# Ground Fault Protection of Pilot Schemes: Basics and Applications

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***Abstract*- The detection of ground fault and its direction is essential to transmission line protection. In a carrier based pilot scheme, the directional overcurrent relay is typically used to detect ground faults on the line. In many pilot scheme mis-operation cases, the ground directional element was involved - it may be due to relay settings or algorithm under specific system condition or configuration. This paper will discuss the basics of ground fault detection, the directional element design, and pilot scheme applications. Based on the analysis of a few mis-operation cases, some setting recommendations are provided.**

## I. Introduction

The ground fault relaying provides the most important protection in high voltage power systems because majority of faults in the transmission and distribution system are ground faults. A ground fault may be detected by stand-alone relay or through communication-aided pilot scheme. A stand-alone relay can detect the fault and its direction by evaluating the zero sequence current ($I_0$), zero sequence voltage ($V_0$), negative sequence current ($I_2$) or negative sequence voltage ($V_2$). In a pilot scheme, a relay can have information from both local and remote terminals to discriminate internal or external faults. The pilot schemes include current differential (87L) scheme, phase comparison scheme, direction comparison blocking (DCB) scheme, permissive overreach transfer trip (POTT), etc. The 87L is superior but the communication channel it relies on can be costly. The phase comparison scheme has similar advantages like 87L and it uses low cost power line carrier (PLC) to exchange the local and remote current information in the form of ON/OFF signaling, but the scheme is very susceptible to channel problem. So far, majority of pilot schemes in existing power systems are still PLC-based schemes such as DCB or POTT. This paper will focus on these prevailing schemes and discuss how we can improve their reliability for ground fault protection.

In a pilot scheme like DCB or POTT, the ground fault and the fault direction are detected by each terminal relay independently, so the prerequisite of correct operation is that each individual relay must be able to identify the fault direction correctly. This could be a challenge because the relays are typically installed in a meshed network where the fault currents are fed from multiple sources, and some system conditions can have adverse effect to relay's ground fault detection.

As part of a DCB or POTT scheme, a line protection relay typically includes phase distance elements for phase-to-phase faults and directional overcurrent elements for ground faults. The ground distance elements usually play the supplemental role because they have limitation to detect high impedance ground faults. From Utility operational experience, many pilot scheme mis-operations were associated with the directional overcurrent elements. To reduce mis-operations, the relay setters should have a clear understanding of the fundamentals of ground fault and how the protection elements are designed in digital relays. This paper is trying to help the readers to gain some insights from the review of basic theories and the lessons learned from mis-operation cases.

## II. Basics on Ground Fault and Ground Fault Direction

In order to perform ground fault analysis in this section, two basic points should be kept in mind:

- The current flow direction for fault analysis

To illustrate AC current direction, an arrow is used to indicate the flow direction during the positive half-cycle of the sine wave. In theory, one can define the reference direction arbitrarily. But from protective relaying standpoint, *the fault current should always flow from the relay to the fault location*, which is in line with the typical arrangement of CT polarity. An example is given in Figure II. 1.

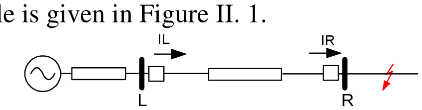



Figure II.1. Current flowing direction under fault condition

- The source in sequence networks

The sequence networks are used to analyze asymmetrical faults in three-phase power network. *The physical source exists only in positive sequence network*. In another word, there is no physical source in zero sequence or negative sequence network. The transformer neutral point is commonly called "grounding source", which has its practical meaning but is incorrect in strict sense. For a balanced system under normal condition, the positive-, negative- and zero sequence networks are decoupled. So there is no zero- and negative sequence current. When fault occurs, the zero- and/or negative sequence network will be connected to the positive sequence network, such that $I_0$, $V_0$, $I_2$, $V_2$ are driven by the source in positive sequence network.

A simple two-source system in Figure II.2 is used as example for ground fault analysis. The two sources, each includes a voltage source in series with source impedance ($Z_L$ or $Z_R$), are Thevenin equivalence representing the system behind L and R terminals. The fault is at point F on the line that has impedance Z.

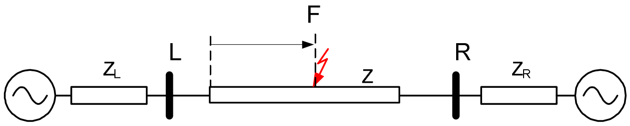



Figure II.2. A simple system example

For a single phase to ground (1LG) fault, the corresponding sequence networks are illustrated in Figure II.3. Prior to the fault, the three sequence networks were decoupled. Because of the fault, they are connected in series and the connection point is the fault location F, which is decomposed as F1, F2, and F0 in corresponding network.

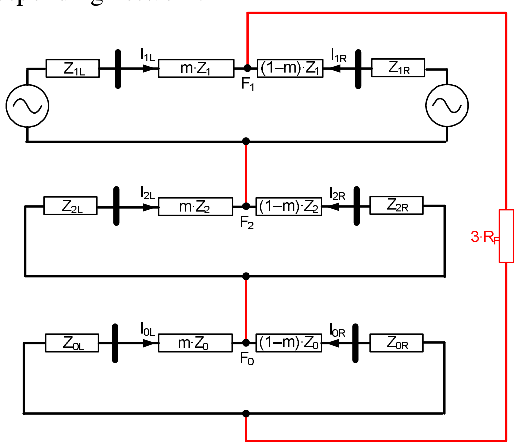



Figure II.3. The sequence network for 1LG fault

If the fault is a phase-to-phase-to-ground (2LG) fault, the three sequence networks will be connected in parallel, as illustrated in Figure II.4. The connection point is still the fault location F.

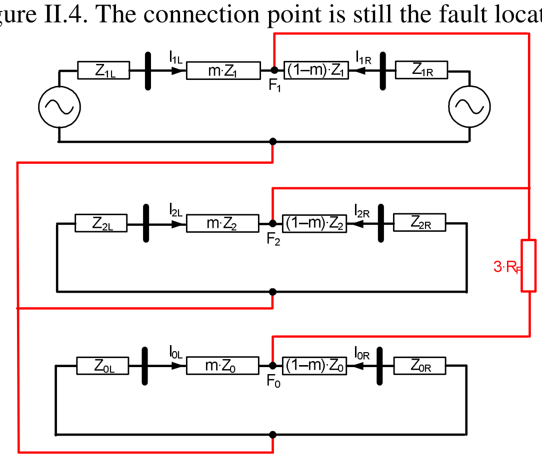



Figure II.4. The sequence network for a 2LG fault

From Figure II.3 & 4, the difference between 1LG and 2LG faults is the way how the sequence networks are connected. The phasor analysis within each individual sequence network would be the same. For simpler illustration, the zero sequence network is taken out and analyzed separately in Figure II.5.

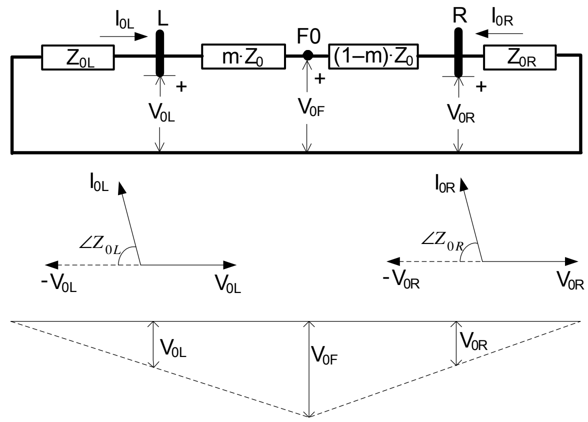



Figure II.5. The zero sequence currents and voltages for a line internal ground fault

Since there is no source in zero sequence network and the $I_0$ is produced by external sources through the connection point (F0 in Fig. II.5), the $V_{0F}$ at fault location should have the highest magnitude in the voltage profile along the line. The magnitude of $V_{0L}$ and $V_{0R}$ measured by relays at L and R terminals are lower and they could be very small if the fault is a high impedance ground fault, or the system impedance $Z_{0L}$ ($Z_{0R}$) is much lower than the line impedance.

Per fault current direction and the voltage drop in Figure II.5, there are

$$\begin{cases} V_{0L} = -I_{0L} \cdot Z_{0L} \\ V_{0R} = -I_{0R} \cdot Z_{0R} \end{cases} \qquad (1)$$

The negative signs in above equation are based on current direction in Figure II.5., meaning the $I_{0L}$ lags $-V_{0L}$ by impedance angle $\angle Z_{0L}$ at L terminal. Similarly, the $I_{0R}$ lags the $-V_{0R}$ by impedance angle $\angle Z_{0R}$ at R terminal. Such angular relationship is the base of zero sequence voltage polarizing method used by digital relays for ground fault direction, because it conveys the difference between forward and reverse fault. For example, if the ground fault is behind the L terminal, the corresponding zero sequence network and phasors are given in Figure II. 6.

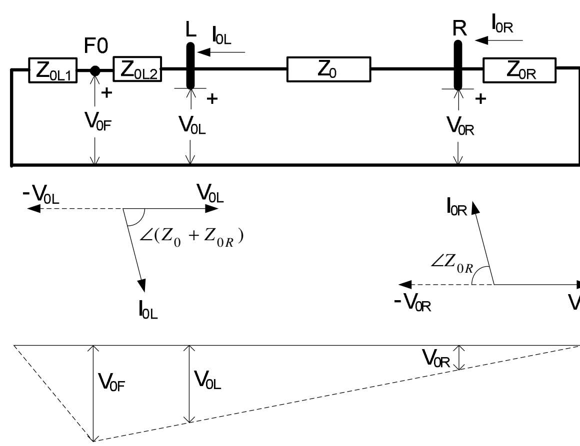



Figure II.6. The zero sequence currents and voltages for a line external ground fault

For this fault, the system impedance $Z_{0L}$ is divided into $Z_{0L1}$ and $Z_{0L2}$ by the fault point F0. Again, the $V_{0F}$ should have the highest magnitude in the voltage profile. And the V0 and I0 will have following relationship,

$$\begin{cases} V_{0L} = I_{0L} \cdot (Z_0 + Z_{0R}) \\ V_{0R} = -I_{0R} \cdot Z_{0R} \end{cases} \qquad (2)$$

For L terminal relay, the $I_{0L}$ will lag $V_{0L}$, or lead $-V_{0L}$ by 180º-∠($Z_0$+$Z_{0R}$), which is a signature for reverse ground fault. It also shows that the angle between the apparent $I_0$ and $V_0$ for a reverse ground fault is up to the total zero sequence impedance in front of the relay.

The above analysis applies to the negative sequence network as well. For a forward ground fault, the $I_2$ will lag $-V_2$ by about 60º~90º (the typical angle of system impedance behind the relay). For a reverse ground fault, the $I_2$ will lead $-V_2$ by about 90º~120º (180º minus the typical angle of system impedance in front of relay). This is the base of negative sequence voltage polarizing method for ground fault direction.

Another way to get the ground fault direction is to take the advantage of transformers in the substations. An example is given in Figure II.7. Under normal conditions, there is no current or very small amount of current flowing through transformer neutral point. When ground fault occurs, the transformer neutral point facilitates a return path for fault current. For a Y-D transformer, the current will always flow up the transformer neutral point. For a 3-winding autotransformer, circulating current will be induced within the transformer tertiary winding and flow in only one direction in most cases. If the transformer neutral current ($I_n$) or tertiary winding current ($I_t$) can maintain the same direction for all the ground faults in the vicinity, they can be used as reference to determine the ground fault direction. For example, if the fault is at location F1 in Fig. II.7, the relay at CB-A will see $3I_0$ in phase with $I_n$. If the fault is on another feeder, such as location F2, the relay at CB-A will see $3I_0$ in opposite direction with $I_n$. The ground fault direction is therefore discriminated by relay at CB-A. This is called the current polarizing method for ground fault direction.

