Application Considerations When Protecting Lines With Tapped and In-Line Transformers

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Application Considerations When Protecting Lines With Tapped and In-Line Transformers

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***Abstract*—Transmission power lines can feed distribution networks or either serve loads or interconnect generation directly via tapped transformers. In some utilities, as many as three to five taps may be used on some lines. As a part of the bulk electric system, tapped transmission lines must be protected with instantaneous fault-clearing times and proper selectivity and sensitivity.**

This paper reviews various approaches to protecting tapped lines, including pilot protection schemes with distance and zero- and negative-sequence directional elements, time-overcurrent elements, line current differential schemes, and stepped distance backup.

In addition, this paper discusses protection applications for in-line transformers where a transmission line terminates on a transformer and a single protection zone includes both the line and the transformer.

I. Introduction

Transmission and subtransmission lines can be tapped to either serve loads or integrate medium-sized generation, such as wind or solar farms. Using a line tap instead of building a new station is an economical solution, but it creates a few operational and protection challenges. This paper reviews protection challenges and solutions related to tapped loads.

This paper starts with a review of the need for and sample practices of tapping loads directly from transmission lines (Section II). After considering protection challenges related to tapped loads (Section III), we review in detail the application of overcurrent elements (Section IV), distance elements (Section V), directional comparison schemes (Section VI), line current differential schemes (Section VII), autoreclosing (Section VIII), and breaker failure protection (Section IX).

This paper also addresses protection applications with in-line transformers (Section X). In-line transformers avoid the installation of circuit breakers (CBs) between the line and the transformer, which creates additional protection challenges.

II. The Need for and Current Practice of Tapping Into Transmission Lines

Tapping loads directly from transmission or subtransmission lines is an economically attractive solution in cases when the generation and major load centers are far apart and small communities or industrial facilities are located along the right of way.

Loads can be tapped from 230 kV transmission lines or 115 kV subtransmission lines that are sometimes as short as 50 kilometers and as long as 300 kilometers. Three to five load networks can be served on average from a tapped transmission line, with voltages ranging from 13.8 to 44 kV. In some cases, the step-down transformers are located in the switching station itself (the main line terminal) but are tapped to the line rather than supplied from the high-voltage bus.

Fig. 1 presents one possible configuration of a station tapped directly from a transmission line. This design is commonly referred to as a dual element spot network (DESN) and consists of two transformers typically rated in the order of 83 to 125 MVA, tapped from two transmission lines typically sharing the same towers or the same right of way. There are no CBs installed between the line and the high-side windings of the transformers. Instead, motor-operated disconnect switches (MODs) are applied. Historically, utilities achieved considerable savings by using MODs in place of CBs. Presently, there is less justification for this practice.

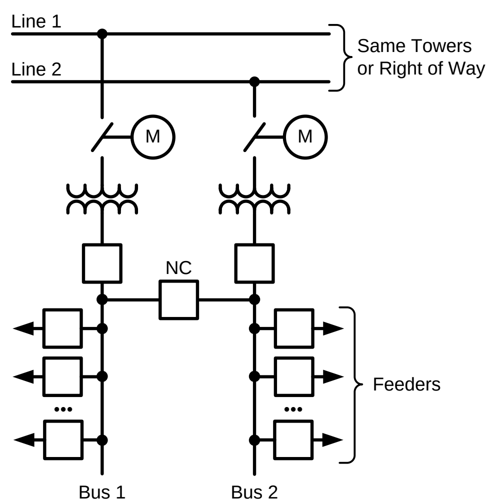

Fig. 1. Typical DESN station configuration.

The two transformers are connected to two buses via low-side CBs. The bus-tie CB is operated as normally closed (NC), and the feeder CBs are rated for the total fault current with both transformers in parallel. Each transformer is rated to carry the entire load should the other transformer become unavailable. In this way, the feeders are served without interruption even when one line is tripped or there is a transformer fault. Furthermore, feeder pairs have disconnect switches installed downstream from the feeder CBs (not shown in Fig. 1) to enable serving two feeders from one CB when the companion CB is out of service.

The transformer windings can be connected in a number of ways, including grounded and ungrounded wye or delta on the line side. Grounded wye creates a zero-sequence path and results in an infeed effect on a faulted line, as well as creating a zero-sequence source (path) for the parallel mutually coupled healthy line. The ungrounded wye- or delta-connected transformers avoid this effect but are typically more expensive, having to support higher insulation levels to deal with overvoltage conditions.

Even with ungrounded-wye windings, there is a small positive- and negative-sequence backfeed for line faults because the low-voltage sides of the two transformers are tied together by the normally closed bus tie.

The low-voltage winding can be connected in delta with a zig-zag grounding bank or can be connected as a power zig-zag.

Fig. 2 shows other variants of the tapped stations.

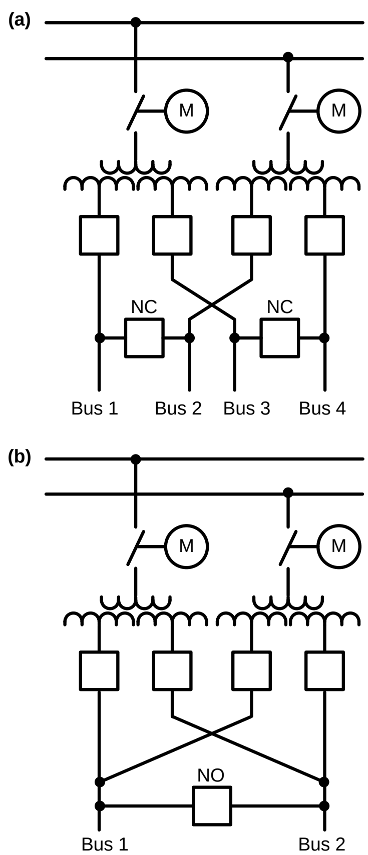

Fig. 2. Alternative tapped station configurations: dual-voltage configuration (a) and dual-secondary configuration with the tie normally open (NO) (b).

