Evaluation of Distance and Directional Relay Elements on Lines With Power Transformers or Open-Delta VTs

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I. Introduction

Many utilities apply line protection using alternate input sources, for example, CTs and VTs from the low-voltage side of a transformer bank or two VTs instead of three. This is most often driven by economics—reducing costs of a project without compromising the protection. In addition, some system configurations (e.g., tapped transformers) can change the performance of the line protection.

This paper discusses the performance of popular distance and directional elements for several system configurations. In particular, it addresses the application of distance and directional relays for line protection when instrument transformer inputs (CTs and VTs) are located on the low side of a power transformer or on opposite sides of the transformer bank. We also evaluate the elements with changes in source locations.

We must consider the principles of operation for the relays under study. In this paper, we evaluate two types of phase distance elements:

1. Phase distance elements using phase-pairs (AB, BC, and CA) and positive-sequence voltage memory polarization.
2. Compensator Distance Element principle.

For phase fault protection using directional overcurrent elements, we evaluate the performance of elements that apply:

1. Negative-sequence impedance directional element when there is enough negative-sequence current available to operate (phase-phase, phase-phase-ground, and phase-ground faults).
2. Use of positive-sequence directional element for three-phase faults to supervise directional overcurrent element pickup.

II. Description of Elements and Test System to Be Evaluated

The theory of operation for the elements to be evaluated can be found in [1] and [2]. Reference [1] provides the background for the Compensator Distance Element principle. The Compensator Distance Element principle has a three-phase and a phase-phase element. The mathematical model used to evaluate its performance for phase-phase and phase-phase-ground faults is expressed in Equations 1, 2, and 3. The Compensator Distance Element torque is the imaginary part of the product between Phasor A and the complex conjugate of Phasor B (complex conjugate is indicated by an asterisk (*) above the expression).

$$T := \mathrm{Im}\left[A \bullet (B)^{*}\right] \tag{1}$$

$$\begin{aligned} A &:= Vab - Z1R \bullet Iab \\ B &:= Vbc - Z1R \bullet Ibc \end{aligned} \tag{2}$$

Vab and Vbc are measured line voltages, Iab and Ibc are measured currents, and $Z1R$ is the reach setting, where $Z1 \bullet ang$ is the line impedance of the protected line at its angle of maximum torque. The value of r indicates the per-unit reach needed to operate the element:

$$Z1R := r \bullet Z1 \bullet ang \tag{3}$$

Equation 4 shows the phase-pair positive-sequence voltage memory polarized mho element for the B-C phase-phase element (repeated for A-B and C-A) [2].

$$MBC := \frac{\mathrm{Re}\left[(Vbc) \bullet (VB1 - VC1)^{*}\right]}{\mathrm{Re}\left[Z1 \bullet (Ibc) \bullet (VB1 - VC1)^{*}\right]} \tag{4}$$

The value of MBC indicates the per-unit reach that would be required to operate the element for given system fault quantities (Vbc, Ibc). Z1 is the positive-sequence impedance of the protected line and $VB1$ and $VC1$ are “healthy” pre-fault positive-sequence voltages referenced to B-phase and C-phase, respectively.

Also in [2] is the description of the negative-sequence impedance directional element. Equation 5 shows the expression used for evaluation. $V2$ and $I2$ are the negative-sequence voltage and current calculated from the measured phase voltages and currents. $Z2L$ is the negative-sequence impedance angle of the line, typically set equal to the positive-sequence line impedance angle. Element $Z2$, when negative, indicates a forward fault for all fault types except three-phase faults.

$$Z2 := \frac{\mathrm{Re}\left(V2 \bullet \left[I2 \bullet (\cos(Z2L) + j \bullet \sin(Z2L))\right]^{*}\right)}{(|I2|)^{2}} \tag{5}$$

Finally, if Z2 does not assert, the phase directional element uses a positive-sequence element to determine direction. Specifically, this element allows us to determine direction for three-phase faults. $V1$ and $I1$ are positive-sequence voltage and current calculated from the measured phase voltage and current. $Z1$ is the positive-sequence line impedance setting. Equation 6 shows a simplified expression (actual implementations include memory voltage polarized quantities). In Equation 6, T32P, when positive, indicates a forward fault.

$$T32P := |3V1| \bullet |3I1| \bullet \cos\left[\arg(V1) - (\arg(I1) + \arg(Z1))\right] \quad (6)$$

The test system chosen for evaluation is a 34.5 kV and 138 kV system connected by a transformer. Different line and transformer impedances, transformer connections, and load and remote sources were added to simulate different system conditions.