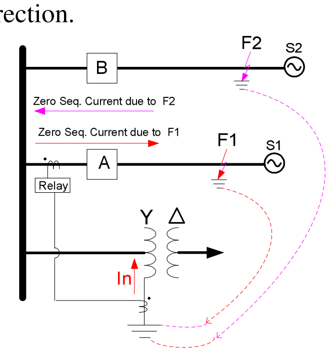



Figure II.7. The detection of fault direction by using transformer neutral current as polarizing quantity

There could be a few issues with current polarization method. Depending on the system and transformer parameters, the transformer neutral current may or may not always flow in one direction. The circulating current within the tertiary winding of 3-winding autotransformer is more stable but there still could be exception. More details will be discussed in next Section.

## III. THE GROUND FAULT DETECTION IN DIGITAL RELAYS

### *A. Directional Element Using Zero Sequence Voltage Polarization*

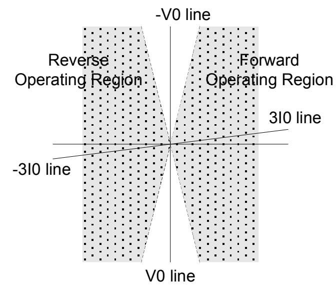



Figure III.1. A directional element characteristic based on zero sequence voltage polarizing

The zero sequence voltage ($V_0$) polarizing method has long history since the era of electro-mechanical (EM) relays. In the past, the $3V_0$ was taken from broken delta winding of PT and $3I_0$ was obtained from CT neutral point. The wiring mistake was a concern at the time. For a digital relay, since it can easily compute $V_0$ and $I_0$ from the 3-phase voltages and currents, the risk of wrong polarity on $V_0$ or $I_0$ is almost eliminated. From previous Section, the signature of forward ground fault is that $I_0$ will lag $-V_0$ by 60~90º, and the reverse fault will cause $I_0$ to lead $-V_0$. The range of angle comparison can be extended to get the 67N relay characteristic, which is shown in Figure III.1.

Equivalent to angle comparison, a digital relay may also use a torque equation to determine the fault direction,

$$Torque = |V_0| \cdot |I_0| \cdot \cos[\angle -V_0 - (\angle I_0 + \angle MTA)] \qquad (3)$$

where MTA is relay setting typically set to 60~90º. A positive torque will indicate a forward fault and a negative torque gives reverse direction. The equation is just another way to show the angular relationship between $3I_0$ and $V_0$.

In some applications, because the system impedance behind the relay is so small or the fault is far from the relay, the $V_0$ seen by the relay could be small. The above method will face challenge because the $V_0$ and $I_0$ phasor calculations are more affected by error from instrument transformers, load unbalance, noise, etc. To prevent wrong direction, a threshold should be set for the polarizing $V_0$. However, such threshold may bring sensitivity issue especially when the directional element is used by the relay as a torque (must be asserted for overcurrent or distance elements to operate) instead of a blocker.

Some digital relays include supplemental methods to increase the sensitivity or security of the directional element using $V_0$ polarizing. For example, a relay [10] can utilize a small portion of the measured 3I0 to enhance the polarizing quantity as follows,

$$V_{polarize} = -V_0 + Z_{offset} \cdot I_0 \qquad (4)$$

where Zoffset is a setting. Since the additional term $Z_{offset} * I_0$ is in phase with I0, the polarizing voltage is increased for forward ground fault. Meanwhile, the sensitivity for reverse fault is reduced. Depending on the application, such method may or may not be applicable.

### *B. Directional Element using Negative Sequence Voltage Polarizing*

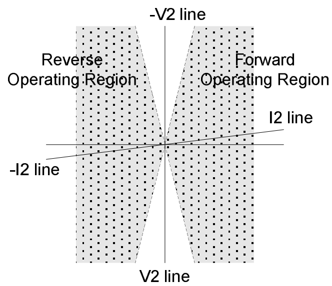



Figure III.2. A directional element characteristic based on negative sequence voltage polarizing

From the sequence networks in Figure II.3 and II.4, the current flowing in a negative sequence network is the same as that in a zero sequence network for ground fault. So the phase angle between V2 and I2 can be used for fault direction too. If I2 lags –V2 by about 60º~90º (typical system impedance angle), it will be a forward fault. If I2 lags V2, it will be a reverse fault. A relay characteristic using negative sequence voltage polarizing is shown in Figure III.2, which is almost the same as that for V0 polarizing method. Similarly, a torque equation can also be used to determine the fault direction.

$$Torque = |V_2| \cdot |I_2| \cdot \cos[\angle -V_2 - (\angle I_2 + \angle MTA)] \qquad (5)$$

With all the similarity, the negative sequence voltage and current are typically used only for fault direction. The operating quantity for ground faults are still 3I0 in most applications.

In the EM relay era, it was not easy to produce the mechanical torques from V2 or I2, so the V2 polarizing method was less used. Since the digital relay can easily compute V2 and I2, the V2 polarizing has gained its popularity because it is not susceptible to zero sequence mutual coupling effect. However, similar to the problem with V0 polarizing, the apparent V2 and I2 can be very small and cause problem on fault direction.

### *C. Directional Element Using Zero & Negative-sequence Impedance*

Some relays use negative sequence impedance (z2) or zero sequence impedance (z0) for ground fault direction. Comparing the negative sequence networks in Figure III.3(a) & (b), the relay at the L terminal will see fault currents in opposite direction for internal and external fault. In Fig. III.(a), the relay at L terminal will see the following z2 for the forward ground fault,

$$z2 = \frac{V_{2L}}{I_{2L}} = -|Z_{2L}| \qquad (6)$$

And in Fig. III.(b), the relay at L terminal will see the following z2 for the reverse fault,

$$z2 = \frac{V_{2L}}{I_{2L}} = |Z_2 + Z_{2R}| \qquad (7)$$

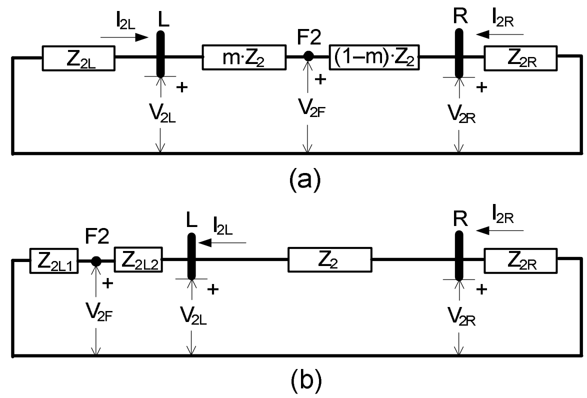



Figure III.3. The negative sequence networks for (a) forward ground fault and (b) reverse ground fault with regards to L terminal relays

The z2 is calculated as a signed value and the sign is determined by the angle between V2 and I2. If I2 lags V2 (or leads –V2), the sign is positive; if I2 leads V2 (or lags –V2) , the sign is negative. This is in line with the previous V2 polarizing method.

A specific digital relay [11] would use Eqn. (8) for z2 calculation,

$$z2 = \frac{\mathrm{Re}\left[V_2 \cdot \overline{(I_2 \cdot 1\angle Z1)}\right]}{|I_2|^2} \qquad (8)$$

which is not straightforward but is equivalent to Eqn.(6) & (7).

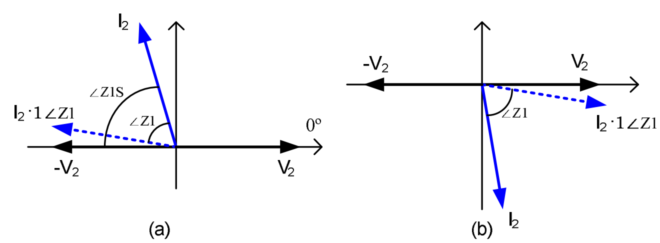



Figure III.4. The negative sequence phasors for (a) forward ground fault and (b) reverse ground fault behind L terminal.

The Figure III.4 (a) & (b) can be used to explain Eqn. (8). For a forward ground fault, the Eqn. (8) can be re-written as,

$$z2 = \frac{|V_2| \cdot |I_2| \cdot \cos(180° - \angle Z_{1S} + \angle Z_1)}{|I_2|^2} \approx -\left|\frac{V_2}{I_2}\right| \qquad (9)$$

which is almost the same as Eqn. (6). Similarly, the Eqn. (8) will be almost the same as Eqn. (7) for a reverse fault. The

slight difference is that line's impedance angle $\angle Z1$ is used by relay to approximate the system impedance angles $\angle Z1S$.
The above analysis applies to zero sequence network as well. A negative z0 value will indicate a forward ground fault, and a positive z0 will indicate a reverse ground fault.

In addition to the sign of the calculated impedance, the magnitude of z2 or z0 can provide one more handle to manipulate for fault direction. By using threshold settings Z2R and Z2F, the sensitivity for forward and reverse ground fault detection can be adjusted. If the threshold is moving up away from zero, the sensitivity for forward direction is increased. Meanwhile, the sensitivity for reverse direction is reduced. And vice versa.

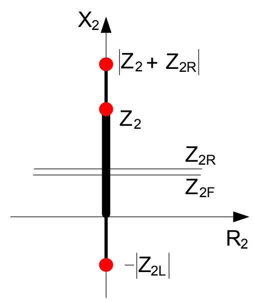



Figure III.5. The negative sequence impedance plane for ground fault direction

From Figure III.5, there is a wide range to set the two thresholds Z2R and Z2F, as long as the threshold settings satisfy Eqn. (10), they are valid in general sense.

$$-|Z_{2L}| < Z_{2F} < Z_{2R} < |Z_2 + Z_{2R}| \qquad (10)$$

To help the users, this specific type of relay [11] includes "AUTO" threshold settings, which are based on half the line impedance that satisfies Eqn. (10) obviously. In addition, this type of relay uses the following equations to adjust the thresholds for different source impedance ratio (SIR).

$$Z2FTH = \begin{cases} 0.75 \cdot Z_{2F} - 0.25 \cdot |V_2 / I_2| & \text{If}\,(Z_{2F} \le 0) \\ 1.25 \cdot Z_{2F} - 0.25 \cdot |V_2 / I_2| & \text{If}\,(Z_{2F} > 0) \end{cases} \qquad (11)$$

$$Z2RTH = \begin{cases} 0.75 \cdot Z_{2R} + 0.25 \cdot |V_2 / I_2| & \text{If}\,(Z_{2R} \ge 0) \\ 1.25 \cdot Z_{2R} + 0.25 \cdot |V_2 / I_2| & \text{If}\,(Z_{2R} < 0) \end{cases} \qquad (12)$$

Assuming the "AUTO" settings are used, the following figure shows the actual thresholds used by the relay for a long line and a short line.

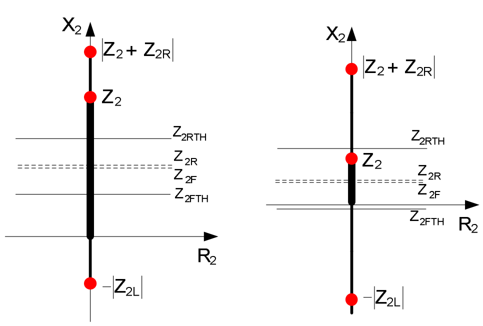



Figure III.6. The negative sequence impedance thresholds for ground fault direction

From above analysis, there is no fundamental difference between the impedance based method and the traditional phase angle comparison method. The phase angle between V2 & I2, or V0 & I0, is still the foundation for ground fault direction. The impedance method can provide more flexibility for user to adjust sensitivity for forward or reverse faults. Depending on the threshold settings, the impedance method is able to declare fault direction even if V0 or V2 is close to zero. This is attractive feature for some applications, but could also cause problem if the threshold settings were not well conceived.