Because the tapped transformers are directly connected to the bulk electric system (BES) lines, they require high protection dependability. In addition, it would be difficult to provide any remote backup from the main line terminals for transformer or low-voltage bus faults. Therefore, the transformers and buses are often protected using dual-redundant protection systems that apply breaker failure protection and issue direct transfer trip (DTT) commands to the line CBs, often via redundant communications channels.

Often, the tapped stations are not equipped with highly dependable teleprotection channels, such as synchronous optical network (SONET) or direct fiber, but typically use analog voice frequency channels over leased lines for communications with one of the main line terminals. It is a good practice to request nonswitchable circuits for these leased channels from the local telecommunications company.

One operational disadvantage of tapping stations directly to transmission lines is exposing the BES assets (transmission lines) to problems with the tapped station equipment, including transformer faults, transformer relay misoperations, and low-voltage CB failures. For example, a misoperation of the transformer relay on magnetizing inrush due to low levels of harmonics results in tripping and locking out the transmission line.

When tapping generation to transmission lines, many utilities typically require the installation of a CB between the line and the interfacing transformer, as well as a high-speed digital teleprotection channel. This arrangement constitutes a multiterminal application (see Fig. 11 later in this paper) rather than a tapped line application and therefore is outside of the scope of this paper.

III. Overview of Challenges When Protecting Tapped Lines

In this section, we consider the typical tapped load application outlined in the previous section and describe protection challenges, as well as some general solutions.

A. Protection Challenges

Grounded-wye windings connected to the line act as zero-sequence sources (paths) during ground faults on the lines. These sources create an infeed effect, impacting the sensitivity of ground directional (67N) elements and ground distance (21G) elements on the faulted line. In addition, these sources create a zero-sequence unbalance for the parallel mutually coupled healthy line, jeopardizing the security of 67N and line current differential (87L) elements.

Overreaching distance Zone 2 (Z2) elements used in directional comparison (DC) schemes must overreach the farthest line terminal for dependability, but for security, they must not respond to faults on the low-voltage side of the tapped transformers. This reach coordination may become difficult or impossible when the tap is located close to one of the main terminals on a long line. In such cases, a blocking signal is required from the tap to ensure the security of the line protection scheme.

The same concern applies to the underreaching directly tripping distance Zone 1 (Z1) elements. However, Z1 reach can be shortened, if needed, to avoid overreaching for low-voltage faults at the expense of providing instantaneous fault clearance from the Z1 elements for a smaller portion of the transmission line.

Also, distance elements must not pick up for transformer inrush currents when autoreclosing the line with the connected transformers. Transformer inrush is especially challenging for 87L schemes because the total inrush current of four or five 125 MVA transformers can be significant, while the 87L elements do not have any means to restrain when energizing the line with transformers (see Section VII for more details on 87L scheme applications).

B. Typical Protection Philosophy for Tapped Lines

Typically, utilities use dual-redundant protection schemes for tapped lines, following the same application practice as for any BES-class asset. This typically includes two DC schemes or a DC scheme and an 87L scheme. In many applications, digital redundant teleprotection channels over SONET, preferably with IEEE C37.94 relay interfaces, are used for the DC or 87L schemes. The SONET circuits can be allowed to switch or can be provisioned as redundant with maximum possible path diversity but configured as nonswitchable (pinned) for ease of testing and predictability of performance. Older applications may still use a power line carrier (PLC) as a teleprotection channel. Application of PLCs on tapped lines is, however, more involved when compared with nontapped lines because of the tapped transformers.

Typically, directional comparison blocking (DCB) schemes are used with PLC channels, on very short lines, and on three-terminal lines. In all other circumstances, permissive overreaching transfer trip (POTT) schemes can be used.

Tapped lines are tripped from the main terminals, typically with no communications signals from the taps except blocking signals when absolutely unavoidable.

The DC schemes can use ground distance (21G), phase distance (21P), and 67N elements for fault detection. If the Z2 elements cannot coordinate between the line-end faults and faults on the low-voltage side of the tapped transformers, a blocking signal from the tap is added to the main terminal logic as an exception.

The 87L schemes are made secure against the transformer inrush current and the zero-sequence current unbalance by either applying distance supervision with the overreaching Z2 elements or applying 87L designs that are immune to inrush currents and do not use zero-sequence currents in the differential calculations.

Transfer tripping for the line CBs is applied for transformer faults and breaker failure conditions for the low-voltage transformer CBs.

Autoreclosing is applied for line faults.

Remote backup for the tapped stations can be applied conservatively if the protection systems for the tapped stations are engineered as dual redundant, including communications channels, breaker failure protection, and transfer tripping.

The following sections describe possible solutions in more detail.

IV. Overcurrent Elements

A. Directional Overcurrent Elements

Zero-sequence directional elements are used in DC schemes to detect high-resistance ground faults on transmission lines. It is worth emphasizing that the zero-sequence current paths are complex during ground faults.

Fig. 3 shows a zero-sequence network for two mutually coupled lines and three tapped stations for a fault on Line 1 (L1). Note that the transformer zero-sequence impedances (assuming grounded-wye connections on the high-voltage side) act as shunts, diverting the fault current away from the relay locations on the faulted line (L1). At the same time, the healthy line (L2) sees some zero-sequence current, but this current can be different at both ends of the healthy line because of the zero-sequence transformer impedances in the zero-sequence network. In addition, mutual coupling between the two lines complicates the current flow.

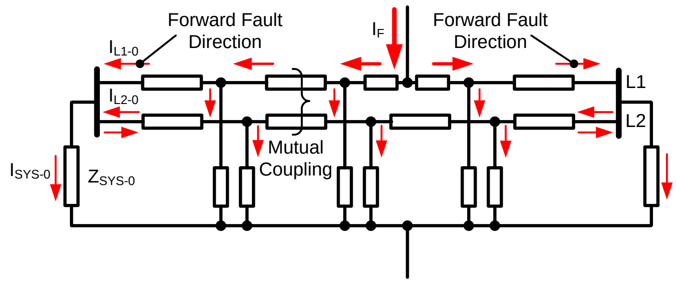

Fig. 3. Zero-sequence network for two mutually coupled lines with three taps and wye-grounded transformers.