III. Application of Distance Relays Protecting a High-Voltage Line Using CT and VT Inputs From a Medium-Voltage System

A. High-Side Delta, Low-Side Grounded-Wye Transformer Bank

On applications where CTs and VTs are not available from the high-side system, some utilities apply distance relays using CT and VT inputs from the low-side system. Fig. 1 shows an example system for evaluation. In this example, the relay is applied to protect a 138 kV line using inputs from the 34.5 kV system. The transformer bank is connected delta-grounded-wye, with the low-side grounded-wye.

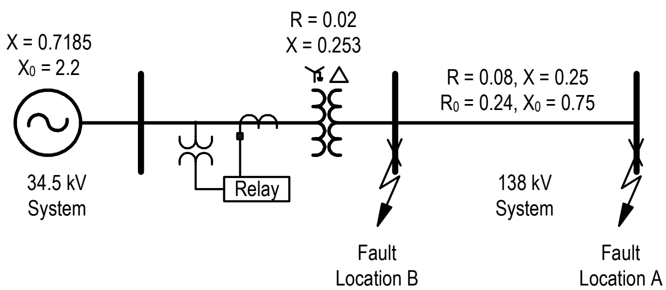

Fig. 1. 138 kV Delta, 34.5 kV Grounded-Wye System Diagram

We simulated faults at the transformer high side and also at the remote bus using a short circuit study. From the short circuit study, we used a mathematical model of the relay elements to determine the measured reach of each element under test. We did not simulate phase-ground faults because no zero-sequence current flows through the delta-grounded-wye transformer connection.

TABLE 1
REQUIRED REACH OF PHASE-PAIR AND COMPENSATOR DISTANCE ELEMENTS TO DETECT FAULTS ON 138 KV SYSTEM THROUGH HIGH-SIDE DELTA WYE-GROUNDED TRANSFORMER BANK

Fault Type	Fault Location	MAB	MBC	MCA	*r*
B-C	B, High-Side XFMR	*	1.97	2.76	1.01
B-C-G	"	*	1.97	2.76	1.01
3LG	"	1.01	1.01	1.01	1.01
B-C	A, Remote Bus	*	3.29	3.97	1.99
B-C-G	"	*	3.29	3.97	1.99
3LG	"	1.99	1.99	1.99	2

In Table 1, MAB, MBC, and MCA are the respective reaches required for the phase-phase mho elements to operate. The required reach for the Compensator Distance Element is *r*. For simplicity, we initially modeled the transformer and line impedance at approximately the same magnitudes.

The reaches (MAB, MBC, MCA, and *r*) in Tables 1–5B are shown in per unit of the line impedance. Thus, a fault should yield a measured impedance of 1 per unit at the transformer high side and of 2 per unit at the remote bus.

Table 1 shows the phase-pair elements (MAB, MBC, and MCA) reach correctly only for the three-phase fault. The Compensator Distance Element, *r*, provides an accurate reach for all fault types.

For phase-phase and phase-phase-ground faults, the phase pair elements measure impedance much higher for faults on the opposite side of the transformer. This is expected because the measuring principle is phase dependent, and the phase-shift through the transformer would directly affect the input quantities. For this example, the reach would have to be set about 1.97 times the line impedance to detect all phase-phase and phase-phase-ground faults on the high side of the transformer.

B. High-Side Grounded-Wye, Low-Side Delta Transformer Connection

Next, we simulated the same faults for a transformer bank with a low-side delta connection as shown in Fig. 2 with similar results. Table 2 shows the calculated reaches.