### *D. Directional Element Using Current Polarization*

As mentioned previously, if there is a transformer inside the station, the transformer neutral current or tertiary winding current may be used as polarizing quantity for ground fault direction. The following figure was taken from a real event. Since the tertiary winding current IG is in phase with the measured 3I0, the relay declared forward ground fault.

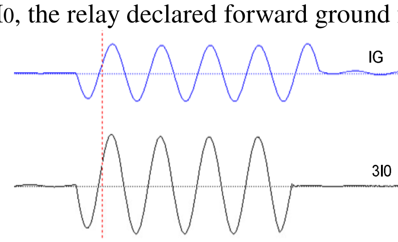



Figure III.7. The IG and 3I0 from a real event

The digital relay can compare the angle of polarizing current and measured 3I0, or use the following equation to check the sign of torque equation, i.e., a positive sign indicates forward ground fault and a negative sign indicates reverse fault.

$$Torque = \mathrm{Re}(3I_0 \cdot I_{Polarizing}{}^*) \qquad (13)$$

As reference, the polarizing current should have consistent direction for ground faults anywhere in the area. However, not every transformer can be utilized for current polarizing. In practice, only two types of transformer can be used to provide reliable polarizing current,

- The neutral current of a two winding Y/D transformer
- The tertiary winding current of autotransformer, or a Y/D/Y transformer

The neutral current of an autotransformer is not appropriate for polarizing because it may have opposite direction for ground fault at HV or LV side [1]. The current in tertiary winding of autotransformer typically flows in one direction for fault at either side of the transformer. However, depending on the system and transformer parameters, it may reverse its direction. An example system is given in Fig. III.8.

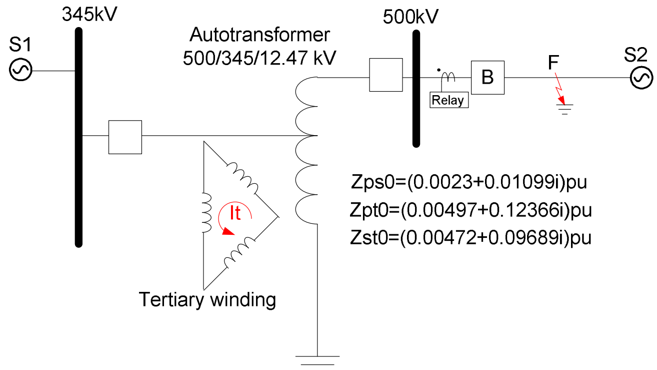



Figure III.8. An example system using autotransformer tertiary winding current as polarizing quantity

The zero sequence network of this example is plotted in Fig. III.9. Based on the given data of short circuit impedance $Z_{ps0}$, $Z_{pt0}$, $Z_{st0}$, the zero sequence impedance $Z_{p0}$, $Z_{s0}$, $Z_{t0}$ of the transformer are calculated by

$$\begin{cases} Z_{p0} = 1/2(Z_{ps0} + Z_{pt0} - Z_{st0}) = 0.019\angle 86^\circ pu \\ Z_{s0} = 1/2(Z_{ps0} + Z_{st0} - Z_{pt0}) = -0.008\angle 277^\circ pu \\ Z_{t0} = 1/2(Z_{pt0} + Z_{st0} - Z_{ps0}) = 0.105\angle 88^\circ pu \end{cases} \quad (14)$$

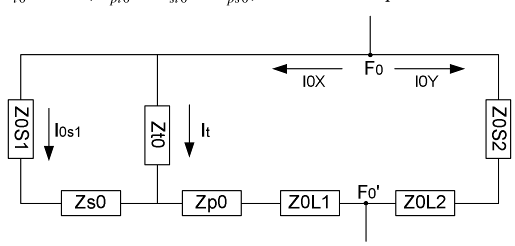



Figure III.9. The zero sequence network of example system

From Eqn. (14), $Z_{S0}$ is a negative value in this example. If the system impedance $|Z_{0S1}|$ is less than $|Z_{s0}|$, the tertiary winding current *It* will be a negative value per Eqn. (15), meaning its direction will be opposite to that is shown in the Fig. III.8 & 9.

$$It = \frac{Z0s1 + Zs0}{Z0s1 + Zs0 + Zt0} \cdot I0X \quad (15)$$

Therefore, if the system connecting to the low voltage side of the autotransformer is very strong (low system impedance), the tertiary winding current might flow in the direction that is opposite to what is expected.

After verification, the tertiary winding current can be used as polarizing quantity for line protection. The main issue associated with current polarizing method is actually the human error, because correct wiring to CT and relay inputs becomes critical. If the CT polarity was not verified, or because the two wires were swapped somehow during construction or maintenance, the current polarizing method will cause mis-operation of pilot scheme. And the error is usually not found until mis-operation happens.

For autotransformer, another issue is that current of the tertiary winding could be very high for ground faults. If the CT is not properly selected, it may be saturated by the circulating current in tertiary winding.

### E. *Directional Element Using Combined Polarization*

Categorized by polarizing quantity, the two methods for ground fault direction are: voltage polarizing and current polarizing. The former includes $V_0$ polarizing and $V_2$ polarizing. Each of these methods has its merit and weakness. Depending on the application, a combination of two or three methods may be applied.

Compared with voltage polarizing, the current polarizing method is more susceptible to human error. If the tertiary current of autotransformer is used for polarizing, the relay engineer needs to check if the situation in example of Fig III.8 may occur. In addition, the current polarizing could also be affected by zero sequence mutual coupling effect, which will be discussed later.

In digital relays, the $V_0$ and $V_2$ are calculated internally so there is less probability of human error. However, in some applications the apparent $V_0$ and $V_2$ could be too small to provide proper polarizing for ground faults.

Comparing $V_0$ polarizing and $V_2$ polarizing, the $V_0$ is susceptible to zero sequence mutual coupling effect. The $V_2$ is not so affected by mutual coupling, but in many applications the magnitude of $V_2$ at relay location is even less than $V_0$ for internal ground faults.

The relay vendors typically provide two or three polarizing methods, and let the user select or combine the polarizing method. There are a few ways to make the combination:

a) *Priority-based combination*: One of the two or three polarizing methods will be used as the primary. If the primary method failed to provide fault direction (because the polarizing quantity is too small), the result of the alternative method would be used.
b) *Dual polarizing*: Two polarizing methods will be used but none of them has priority. If the two methods do not agree with each other on fault direction, the forward ground fault will be asserted by the relay.
c) *Modified polarizing*: the vector sum of the polarizing voltage and the polarizing current are used to create a new polarizing quantity, e.g., in one relay[12], the polarizing voltage is

$$V_{pol} = -V_2 + Z_{pol} \times I_{pol}$$

where $Z_{pol}$ is the line impedance and $I_{pol}$ is taken from transformer neutral or tertiary winding.

It is hard to judge which way of combination is better because it is up to the application. E.g., assuming the dual polarizing is used, the directional element will bias towards forward fault when there is discrepancy between the two polarizing methods. This may be acceptable in some applications, but is undesirable for transmission line pilot scheme since the mis-operation would be unavoidable when human error was made to one of the polarizing methods, such as current polarizing. Actually, any type of combination might cause problem to the pilot scheme like DCB or POTT, because the combination could end up with mis-matching between local and remote terminals. As will be shown later, any types of mis-matching in DCB or POTT scheme should be avoided as they may impair the coordination and cause mis-operations.

### *F. Ground Distance Elements*

Distance relays are widely used for transmission line protection. A modern digital relay typically includes six independent fault loop measurements for phase-to-phase faults and ground faults. Using A-phase ground fault as example, the relationship between the measured phase voltage and the phase current is,

$$V_a = I_1 Z_1 + I_2 Z_2 + I_0 Z_0 = (I_1 + I_2 + I_0) Z_1 - I_0 Z_1 + I_0 Z_0$$
$$= I_a Z_1 + 3I_0 \cdot \frac{Z_0 - Z_1}{3Z_1} \cdot Z_1 = (I_a + 3I_0 k) \cdot Z_1 \qquad (17)$$

where *k* is the zero sequence compensation factor that can be derived from the line impedance. From this equation, the reach setting of ground distance zone should be a percentage of positive sequence line impedance instead of zero sequence impedance.

The distance element in a digital relay may be designed with amplitude comparators or phase angle comparators. The latter is commonly used. For example, a mho type distance relay will compare the phase angles of V and IZ-V to determine if the element should operate. If the angle between V and IZ-V is between 90º and 270º, the relay will operate. In Figure III.10, if the measured voltage is $V_m$, the distance element will pick up; if the measured voltage is $V_n$, the relay will conclude that fault is outside protection zone.

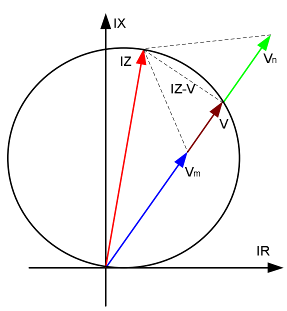



Figure III.10. The distance element using phase comparator (V and I are measured quantities; Z is the reach setting)

The "I" and "V" in Fig.III.10 are defined differently for different type of faults. For a AB fault, the phase angle comparison is between $(I_a - I_b) \cdot Z - (V_a - V_b)$ and $(V_a - V_b)$; For AG fault, the phase angle comparison is between $I_a \cdot Z + 3I_0 \cdot k \cdot Z - V_a$ and $V_a$. The stand-alone "V" for the comparator is also call polarizing voltage. It may be pre-fault phasor (memory polarization) or during-the-fault phasor (self-polarization), depending on the specific relay design.

There are other ways to implement a distance element, but all can be regarded as equivalence of impedance measurement. Among various characteristics, the mho and the quadrilateral are the mostly used. Typically, multiple zones of distance element are used to provide primary and backup protection. The ground distance element zone 1 (Z1G) setting should avoid transient over-reach. Practically, the Z1G reach can be set to 60~80% line impedance to account for instrument transformer error, relay error, and the error brought by the zero sequence compensation (*k*) factor. In Eqn. (17), the *k* factor is taken as constant, but it is actually affected by non-homogeneity of the line, variation of ground resistivity and other errors related to zero sequence impedance. The overreaching zone 2 (Z2G) or zone 3 (Z3G) can be used as building blocks of a pilot scheme or time delayed back up protection. In a pilot scheme for internal ground fault detection, the Z2G may be set at 125~150% line impedance.

The reach setting of ground distance element needs to be carefully evaluated in a complex transmission network, since the ground distance element reach may be affected by source impedance ratio, mutual coupling, cross-feeding of multi-terminal lines, series compensation, etc. Using parallel lines as example, the Z1G may over-reach when one of the parallel lines is out-of-service and grounded at both ends. To avoid over-reach, the Z1G may be set to less than 60% in some applications. Meanwhile, the Z2G may under-reach due to mutual coupling, so the Z2G under mutual coupling can be set more than 150% line impedance in order to cover the entire line. With the aid of modern short circuit software, it is easy to check the apparent impedance under different conditions to avoid under-reach or over-reach.