This complex zero-sequence network affects the zero-sequence current level, but not its directionality, at least on the faulted line. Directional integrity of the 67N elements is ensured by the core operating principle of the elements: for any forward fault, the zero-sequence voltage at the relay equals the voltage drop across the equivalent local system impedance caused by the zero-sequence current flowing through this impedance:

$$V_0 = -Z_{SYS\text{-}0} \bullet I_{SYS\text{-}0} \tag{1}$$

The current closing through the local system is not measured by the relays, but instead, the equivalent system current is the sum of the currents in the two parallel lines (currents measured by the relays):

$$I_{SYS\text{-}0} = I_{L1\text{-}0} + I_{L2\text{-}0} \tag{2}$$

Because the entire zero-sequence network of Fig. 3 is passive and relatively homogeneous, the current in the faulted line $I_{L1\text{-}0}$ has the same direction as the system current $I_{SYS\text{-}0}$. Simply, the portion of the fault current flowing toward the left terminal divides between the parallel line and the system, and therefore, the system and faulted line current are practically in phase.

The healthy line currents may flow in a more complex way, however. When the zero-sequence voltages at both ends of the line are similar, there is no through zero-sequence current in the healthy line and both ends of the healthy line will see a current sinking into the line toward the transformer impedances. With some through zero-sequence current, however, the current at one end of the healthy line may reverse its direction, jeopardizing security of the healthy line DC protection scheme. Of course, the line mutual coupling complicates this problem even further. In addition, the zero-sequence voltage at the terminals can be very low, affecting the accuracy of directional polarization. Therefore, it is a good practice to verify the settings (especially directionality) of the 67N elements using short-circuit computer programs.

The negative-sequence network is simpler to analyze (Fig. 4). There is no mutual coupling for the negative sequence, and the negative-sequence transformer impedances connecting the two lines on the low-voltage side are larger than the zero-sequence impedances.

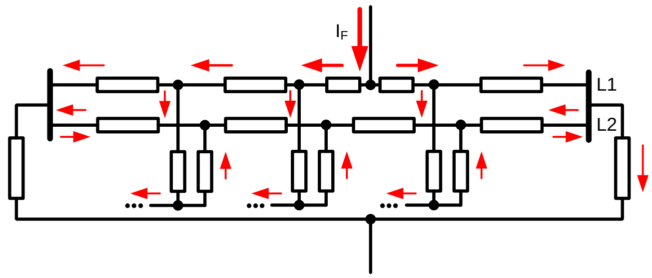

Fig. 4. Negative-sequence network for two mutually coupled lines with three taps and transformers paralleled on the low-voltage side.

Note that for wye-grounded/delta transformer connections and wye-ungrounded/zig-zag transformer connections, the 67N elements do not reach past the transformers, and therefore, they provide natural selectivity for line faults. This is not the case for negative-sequence directional (67Q) elements: they would reach past the tapped transformers, making them difficult to apply in DC schemes without communications to the tapped stations.

Because the 67N elements are very sensitive and their primary purpose is to detect high-resistance faults [1], they are often used in DC schemes with an intentional time delay of a few cycles.

B. Nondirectional Time-Overcurrent Elements

Nondirectional, time-coordinated 51N elements are often used to detect high-resistance faults beyond the coverage of the 67N elements and as part of the breaker pole discrepancy logic.

This element coordinates properly despite the tapped transformers. Moreover, as shown in Fig. 5, the tapped transformers divert the current, making the zero-sequence current at the terminal farther away from the external fault lower, thus increasing coordination margins between the 51N elements throughout the system.

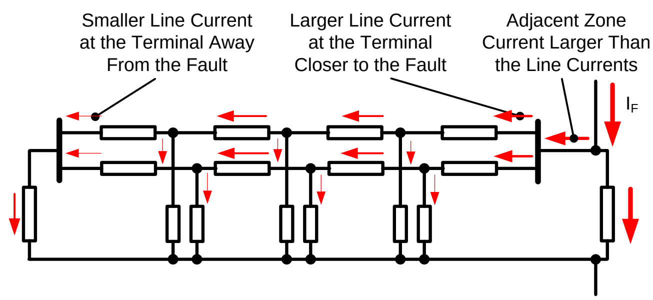

Fig. 5. Zero-sequence network for two mutually coupled lines with three taps and wye-grounded transformers for an external fault. The current at the remote terminal is lower than at the local terminal, improving coordination for the 51N elements.

V. Distance Elements

A. Reach Settings

The overreaching distance (Z2) elements are normally set to dependably overreach the remote line terminal(s). A typical setting is 125 percent of the line impedance. This initial value must, however, be verified and potentially adjusted to account for the infeed effect on three-terminal lines and because of the zero-sequence current contribution at the taps. In some cases, the 125 percent setting needs to be increased to dependably cover the entire line and the remote bus.

At the same time, for selectivity, the overreaching distance elements must be set short of the low-voltage bus faults at the tapped stations (Fig. 6a). This condition may be impossible to meet for long lines and transformers tapped close to one of the main line terminals (Fig. 6b). Again, verifying the security of Z2 elements for low-voltage bus faults must be done using short-circuit programs in order to account for the infeed effect.

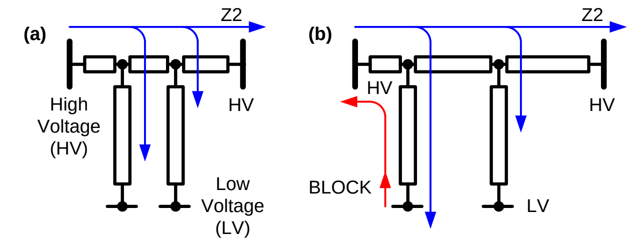

Fig. 6. Z2 coordinates well with low-voltage bus faults (a). A blocking signal is required from the first tapped station to avoid overreaching for low-voltage bus faults (b).

In cases where Z2 elements see low-voltage bus faults, a blocking signal may be needed from the tapped station. This signal can be asserted from directional overcurrent elements and is used as explained in Section VI.

This blocking signal must be applied if a DCB scheme is used and any of the Z2 elements see low-voltage bus faults. When using POTT schemes, the blocking signal is required only if both line terminals see a given low-voltage bus fault with their Z2 elements.