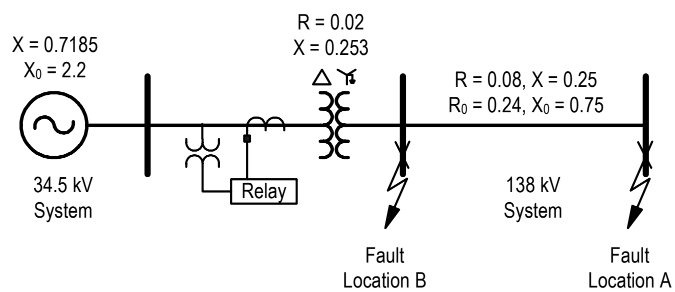

Fig. 2. 138 kV Grounded-Wye, 34.5 kV Delta System Diagram

TABLE 2
REQUIRED REACH OF PHASE-PAIR AND COMPENSATOR DISTANCE ELEMENTS TO DETECT FAULTS ON 138 KV SYSTEM THROUGH HIGH-SIDE DELTA-GROUNDED-WYE TRANSFORMER BANK

Fault Type	Fault Location	MAB	MBC	MCA	*r*
B-C	B, High-Side XFMR	*	1.97	2.76	1.01
B-C-G	"	2.99	1.29	1.47	1.04
3LG	"	1.01	1.01	1.01	1.01
B-C	A, Remote Bus	*	3.29	3.97	1.99
B-C-G	"	9.99	2.66	3.15	1.99
3LG	"	1.99	1.99	1.99	2

C. High-Side Delta, Low-Side Grounded-Wye, With Ztransformer >> Zline

In order to validate the results, the transformer impedance (Z_{TR}) was increased to about ten times the line impedance (Z_{LINE}). For this case, we would expect the reach to be about 10.9 per unit for Fault Location A.

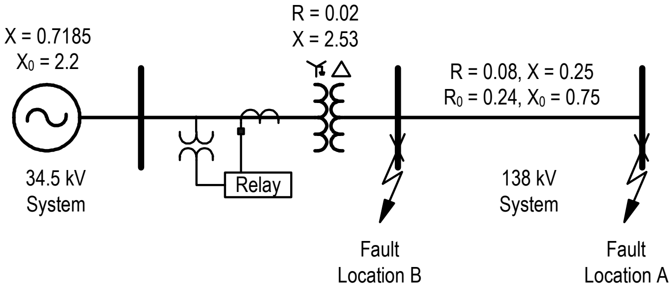

Fig. 3. 138 kV Delta, 34.5 kV Grounded-Wye System Diagram

TABLE 3
REQUIRED REACH OF PHASE-PAIR AND COMPENSATOR DISTANCE ELEMENTS TO DETECT FAULTS ON 138 KV SYSTEM THROUGH HIGH-SIDE DELTA-GROUNDED-WYE TRANSFORMER BANK (WITH ZTR ~ 10 • ZLINE)

Fault Type	Fault Location	MAB	MBC	MCA	r
B-C	A, Remote Bus	–2.76E+03	13.86	17.79	10.92
B-C-G	"	–2.76E+03	13.86	17.79	10.92
3LG	"	10.91	10.91	10.91	10.91

Table 3 shows that the Compensator Distance Element, *r*, correctly measures the fault impedance for all fault types. Similar results were found for the high-side grounded-wye-delta transformer bank.

D. High-Side Delta, Low-Side Grounded-Wye, With 138 kV Source and Load Flow Added

Another important consideration is the effect of load on the performance of the distance elements. For this example, we added a source at the remote 138 kV bus and a significant load angle (30-degree, not including phase shift through the transformer) to simulate a heavy load flow, as shown in Fig. 4. Table 4 shows the distance element reach data.