From the example in Fig.III.10, a distance element is inherently directional. In a modern digital relay, additional comparators or algorithms are used to ensure that relay can have correct distance reach, correct fault type identification and correct direction for the fault. For example, in one type of relay [10], the ground distance element incorporates seven comparators - it will pick up only if all the comparators satisfied the operation criteria.

| **Comparator Inputs of a ground distance element** | | **Comments** |
|---|---|---|
| IA × Z + I0 × K0 × Z − VA | VA_1M | Variable mho |
| IA × Z + I0 × K0 × Z − VA | I_0 ×Z | Reactance char. |
| I0 × 1∠DIR_RCA | V_1M | Fault direction 1 |
| I2 × 1∠DIR_RCA | V_1M | Fault direction 2 |
| I0 × 1∠DIR_RCA | −V_0 | Fault direction 3 |
| I0 | I_2 | Fault type identity |
| \|3I0\| | setting | Supervision |

Table III.1. The ground distance element of a digital relay

In another type of relay [11], the distance element is supervised by multiple conditions, including the ground directional element that is based on the combination of negative sequence impedance method, zero sequence impedance method or current polarization method.

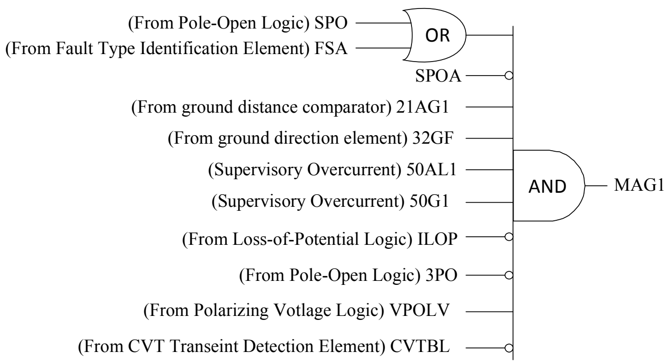



Figure III.11. The ground distance element of another relay

These two examples showcase that modern relays have comprehensive design on ground distance elements to ensure both dependability and security. Therefore, it is justifiable to use ground distance element instead of the directional overcurrent element as the main detector for ground faults in pilot schemes such as DCB or POTT. Due to the limitation of ground distance element with high impedance faults, a time-delayed directional overcurrent element can be used to supplement it in the pilot scheme.

### *G. Other Ground Fault Detection Elements*

Some line terminal has weak source behind it such that zero sequence current or negative sequence current are too small for ground fault detection. And in a non-grounded system, the zero-/negative sequence current is almost zero when ground fault occurs. The zero sequence voltage or negative sequence voltage may be the only quantity that relay can rely on to detect ground faults. A pilot scheme can use zero sequence overvoltage to detect ground fault with certain selectivity. Such scheme will be discussed later.

There are other algorithms and principles to detect ground faults, such as the current differential scheme, phase comparison scheme, traveling wave principle, etc., but they will not be covered by this paper.

## IV. THE IMPACT OF SYSTEM CONFIGURATION TO GROUND FAULT PROTECTION

For a regular 2-terminal line, the settings of ground direction element are relatively easy, even the default settings may work without problem. But for some applications, such as parallel line, series compensated line, three terminal line, tapped line, line with weak sources, etc., different settings or different polarizing methods may have different outcomes, especially for a high speed pilot scheme.

### *A. Impact of Mutual Coupling*

The zero sequence mutual coupling between the parallel lines is one of the major challenges for ground fault protection. In power network, it is common to build parallel lines on the same towers or on the same right-of-way. If a ground fault occurs on one of the parallel lines, the zero sequence voltage and current can be induced onto the other line. For directional relay using $V_0$ polarizing or current polarizing, the induced voltage or current could cause false direction judgment and mis-operation of the healthy line. This is most likely for two lines that are electrically isolated, such as the example in Figure IV.1.

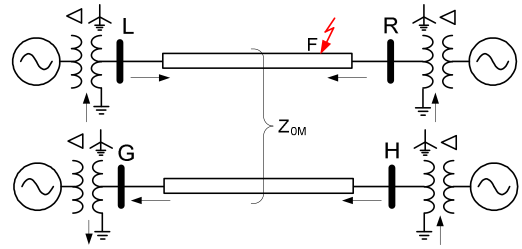



Figure IV.1. The parallel lines isolated electrically

In this example, assuming current polarizing method is used and the current from transformer neutral CT is used as polarizing quantity. When a ground fault occurs on the L-R line, $I_0$ and $V_0$ will be induced to the G-H line. The induced $I_0$ will flow in one direction along G-H line to find its path into the ground. As illustrated, the polarizing current from G station transformer neutral point will flow down towards the ground, and it is in phase with the $3I_0$ seen by line relay at G station. So the relay at G Station will take it as caused by forward ground fault. Similarly, the relay at H station will also assert forward direction. Since both relays for G-H line see fault in forward direction, when the $3I_0$ magnitude is above the pickup settings, the pilot scheme such as DCB or POTT will falsely trip the G-H line.

If the relays at G or H station use $V_0$ polarizing, the false trip may also happen due to $V_0$ inversion. The zero sequence network of the above system is shown in Figure IV.2(a). The mutual coupling effect can be represented by a 1:1 transformer.

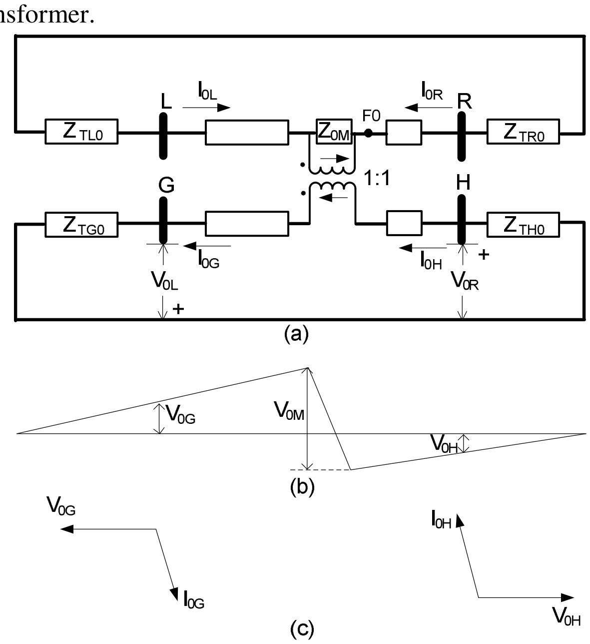



Figure IV.2. The (a) zero sequence network, (b) zero sequence voltage profile and (c) phasors at the line terminal

From the phasor relationship of the induced current and voltage, the relay at H terminal will assert forward fault, since the $I_{0H}$ flowing out of H bus lags $-V_{0H}$. The relay at G bus may also assert forward fault, because the induced $I_{0G}$ may lag $-V_{0G}$ by $\angle Z_{G0}$, even though it flows towards the G bus. This is different from the regular line fault. Assuming there is no mutual coupling, the $V_{0H}$ and $V_{0G}$ should be in phase for a typical external ground fault. But due to mutual coupling, the induced $V_0$ at a certain point on G-H line may inverse its direction, consequently the $V_{0H}$ and $V_{0G}$ will be 180º apart.

If the parallel lines are tightly coupled at both terminals, such as the example in Figure IV.3, the $V_0$ inversion generally should not happen. Because the two lines are in the same zero sequence network and the fault current flow will dominate the induced current. However, if the directional element is based on zero sequence impedance, the apparent impedance can still be affected by the induced current and could still cause problem if the threshold settings were not well selected.

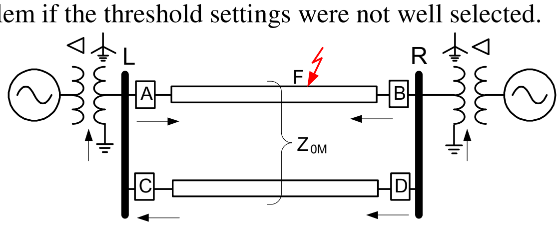



Figure IV.3. Parallel lines that are tightly coupled at both ends

The current polarizing method typically should not cause problem in configuration like that in Fig.IV.4, because the same polarizing current at each terminal would have consistent direction for internal or external ground faults.

Another problem for parallel lines is the ground distance relay over-reach and under-reach, and current reversal in pilot scheme. As the induced current is brought into the zero sequence loop, the ground distance element may under-reach for ground faults at the remote end under normal condition, and over-reach when the parallel line is under maintenance. This can be resolved by adjusting the reach of ground distance element. Depending on the mutual coupling impedance, the Z1G may have to be reduced to 50% to 65% line length to prevent over-reach, and the Z2G for pilot scheme or backup may be extended to be more than 150% line length to prevent under-reach. The current reversal problem is caused by a race condition. For example, if the CB-B in Figure IV.3 is slightly slower than the CB-A for fault clearance, the current flow at C and D will change direction instantly after CB-A is tripped. Under a race condition, both C and D terminal may see fault in forward direction. This issue however can be resolved by extending the dropout timer of reverse element in a pilot scheme.

For parallel lines that are tightly coupled at one terminal only, the mutual coupling may also cause problem. For example, if the CB-B in Figure IV.4 trips faster than breaker A, the parallel line G-R will be isolated from line L-R in zero sequence network while the fault current is still fed through CB-A. Or, if the line L-R is tripped and CB-A as lead breaker recloses onto the permanent fault, the line G-R may be falsely tripped too.

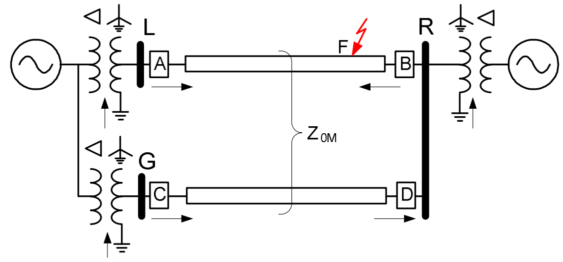



Figure IV.5. Parallel lines that are tightly coupled at one end

In a complex transmission network, the mutual coupling brings risk to ground protection, no matter the parallel lines are electrically isolated or partially isolated or not isolated at both terminals. To avoid mis-operation, it is recommended to use the $V_2$ polarizing method for fault direction. It can be based on either $V_2$ & $I_2$ angular comparison or negative sequence impedance. Because of the three-phase canceling, the impact of mutual coupling to negative sequence network is usually negligible.

## *B. Impact of Series Compensation*

The installation of series capacitors for long transmission lines can improve the power transfer capability and system stability. However the capacitors can bring significant challenge to line protection. Most line protection relays are designed to deal with the inductive network. The insertion of series capacitors may change the inductive network for line relays nearby, depending on the compensation degree and the location of the capacitors. The current differential protection would be ideal for series compensated lines. If the pilot schemes like DCB or POTT have to be applied, extensive study including real time simulations should be performed to verify relay settings. It is well known that the distance and directional overcurrent elements can be challenged by voltage inversion, current inversion, non-linearity brought by MOV, sub-synchronous resonance, etc., which are brought by series capacitor and its auxiliary equipment.