The underreaching directly tripping distance (Z1) elements are typically set to 80 percent of the line length (21P) or 75 percent (21G) of the line length. These margins account for line impedance uncertainty and variability, transient overreach (transient relay measuring errors), static relay errors, and voltage transformer and current transformer (CT) errors. These settings need to be verified for security against remote bus faults and low-voltage bus faults at the tapped stations using a short-circuit program and accounting for the infeed effect. In some cases, it may be necessary to pull the reach back, resulting in lower coverage of line faults with the instantaneous Z1 elements.

B. Stepped Distance Protection

Z2 elements are typically used with a coordination time delay as remote backup protection for remote main terminal bus faults. A time delay in the order of 400 milliseconds is used to coordinate with the critical fault-clearing time, including breaker failure trip time.

Normally, Z2 elements do not reach to low-voltage buses at the tapped stations, and therefore, they do not provide remote backup for the taps. As a result, the tapped stations must use fully redundant protection and breaker failure protection.

C. Transformer Inrush and Distance Elements

Transformer inrush can cause distance elements to pick up, especially when a number of transformers are tapped to the transmission line. For example, with five 125 MVA transformers tapped to a 230 kV line, the total tap current is 1.57 kA. Assuming the inrush current is as high as five times the load current for each of the transformers, the total inrush current can be as high as 7.9 kA. The actual value measured by the distance elements can, however, be lower due to relay filtering and the natural randomness of the inrush currents (not all transformers would have high inrush current for any given energization).

This problem is well described in [2] and has solutions such as harmonic blocking or increasing an overcurrent supervision pickup setting.

VI. Directional Comparison Schemes

DCB or POTT schemes are typically used based on the line length (DCB for short lines), number of terminals (DCB for three-terminal lines), and channel availability (DCB for PLC channels). The scheme selection is not driven by the tapped stations. Instead, the standard DCB and POTT schemes can be appropriately adjusted to accommodate the taps.

The basic simplified DCB logic is shown in Fig. 7a.

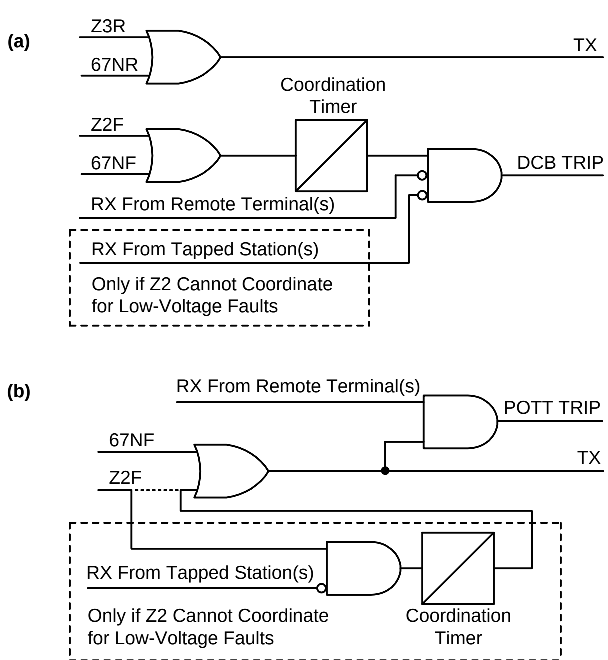

Fig. 7. Simplified DCB logic (a). Simplified POTT logic (b).

The DCB scheme trips upon detecting a line fault via the forward-looking overreaching 67NF and Z2F (21P or 21G) elements and not receiving a blocking signal from either the remote line terminal(s) or any of the tapped stations for which the distance elements could overreach. Application of the blocking signal from the tapped stations is an exception and is used only if the Z2 element cannot be set short of the low-voltage bus. The DCB scheme asserts the blocking signal (Bit TX asserts) via the reverse-looking 67NR and Z3R (21P and 21G) elements. Proper coordination is required between the forward-looking overreaching elements and the reverse-looking blocking elements as per the art of DCB protection (reach, sensitivity, and duration of the coordination timer).

The basic simplified POTT logic is shown in Fig. 7b. The POTT scheme trips upon detecting a line fault via the forward-looking overreaching 67NF and Z2F (21P or 21G) elements and receiving permission from all the other main line terminal(s). The Z2 elements that can overreach for low-voltage faults are blocked from the tapped stations via communications. Note that the permission logic already includes the blocking action for the Z2 elements that overreach the low-voltage buses. This way, the remote terminals do not require a blocking signal from the tapped station.

VII. Line Current Differential Schemes

In general, there are two methods of applying 87L schemes to tapped lines. Of course, we assume that the currents are measured only at the main line terminals, and therefore, the 87L application is effectively a partial differential scheme facing security issues due to transformer inrush and zero-sequence current paths. These solutions are described in the following subsections.

A. Solution Based on 87LQ and 87LP

One particular 87L relay applies an intentionally less sensitive phase differential (87LP) element and very sensitive zero-sequence (87LG) and negative-sequence (87LQ) differential elements using the Alpha Plane operating principle [3]. When applying this relay to tapped lines, we disable the 87LG element because this element would respond to the zero-sequence current unbalance from the in-line grounds created by the tapped transformers (see the healthy line in Fig. 3). Theoretically, the 87LP elements are impacted as well by this zero-sequence unbalance, but practically, they remain secure due to the intentionally less sensitive 87LP settings. Sensitive differential protection for line faults is provided by the 87LQ elements. These elements see faults beyond the transformers (see the healthy line in Fig. 4), but they can be made secure by increasing the pickup threshold above the negative-sequence current level seen during low-voltage bus faults. This coordination is relatively easy to apply because the transformer impedance considerably limits the current for low-voltage bus faults. Note that the same consideration applies to the 67Q elements, as described previously.

This solution does not require any extra signals, either local to the main terminal 87L relay or from the tapped stations.

B. 87L With Permissive Distance Supervision

A different 87L relay design provides an option to remove the zero-sequence current from the operating signal of the 87LP elements [4]. This solution makes the 87LP element secure for the zero-sequence current unbalance due to the grounded taps. However, this relay design does not offer the 87Q element, and therefore, the 87LP element must be set more sensitive than in the 87L scheme described previously. When set more sensitive, however, the 87LP element is susceptible to low-voltage bus faults.