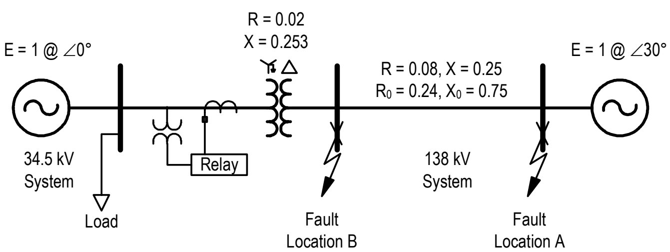

Fig. 4. Source Added, Heavy Load Flow Into 34.5 kV System

TABLE 4
REQUIRED REACH OF DISTANCE ELEMENTS TO DETECT FAULTS ON 138 KV SYSTEM THROUGH HIGH-SIDE DELTA-GROUNDED-WYE TRANSFORMER BANK WITH HEAVY LOAD AND REMOTE SOURCES ADDED

Fault Type	Fault Location	MAB	MBC	MCA	*r*
B-C	B, High-Side XFMR	–27.6	2.18	2.41	1.04
B-C-G	"	–72.7	2.09	2.25	1.05
3LG	"	1.02	1.02	1.02	1.03
B-C	A, Remote Bus	–28.1	3.99	3.53	2.07
B-C-G	"	–64.08	3.74	3.36	2.06
3LG	"	2.03	2.03	2.03	2.03

The Compensator Distance Element underreaches slightly due to the heavy load into the 34 kV system. If load were reversed (into the 138 kV system), Compensator Distance would overreach slightly.

IV. APPLICATION OF DISTANCE RELAYS WITH LOW-SIDE VT, HIGH-SIDE CT CONNECTIONS

A. High-Side Delta, Low-Side Grounded-Wye Transformer Bank

Sometimes distance relays are used to protect lines, but only the currents are available from the high-voltage line; the voltage inputs must be taken from the medium-voltage system. Fig. 5A shows such a system.

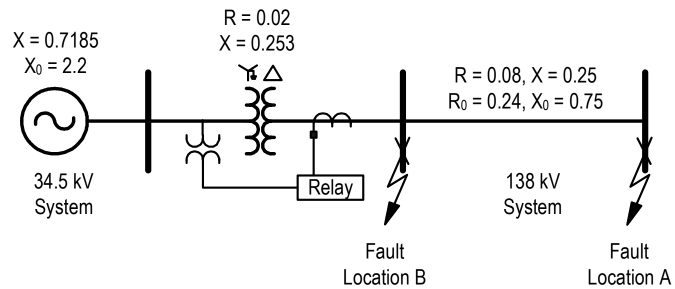

Fig. 5A. 138 kV Delta, 34.5 kV Grounded-Wye System Diagram With 138 kV CTs, 34.5 kV VTs

The obvious complication of this connection is the currents and voltages are out of phase by 30 degrees, such that the voltages applied to the relay experience a voltage drop through the transformer. Table 5A shows the distance element performance for this system.

The values in parentheses show the reach calculated with the VT connections in delta-wye to simulate the transformer. That is, if the transformer connection is high-side delta-grounded-wye, we connect the VTs on the low side as grounded-wye-delta to "undo" the effect of the transformer.

TABLE 5A
PERFORMANCE OF DISTANCE ELEMENTS WITH 34.5 KV VT CONNECTION

Fault Type	Fault Location	MAB	MBC	MCA	*r*
B-C	B, High-Side XFMR	25.70	1.71 (0.84)	4.77	1.12 (1.02)
A-G	"	*	*	*	
B-C-G	"	25.70	1.71 (0.84)	4.77	1.12 (1.02)
3LG	"	0.99	0.99	0.99	1
B-C	A, Remote Bus	42.29	2.84 (1.87)	6.87	2.24 (2.00)
A-G	"	*	*	*	
B-C-G		42.29	2.84 (1.87)	6.87	2.24 (2.00)
3LG		2.03	2.03	2.03	2.04

The Compensator Distance Element displays about a 10% error if no correction is performed on the VT connections. When the VT connections are modified to delta-wye to simulate the transformer connection, the Compensator Distance Element performs with precision.

The performance of the phase-pair element is very erratic and should be tested or modeled if used on this type of system.

B. High-Side Grounded-Wye, Low-Side Delta Transformer Connection

The high-side grounded-wye, low-side delta transformer connection produces similar results as the high-side delta in the previous example, as shown in Fig. 5B and Table 5B.