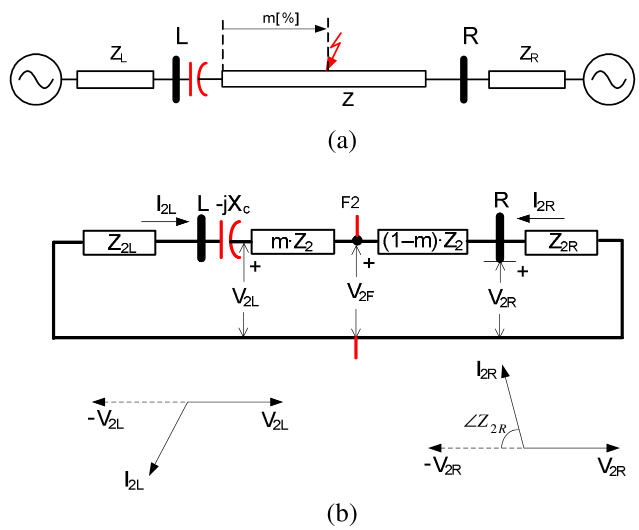


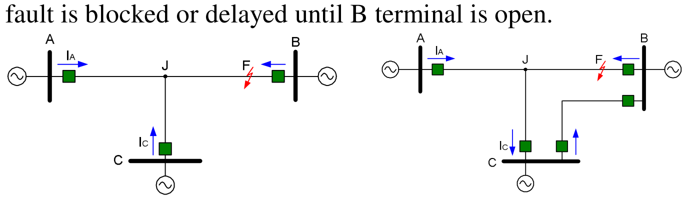

Figure IV.6. Impact of series compensation to protection

The voltage inversion is one of the major concerns for pilot scheme because it results in wrong direction and mis-operation. The voltage inversion actually means the normal angular relationship between voltage and current are shifted by the series capacitor. It may happen to phase voltages as well as sequence voltages including negative sequence voltage. For a regular line, if a forward ground fault occurs, the apparent $I_2$ should lag $-V_2$, which is the base of $V_2$ polarizing method. With the insertion of series capacitor, the $I_2$ could lead $-V_2$ for a forward ground fault, such that the relay will regard it as reverse fault. The distance element can use memory voltage to avoid voltage inversion. But most directional overcurrent relays do not use memory voltage. Some relay has special design to deal with voltage inversion, e.g., the polarizing voltage may be supplemented by measured current and pre-defined impedance [10], or the negative sequence impedance threshold may be adjusted [11] per simulation results. But cautions must be taken to let the settings account for all kinds of operational conditions. Sometimes the problem with relay settings may only be found by real time simulation tests.

### *C. Impact of multi-terminal line configuration*

Three terminal lines are not uncommon in power system. Sometimes a line may have even more than three terminals. From protection and control standpoint, multi-terminal lines should be avoided as much as possible because problems are created for protection and operation. However, the reality is that we have to deal with multi-terminal lines from time to time.

The main issues of three-terminal line protection are current infeed or outfeed, which will make the apparent impedance or apparent current different from the normal and cause coordination problem. In Figure IV.6(a), due to the infeed current from Terminal C, the apparent impedance seen by terminal A relay is more than the impedance from A to the fault location F, so the distance protection of relay A could under-reach. In Figure IV.6(b), the current may outfeed from terminal C, such that apparent impedance for relay A is less than the impedance from A to F, so the relay may overreach. If DCB scheme was applied and outfeed situation occurred, the relay at terminal C could send carrier block signal to terminal A and B, such that high speed tripping for internal fault is blocked or delayed until B terminal is open.




$$Z_{AF\_App} = \frac{I_A Z_{AJ} + (I_A + I_C) Z_{JF}}{I_A} = Z_{AF} + \frac{I_C}{I_A} Z_{JF}$$

$$Z_{AF\_App} = \frac{I_A Z_{AJ} + (I_A - I_C) Z_{JF}}{I_A} = Z_{AF} - \frac{I_C}{I_A} Z_{JF}$$

(a) (b)

Figure IV.7. Three-terminal line and fault (a) with current infeed; (b) with current outfeed.

Because of infeed current, the overreaching element in a pilot scheme has to be set very far to ensure the coverage for all internal faults. A very long reach may reduce the security of the scheme under contingency that the third terminal is out of service. For a DCB scheme, the distance under-reach might be acceptable if sequential tripping is acceptable. But for a POTT scheme, since the scheme trip has to be permitted by all the terminals, the distance reach setting cannot be compromised.

For ground directional element using negative sequence impedance or zero sequence impedance, the relay setter should pay attention to the “AUTO” setting that use half the line impedance as the threshold. The impedance thresholds for all the terminals should be calculated carefully [14]. To make it simpler, the thresholds may be based on half the shortest line section, or just be close to zero [3], in order to ensure the sensitivity for reverse ground faults.

The directional overcurrent coordination in a pilot scheme may also have problem with 3-terminal lines. The general practice such as using $3I_0$ as operating quantity and using $V_2$ & $I_2$ for fault direction, or using the 1:2 coordination factor (the reverse overcurrent pickup setting is half the remote forward overcurrent pickup setting) are good for most 2-terminal lines. But as shown in a mis-operation case later, due to the infeed $3I_0$ of the third terminal, such general practice may cause problem for a 3-terminal line.

In the end, the carrier equipment may need adjustment for a 3-terminal line. The DCB scheme would use simple ON/OFF AM transceiver with the same signal frequency at each terminal. When two terminals start the carrier simultaneously, the carrier signal may cancel each other such that the third terminal does not receive the block signal. To avoid frequency cancellation, it is good practice to shift the frequency slightly for each terminal.

## V. THE PILOT SCHEME FOR GROUND FAULT PROTECTION

In a pilot scheme, the relays at local and remote line terminals use communication channel to exchange data, which helps the relays to discriminate internal or external faults with high speed. This section will briefly present two prevailing pilot schemes that use power line carrier channel(s).

### *A. The DCB Scheme*

A PLC-based DCB scheme is composed of relays, the transmission line and PLC equipment. The communication channel includes the line itself, wave trap, CCVT, transmitter, receiver, etc. In a typical DCB scheme, each relay includes phase distance elements (21P) to detect phase-to-phase faults, ground directional overcurrent elements (67N) and/or ground distance elements (21G) for ground faults. And there should be a pair for each protection type: a forward-looking element to detect faults in front of the relay, and a reverse-looking element to detect faults behind the relay. The scheme elements and logic are illustrated in Figure V.1 & 2. The forward element will actuate high speed trip if no block signal is received. Once fault is detected behind the relay, the reverse element will key carrier signal to remote terminal to prevent the remote relay from tripping. An important rule of pilot scheme is to have matching elements and to coordinate their settings at each terminal.

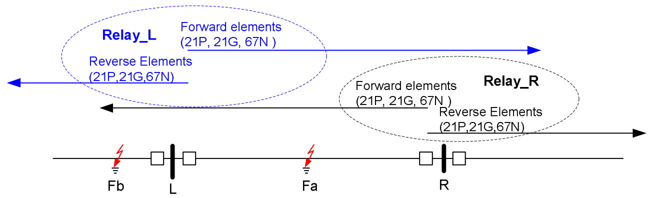



Figure V.1. Protection Elements in a DCB Scheme

To clarify how these elements coordinate in a DCB scheme, let us use a ground fault at point “Fa” in Fig. V.1 as example. At fault inception, the forward 21G or forward 67N elements at both L and R terminals should pick up instantly and assert signals “$FP_L$” and “$FP_R$”. Without local or remote block signal, the breakers at both terminals can be tripped with high speed.

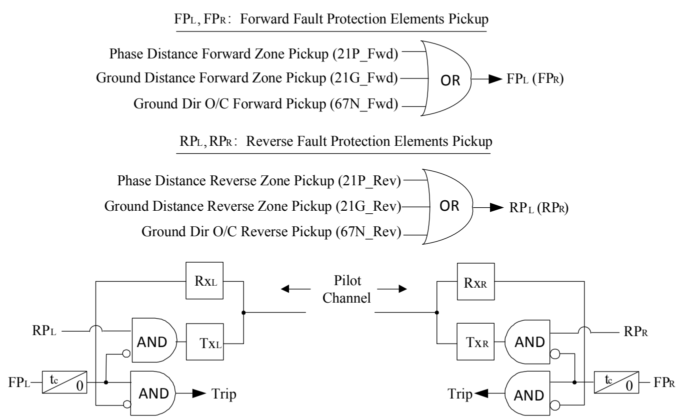



Figure V.2. Simplified DCB Logic

If a fault is external to the line, such as the ground fault at point “Fb” in Fig. V.1, the reverse 67N or reverse 21G element at L terminal should pick up. Meanwhile, the forward 67N or forward 21G element at R terminal may also pick up. The relay and carrier transmitter at L terminal will immediately key the carrier signal to R terminal. The coordination timer (tc) is needed to account for small delay that may be caused by relay or PLC channel. The typical setting of the timer is 1.0~1.5 cycles.

In order to cover all internal faults, the DCB scheme requires that forward elements must reach beyond the protected line with good margins. However, the forward elements must not reach beyond the reverse elements of the remote terminal. Compared to the distance elements, the 67N elements do not have a well-defined boundary on protection zone. For a 2-terminal line, the 1:2 coordination factor may be generally used for overcurrent coordination, i.e., the local reverse 67N pickup is set half the remote forward 67N pickup value.

In some applications, the source behind the line terminal could be so weak that Z2P, Z2G or 67N elements may not pick up for internal faults. Under such condition, it is still expected that DCB scheme can trip all the terminals to isolate the line, otherwise, the fault arc may sustain and the high speed reclosing may fail. The Figure V.3 & 4 shows the supplemental logic for the weak terminal and strong terminal respectively. At the weak terminal, the phase-to-phase undervoltage (27P) element and/or the zero sequence overvoltage (59N) element can be used to supplement fault detection. Correspondingly, the strong terminal must have matching 27P and/or 59N elements to start the blocking signal. For internal faults, the 27P or 59N of strong terminal may pick up and send carrier signal as well when fault occurs, but the carrier signal will be cut off immediately after the forward elements pick up. In a DCB scheme, the forward tripping elements should always have higher priority to stop the carrier keying. Such logic appears to work nicely but the weak feed option should be used only when it is necessary, because the strong terminal and weak terminal has different logic, which is undesirable for a DCB scheme. And, attention must be paid to coordinate the non-directional 59N and 27P elements. If the strong terminal sees different level of $V_2$ or $V_0$ from that of weak terminal, which is not uncommon in a complex network, mis-operation may occur.

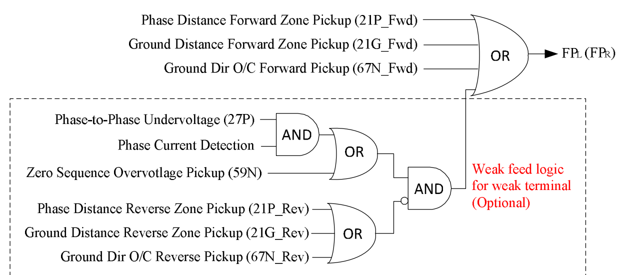



Figure V.3. Week feed logic at the weak terminal

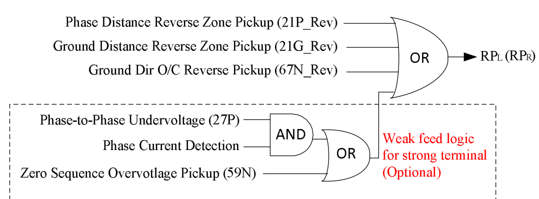



Figure V.4. Week feed logic at the strong terminal

In many applications, the 21G element is auxiliary in the DCB scheme because of its limitation for high impedance ground faults. As mentioned previously, the 21G element of modern digital relay is more secure than 67N elements with regards to fault direction, and it has well-defined reach for ground faults. Therefore, we may consider using 21G as the primary ground fault detector in a DCB scheme.