One solution to this problem is to supervise the 87LP element with the permissive Z2F signal, as per Fig. 7b. However, in this case, permission from the 87L elements of all terminals must be communicated to all terminals with active 87L elements, as illustrated in Fig. 8a. This solution requires extra signals from all terminals and potentially from the tapped stations to supervise the 87L element. The supervisory signals can be conveniently created within the same multifunction 87L relay and sent over the 87L channel as a user-programmable bit. Alternatively, only the local Z2 permission can be used, and the scheme depends on DTT for dependable operation (Fig. 8b).

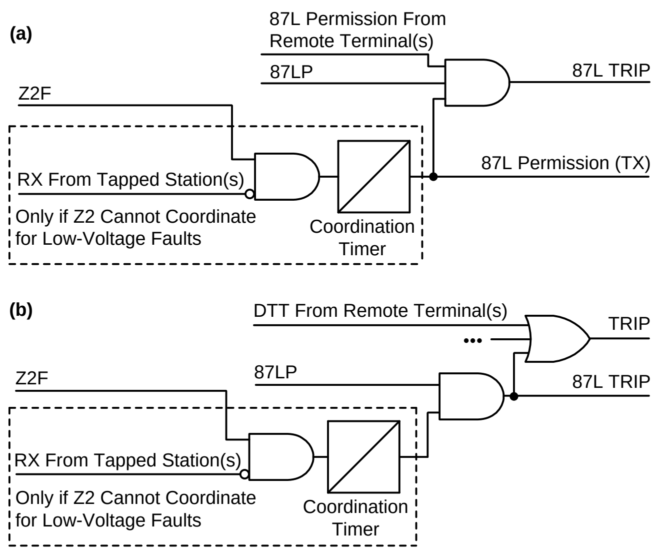

Fig. 8. Supervisory logic for the 87LP elements if the 87LQ element cannot be used for sensitivity. Solution with sharing a Z2 permissive signal (a). Solution with local Z2 supervision and DTT (b).

C. Solution for Lines With a Single Tap

A different way to ensure security without measuring the current at the tap while providing the sensitivity required by line protection is to use an inverse-time differential overcurrent element coordinated with the protection of the tapped network [3].

Similar to the two approaches outlined earlier, the 87L elements must not respond to faults in the tapped load network. This condition can be accomplished by increasing the pickup threshold (87LQ and 87LP), disabling 87LG, or by using distance supervision for the 87L trips. As a result, the 87L scheme is instantaneous and secure but is not sensitive enough to cover high-resistance line faults.

Sensitivity of protection can be restored by using a time-overcurrent element in the 87L relay responding to the differential current. Neglecting the line charging current in applications with a single tap, the differential current equals the current flowing into the tap (Fig. 9). As a result, the line terminal relays can easily coordinate with the overcurrent protection of the tapped network. This 51/87 element can be set to respond to the phase or negative-sequence current to match the type of protection applied in the tapped network. This way, the differential time-overcurrent protection provides sensitive but time-coordinated protection for low-current line faults, and some internal faults in the tapped transformers, as well as remote backup for short-circuit protection in the load network.

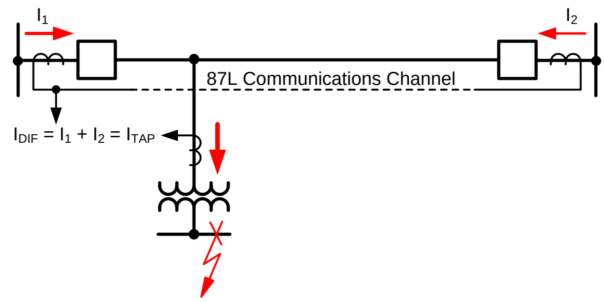

Fig. 9. The differential current equals the tap current in lines with single tap.

Typically, the differential current magnitude is a filtered fundamental frequency component, so the 51/87 element coordinates naturally with microprocessor-based relays protecting the tapped load network because they also respond to the fundamental frequency component. Coordination with fuses and electromechanical relays may be less accurate. Fuses and electromechanical relays respond to dc components in the short-circuit currents, so they time out faster if decaying dc components are present in the currents than do the upstream 51/87 elements that use filtered quantities. As a result, this application yields an extra time margin but does not miscoordinate with fuses or electromechanical relays.

This method is simple to use, but it works only with a single tap. With multiple taps, the differential current may not accurately reflect the fault current in one of the tapped networks due to the backfeed effects.

VIII. Autoreclosing Considerations

Normally, autoreclosing (AR) is applied for all instantaneous line trips. A subsequent manual attempt can be made after a few minutes at the discretion of the operators.

In the case of tapped lines, the low-voltage CBs should be tripped via teleprotection channels for all line faults; otherwise, line faults would be fed via the paralleled transformers from the healthy line (Fig. 1 and Fig. 2). No loads are lost as a result because both buses are tied together and the remaining transformer is rated to carry the entire load. The MOD on the high-voltage side remains closed. As a result, the lead CB picks up the line with all the tapped transformers connected. This, of course, creates considerable inrush current. At this time, the line operates with a single-end feed from the lead CB with the following consequences:

- Z2 elements may potentially pick up, but this is not a problem with permissive schemes.
- Z1 elements are less susceptible because of shorter reach.

- 87LG elements would be unstable, but they are not used, as explained previously.
- 87LP elements would be unstable, but they are intentionally desensitized or supervised with the Z2 elements, as explained previously.
- 67N elements may pick up, especially if there is some voltage unbalance or a principle of offset impedance is used. This could be a problem when using blocking schemes but can be easily addressed with supervision from the AR-in-progress signal.

Upon successful AR, the remote terminal(s) closes on synchronism check, and the low-voltage CBs at the tapped stations close on synchronism check or live-line/dead-bus logic.

IX. Breaker Failure and Other Considerations

A. Protection of the Tapped Stations

In reference to Fig. 10, the tapped stations may use dual-transformer differential protection (87T), overcurrent protection on low-voltage windings for transformer overload, bus and feeder backup (50/51 and 50N/51N), and bus differential or zone-interlocking protection for the low-voltage buses (87B). These protection schemes should be fully redundant because they protect assets directly connected to the BES (no CBs on the line side).