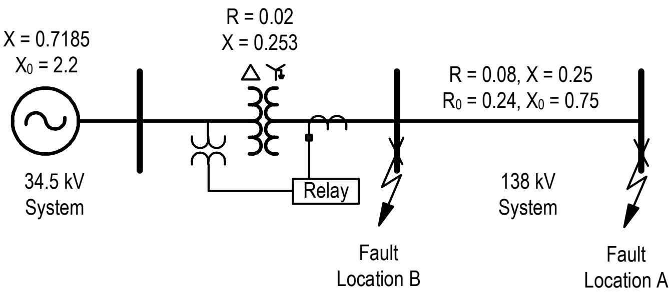

Fig. 5B. 138 kV Grounded-Wye, 34.5 kV Delta System Diagram With 138 kV CTs, 34.5 kV VTs

TABLE 5B
PERFORMANCE OF DISTANCE ELEMENTS WITH LOW-SIDE VT CONNECTION

Fault Type	Fault Location	MAB	MBC	MCA	*r*
B-C	B, High-Side XFMR	25.70	1.71 (0.84)	4.77	1.12 (1.02)
A-G	“	1.74	*	4.35	1.64
B-C-G	“	2.75	1.23	1.62	1.13
3LG	“	0.99	0.99	0.99	1.00
B-C	A, Remote Bus	42.29	2.84 (1.87)	6.87	2.24 (2.00)
A-G	“	4.56	*	11.02	4.44
B-C-G	“	7.75	2.50	4.79	3.08
3LG	“	2.03	2.03	2.03	2.04

V. APPLICATION OF PHASE OVERCURRENT RELAYS

In the following figures and tables, the performance of phase directional elements is analyzed.

Some traditional relay designs use a 60- or 90-degree connection between polarizing and operating quantities to determine current direction. Other designs use the mho “torque” quantities discussed earlier in this paper.

In this section, we analyze a design that uses the following criteria:

1. If enough negative-sequence current flows (above a pickup threshold), a negative-sequence impedance directional element (Z2) is used to determine direction. This ensures the element operates for phase-phase and phase-phase-ground faults. If the measured quantity of Z2 is less than zero, a forward fault is declared. If Z2 is greater than zero, a reverse fault is declared.
2. If the magnitude of negative-sequence current is too low, a positive-sequence impedance directional element (T32P) takes precedence. This element uses a memory voltage in case of a bolted close-in three-phase fault. This element is always active but only operates if the negative-sequence element does not operate.

For this analysis, we simulated three fault types: phase-phase, phase-phase-ground and three-phase. Tables 6, 7, and 8 display two values: Z2, in per unit, for phase-phase faults and T32P for three-phase faults. Fig. 6 shows a system with CTs and VTs on the 138 kV-side of the transformer bank. Table 6 shows that directional elements perform well for all fault locations and fault types.

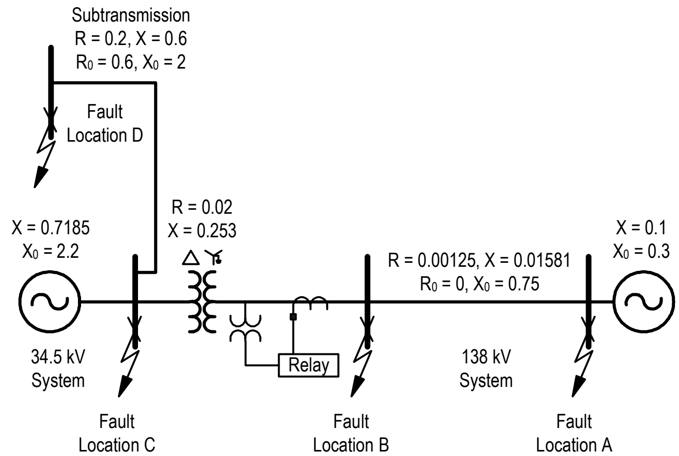

Fig. 6. One-Line Diagram of Phase-Directional Relay With VTs and CTs From 138 kV-Side of Transformer

TABLE 6
TORQUE QUANTITIES MEASURED FOR NEGATIVE- AND POSITIVE-SEQUENCE DIRECTIONAL ELEMENTS

Fault Location	Z2 (per unit) Negative Value Indicates Forward	T32P, Three-Phase Fault Positive Value Indicates Forward
A, Remote Bus	–0.97	0.15
B, High-Side XFMR	–0.97	+ value
C, Low-Side XFMR	0.12	–16.73
D, Subtransmission	0.12	–6.41

Figure 7 and Table 7 show the system diagram and directional element performance, respectively, for systems in which the CTs and VTs are located at the low-voltage (34.5 kV) side of the transformer. The directional elements perform well for all fault types and locations.