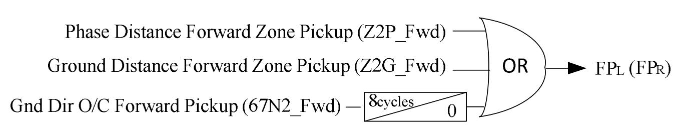



Figure V.5. DCB Scheme with 8-cycle delay for 67N element

In above figure, the 67N is still used but a time delay is added onto it. Since high impedance ground faults have less impact to system stability, it is justifiable to put 67N in a supplemental role. The 67N will actuate the DCB trip only if

21G cannot see the fault. With 8~10 cycles delay, it is expected that external ground fault should be cleared within this time frame such that DCB mis-operations caused by 67N can be significantly reduced.

Some utilities may also use non-directional overcurrent element (50G) to start the carrier signal in DCB scheme. Since the forward elements have priority, the keying caused by 50G can be stopped immediately if the fault is internal. The carrier start by non-directional 50G element may help on security side of the DCB scheme when the scheme is composed of EM relays or some old digital relays. For a modern digital relays, the difference between 67N and 50G elements with regards to speed or sensitivity is negligible, so the directional start should be used to have dependable trips for internal faults.

### B. The POTT Scheme

Similar to DCB, the POTT scheme also uses 21P, 21G and 67N elements of local relay to determine the fault direction. If all the line terminal relays detect fault in forward direction, they will key permissive signal to each other. The POTT will trip only if the permissive signal from remote end is received. A simplified POTT scheme is illustrated in Figure V.6.

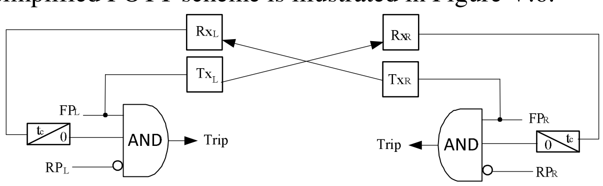



Figure V.6. Simplified POTT Logic

If PLC is used as communication channel, the POTT scheme typically uses frequency-shifting type of transceiver. During normal operation, the transmitter at one terminal will send continuous guard signal with central frequency. To transmit the permissive signal, the carrier signal will shift its frequency.

If one of the line terminals is open, it is expected that POTT can still work for line energization or for tapped load. So many POTT schemes incorporate ECHO logic that will key back the received signal to the remote end if the local breaker is open or no fault is detected behind the relay. The latter condition is adopted in many digital relays because it also helps with weak feed condition.

If there is a weak source behind the relay, the ECHO logic can only help to trip the strong terminal. The voltage elements can be added at the weak terminal for fault detection. Similar to weak feed DCB scheme, the 27P element and 59N may be used as supplemental fault detector at the weak terminal. Because of POTT trip has to be permitted by the strong terminal fault detector, the weak feed option of POTT is less dangerous than that in DCB scheme. But again, the weak feed option should be used only when it is necessary.

### C. Cause of Mis-operation of Pilot Scheme

In general, the DCB scheme is biased towards dependability because the scheme will trip if the block signal from the remote end is not received. The POTT is slightly biased towards security since the scheme is not supposed to trip without permissive signal from remote end. However, with ECHO logic, the dependability of POTT is enhanced but the security is reduced. An UNBLOCK scheme is very similar to POTT, except that the scheme will allow trip during a small time window if the channel failure is detected.

From time to time, mis-operation of pilot scheme occurs. In most cases, it was the security side that was breached. i.e., the pilot scheme falsely tripped for out-of-zone fault. The root cause of mis-operations may be categorized as relaying error, pilot channel problem, or human error.

Compared with relaying error especially the application problems, the probability of relay hardware failure, channel failure or human error is relatively low. Experience shows that many pilot scheme mis-operations were associated with ground faults and 67N elements. In comparison, few mis-operations were directly caused by the distance elements (21P/21G).

If one relay in the scheme asserted wrong direction, mis-operation will occur, not matter it is DCB or POTT. The 67N element may be fooled by a number of issues, e.g., the wiring for current polarizing was incorrect, the zero sequence voltage inversion due to mutual coupling, the negative sequence current was too small, the error with coordination of three-terminal line relays, etc. A few events that happened in real system will be discussed in the following section.

## VI. Mis-operation Events and Analysis

Since the transmission lines are exposed to all kinds of environments, the line protection systems are put to test from time to time. This section presents a few DCB mis-operation events and the analysis.

### A. DCB Scheme Using Two Types of Directional Elements

*Event Description:* A persistent ground fault occurred in the middle of one of the parallel lines between **T** and **D** stations. The faulty line was correctly tripped by pilot scheme after fault inception. But after the high speed auto-reclosing, not only the faulty line was tripped, the **D** terminal of the healthy line was also tripped. The parallel line and the system equivalence are shown in Fig.VI.1. The color of magenta represents mis-operation in this section.

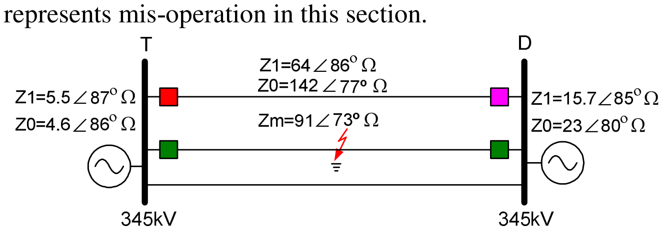



Figure VI.1. The equivalent system one-line diagram of a DCB scheme mis-operation event

The event records of relays for the mis-operated line are given in Figure VI.2 & 3.

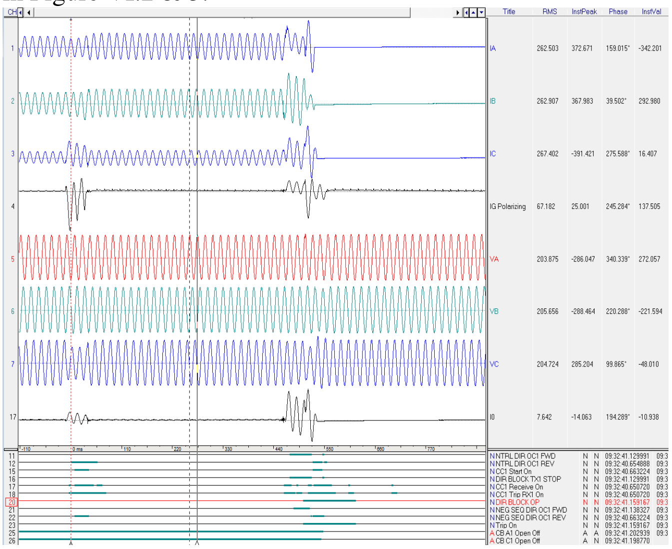


Figure VI.2. The event records of **D**-terminal

From the records, there were two disturbances because of the persistent ground fault on the adjacent line and the auto-reclosing. At fault inception, both relays asserted correct directions, i.e., the **D** relay determined it was reverse fault and the **T** relay saw it as forward fault, such that DCB scheme did not operate. After the adjacent line breakers made high speed reclosing, both relays of the healthy line declared forward ground faults. However, only **D** relay mis-operated. So there were two questions: 1. Why would both terminals of the healthy line declare forward fault directions? 2. Why was there only one terminal mis-operated?

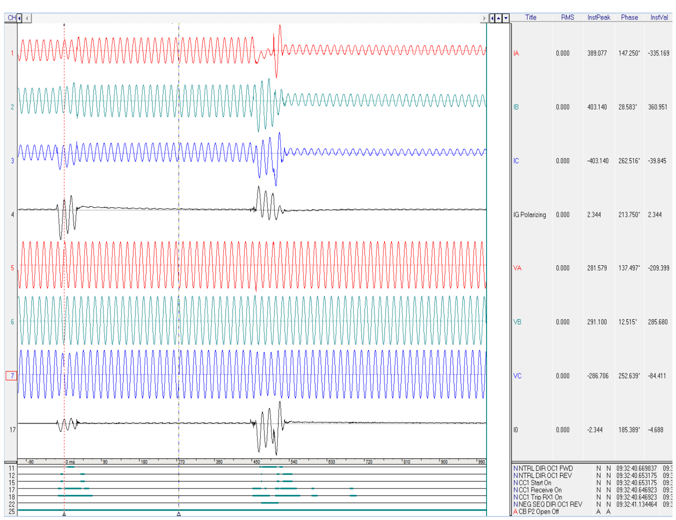


Figure VI.3. The event records of **T**-terminal

*Scheme & Relay Settings:* The DCB scheme was applied as primary protection for each of these 345kV lines. The relevant relay settings are shown in Fig.VI.4. The digital relays used both negative sequence directional overcurrent elements (67Q) and neutral directional overcurrent elements (67N) to determine ground fault direction. With different polarizing methods for fault direction, both 67Q and 67N elements use $3I_0$ as operating quantity. The reason of using both 67Q and 67N is due to the limited range of 67Q reverse pickup setting in that particular type of relay.

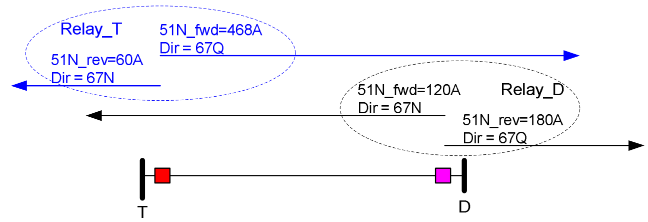



Figure VI.4. The relevant relay settings for the event

*Fault Analysis:* The **D** relay mis-operated because the 67N reverse element of **T** relay did not pick up to key the carrier block signal. From the record, the 67N element of **T** relay asserted forward direction. The phasors of **T** terminal at the moment before mis-operation are shown in Figure VI.5.

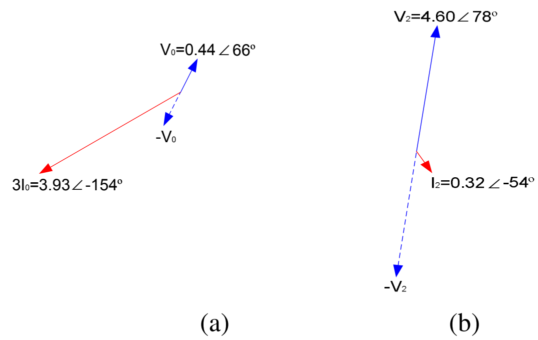



Figure VI.5. The phasors seen by **T** terminal relay at the moment before mis-operation: (a) $V_0$ and $3I_0$; (b) $V_2$ and $I_2$

From the Fig.VI.5(a), the $3I_0$ was lagging $-V_0$ by $40^o$, which explain why the 67N would give forward direction. It can be regarded as the zero sequence voltage inversion caused by mutual coupling. If 67Q was used, it would declare reverse direction per Fig.VI.5(b), which was also confirmed by the event record. This also explains why the **T** terminal did not trip, because the DCB tripping at **T** terminal is up to 67Q element, while the carrier start is up to 67N.

*Solution:* The case shows that even the parallel line terminals are tightly coupled in zero sequence network, the usage of 67N in a DCB scheme is still risky. The $V_2$ polarizing is more reliable for parallel lines. It was not a good idea to mix different directional elements (using different polarizing) in a DCB scheme. The solution was that only 67Q element was used for the DCB, i.e., the 67Q-forward and 67Q-reverse were coordinated at both terminals for either fault direction. The sensitivity of DCB scheme was compromised due to the relay. Since the minimum setting of 67Q-reverse pickup (3I0) of **T** relay is 180A for that relay, the 67Q-forward pickup(3I0) setting has to be raised to above 270A for the **D** relay. The overall reliability is not so affected though, since the sensitivity can be supplemented by another time delayed overcurrent element. After all, the system can tolerate a high impedance ground fault for a longer delay. The relay vendor was aware of the issue and has changed their relay setting range in the newer version of firmware.