The feeders are protected using standard practices with time-coordinated overcurrent elements (not shown in Fig. 10).

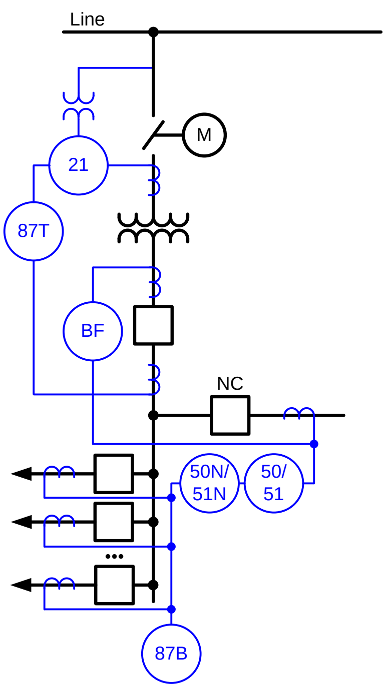

Fig. 10. Tapped station protection schemes.

B. Low-Voltage Breaker Failure Protection

In addition, the low-voltage CBs should be equipped with breaker failure (BF) protection. The BF protection is initiated on all transformer and bus fault trips. If it operates, it trips the tie CB and sends a DTT signal to one of the main line terminals. This line terminal trips the CB(s) and cascades the DTT to all the other line terminals so all the line CBs are tripped. The main line terminals send a DTT to all tapped stations to trip their low-voltage CBs. Note that all tapped stations are connected to at least one main terminal via redundant communications channels. This way, the line, as well as all low-voltage CBs, is tripped for a BF condition of any of the low-voltage CBs. This is a consequence of not having CBs on the high-voltage side of the transformers.

When the current flow through the transformer at the affected tapped station subsides, the MOD is operated to open (Fig. 10). If it opens and there is no current flow through the transformer, the DTT signal is deasserted and the line is allowed to reclose. If the MOD fails to open, the DTT is keyed continuously, resulting in a lockout of the line AR scheme.

Because of MOD operation, the tapped station with a BF operation serves all its loads through a single transformer. The other tapped stations will automatically restore their transformers back into load sharing by closing the low-voltage CBs (their MODs stayed closed).

C. Line Breaker Failure Protection

The situation is similar when a line CB fails to open. The affected line terminal sends a DTT command to all the other line terminals. This DTT is cascaded to all the tapped stations, resulting in tripping all the low-voltage CBs associated with the troubled line. The line protection locks out. All tapped stations operate with one of their transformers fed from the other line and continue serving all their loads.

D. Transformer Protection

Upon operation, the transformer protection scheme trips the low-voltage CB, initiates its BF protection, operates the MOD to open, and sends a DTT signal to one of the main line terminals. This line terminal trips the line CB(s) and sends the DTT to all the other terminals. The other terminals cascade the DTT to all the tapped stations to trip all the low-voltage CBs.

The DTT signal is keyed until the fault current subsides. If the current flow continues, the main line terminals lock out and do not initiate AR.

E. Backup for Line Faults and Blocking Logic for Downstream Faults

Backup for line faults is required to account for cases when the DTT signals from the main line terminals are not reliable. This concern is related to using analog leased lines, especially when the lack of path diversity in the telecommunications company or a common isolating transformer for the phone circuits can cause common-mode failures.

Distance elements with some time delay looking into the line from the transformer high-voltage side are used for backup (Fig. 10). These elements may have problems detecting faults when the main line CBs are closed (very large infeed effect), but they will operate once some main CBs open and remove the infeed.

These distance elements may also be used to assert a blocking signal for the main terminal Z2 elements if needed. In some cases, directional overcurrent elements are used instead of distance elements. Alternatively, the 50N element shown in Fig. 10 can be used for blocking for faults on the low-voltage bus or feeder if the transformer primary winding is grounded. If the primary is ungrounded, a neutral overvoltage element can be used.

If the low-voltage CB is tripped by the local backup for line faults rather than through DTT, the tapped station logic keys the DTT back to the main terminals, intentionally preventing reclosing of the line.

X. Protecting In-Line Transformers

The term *in-line transformer* refers to an application where a power transformer is located inside the line zone of instantaneous protection zone.

A. In-Line Transformer Application Scenarios

Fig. 11 shows the difference between the 87L protection of multiterminal lines, tapped lines, and lines with in-line transformers.

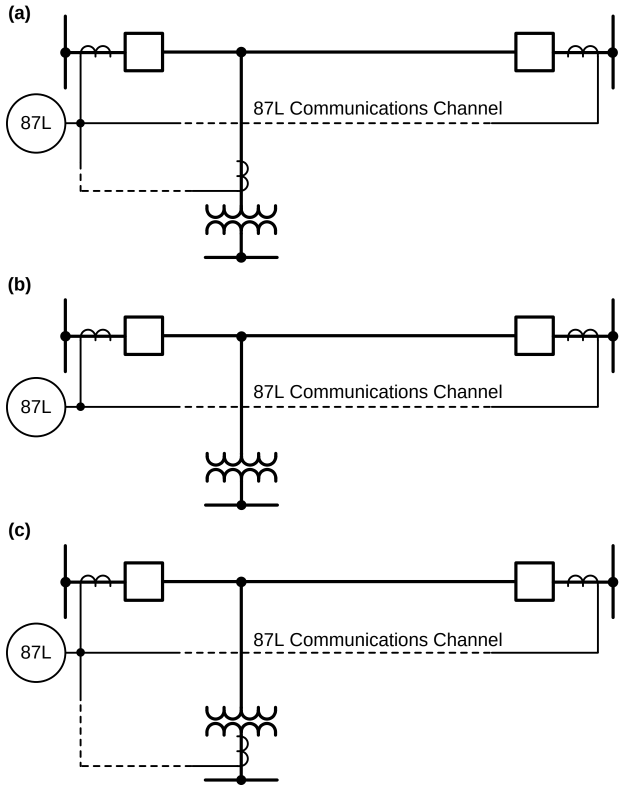

Fig. 11. Three-terminal line (a), two-terminal line with a tapped transformer (b), and two-terminal line with an in-line transformer (c).