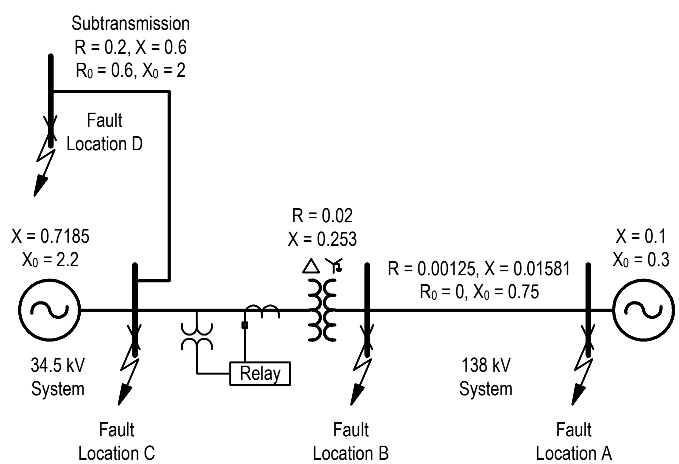

Fig. 7. One-Line Diagram of Phase-Directional Relay With VTs and CTs From 34.5 kV-Side of Transformer

TABLE 7
TORQUE QUANTITIES MEASURED FOR NEGATIVE- AND POSITIVE-SEQUENCE DIRECTIONAL ELEMENTS

Fault Location	Z2 (per unit) Negative Value Indicates Forward	T32P, Three-Phase Fault Positive Value Indicates Forward
A, Remote Bus	–0.72	2.49
B, High-Side XFMR	–0.72	2.42
C, Low-Side XFMR	0.28	– value
D, Subtransmission	0.37	–4.88

Fig. 8 shows an interesting case with VTs and CTs on the opposite side of the transformer bank. The location of the CT determines current direction. Thus, for the system shown in Fig. 8, for a fault in the transformer, the directional elements would declare a reverse fault.

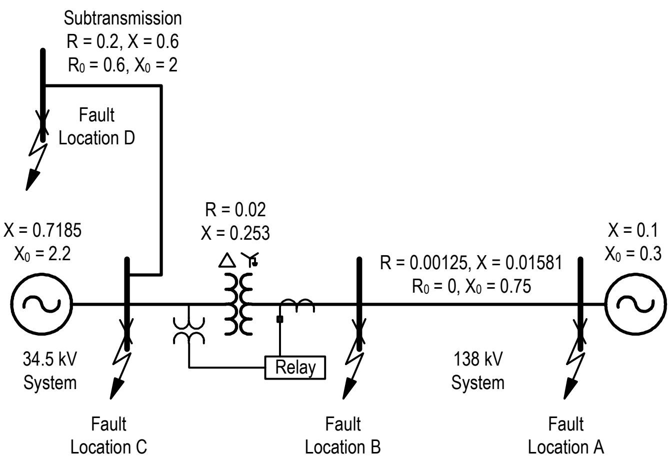

Fig. 8. One-Line Diagram of Phase-Directional Relay With VTs From 34.5 kV-Side and CTs From 138 kV-Side of Transformer

TABLE 8
TORQUE QUANTITIES MEASURED FOR NEGATIVE- AND POSITIVE-SEQUENCE DIRECTIONAL ELEMENTS

Fault Location	Z2 (per unit) Negative Value Indicates Forward	T32P, Three-Phase Fault Positive Value Indicates Forward
A, Remote Bus	–0.60	2.17
B, High-Side XFMR	–0.60	2.01
C, Low-Side XFMR	0.32	– value
D, Subtransmission	0.32	–5.14

Although all of the results are shown in per unit, most relay thresholds for Z2 are set in ohms. Thus, the VT and CT ratio must be used to determine the pickup threshold, or set Z2 pickup values at or near zero.