### *B. DCB Scheme Using a Combination of Polarizing Methods*

*Event Description:* A three-terminal 345kV line **S-C-R** is shown in Figure VI.6. The **S** station is the terminal of a large industrial customer. On 04/11/2011, when a ground fault occurred in the 138kV system behind **R** terminal, the **S** terminal mis-operated by DCB scheme.

*Scheme & Relay Settings:* The DCB scheme including weak feed logic was deployed to protect the 3-terminal 345kV line. The same type of relay was used at each terminal to coordinate on ground fault protection in DCB scheme. The relevant relay settings are also shown in Figure VI.6.

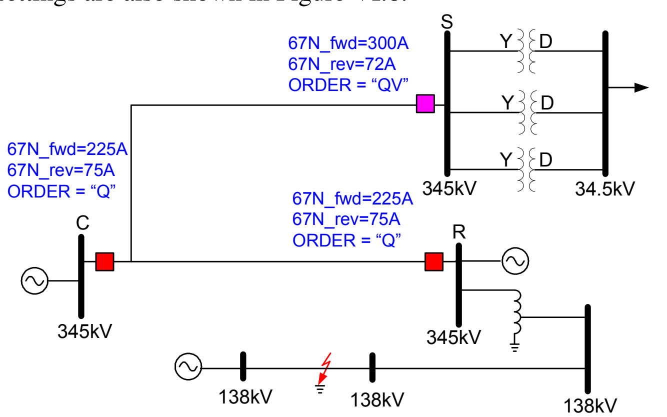


Figure VI.6. The equivalent system one-line diagram of a DCB mis-operation event

The sequence impedance methods were used by the relay to determine ground fault direction. This type of relay has an "ORDER" setting to combine and prioritize three polarizing methods: the negative sequence impedance (Q) method, the zero sequence impedance (V) method, and current polarizing method (I). For this setting, the relay at **C** and **R** terminal were set with "Q", while the relay at **S** terminal was set with "QV", meaning if the "Q" method does not give fault direction, the result of "V" method will be used instead.

*Fault Analysis:*

The event record of **S** terminal is shown in Figure VI.7. The DCB operated because the **S** relay saw sufficient $3I_0$ and its directional element asserted "forward" direction. But there was no blocking signal received from either **C** or **R** terminal, which is verified by the corresponding event records. The apparent $3I_0$ at **C** and **R** terminal was actually high enough, but the relays did not declare fault direction to start the carrier. With a closer look of event records at **S** terminal, the "Q" method did not give fault direction either. It was because there was no generating source behind the **S** terminal. Since the **S** relay had ORDER setting of "QV", the "V" method is used instead. Because the Y/D transformers behind the terminal facilitate a return path for the $I_0$ in the zero sequence network, the $I_0$ and $V_0$ at **S** terminal were high enough to declare forward fault direction. Without blocking signal, the DCB scheme at **S** terminal assumed internal fault and mis-operated.

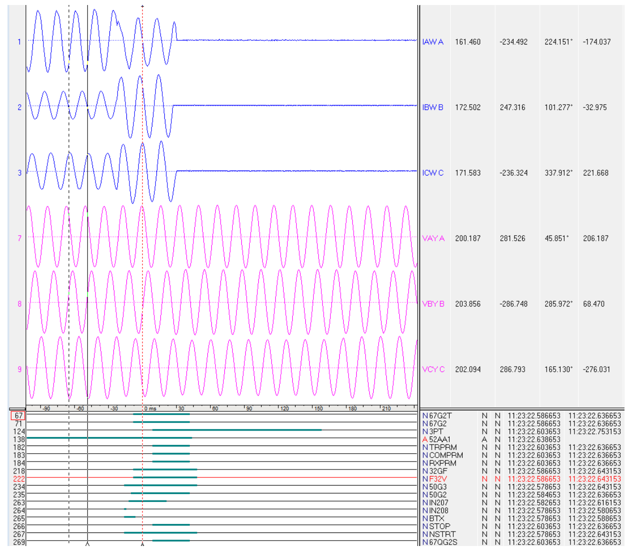


Figure VI.7. The event records of **S**-terminal

*Solution:* The event demonstrated again it was important to match the protection elements in a DCB scheme. The relay setter used "QV" for **S** terminal because he realized that "Q" method may not work, and the "V" method can supplement for internal ground faults. However, such mis-match still caused mis-operation. The solution is to use "Q" method only for all three terminals. For internal phase-phase faults, the tripping of **S** terminals will be relying on the weak feed logic. Even though there is no generating source behind **S** terminal, it is still desirable to trip it with high speed for internal fault, such that the fault can be isolated and the probability of successful auto-reclosing is increased.

### *C. Directional Element with Combination of Polarizing Methods and "AUTO" Settings*

*Event Description:* On 06/24/2013, the **T-M** 345kV line operated for a ground fault on the **D-S** 345kV line, which is in parallel with the **T-M** line. The mis-operation was caused by the DCB scheme: both terminal relays of the **T-M** line saw the ground fault in forward direction and therefore determined it was an internal fault.

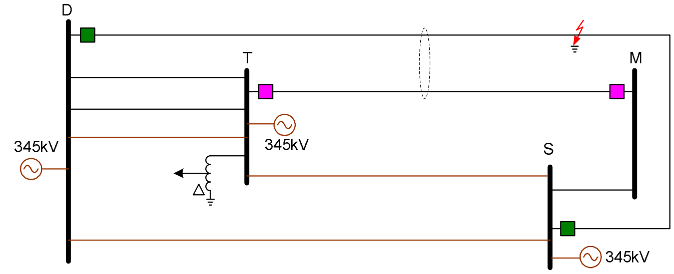


Figure VI.8. The equivalent system one-line diagram of a DCB mis-operation event

*Scheme & Relay Settings:* Dual DCB schemes were applied for this 345kV line. The mis-operated relays used impedance based directional element for ground fault direction. The relevant relay settings are shown in Table 1.

| Relevant Relay Settings | M-Terminal | T-Terminal |
|---|---|---|
| Line Pos. Seq. Impedance (LZ1) | 6.2 ∠84.9º | 6.2 ∠84.9º |
| Line Zero. Seq. Impedance (LZ0) | 14.57∠78.5º | 14.57∠78.5º |
| PT Ratio | 3000 | 3000 |
| CT Ratio | 400 | 400 |
| DCB Trip for Forward Fault (50G2P) | 1.0 A | 1.5 A |
| DCB Block for Reverse Fault (50G3P) | 0.25 A | 0.25 A |
| ORDER | QV | QIV |
| Dir. Element Threshold - 50FP | 0.6 A | 1.0 A |
| Dir. Element Threshold – 50RP | 0.25 A | 0.25 A |
| Dir. Element Threshold – Z0F | 7.29 Ω | 7.29 Ω |
| Dir. Element Threshold – Z0R | 7.39 Ω | 7.39 Ω |

Table 1. The relevant settings of **T** and **M** terminal relays

*Fault Analysis:*
The event record of **T** and **M** relays are shown in Figure VI.9. and VI.10.

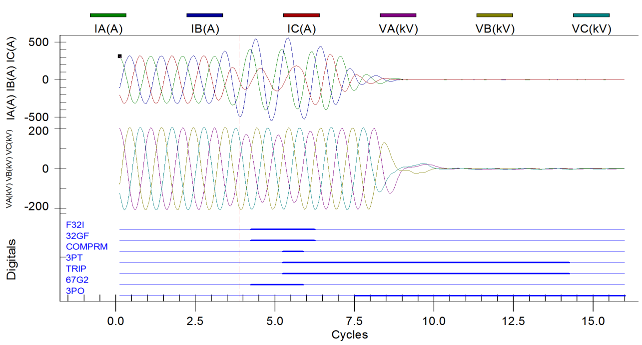


Figure VI.9. **T**-terminal Event Record

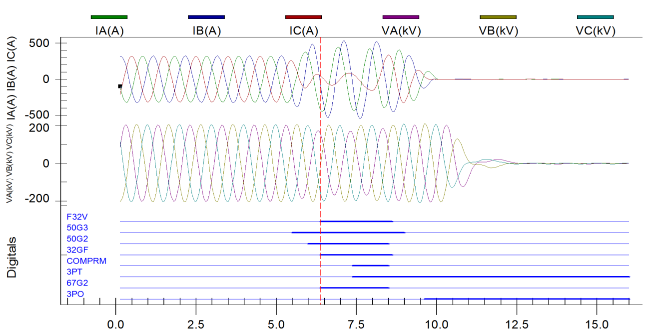


Figure VI.10. **M**-terminal Event Record

From both records, the apparent I2 was so low that "Q" method was skipped by both the **T** relay and **M** relay. The **T** relay asserted "F32I" (forward direction from "I" method). and the **M** relay asserted "F32V" " (forward direction from "V" method) for the external ground fault on the parallel line. According to the actual fault location, the **M** relay was giving the wrong direction.

The relevant phasors of **M** relay at the moment of 7.0-cycle in the event record are listed in the following table.

| Seq. Component | Primary Value | Secondary Value |
|---|---|---|
| V2 | 13800 ∠180.9º V | 4.6 ∠180.9º V |
| I2 | 20.7 ∠230.3º A | 0.052 ∠230.3º A |
| V0 | 6600 ∠190.4º V | 2.2 ∠190.4º V |
| IG (3I0) | 848.6 ∠97.5º A | 2.12 ∠97.5º A |

Table 2. The phasors from event record of **M** terminal relay

Using the equations in [12], the Z0, Z0FTH and Z0RTH are calculated as follow:

$$Z0 = \frac{\mathrm{Re}\left[3V_0 \cdot \left(I_G \cdot 1\angle LZ_0\right)^*\right]}{\left|I_G\right|^2} = 3.01$$

$$Z0FTH = \begin{cases} 0.75 \cdot Z_{0F} - 0.25 \cdot \left|3V_0 / I_G\right| & If\left(Z_{0F} \le 0\right) \\ 1.25 \cdot Z_{0F} - 0.25 \cdot \left|3V_0 / I_G\right| & If\left(Z_{0F} > 0\right) \end{cases} = 8.33$$

$$Z0RTH = \begin{cases} 0.75 \cdot Z_{0R} + 0.25 \cdot \left|3V_0 / I_G\right| & If\left(Z_{0R} \ge 0\right) \\ 1.25 \cdot Z_{0R} + 0.25 \cdot \left|3V_0 / I_G\right| & If\left(Z_{0R} < 0\right) \end{cases} = 6.32$$

Since Z0 < Z0FTH, it verifies that the forward fault direction from **M** relay was given per relay settings and design.

The mis-operation was attributed to mutual coupling effect. However, was it due to zero sequence voltage inversion? From the following plot per Table 2, the voltage inversion actually did not occur. The 3I0 was leading –V0 by 87.1°, a signature for reverse ground fault. And, the record of the redundant relay for **T-M** line also confirms that voltage inversion did not happen.

This case tells us that the zero sequence impedance based directional element may be more susceptible to mutual coupling effect when the "V" method is in use and the "AUTO" settings are applied, because no matter the V0 inversion happens or not, the apparent Z0 will be shifted by the induced voltage and current.