In a multiterminal line protection scenario, the 87L element measures all line terminal currents and the transformer is outside of the line protection zone (Fig. 11a); the line protection scheme will not respond to transformer faults. It may need to trip the transformer for line faults if there is no CB installed on the line side of the transformer.

In a line with a tapped transformer (Fig. 11b), the 87L element measures the line main terminal currents and not the tap current. As explained in this paper, line protection may trip the line CBs for transformer faults via instantaneous overreaching elements (unintentionally), time-coordinated overcurrent elements (remote backup), or received DTT from the local transformer protection.

By contrast, an in-line transformer is within the line protection zone (Fig. 11c). As a result, the combined line and transformer protection must meet the sensitivity requirements for transformer protection. In addition, the protection scheme must be secure for magnetizing inrush conditions of the transformer. As a result, in-line transformers are typically protected with differential schemes rather than distance or overcurrent schemes.

Distance protection schemes are sometimes used for backup transformer protection. They are rarely considered for primary protection because they have sensitivity limitations for transformer faults. Also, because of the zero-sequence discontinuity introduced by the transformer delta-connected windings, ground distance protection faces major application challenges or it cannot be applied at all. This problem, in turn, impairs ground fault protection for the transmission line.

Directional comparison schemes based on sensitive directional overcurrent elements such as the 67Q element may have adequate sensitivity for both transformer and line faults, but they require solutions to the magnetizing inrush current problem.

Magnetizing inrush current can be easily accommodated by differential relays because it is measured as a differential signal. Distance or directional overcurrent elements respond to local currents (not the differential current) and may not work correctly. For example, the harmonic blocking principle working with the harmonic ratio of the local current can block a sensitive overcurrent element permanently if there is a high harmonic content in the load current supplied to nonlinear loads. Differential elements do not have this problem because the load harmonics flow in and out of the protected zone and cancel out in the differential signal.

In this section, we focus on differential protection schemes for in-line transformers.

Fig. 12 presents typical line current differential applications with in-line transformers.

Some 87L elements can accommodate in-line power transformers [3], as illustrated in Fig. 12a. This application, typically encountered where no CB is installed to separate the line and the transformer under fault conditions, allows the differential element to protect both the transformer and the line. The 87L element performs vector group, ratio, and zero-sequence compensation as per the art of transformer protection. It provides for overexcitation inhibit as well as harmonic blocking and/or restraint for magnetizing inrush conditions.

Typically, this application does not provide a full set of transformer protection or monitoring features, as would be the case for the dedicated transformer protection relay shown in Fig. 12b. Application of Fig. 12b offers better protection for the transformer, improves operational information, and allows autoreclosing by discriminating between transformer faults (87T operation) and line faults (87L operation), with accurate fault location for the line faults provided by the line protection scheme. The line differential relay can be used to execute DTT of the remote CB(s) from the transformer relay.

As illustrated in Fig. 12c, the combined transformer and line protection application can be used as the backup system or for the protection of transformers in very large substations with very long CT leads between the control house and the breaker CTs. The combined zone can be used to protect the transformer and its connections while a full-featured transformer relay can be used to protect the transformer alone from the bushing CTs.

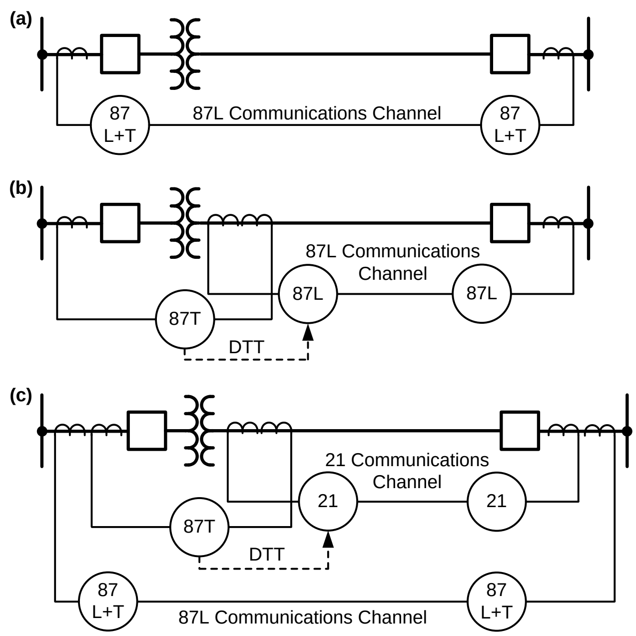

Fig. 12. A combined transformer and line protection scheme with a single line differential relay capable of handling in-line transformers (a), with dedicated transformer and line relays (b), and with the primary protection following the dedicated relay approach and the backup protection utilizing a single 87L relay (c).

B. 87L Relay Design for In-Line Transformers

In order to accommodate an in-line transformer, the 87L element must perform proper ratio (tap) and vector group compensation [5], as illustrated in Fig. 13. The compensation can be done at the receiving relay or more conveniently at the sending relay [3].

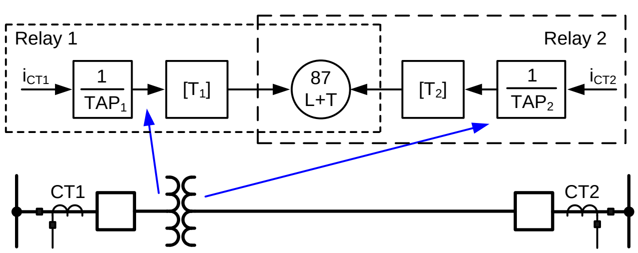

Fig. 13. Illustration of ratio (tap) and vector group compensation.

In a matrix notation, we write the compensation equations in the following general form:

$$\begin{bmatrix} i_{XFMR(A)} \\ i_{XFMR(B)} \\ i_{XFMR(C)} \end{bmatrix} = \frac{1}{TAP} \bullet [T] \bullet \begin{bmatrix} i_{CT(A)} \\ i_{CT(B)} \\ i_{CT(C)} \end{bmatrix} \quad (3)$$

where:

The 3x3 matrix [T] reflects the winding connection associated with a given CT set (typically, all CTs are assumed to be connected in wye).