VI. IMPLICATIONS OF DELTA-CONNECTED VTS FOR DISTANCE AND DIRECTIONAL PERFORMANCE

For economic reasons, some users apply three-phase, three-wire (open delta-connected) VTs. Generally, it is recommended to apply three-phase, four-wire (wye-connected) VTs for all distance relay applications. Wye-connected VTs have several advantages over delta-connected VTs:

1. Fault location can be calculated for ground faults without source data.
2. Fault analysis can be performed on all fault types.
3. Zero-sequence voltages can be calculated from phase-ground voltages and applied for ground fault protection and monitoring.
4. Individual phase voltage and power metering quantities are available for testing, commissioning, and operating.

Still, for many applications, it is acceptable to use delta-connected VTs with no loss of protection, as long as none of the above conditions prohibit their use.

A. Phase Distance Applications

The original Compensator Distance Element designs used phase-phase voltage connections and phase currents. Thus, the Compensator Distance Elements can easily withstand phase shifts in phase-ground quantities as long as the phase-phase quantities are correct. Compensator Distance is a superior choice to accommodate the delta-connected VTs and can be applied even if the relay design calls for phase-ground VT connections. This is true of traditional designs and new designs.

Phase-pair elements handle phase-phase and three-phase faults with no problem.

However, on phase-phase-ground faults with fault resistance, the fault selection logic in some relay designs may be affected by phase shifts in the phase-ground voltage quantities. Thus, phase-pair could theoretically select the wrong fault type when using delta VTs and thus operate incorrectly or not operate as desired. In general, using delta VTs with phase-pair designs is not recommended.

B. Phase Directional Overcurrent

Phase directional overcurrent elements can use several different approaches to discern direction. Some use phase distance elements or a 60- or 90-degree connection between measured quantities (discussed in the previous section).

One design uses both negative- and positive-sequence elements as discussed in the previous section. This method selects the negative-sequence directional element if it asserts; otherwise, it selects the positive-sequence element.

These designs usually can be applied with delta VTs. It is best to select relays that are specifically designed to handle delta VTs by model or setting change.

C. Ground Directional

Most modern ground directional relays have negative-sequence directional elements that can be applied for reliable and secure ground fault protection.

Many relays accommodate delta VTs. It is always best to select relays that are specifically designed to handle delta VTs, either by setting or model number.

VII. Application of Phase and Ground Distance Relays on Autotransformer Banks

Both phase-pair and Compensator Distance Elements reach correctly through an autotransformer with a delta tertiary for phase faults, as shown in Fig. 9. This assumes no source at the delta tertiary.

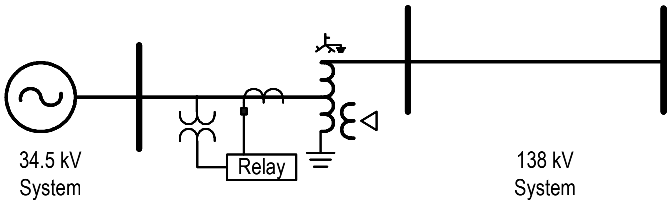

Fig. 9: Autotransformer System Diagram

Ground distance relays can also be applied, but an apparent-impedance calculation is recommended to determine reach due to the zero-sequence source at the autotransformer. Simulate faults at the remote fault location desired and calculate the apparent impedance using Equation 7 [4]:

$$Z_{APP} = \frac{V_\phi}{I_\phi + k_0 \bullet I_r} \tag{7}$$

where:

V_ϕ = faulted phase voltage measured by the relay

I_ϕ = faulted phase current measured by the relay

I_r = ground current measured by the relay

k_0 = ground distance element zero-sequence compensation factor

VIII. Impact of Load Tap Changers on Distance Element Reach

Load Tap Changers (LTCs) raise or lower the voltage on the high or low side of the transformer. This effectively changes the base voltage.

For example, if the tap is reduced on the low-voltage winding by 10%, the base impedance is reduced by approximately 20%, thus a distance relay could overreach by about 20%. Conversely, if the low voltage tap is increased by 10%, the distance relay could underreach by 20%.

