTECTION OF LOCAL SUBSTATIONS

With three terminal lines, the ability to provide remote backup is often eliminated due to infeed or outfeed conditions. Referring again to figure 4, suppose you have a three terminal tee right in the middle of the line between terminal B & C. The Zone 2 and Zone 3 relays at terminal A can be set to detect faults beyond terminal B so that if a breaker fails to trip for a close-in fault near terminal B, (e.g. a high speed bus differential fails to trip, or the substation battery control voltage is lost), the energy source from terminal A can be eliminated. This is an inherent and intentional design for any protection scheme. However, terminal B may not be able to act as a backup for terminal C if the infeed is orders of magnitude higher and created by the third leg. As mentioned above, a CAPS can be used to mitigate this issue. Another CAPS called Direct Transfer Tripping (DTT) can often be employed to send a tripping signal to a remote terminal to immediately isolate that source if an imminent threat to the local station exists and cannot be quickly removed, such as in the case of a breaker failure condition. As with any other CAPS, this design requires a reliable and redundant communication medium.

Referring to the same example above, consider the situation where the energy sources at terminals C and the additional energy source when combined, create a much greater energy source than terminal A causing terminal A to be a much weaker source to the fault. This is called a weak feed condition. This situation creates the same type of scenario as above with the possibility of voltage drop at terminal A being so low as not to be able to detect phase faults at or beyond terminal B. CAPS will probably be required to mitigate a remote fault at or beyond terminal B depending on how weak the source is. DTT CAPS can also be employed here to assist in the quick isolation of the system disturbance.

CONCLUSIONS

From the discussion above, regardless of the reason for constructing three terminal lines will always result in a compromise with the transmission line protection system.

So when do three terminal lines make sense to implement? Let's look at the justifications and some of the reasons it may or may not be justified:

ECONOMIC BENEFITS IN COST OF CONSTRUCTION

From a strict focus on the added infrastructure cost of a substation and transmission line costs, the 3-terminal line tap onto an existing transmission line may initially seem appealing but with the additional source comes added costs to the protection system to prevent misoperations and to remove faults not only on the affected lines, but also in adjacent lines. Often protection entails other considerations that are not apparent to others outside the protection arena. For example, protection also includes remote backup protection for situations affecting local problems such as breaker failure and loss of station DC supply. High infeed situations can block this capability and provide more risk to security and reliability for affected customers. If the added third leg is from a generating facility, then communication lines must be added to provide Permissive Overreach Transfer Tripping (POTT), Direct Transfer Tripping (DTT), Permissive Transfer Tripping (PTT), or a line differential pilot scheme to ensure that all ends will operate to isolate an internal fault. Depending on the existing protection and communication technology, additional protection system equipment may be needed to ensure proper protection and isolation. Issues with misoperations due to stable power swings and load limitations will also need to be studied to determine if they need to be addressed in protection speed of isolation. Added cost in testing and maintenance of the communications equipment also becomes a factor if those systems are required. This added complexity is also an issue in the NERC PRC-004 and PRC-005 Standards due to the added record keeping. The reliability of the line may also suffer depending on how high the infeed effect is and if a CAPS scheme is needed. The additional cost of fiber optic cable can be in the millions of dollars depending on where it already exists, the length of the line needing the fiber, and the type of fiber used (ADSS vs OPWG).

POTENTIAL REDUCED LEAD TIME

The question here is lead time for whom. The entity requesting the additional source to an existing line wants the connection as soon as possible and the transmission owner trying to mitigate the problems resulting from the tap requires time for infrastructure changes. Depending on the additional protection equipment and communication channels needed when connecting a third leg to an existing transmission line, the time required to engineer the changes, order the equipment, and install and implement a new protection scheme can be substantial. This does not even address the time needed by the planning department to study the added source, the permitting, the environmental impact study, etc. And as mentioned above there are also other cost and risk factors that must be weighed, all in the name of expediency.

LESS OF AN IMPACT ON CHANGES TO RIGHT OF WAY DUE TO AVAILABILITY AND REGULATORY PUSH BACK

Of all the justifications provided, this is by far the most common reason to add a three terminal line. However, the physical design needs to be studied in great detail to determine just how difficult it might be to add additional right of way or just expand the ROW width to accommodate an in-and–out "hairpin" transmission line. In crowded urban areas, this may not be feasible but in more rural settings, often this can be accommodated.

THREE TERMINAL LINES MAY MITIGATE SOME OVERLOADS

This mitigation rarely works in the favor of reduced overloads without some additions to the existing infrastructure either from tying two transmission systems together with an additional transformer in a substation or adding additional transmission lines to re-route the load somewhere else.

What are the possible alternatives that can facilitate another "tapped" three terminal line?

Here are two alternatives to a 3-terminal line.

Option 1 – Install a tap substation with 3 breakers at the Tee location. The tapped line then becomes two feeders and would have breaker protection on both ends of the now-segmented transmission line going back from the tap. The tapping line would also be breakered back toward its source location, thus protecting the initial line from faults on the new tap line.

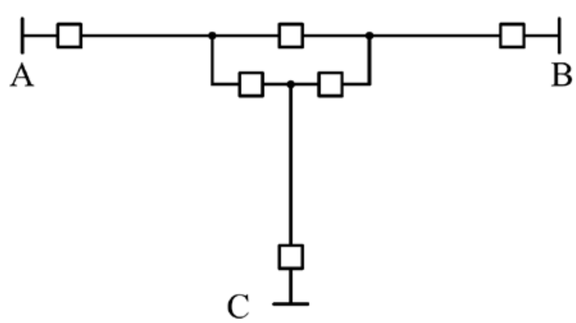

Figure 6 - Tap Substation with 3 Breakers at Tee Location

Option 2 – Install a "hair-pin" (i.e. double-circuit) transmission line from the tap point back to the new tap source location. Break the feeder at the tap point and tie one side of the hairpin onto each side of the break. Necessary breakers on the two "hair-pin" lines would then be installed in the tapping entity's interconnection substation. Each line would have its own protection system back to the original ends of the initial transmission line.

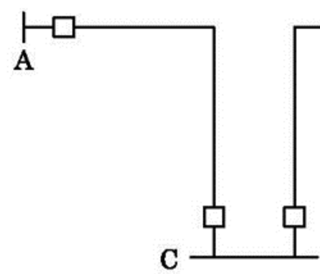

Figure 7 - "Hair-pin" Transmission Line

The protection systems for both of these options revert to those normally used for looped transmission lines.

It is the belief by the SPCWG that just tapping a third source into an existing transmission line adds much complexity, risk and cost to the protection of a transmission line. In some cases the costs associated with upgrading the protection system and communications system may exceed the costs of the added substation infrastructure that would have eliminated the need for those expenditures. Other factors such as, increased equipment maintenance expenses, added NERC testing and documentation requirements, as well as security and increased risk of misoperations rarely justifies this Tee-tap type of design. Infrastructure changes such as option 1 and 2 above provide a much improved design and remove all the risks discussed in this paper.

RECOMMENDATION

Creation of multi-terminal lines (three or more sources) should be avoided due to the complexities associated with protecting them. When Independent Power Producers request interconnection within the SPP transmission system, multi-terminal lines should be disallowed through the interconnect process or the Generator Interconnect Agreement. When tapping an existing two-terminal line, acceptable alternatives to the creation of a three terminal line include creation of a switching station at the tap or creation of a hair-pin tap.

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