For example, for a wye-connected winding of a power transformer, we can use:

$$[T] = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \quad (4)$$

while a power zig-zag winding may require:

$$[T] = \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \quad (5)$$

or a delta-connected winding may need:

$$[T] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (6)$$

Some line current differential relays support multiple CT inputs, allowing one transformer winding per CT input of the relay. For example, a dual-CT input relay may be connected to measure currents from two different windings of an in-line transformer, each having different connections and thus requiring different compensating matrix settings. For windings connected as dual-breaker terminations, the settings for both current inputs are identical as they measure currents from the same transformer winding (Fig. 14).

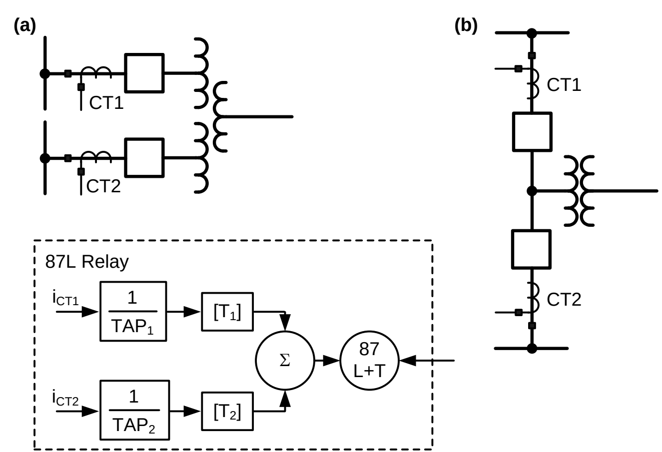

Fig. 14. Line current differential relays with multiple CT inputs measure currents from different in-line transformer windings (a) or from dual-breaker terminations of the same transformer winding (b).

Applying (3) to transform the measured currents at the early stage of signal processing has the advantage of using the same unified logic for applications with and without in-line transformers [3]. Applications without in-line transformers simply use (6) for current transformation. As a result, the remainder of the 87L algorithm (87L elements, external fault detection, charging current compensation, and so on) can be executed without any additional modifications. In particular, the 87LP and 87LQ elements are available, providing phase and sensitive negative-sequence differential protection for the line and transformer.

The 87L relay capable of in-line transformer protection must apply harmonic blocking to cope with power transformer overexcitation conditions. This logic measures the level of fifth harmonic in the differential current relative to the fundamental frequency component in the differential current and asserts a blocking signal if the harmonic level is above the user-selected threshold.

The 87L relay must also support harmonic blocking and/or restraint for transformer magnetizing inrush conditions. The harmonic blocking logic typically measures the levels of second and fourth harmonics in the differential current and asserts a blocking signal if any of them is above a user-selected threshold. The harmonic restraint logic adds the second and fourth harmonics, with selected multipliers, to the restraining signal of the 87LP function. The second harmonic is also used to block the negative-sequence differential element 87LQ, if the harmonic level is above the user-selected threshold. The coefficients are selected in such a way that the total restraint is sufficient to hold back the function under the worst-case scenario of transformer energization.

C. Application Considerations

When considered for primary protection, the combined transformer and line differential scheme faces the following challenges:

- Sensitivity to line ground faults, especially if the level of the negative-sequence currents is low, limiting the 87LQ element and favoring the 87LG element while the latter cannot be used with transformers.
- Sensitivity to transformer faults.
- The need to provide other protection functions in addition to the 87 function for the transformer, especially for large transformers.
- Difficulties in initiating autoreclosing (lack of distinction between line and transformer faults).
- Difficulties in fault locating (at least from some line terminals).

Nonetheless, modern 87L relays allow the protection of lines with in-line transformers. This application may be attractive as a backup scheme in high-voltage networks or may be considered as an economical solution in subtransmission and medium-voltage networks.

Typically, 87L relays are designed to protect in-line transformers of standard connections. However, these relays can be applied (with some limitations) to protect phase-shifting transformers (PSTs). This application is worth noting because PSTs are sometimes installed as in-line transformers.

XI. Conclusion

This paper presents practical solutions to protect transmission lines with multiple taps.

We describe a standard design for the tapped stations using two transformers tapped to two lines sharing the same towers or right of way. With this design, the tapped stations allow for transformer and line redundancy when supplying loads. If the tapped transformers are connected via MODs rather than CBs, extra operational and protection challenges are created.

We describe a protection philosophy that is based on using Z2 elements to detect line faults but stop short of responding to low-voltage bus faults. If this coordination cannot be provided, a blocking signal from the tapped station is used for tripping selectivity. The 67N elements are also used in the DC schemes. This paper explains the setting and application principles for the 21 and 67N elements used in a DC scheme or in a stepped distance scheme.

This paper also explains how to apply 87L schemes to tapped lines. In this respect, three different methods are presented.

This paper also describes the fundamentals, relay design, and application considerations for protecting in-line transformers.

XII. Acknowledgment

The authors would like to thank Mr. Steven Hodder of Hydro One Networks, Inc. for his assistance in writing and reviewing this paper.

XIII. References

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XIV. Biographies

Rohan Perera received his master's degree in engineering from the University of Waterloo and B.S.E.E. with honors from the University of Western Ontario. He has been working for Hydro One Networks, Inc. for the past 12 years and presently holds the position of senior protection and controls engineer.

Bogdan Kasztenny is the R&D director of technology at Schweitzer Engineering Laboratories, Inc. He has over 23 years of expertise in power system protection and control, including ten years of academic career and ten years of industrial experience, developing, promoting, and supporting many protection and control products.

Bogdan is an IEEE Fellow, Senior Fulbright Fellow, Canadian representative of CIGRE Study Committee B5, registered professional engineer in the province of Ontario, and an adjunct professor at the University of Western Ontario. Since 2011, Bogdan has served on the Western Protective Relay Conference Program Committee. Bogdan has authored about 200 technical papers and holds 20 patents.

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