IX. Other Considerations

Occasionally on older delta systems, only two CTs and two VTs are available. It is always preferred to have three CTs and VTs for complete protection, metering, and fault analysis. However, Fig. 10 shows a connection that at least one utility has used.

Although this connection is not generally recommended, a relay can detect three-phase and phase-phase faults that are typical of those found on delta systems. The positive- and negative-sequence directional elements can accommodate open-delta VTs.

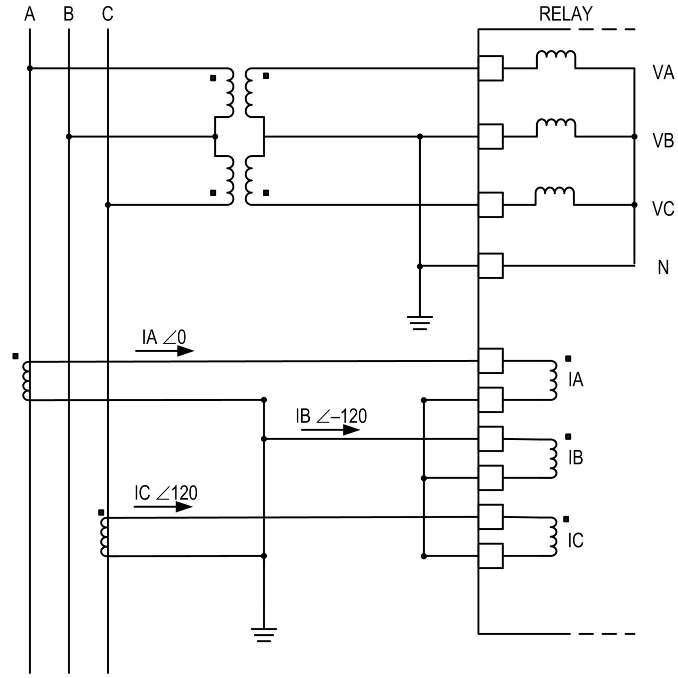

Fig. 10: Two-VT, Two-CT Connection

X. Conclusions

1. Phase distance relays are commonly applied on the low-voltage side of a transformer to protect higher voltage lines.
2. The Compensator Distance Element Principle is a superior design for accurately applying distance relays through transformers. It is unaffected by common delta-wye transformer connections and basically measures positive-sequence impedance.
3. Phase-pair distance relay designs can be applied, but relay reaches must be analyzed when reaching through transformer banks.
4. Compensator Distance Elements can be affected by load, causing the relay to over- or underreach.
5. Compensator Distance Elements perform reasonably well even when CTs and VTs are applied from opposite sides of the transformer bank. A 30-degree phase shift results in modest error and must be analyzed; however, the reach is only off by 10 to 15 percent for most systems.
6. Negative-sequence impedance directional elements provide stable performance looking through transformer banks for all unbalanced fault types.
7. Both phase-pair distance elements and positive-sequence memory voltage polarized directional elements provide stable directional performance looking through transformer banks.
8. Delta-connected VTs can be successfully applied for phase- and ground-fault detection using negative-sequence directional elements.
9. Delta-connected VTs can be used for phase distance protection but lose the benefits of fault location and event analysis for ground faults.

XI. References

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XII. Biographies

Karl Zimmerman is a Senior Application Engineer with Schweitzer Engineering Laboratories in Belleville, Illinois. His work includes providing application support and technical training for protective relay users.

He is an active member of the IEEE Power System Relaying Committee and is the Chairman of the Working Group on Arc-Flash Protection.

Karl received his BSEE degree at the University of Illinois at Urbana-Champaign and has over 20 years of experience in the area of system protection. He is a past speaker at many technical conferences and has authored over 20 papers and application guides on protective relaying.

Dan Roth served as an Associate Field Application Engineer for Schweitzer Engineering Laboratories in New Berlin, WI. His work included authoring several application guides and providing other technical support to customers. He graduated from the University of Illinois at Urbana-Champaign with a BSEE in 2003. Dan is also an IEEE member.

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