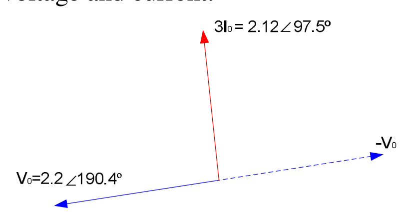


Figure VI.11. The V0 and 3I0 of M-terminal relay

*Solution:* First of all, the mis-match of "ORDER" setting should be avoided in a DCB scheme. And, the "V" method should be avoided as much as possible for mutually coupled lines. If the "V" method has to be applied in some cases, the relay setter needs to be careful with the "AUTO" settings that are based on half line impedance value. In this case, if the Z0F and Z0R were set close to 0, which is the theoretical boundary between forward and reverse direction for a ground fault, the mis-operation could have been avoided. In the end, the "Q" only settings were applied for both terminals since the study shows there will be sufficient V2 and I2 for internal faults.

*D. Application of Weak Feed DCB Scheme*

Nowadays, more and more wind farms are built and connected to the transmission systems. Because wind brings variable energy and the fault current contribution from wind generator is low, a wind farm is typically treated as weak source from line protection standpoint. With this concept in mind, some relay setter tends to apply weak feed pilot schemes for all the lines adjacent to the wind farm. In one case, the weak feed DCB scheme was applied to 69kV **M-P** line that is adjacent to the wind farm interconnection, as illustrated in Fig. VI.12. The argument of weak feed option was that wind farm would be the only source behind the CB1 under the single contingency that **M-S** line was out of service.

In 2008, the CB1 of **M-P** line mis-operated by DCB scheme. The fault was an external ground fault and it turned out that 59N element of the weak feed DCB scheme falsely tripped. From that event, the relay setter realized that $3I_0$ was actually high enough because the wind farm collector transformer has a Y/D/Y configuration. So the 59N elements were removed from the DCB scheme. But the 27P was still kept for DCB.

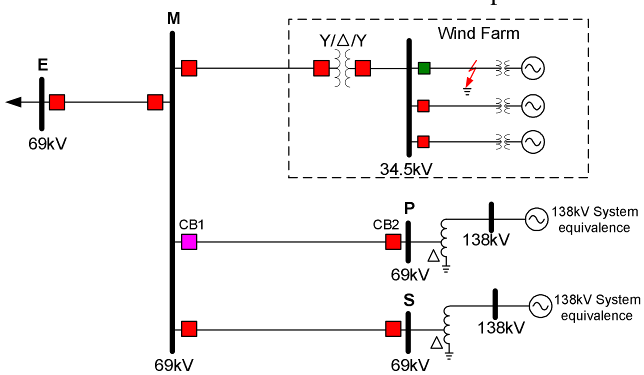



Figure VI.12. A Weak feed DCB Mis-operation Event

In 2013, a phase-to-phase faults in the wind farm feeder caused the CB1 to mis-operate again. And it was due to the 27P in DCB scheme. The reverse-looking phase distance zone (Z4P) at **P** terminal actually picked up and reset, showing the fault was just out of boundary of Z4P element.

These events tell us that the risk should be evaluated carefully before applying voltage elements in a pilot scheme, because the 59N and 27P have no directionality. The coordination of voltage settings between local and remote terminals needs extensive study. Actually, the weak feed option of DCB should be avoided unless it is absolutely necessary. For a line that is directly associated with the weak source, the weak feed option may have to be used but it is also up to the type of the weak source. In this case, the wind farm interconnection line is protected by dual 87L schemes, which are immune to weak feed problem. The **M-P** line and **M-S** line are indirectly associated with the wind farm, is weak feed option necessary for the DCB scheme of these lines? Assuming weak feed option was not used, when **M-S** line is out of service and there is an internal fault on the **M-P** line. The relay for CB1 may not be able to see the fault such that only CB2 at **P** terminal can be tripped by DCB. However, the wind generators will trip their breakers anyway since they cannot ride through the extended under-voltage condition. The fault can still be isolated but just slightly slower under such contingency. The only thing to avoid is the high speed reclosing of CB2 under such condition. The high speed reclosing may be disabled under contingency or slow auto-reclosing could be applied instead. Some transfer tripping scheme may also be considered. The conclusion is that the weak feed option is not absolutely necessary for **M-P** and **M-S** 69kV lines in this case and the solution was just to remove the week feed option in the DCB scheme.

### *E. Three-terminal DCB Scheme*

*Event Description:* A three-terminal 138kV line **S-B-T** is shown in Figure VI.6. Due to surge arrester failure, there was a ground fault at the tap station on the **S-K** line. The CB at **B** terminal was falsely tripped by DCB scheme.

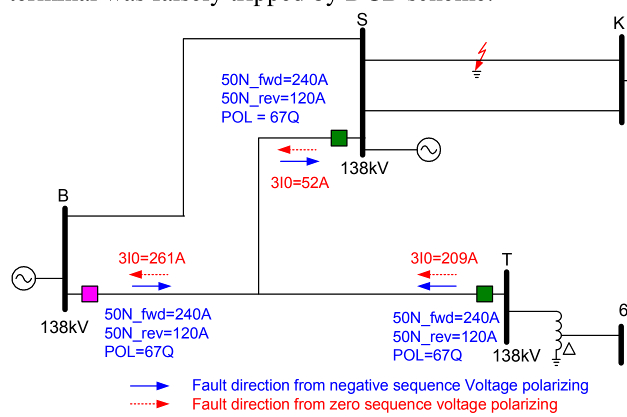



Figure VI.13. A 3-terminal Line DCB Scheme Mis-operation

*Scheme & Relay Settings:* The negative sequence element (67Q) was used at each terminal for ground fault direction in DCB. The ground overcurrent (50N) elements are used at each terminal to coordinate on $3I_0$ pickup settings, which are given in Figure VI.13. The coordination between local and remote relays has the typical 1:2 coordination. E.g., the reverse 50N pickup setting is 120A at local terminal, and the forward 50N pickup setting is 240A at the remote terminal.

*Fault Analysis:* In this case, there was no generating source behind the **T** terminal, so there was negligible $I_2$ out of **T** terminal for the fault. But there is autotransformer behind **T** terminal, a "grounding source" that elicited significant amount of $3I_0$ towards the external fault. The difference between $I_2$ and $I_0$ was the main reason of this mis-operation. The **B** terminal relay mis-operated because the **S** relay did not start carrier for the fault behind it. Since the 67Q element was used at each terminal, there was no DCB mis-match problem or problem caused by mutual coupling (even though the line was in parallel with another line). The event records proved that fault direction at each terminal can coordinate with remote terminals. However, it was also noted that the fault direction out of $V_2$ polarizing method would be different from $V_0$ polarizing method at **B** and **S** terminals. Using either polarizing for this external fault, the direction coordination would not cause trouble, as illustrated in Fig. VI.13. However, the 67Q element of the relay would use $V_2$ & $I_2$ to determine fault direction, and the magnitude of $3I_0$ is used as operating quantity. Since the **S** relay saw only 52A of $3I_0$, lower than the pickup setting of the reverse 50N, it did not send output to start carrier. Meanwhile, the **B** relay saw 261A of $3I_0$, and the fault direction was forward per $V_2$ polarizing, which allowed the DCB to trip. This case shows that for a 3-terminal line, the relay setter has to be very careful with the coordination, which is required not only among the local and remote terminals, but also tied to the polarizing method and the operating quantity. The regular rule of thumb may not work for a 3-terminal line. To resolve the problem in this case, either the $V_0$ polarizing should be used in junction with $3I_0$ as operating quantity, or the $I_2$ should be used as operating quantity in junction with $V_2$ polarizing. Alternatively, the 1:2 coordination factor for $3I_0$ coordination should be changed.

By using commercial short circuit software, the cause of mis-coordination was verified. However, for this application, it would be hard to find such mis-coordination in the beginning unless the external fault was simulated at right location, which is located far from the protected line.

*Solution:* Since the protected line is in parallel with another line, the $V_2$ polarizing was still preferred. And, since it is a standard practice to use $3I_0$ as operating quantity, the relay setter decided to change the overcurrent($3I_0$) pickup settings to achieve the coordination. From the event and the simulations, the forward element of **B** relay can see 5 times more $3I_0$ than the **S** relay. So a higher coordination factor was needed. In the end, the **T** relay forward 50N pickup setting was changed to 420A and the S relay reverse 50N setting was changed to 60A. The lesson from this event is that protection engineer must be careful with 3-terminal lines. In addition to the known problems of distance element coordination, the directional overcurrent coordination in a DCB scheme may also be an issue and it is harder to find the problem with it. Extensive coordination study is needed for proper settings. Of course, the best solution would be avoiding three-terminal configuration at the planning stage.

## VII. Summary and Recommendations

This paper has reviewed the basics of ground fault protection elements and their applications in traditional carrier-based pilot schemes. There are various methods for a stand-alone relay to determine ground fault direction. However, the ground directional elements of most digital relays are based on either one of three methods: $V_0$ polarizing, $V_2$ polarizing or current polarizing. The first two are looking at the phase angle between $I_{0(2)}$ and $V_{0(2)}$, or the value of impedance $Z_{0(2)}$. The signature of forward ground fault is that $I_{0(2)}$ lags $-V_{0(2)}$ by 60º~90º, the signature of reverse ground fault is that $I_{0(2)}$ leads $-V_{0(2)}$ by 90º~120º. The zero/negative impedance-based methods are based on the same characteristics, with the difference that the angular relationship of $I_{0(2)}$ and $V_{0(2)}$ is transformed to +/- signs of the impedance value. In addition, the impedance thresholds can be used to adjust the sensitivity and the bias towards reverse or forward ground faults.

The traditional carrier-based pilot schemes such as DCB or POTT are relying on each relay to assert correct fault direction. The utility operating experience shows that the coordination of ground directional overcurrent is the weakest link with regards to relay settings in those pilot schemes. From some mis-operation events, the following are recommended for relay setters:

- The DCB or POTT scheme should match the local and remote terminals on tripping and blocking elements, especially on directional ground overcurrent elements. Not only the same type of relay should be applied at each terminal, the same polarizing method should also be used. Some relays provide the option to combine different polarizing methods. Caution needs to be taken on such combination because it may end up with mis-matching of the pilot scheme.

- Since the $V_2$ polarizing method is not susceptible to the mutual coupling effect, it should be used for parallel lines. And the $V_0$ polarizing should be avoided for parallel lines. If the apparent $V_2$ or $I_2$ are too small to provide reliable polarizing, other polarizing method may be considered but careful fault study needs to be performed.

- The current polarizing method can be useful when the apparent $V_2$ or $V_0$ are low, especially for relays that compares the phase angle for fault direction. However, caution must be taken to apply current polarizing. First, not all the transformer natural current or tertiary winding current can be used to provide reliable polarizing; Second, the wiring from proper CT polarity to relay inputs needs to be verified all the way through.

- If zero sequence impedance method has to be used for parallel lines, the "AUTO" settings that are based on half line impedance should be avoided. Actually, it is recommended to do some calculations on directional element threshold settings for sanity check whenever "AUTO" settings are applied. Note the "AUTO" settings are biased towards forward fault direction. The threshold settings closer to zero may be considered in some pilot schemes to balance forward and reverse ground fault direction.

- Be careful with weak feed option of pilot schemes. Try to avoid weak feed options of a pilot scheme unless they are necessary, because there is risk and difficulty to coordinate the voltage elements used as fault detector in the weak feed scheme. If the weak feed option has to be used, careful study has to be performed.

- Series compensation can bring significant challenge to the traditional protection elements. If PLC-based pilot schemes have to be used, the real time digital simulation tests should be performed to fine tune the directional element settings as well as other settings.

• For 3-terminal lines, the relay setters should be cautious with not only the coordination of the distance elements, but also the coordination of ground directional overcurrent elements in a pilot scheme. The general scheme or coordination factor may encounter problems in a 3-temrinal line configuration. Extensive fault studies are needed to identify the problem. If possible, the 3-terminal line configuration should be avoided at planning stage.

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